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Pareto-Optimal Resource Allocation in Decentralized Wireless Powered Networks

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***Abstract*—One of the main challenges in wireless powered networks (WPNs) is the doubly near-far problem, i.e., the twofold degradation of the users' performance due to different path-loss values that affects both the energy harvesting and the information transmission efficiency. To this end, we propose and optimize the application of decentralized power transfer and radio access in WPNs, which is implemented by using multiple remote radio heads (RRHs) with the capability to both transfer energy and receive information. More specifically, the use of non-orthogonal multiple access (NOMA) and time division multiple access (TDMA) is investigated, while two novel schemes are proposed, hereinafter termed as partially and fully *asynchronous transmission TDMA* (AT-TDMA). According to the proposed schemes, the users harvest energy and transmit information to the RRHs in different portions of time. Furthermore, the sum and minimum throughput among users are jointly maximized by obtaining the Pareto optimal solutions for the scheduling of power transfer and information transmission. To evaluate the performance of the decentralized architecture compared to the centralized one, we solve the aforementioned optimization problem for both architectures, taking also into account the circuit power consumption. Simulations show that the use of multiple RRHs improves spectral efficiency compared to the centralized implementation, since it can tackle more efficiently the doubly near-far problem. In addition, the proposed AT-TDMA schemes increase the achievable data rate.**

***Index Terms*—Decentralized WPNs, Pareto-optimal, asynchronous transmission, NOMA**

I. Introduction

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THE explosive growth of the number of connected devices is giving rise to Internet-of-Things (IoT) applications, as reported in [1]. Thus, with such a vast amount of operating devices, the limited lifetime of batteries is a crucial issue, which can significantly affect the quality-of-service in wireless networks. By recharging and replacing the batteries, their operational time can be extended, although this process can be costly or even infeasible (e.g., human body implanted sensors). An alternative solution to prolong devices' lifetime is energy harvesting (EH), e.g., by using radio frequency (RF) signals [2]–[5]. A technique, which leverages the EH operation, is the simultaneous wireless information and power transfer (SWIPT) [6]–[9], where information and energy are simultaneously transmitted. Furthermore, the received energy could be also used for communication purposes, i.e., to enable devices to transmit data to the base station (BS), which is the main principle of wireless powered networks (WPNs). In such networks, the users can adopt the *harvest-then-transmit* protocol, where in the first phase the BS transfers energy to the devices, while in the second phase, the harvested energy is used for information transmission [8], [10].

A. Motivation

The *doubly near-far* phenomenon is present in WPNs and can lead to the deterioration of user's achievable data rate [10]. More specifically, a far-user from the BS, receives less amount of wireless energy compared to a near-user, but also has to transmit with more power in the uplink transmission for reliable communication. To this end, a policy for ensuring fairness among users is imperative. In order to mitigate this problem, minimum throughput maximization was proposed in [10] and [11], in order to ensure fairness among users, since a sum throughput maximization policy may lead to an unfair rate allocation.

Furthermore, the use of non-orthogonal multiple access (NOMA) in WPNs was proposed, in order to overcome the doubly near-far issue and provide fairness [11]–[14]. The fundamental difference of NOMA, compared to conventional multiple access schemes e.g., TDMA, is the ability of serving multiple users in a single resource block in the time/frequency/code domain. By utilizing advanced signal processing techniques in the decoding process, such as a successive interference cancellation (SIC), the intra-user interference can be mitigated. In addition, time-sharing has been proposed for uplink NOMA, where multiple decoding orders for users are implemented for different portions of time. This enlarges the capacity region and improves the fairness among users [11], [13], [14].

Moreover, in [15], the use of TDMA in WPNs was proposed, when the aim is to maximize the sum throughput, while the circuit power consumption of the devices is non-negligible. However, this policy leads to an unfair rate allocation among users, since the sum data rate improvement favors users with better channel conditions, while users with weak channel conditions are almost prevented to access the resource block, as was observed in [14]. Furthermore, in [14], the use of non-orthogonal multiple access (NOMA) in WPNs was proposed, with the goal to maximize minimum throughput, which might lead though to a reduction of sum throughput, since users strive to achieve an improved minimum data rate. As a matter of fact, it becomes evident that a trade-off between sum and minimum throughput arises, since the maximization of one can lead to the decrease of the other. Furthermore, NOMA and TDMA still compete for their consolidation in WPNs, especially when the circuit power consumption is non-negligible. Also, it is noted that the joint optimization of sum and minimum rate among users in WPNs has not been investigated in the existing literature.

Finally, the decentralized architecture of wireless networks and their evolution to cloud radio access networks (C-RAN) have drawn significant attention by both the industry and research community [16], [17], owning to its advantage of reducing the network cost and meeting the requirements of high spectral efficiency. The key aspect of this configuration, is the use of multiple distributed remote radio heads (RRHs) in a cell, connected with fronthaul links to baseband units (BBUs), clustered as a BBU pool in a centralized location. In this architecture, the traditional BS is replaced by the RRHs that are implemented in a distributed manner through the cell and a central processor, which coordinates the RRHs [18], [19]. By adopting this dense-cell architecture perspective, its possible to improve users' capacity, since the average distance of propagation is reduced, compared to a centralized network implementation. Taking into account the aforementioned advantages, CRAN architecture has also been explored in the context of SWIPT. More specifically, in [20], the authors investigated the energy-throughput trade-off in a C-RAN system with SWIPT, while in [21], the problem of minimum rate maximization was investigated. However, none of these works focus on overcoming the doubly near-far problem and examining the performance of various multiple access protocols in WPNs with decentralized network architecture.

B. Contribution

Driven by the aforementioned considerations, we propose the application of decentralized power transfer and radio access in WPNs, in order to mitigate the doubly near-far problem. More specifically, the use of RRHs -which also have the functionality of power beacons- reduces the distance between the access point and the users, making the application of wireless power transfer more feasible and mitigating the doubly near-fear effect. This is because by increasing the number of RRHs in the network, it is unlikely that a user is far from a RRH, reducing the average signal attenuation and, thus, enabling users to achieve higher data rates. In this direction, we aim to jointly optimize the sum and minimum throughput among users, which are usually conflicted performance metrics and try to identify when NOMA outperforms TDMA and vice-versa, for use in the uplink of decentralized WPNs, taking into account the circuit power consumption. To evaluate the performance of the decentralized architecture compared to the centralized one, we solve this problem for both architectures, since as it has already been mentioned, the joint maximization of the considered conflicting metrics has not been considered by the existing literature. This problem belongs to the category of multi-objective optimization (MOO), which can be transformed into a single-objective optimization problem, through the scalarization approach [22], resulting in a weighted sum of the objective functions that is subject to maximization. After solving the corresponding optimization problem, the Pareto Front can be obtained, which is a widely accepted solution, when dealing with MOO problems [22]. The Pareto boundary describes the set of efficient potential operating points, while the network designer is responsible for selecting the point that seems more appropriate for fulfilling the network requirements.

The main contributions of this paper can be summarized as follows:

- For the case of a centralized network implementation, i.e., when the network consists of a single BS, we formulate the MOO problem between the sum and minimum throughput and obtain the Pareto Front.
- For the case of a decentralized network architecture i.e., multi-RRH case, four different protocols are proposed. The first two are based on the existence of two discrete phases in each time-slot, each of which is used either for energy harvesting and information transmission, and the utilization of either NOMA and TDMA. For these protocols, we show that it is beneficial for the users to select the "best" RRH, in order to transmit information, for both the cases of NOMA and TDMA. In the other two protocols, hereinafter termed as *partially* and *fully asynchronous transmission TDMA* (AT-TDMA), each RRH transfers wirelessly energy to the users for a different portion of time, while users are also harvesting energy for different time intervals and transmit information signals to the RRHs in different time instants through TDMA. It is noted that in contrast to partially AT-TDMA (PAT-TDMA), where energy is only transferred at the beginning of a time-slot, in fully AT-TDMA (FAT-TDMA), the sequence between power transfer and information transmission is repeated multiple times within a time-slot. Similarly, to the centralized implementation, the performance of the aforementioned protocols is also jointly optimized in terms of sum and minimum throughput.
- The evaluation of the proposed strategies through extensive simulations reveals that the decentralized network implementation enhances the performance in terms of achievable data rate, in comparison with the centralized implementation. Furthermore, the AT-TDMA schemes can provide a significant improvement. Also, the Pareto Front reveals an interesting trade-off between the considered objectives, i.e, sum and minimum throughput among users, for all the considered

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protocols. Finally, the performance of NOMA and TDMA for use in WPNs is evaluated, in terms of both system throughput improvement and fairness provision, through the Pareto Front.

C. Structure

The rest of this paper is organized as follows. Section II describes the system and energy harvesting model. In Section III, IV, the achievable rate for each proposed protocol is defined, while the joint sum and minimum maximization problem is formulated and solutions are provided, for the single-BS case and decentralized configuration with multiple-RRH, respectively. In the continue, in Section V, the extension of the linear EH model to a non-linear one is considered. Following that, in Section VI, simulations results are provided and discussed. Finally, conclusions are summarized in Section VII.

II. System Model

We consider a wireless network that consists of N users and M RRHs, denoted by $n \in \{1, 2, .., N\}$ and $m \in \{1, 2, .., M\}$, respectively, each of which is equipped with a single antenna. The path loss from the m-th RRH to user n is denoted by $L_{m,n}$, while the channel coefficient is given by $h_{m,n}$, which follows a complex normal distribution, i.e., $h_{m,n} \sim \mathcal{CN}(0, 1)$. The communication is divided into time frames of unitary length, while it is assumed that the channel state remains constant during a time-slot and can be perfectly estimated by the RRHs and reported to the BBU pool. Furthermore, we adopt a partially centralized cloud architecture, where the RRHs have decoding capabilities, while the BBU is able to perform complex calculations or centralized decisions [23], [24]. To enable the effective operation of the RRHs, a unified resource optimizer is assumed, which works in synergy with a global medium access control (MAC) entity, unifying all the resource management operation including allocation, interference management and signaling for different RRHs, which is in line with the envisioned architectures for distributed radio access networks [25]. Finally, it is considered that each RRH is connected with the BBU pool via a high-capacity low-latency fronthaul link. Consequently, we assume that the fronthaul capacity is much higher than that of the wireless medium and overhead during the information and control information delivery can be ignored. The considered model is depicted in Fig. 1.

We further consider that the network adopts the harvest-then-transmit protocol and all nodes operate in half-duplex mode, i.e., they cannot receive and transmit information simultaneously. Furthermore, in the case of TDMA, each user transmits information to the m-th RRH for a portion $t_{m,n}$ of the total transmission time. On the other hand, in NOMA, all users simultaneously transmit information to the RRHs by solely using the harvested energy from the first phase. The available user transmission power is limited by the total harvested energy by each user during the first phase. In order to detect the users' signals, the RRHs employ a joint processing technique, namely SIC according to the NOMA principle, where the already decoded messages are subtracted from the received signal. Also, channel reciprocity is considered, so the channel gain $g_{m,n}$ is the same for both phases and it is given by $g_{m,n} = G_0 G_n L_{m,n} |h_{m,n}|^2$, where G_o, G_n are the antenna gains of transmitter and receiver. Finally, we assume that along with the transmit power, each device also consumes a constant power p_c, for the circuit operation.

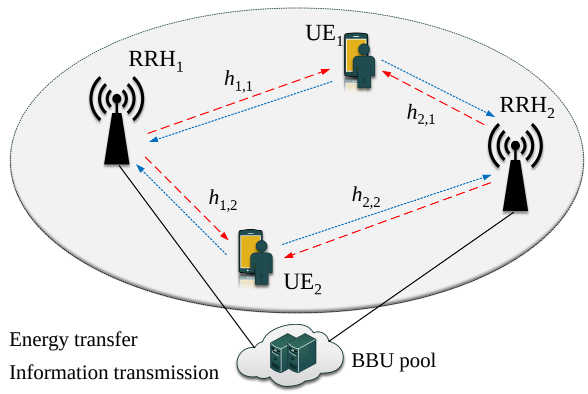

Fig. 1. System model of a decentralized WPN with two users and two RRHs.

During the energy transferring operation, the RRHs broadcast energy signals with constant transmit power P_0. Thus, the harvested power by the n-th user from the m-th RRH can be written as

$$\Phi_{m,n} = \eta_n g_{m,n} P_0, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}, \tag{1}$$

where $0 < \eta_n < 1$ denotes the energy harvesting efficiency at each receiver, while it is assumed that $\eta_n = \eta$, $\forall n \in \mathcal{N}$. Following that, n-th user's total harvested power is given by

$$\Phi_{\mathrm{EH},n} = \sum_{m=1}^{M} \Phi_{m,n}, \quad \forall n \in \mathcal{N}, \tag{2}$$

where $\Phi_{\mathrm{EH},n}$ denotes the n-th users' total harvested power by all RRHs.

III. Centralized Architecture

Next, we assume that the network consists of a single BS and thus the subscript m is being dropped for simplicity. In addition, since users adopt the harvest-then-transmit protocol, the amount of time $1-T$, $0 \leq T \leq 1$ is assigned to the BS to broadcast wireless energy to all users, while the remaining time, T, is assigned for data transmission from the users. Finally, without loss of generality, we assume that the users' channel gains are ordered as $g_1 \geq g_2 \geq ... \geq g_N$.

A. Proposed Protocols

1) NOMA: The consumed power is constrained by

$$p_n + p_c = \frac{E_n}{T} = \frac{\Phi_{\mathrm{EH},n}(1-T)}{T}, \quad \forall n \in \mathcal{N}, \tag{3}$$

where p_n is the transmit power, E_n is the harvested energy of user n and p_c denotes the circuit power consumption. Taking

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into account (3) and that $p_n \geq 0$, i.e., the transmit power has to be greater than or equal to zero, it holds that

$$0 < T \leq \frac{1}{1+\frac{p_c}{\Phi_{\mathrm{EH},n}}}, \quad \forall n \in \mathcal{N}. \tag{4}$$

T is constrained by a set of N inequalities, but finally it will be bounded by the stringent one. Considering that $\Phi_{\mathrm{EH},n}$ is an increasing function with respect to g_n, it yields $\min(\Phi_{\mathrm{EH},n}) = \Phi_{\mathrm{EH},N}$. Thus, (4) can be written as

$$0 < T \leq \frac{1}{1+\frac{p_c}{\min(\Phi_{\mathrm{EH},n})}} = \frac{1}{1+\frac{p_c}{\Phi_{\mathrm{EH},N}}} \triangleq B < 1. \tag{5}$$

Hereinafter, time-sharing is considered, which, in contrast to fixed decoding order that corresponds to the corner points, can achieve any point of the capacity region of uplink NOMA. The later is defined as the convex closed hull of all vectors $(R_1, R_2, ..., R_N)$ satisfying [26], [11]

$$\sum_{n\in\mathcal{M}_k} R_n \leq T\log_2\left(1+\rho\sum_{n\in\mathcal{M}_k} p_n g_n\right), \forall k : \mathcal{M}_k \subseteq \mathcal{N}, \tag{6}$$

where R_n is the rate achieved by the n-th user and $\rho = 1/N_0$, with N_0 being the power spectral density of the additive white Gaussian noise (AWGN). Following that, since $p_n = \frac{\Phi_{\mathrm{EH},n}(1-T)}{T} - p_c$, is a monotonically increasing function with respect to g_n, it also holds that $p_1 g_1 \geq p_2 g_2 \geq ... \geq p_N g_N$. Following that, suppose that the BS cancels out, all the users' messages, except the user with the weakest link. Then, weakest user's throughput, satisfies

$$R_N = T\log_2(1+\rho p_N g_N) \geq R_{\min}^{\mathrm{NOMA}}.$$

Accordingly, for the two users with the weakest links, that is for $n = N$ and $n = N-1$, the BS cancels all other users' messages. Since time-sharing strategy is able to schedule the time portion that each user will be decoded in a certain order, the sum throughput of the two users satisfy

$$R_N + R_{N-1} = T\log_2\left(1+\sum_{n=N-1}^{N} p_n g_n\right) \geq 2R_{\min}^{\mathrm{NOMA}}.$$

By following the same pattern for the rest of the users, it yields that $R_{\min}^{\mathrm{NOMA}}$ is bounded by the set of inequalities

$$R_{\min}^{\mathrm{NOMA}} \leq \frac{T\log_2\left(1+\sum\limits_{i=n}^{N} p_i g_i\right)}{N+1-n}, \quad \forall n \in \mathcal{N},$$

and consequently, $R_{\min}^{\mathrm{NOMA}}$ is given by

$$R_{\min}^{\mathrm{NOMA}} = \min_{n\in\mathcal{N}}\left(\frac{T\log_2\left(1+\rho\sum\limits_{i=n}^{N} p_i g_i\right)}{(N+1-n)}\right), \tag{7}$$

since among the subsets $\mathcal{M}_k, \forall k : \mathcal{M}_k \subseteq \mathcal{N}$ with the same cardinality, $R_{\min}^{\mathrm{NOMA}}$ is constrained by the one that consists of users with the weakest link, i.e., $p_N g_N$. By using (3) and $p_i = \frac{\Phi_{\mathrm{EH},i}(1-T)}{T} - p_c$, (7) can be rewritten as

$$R_{\min}^{\mathrm{NOMA}} = \min_{n\in\mathcal{N}}\left(\frac{T\log_2\left(1+\frac{1-T}{T}\rho\sum\limits_{i=n}^{N} g_i\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum\limits_{i=n}^{N} g_i\right)}{(N+1-n)}\right). \tag{8}$$

Moreover, the sum rate can be expressed as [11], [15]

$$R_{\mathrm{sum}}^{\mathrm{NOMA}} = T\log_2\left(1+\frac{1-T}{T}\rho\sum_{i=1}^{N} g_i\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum_{i=1}^{N} g_i\right). \tag{9}$$

2) TDMA: In TDMA scheme, users transmit information signals in different portions of time with duration t_n. Following that, the achievable throughput of user n, is given by

$$R_n^{\mathrm{TDMA}} = t_n\log_2(1+\rho p_n g_n). \tag{10}$$

The consumed power is constrained by

$$p_n + p_{\mathrm{c}} = \frac{E_n}{t_n} = \frac{\Phi_{\mathrm{EH},n}(1-T)}{t_n}, \quad \forall n \in \mathcal{N}. \tag{11}$$

where $T = \sum\limits_{n=1}^{N} t_n$. By replacing p_n from (11) in (10), the achievable throughput of user n, can be expressed as

$$R_n^{\mathrm{TDMA}} = t_n\log_2\left(1+\frac{1-T}{t_n}\rho g_n\Phi_{\mathrm{EH},n} - \rho p_c g_n\right). \tag{12}$$

Note that, by demanding $p_n \geq 0$, t_n is constrained by

$$t_n \leq \frac{\Phi_{\mathrm{EH},n}(1-T)}{p_c}, \quad \forall n \in \mathcal{N}. \tag{13}$$

Finally, the minimum throughput of the users can be written as

$$R_{\min}^{\mathrm{TDMA}} = \min_{n\in\mathcal{N}}(R_n^{\mathrm{TDMA}}), \tag{14}$$

while the sum throughput can be expressed as

$$\begin{aligned} R_{\mathrm{sum}}^{\mathrm{TDMA}} &= \sum_{n=1}^{N} R_n \\ &= \sum_{n=1}^{N} t_n\log_2\left(1+\frac{1-T}{t_n}\rho g_n\Phi_{\mathrm{EH},n} - \rho p_c g_n\right). \end{aligned} \tag{15}$$

B. Joint Sum and Minimum Throughput Maximization

1) NOMA - Problem Formulation and Solution: The general MOO problem requires the maximization of two objectives, sum data rate and users' minimum data rate. The problem for the case of NOMA can be formulated as follows, while we drop the superscript indices of the rates for simplicity

$$\begin{aligned} &\max_{T,R_{\min}} \quad (R_{\mathrm{sum}}, R_{\min}) \\ &\textbf{\textit{s.t}} \quad \mathrm{C}_n : R_{\min} \leq \frac{T\log_2\left(1+\frac{1-T}{T}\rho\sum_{i=n}^{N} g_i\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum_{i=n}^{N} g_n\right)}{N-n+1}, \\ &\qquad\quad \forall n \in \mathcal{N}. \\ &\quad \mathrm{C}_{N+1} : 0 < T \leq B, \end{aligned} \tag{16}$$

where the constraints C_n in the above maximization problem occur from (8), while the constraint C_{N+1} is related with the transmission time bound in (5).

A widely accepted solution when dealing with MOO problems is to obtain the Pareto Front. All Pareto optimal points have the property that is not possible to further increase one objective, without degrading any other. More specifically, the Pareto domination is defined as follows:

Definition 1: Pareto Domination: Let the vector-valued function $f(x) = [f_1(x), f_2(x), ..., f_k(x)]$, $f : X \to \mathbb{R}^k$. A feasible solution $u \in X$ is said to Pareto dominate another solution $v \in X$, in a maximization context, if and only if:
$f_i(u) \geq f_i(v), \quad \forall i \in \{1, 2, ..., k\}$
and $\exists j \in \{1, 2, ..., k\} : f_j(u) > f_j(v)$.

A solution which is not dominated by any other one is termed as Pareto optimal. The set of all optimal solutions is called the Pareto optimal set and the corresponding objective vectors of the solutions, define the Pareto Front. MOO theory provides several approaches in order to convert a multi-objective problem, into a single-objective one, the maximization of which results in a optimal Pareto point. A widely used approach is the scalarization method, which results in the weighted sum of the objectives [22]. Thus, a popular single objective function is the linear combination of the multiple objectives. Following that, by using the scalarization method, the MOO problem in (16) is converted to a single-objective optimization problem. More specifically, let

$$\tilde{R} = wR_{\text{sum}} + (1-w)R_{\min}, \quad \forall n \in \mathcal{N}, \quad 0 \leq w \leq 1, \tag{17}$$

where w denotes the weighting factor between the two objectives, specifying the priority among the objectives. By tuning the weighting factor and by solving the maximization problem, any point in the Pareto boundary can be achieved. Following that, from (17), $R_{\min}$ is given by

$$R_{\min} = \frac{\tilde{R} - wR_{\text{sum}}}{1-w}. \tag{18}$$

Since $R_{\min}$ is constrained by C_n in (16), (18) leads to

$$\frac{\tilde{R} - wR_{\text{sum}}}{1-w} \leq \frac{T\log_2\left(1+\frac{1-T}{T}\rho\sum_{i=n}^{N} g_i\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum_{i=n}^{N} g_n\right)}{N-n+1}, \quad \forall n \in \mathcal{N}, \tag{19}$$

where R_{sum} is given by (9). Primarily, the optimization problem will be solved for a constant w, which corresponds to a specific point of the front and subsequently one-dimension research will be carried out, in order to construct the complete Pareto boundary. Now we can re-formulate the maximization problem in (16) as follows

$$\begin{aligned} \max_{T,\tilde{R}} \quad & \tilde{R} \\ \textbf{s.t} \quad & \mathrm{C}_n : \tilde{R} \leq wT\log_2\Big(1+\tfrac{1-T}{T}\rho\textstyle\sum_{i=1}^{N} g_i\Phi_{\mathrm{EH},i} \\ & \quad -\rho p_{\mathrm{c}}\textstyle\sum_{i=1}^{N} g_i\Big) + \left(\tfrac{1-w}{N-n+1}\right) \\ & \quad \times T\log_2\Bigg(1+\tfrac{1-T}{T}\rho\textstyle\sum_{i=n}^{N} g_i\Phi_{\mathrm{EH},i} \\ & \quad -\rho p_{\mathrm{c}}\textstyle\sum_{i=n}^{N} g_n\Bigg), \quad \forall n \in \mathcal{N}, \\ & \mathrm{C}_{N+1} : \quad 0 < T \leq B, \end{aligned} \tag{20}$$

where C_n has occurred by manipulating the inequality in (19).

In order to solve the maximization problem in (20), the proposed algorithm in [14] will be utilized. Firstly, the function F_n is defined as

$$\begin{aligned} F_n(T) \triangleq\ & wT\log_2\left(1+\tfrac{1-T}{T}\rho\sum_{i=1}^{N} g_i\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum_{i=1}^{N} g_i\right) \\ & + \left(\tfrac{1-w}{N-n+1}\right)T\log_2\left(1+\tfrac{1-T}{T}\rho\sum_{i=n}^{N} g_i\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum_{i=n}^{N} g_n\right) \\ & , \forall n \in \mathcal{N}, \end{aligned} \tag{21}$$

which represents the right-hand-side of the constraint C_n. It's easy to prove that the function F_n is concave with respect to T, as an aggregation of concave functions, i.e., the first and second term of (21) are concave. As a consequence, there's a unique maximization point of the function F_n, which corresponds to the optimal time $T^* \in (0, B]$. The optimal value of $\tilde{R}$, could be either the minimum of F_n maxima, or a possible intersection point between all the pairs of the function set, intersected below the min-max point, with different slopes.

In order to calculate the maximum of F_n, $\forall n \in \mathcal{N}$, a numerical method, such as *bisection method* [27] should be applied, since a close-formed solution of the maximum is prevented. While, in order to search for all possible intersections between all the pairs of functions, the following set is constructed

$$\begin{aligned} G_{km}(T) = F_k(T) - F_m(T) = (1-w)\times \\ \left(\frac{T\log_2\left(1+\frac{1-T}{T}a_k - b_k\right)}{N_k} - \frac{T\log_2\left(1+\frac{1-T}{T}a_m - b_m\right)}{N_m}\right), \end{aligned} \tag{22}$$

$\forall k, m \in \mathcal{N}, k \neq m$, where $T \in [0, B]$, $a_j = \rho\sum_{i=j}^{N} g_i\Phi_{\mathrm{EH},i}$, $b_j = \rho p_{\mathrm{c}}\sum_{i=j}^{N} g_i$ and $N_i = N+1-i$. By finding the roots of $G_{km}(T)$ it's possible to calculate all the intersections between all the pairs of functions of the set F_n. A numerical method for finding all the intersections is imperative.

Taking these into account, we can use Algorithm 1, as proposed in [14] and briefly described here, in order to solve the maximization problem in (20). In Step 2, the *bisection method* can be applied in order to search for the roots of $G_{km}(T)$. The search intervals of the *bisection method* has been specified in [14], where it has been proved that G_{km} has at most three roots, including zero point i.e., between a pair of F_n there are at most three intersection points, including zero. With this algorithm it's possible to maximize $\tilde{R}$ and calculate

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Algorithm 1 Solution of Maximization Problem in (20)

1: **Step 1:** Find all maxima of $F_n, \forall n \in \mathcal{N}$ and save the minimum of the maxima: $\tilde{R} = \min_{n\in\mathcal{N}}(\max F_n)$.
2: **Step 2:** Find all the intersections between all pairs of F_n, by finding the roots of (22).
3: **Step 3:** For all intersections, check if the intersection point is less than $\tilde{R}$ and update $\tilde{R}$ with the value of the intersection point.

the optimal transmission time $T^* \in (0, B]$, which achieves $\tilde{R}^*$. Note that this algorithm will be applied for a constant weighting factor w, while for every choice of w, a different point on the Pareto front is obtained. By sweeping w and by finding the optimal point $(T^*, \tilde{R}^*)$ in every step, it's possible to characterize the whole Pareto boundary. Finally, according to [14], the upper limit of the algorithm's overall number of iterations, I, is given by

$$I(N,\epsilon) \leq 2(N^2 - N)\log_2 \frac{B}{\epsilon}, \tag{23}$$

where ϵ denotes the convergence tolerance.

2) TDMA - Problem Formulation and Solution: In the case of TDMA, we are aiming again to maximize $\tilde{R}$. Following the same pattern with the problem formulation of NOMA, the maximization problem can be written as follows:

$$\begin{aligned}
&\max_{T,\tilde{R},\mathbf{t}} \quad \tilde{R} \\
&\textbf{\textit{s.t}} \quad \mathrm{C}_n : \tilde{R} \leq w \sum_{i=1}^{N} t_i \log_2\left(1 + \frac{1-T}{t_i}\rho g_i \Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}} g_i\right) \\
&\qquad + (1-w) t_n \log_2\Bigg(1 + \frac{1-T}{t_n}\rho g_n \Phi_{\mathrm{EH},n} \\
&\qquad - \rho p_{\mathrm{c}} g_n\Bigg), \quad \forall n \in \mathcal{N}, \\
&\quad \mathrm{C}_{N+n} : p_{\mathrm{c}} t_n - \Phi_{\mathrm{EH},n}(1-T) \leq 0, \quad \forall n \in \mathcal{N}, \\
&\quad \mathrm{C}_{2N+1} : \sum_{n=1}^{N} t_n = T,
\end{aligned} \tag{24}$$

where the constraint C_{N+n} is related with the upper bound of t_n in (13). It's easy to verify that this problem belongs to the category of convex-optimization. In order to handle the linear objective function we replace it with $\ln(\tilde{R})$. Since the primal problem is concave and satisfies the Slaters condition qualifications, strong duality holds, i.e., solving the dual is equivalent to solving the primal problem [28]. In order to formulate the dual problem, the Lagrangian is needed, which is given by

$$\begin{aligned}
\mathcal{L}(\tilde{R}, T, \mathbf{t}, \boldsymbol{\lambda}, \boldsymbol{\mu}, k) &= \ln(\tilde{R}) \\
&+ \sum_{n=1}^{N} \lambda_n \Bigg(w \sum_{i=1}^{N} t_i \log_2\left(1 + \tfrac{1-T}{t_i} a_i - b_i\right) + (1-w) \\
&\times t_n \log_2\left(1 + \tfrac{1-T}{t_n} a_n - b_n\right) - \tilde{R}\Bigg) \\
&- \sum_{n=1}^{N} \mu_n \left(p_{\mathrm{c}} t_n - \Phi_{\mathrm{EH},n}(1-T)\right) - k\left(\sum_{i=1}^{N} t_i - T\right),
\end{aligned} \tag{25}$$

where λ_n, μ_n, k are the Lagrange Multipliers (LM), which correspond to the constraints $\mathrm{C}_n, \mathrm{C}_{n+N}, \mathrm{C}_{2N+1}$ respectively and $a_n = \rho g_n \Phi_{\mathrm{EH},n}$, $b_n = \rho p_{\mathrm{c}} g_n$. According to the Karush-Kun-Tucker (KKT) conditions, it must hold that, $\frac{\partial \mathcal{L}}{\partial \tilde{R}} = 0$, $\frac{\partial \mathcal{L}}{t_n} = 0$, $\forall n \in \mathcal{N}$, $\frac{\partial \mathcal{L}}{T} = 0$ and the following expressions are provided:

$$\tilde{R}^* = \frac{1}{\sum\limits_{n=1}^{N} \lambda_n}, \tag{26}$$

$$\xi_n \triangleq \frac{1-T^*}{t_n^*} = \frac{1}{a_n}\left[e^{\left[W\left(\frac{b_n-1}{e^{1+c_n}}\right)+1+c_n\right]} + b_n - 1\right], \quad \forall n \in \mathcal{N}, \tag{27}$$

where c_n is given by

$$c_n = \frac{\ln 2(\mu_n p_c + k)}{w \sum\limits_{\substack{i=1 \\ i\neq n}}^{N} \lambda_i + \lambda_n},$$

and $\mathcal{W}$ is the principal branch of Lambert Function [29]. Furthermore, from KKT it occurs

$$\begin{aligned}
&\sum_{n=1}^{N} \lambda_n \left[\sum_{i=1}^{N}\left(\frac{w a_i}{(1 - b_i + a_i \xi_i)\ln 2}\right)\right. \\
&\left. + \frac{(1-w)a_i}{(1 - b_i + a_i\xi_i)\ln 2}\right] + k - \sum_{n=1}^{N} \mu_n \Phi_{\mathrm{EH},n} = 0.
\end{aligned} \tag{28}$$

Note that, ξ_n is an auxiliary variable defined as the ratio of energy harvesting time over transmission time of n-th user, which helps in manipulating the KKT conditions and finally derive the optimal solutions. Following that, according to (27) and constraint C_{2N+1}, it yields

$$T^* = \frac{\sum\limits_{n=1}^{N} \frac{1}{\xi_n}}{1 + \sum\limits_{n=1}^{N} \frac{1}{\xi_n}}. \tag{29}$$

The respective expression for all t_n^* is given by

$$t_n^* = \frac{1}{\left(1 + \sum\limits_{n=1}^{N} \frac{1}{\xi_n}\right)\xi_n}, \quad \forall n \in \mathcal{N}. \tag{30}$$

It should be noted that t_n decreases as ξ_n increases. Therefore, users who present larger ξ_n would require smaller transmission

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time intervals. Furthermore, from equation (26), it is observed that the objective function $\tilde{R}$ is inversely proportional to the sum of the LMs λ_n, associated with the constraints C_n. This indicates that larger λ_n will decrease the objective. This is reasonable, since highly violated constraints which are related with weak users, will result in larger λ_n, i.e., larger penalty term which affects negatively the objective, while that is the physical interpretation of the LMs [28]. To this end, the LMs $\boldsymbol{\lambda}, \boldsymbol{\mu}, k$ can be calculated iteratively, by using the sub-gradient method. Thus, ξ_n^* can be calculated and the procedure of optimization problem resolution can be completed, since it's possible to find the optimal values of $\tilde{R}^*, \mathbf{t}^*, T^*$.

IV. The Case of Multiple RRHs

A. Proposed Protocols

1) Multi-RRH NOMA: In the case of Multi-RRH NOMA the harvest-then-transmit protocol is used. We further assume that users can transmit simultaneously, while SIC is performed to each RRH separately. Therefore, the minimum rate among users in the m-th RRH is given, accordingly to the single-BS case, by

$$R_{\min}^m = \min_{n\in\mathcal{N}} \left(\frac{T\log_2\left(1+\frac{1-T}{T}\rho\sum\limits_{i=n}^{N} g_{m,i}\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum\limits_{i=n}^{N} g_{m,i}\right)}{N+1-n} \right), \tag{31}$$

while the system throughput is written as follows

$$R_{\mathrm{sum}}^m = T\log_2\left(1+\frac{1-T}{T}\rho\sum_{i=1}^{N} g_{m,i}\Phi_{\mathrm{EH},i} - \rho p_{\mathrm{c}}\sum_{i=1}^{N} g_{m,i}\right). \tag{32}$$

2) Multi-RRH TDMA: In the case of Multi-RRH TDMA the harvest-then-transmit protocol is used, while users are able to transmit information signals to the RRHs, but not simultaneously. Let $t_{m,n}$ be the portion of the overall transmission time, that user n transmits an information message to the m-th RRH, while the total transmission time is given by

$$T = \sum_{n=1}^{N}\sum_{m=1}^{M} t_{m,n}. \tag{33}$$

The achievable rate of user n can be written as

$$R_n = \sum_{m=1}^{M} t_{m,n}\log_2\left(1+\rho g_{m,n}\left(\frac{1-T}{t_{m,n}}\Phi_{\mathrm{EH},n} - p_c\right)\right), \tag{34}$$

while the sum rate can be expressed as $R_{\mathrm{sum}} = \sum\limits_{n=1}^{N} R_n$.

3) Partially AT-TDMA: Before we proceed to the analysis of PAT-TDMA, we first discuss the motives behind the construction of the considered protocol. Multi-RRH TDMA, uses the conventional harvest-then-transmit protocol, where all RRHs transfer energy for equal time intervals in the beginning of the time slot. However, the drawback of this method, is that enforces users to harvest energy for equal time intervals. This becomes evident by considering the case where a user has a weak channel gain, while a second user has a strong channel gain. It is more likely that the weak user will demand greater amounts of energy and consequently greater time interval for harvesting energy, in order to improve his performance. On the other hand, the strong user may require less time for harvesting energy. Thus, it may not be optimal for the users to harvest energy for equal portions of time.

Driven by the aforementioned consideration, unlike conventional harvest-then-transmit protocol, we assume asynchronous energy transferring and energy harvesting intervals. This implies that a different energy transferring and energy harvesting duration is assigned to each RRH and user respectively. As long as a user terminates the energy harvesting procedure, the information transmission follows. Moreover, users begin to transmit information signals to the RRHs in different time instants. Furthermore, we assume that the TDMA scheme is being utilized for the information transmission. Following that, let $0 \le \tau_m \le 1$ denote the duration where the m-th RRH is broadcasting wireless energy to the users and $0 \le \tilde{\tau}_n \le 1$ the portion of time that the n-th user is harvesting energy from the RRHs. The amount of harvested energy by the n-th user associated to the m-th RRH is given by

$$E_{H,m,n} = \min(\tau_m, \tilde{\tau}_n)\Phi_{m,n}, \quad \forall m\in\mathcal{M}, n\in\mathcal{N}, \tag{35}$$

where $\Phi_{m,n}$ is the harvested power by the m-th RRH. The total harvested energy of user n, harvested by all RRHs, is the aggregation of $E_{H,m,n}$ and can be written as

$$E_{H,n} = \sum_{m=1}^{M} E_{H,m,n} = \sum_{m=1}^{M} z_{m,n}\Phi_{m,n}, \quad \forall n\in\mathcal{N}, \tag{36}$$

where $z_{m,n}$ is an auxiliary variable given by $z_{m,n} = \min(\tau_m, \tilde{\tau}_n)$ and represents the time portion that user n is harvesting energy from the m-th RRH.

An illustrative example of the protocol is depicted in Fig. 2. In this example, the RRHs transfer wirelessly energy for τ_1, τ_2 and τ_3 portions of the unitary time slot, while user n is harvesting energy for $\tilde{\tau}_n$. In this case, according to (36), the n-th user's harvested energy will be $E_{H,n} = \tau_1\Phi_{1,n} + \tau_2\Phi_{2,n} + \tilde{\tau}_n\Phi_{3,n}$.

We further consider that during the reception mode of an RRH, the signals of the RRHs which operate in energy transferring mode are known a-priori and can be perfectly canceled. Following that, the achievable rate of user n can be expressed as

$$R_n = \sum_{m=1}^{M} t_{m,n}\log_2\left(1+\rho g_{m,n}\left(\frac{E_{m,n}}{t_{m,n}} - p_{\mathrm{c}}\right)\right), \forall n\in\mathcal{N}, \tag{37}$$

while the sum achievable rate is given by

$$R_{\mathrm{sum}} = \sum_{n=1}^{N}\sum_{m=1}^{M} t_{m,n}\log_2\left(1+\rho g_{m,n}\left(\frac{E_{m,n}}{t_{m,n}} - p_{\mathrm{c}}\right)\right), \tag{38}$$

where $t_{m,n}$ denotes the portion of the overall transmission time that user n is transmitting an information message to the m-th RRH, while $E_{m,n}$ is the amount of the energy, which has been consumed by the user for the aforementioned transmission. The aggregation of the consumed energy for the information transmission to each RRH, cannot exceed the total harvested energy by the n-th user, thus $\sum_{m=1}^{M} E_{m,n} \le E_{H,n}$, $\forall n\in\mathcal{N}$.

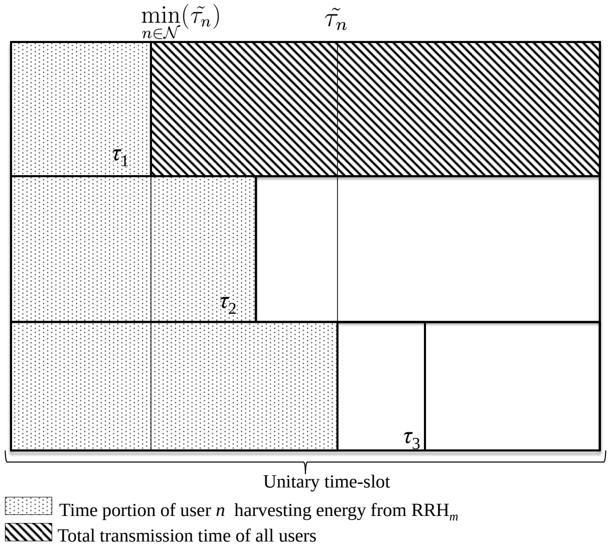

Fig. 2. Illustrative example of PAT-TDMA with three RRHs.

In the next subsection, the constraints which describe the partially AT-TDMA scheme will be carefully discussed.

4) Fully AT-TDMA: In order to achieve a more flexible scheduling of RRHs' energy transferring/information reception time and users' energy harvesting/information transmission time intervals, the FAT-TDMA protocol is introduced. The considered protocol aims at fully utilizing the available resource (time) and adding more degrees of freedom to the system. Following that, we assume that the n-th user selects to transmit information signals to the m-th RRH for a portion $t_{m,n}$ of the time-slot. When the user is not transmitting a message, is able to harvest energy by each RRH, which is not receiving information messages by other users. Unlike PAT-TDMA, it is not required that the RRHs terminate the energy transferring operation in a successive manner, in the beginning of the time slot. Thus, this assumption enables each RRH to transfer energy throughout the whole time-slot length, unless it is operating in the information reception mode. Therefore, we consider a frame as illustrated in Fig. 3. As it can be observed, an amount of harvested energy, specially at the final stages of the frame, cannot be used for information transmission in this particular slot. Due to this fact, we assume that the unitary length frame is divided to an arbitrary large number of mini-slots, i.e., the whole time-slot consists of a sequence of identical mini-slots, as depicted in Fig. 4. It is further assumed, that the harvested energy in each mini-slot will be utilized for information transmission in the subsequent one. Moreover, we consider that the first mini-slot will be used only for energy harvesting purposes, in order to ensure that users in the second mini-slot will have sufficient amount of energy for fulfilling the information transmission requirements. In the continue, the harvested energy of the second mini-slot, will be utilized in the third and so on. Note that the lack of information signals in the first mini-slot will not affect the performance, since it's duration is negligible compared to the time-slot length, considering a large number of mini-slots. Finally, the channel is identical for each mini-slot, since it has been assumed that it remains constant during a time-slot.

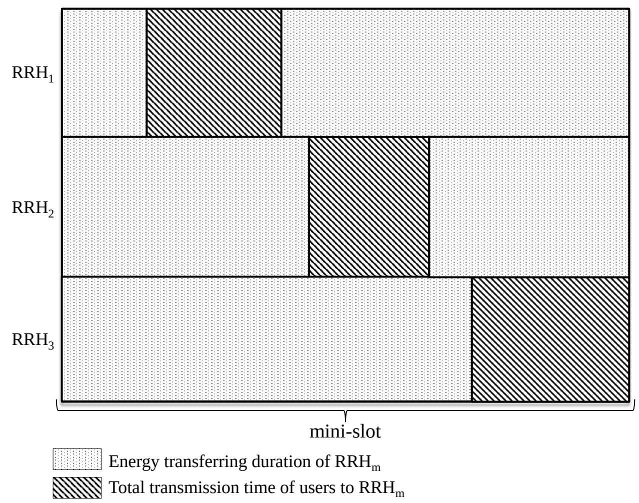

Fig. 3. Illustrative example of a mini-slot. As long as a RRH is not receiving information messages, it can broadcast wirelessly energy to the users.

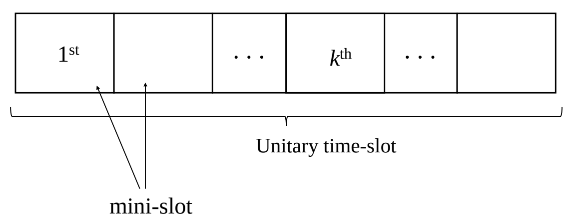

Fig. 4. The time-slot in FAT-TDMA is composed of a sequence of identical mini-slots.

In the continue, the total harvested energy of the n-th user by all RRHs can be written as

$$E_{H,n} = \sum_{m=1}^{M} \Phi_{m,n} - \sum_{m=1}^{M} \sum_{j=1}^{N} t_{m,j} \Phi_{m,n}, \quad \forall n \in \mathcal{N}, \quad (39)$$

where the second term of the right-hand side represents the energy that n-th user was not able to harvest, due to the fact the RRHs were operating in the reception mode, receiving messages from the users during the specified portions of the unitary time-slot. Moreover, the achievable rate of the n-th user and the sum rate of all users can be written similarly to the PAT-TDMA case, in (37) and (38) respectively, while $\sum_{m=1}^{M} E_{m,n} \leq E_{H,n}$, $\forall n \in \mathcal{N}$.

B. Joint Sum and Minimum Throughput Maximization

1) NOMA: When NOMA scheme is used, users will select the RRH which achieves the higher $\tilde{R}$ for the information transmission. Consequently, the single-BS optimization problem in (20) will be solved for the transmission to each possible RRH and finally the one which achieves the higher $\tilde{R}$ will be selected, in order to decode the users' messages.

2) TDMA: As it can be observed in (34), the achievable rate of a user, which transmits to the m-th RRH, is an increasing function with respect to $g_{m,n}$. This yields

$$R_{m,n}(g_{\mathrm{best},n}) > R_{m,n}(g_{m,n}), \tag{40}$$

where $g_{\mathrm{best},n} = \max_{m\in\mathcal{M}}(g_{m,n})$. Accordingly, user n will select the RRH with the best channel gain to transmit information and allocate the whole portion of the available transmission time $t_n = t_{\mathrm{best},n}$ for this transmission, in order to achieve the highest throughput. Consequently, the joint sum and minimum throughput maximization can be reduced to the single-BS case in (24), with each user selecting to transmit information messages only to the RRH with $g_{\mathrm{best},n}$.

3) Partially AT-TDMA: Primarly, the constraints which describe the PAT-TDMA scheme will be discussed. Firstly, by demanding $p_{m,n} \geq 0$, it yields

$$t_{m,n}p_{\mathrm{c}} - E_{m,n} \leq 0, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}, \tag{41}$$

where $p_{m,n} = \frac{E_{m,n}}{t_{m,n}} - p_{\mathrm{c}}$.
In the continue, since it has been set $z_{m,n} = \min(\tau_m, \tilde{\tau}_n)$, we introduce the following constraints

$$z_{m,n} \leq \tau_m, \quad z_{m,n} \leq \tilde{\tau}_n, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}, \tag{42}$$

in order to drop the "min" operator. Following that, the next constraint represents the upper bound of $t_{m,n}$, i.e., the maximum portion of time that user n can transmit a message to the m-th RRH and is given by

$$t_{m,n} + \max(\tau_m, \tilde{\tau}_n) \leq 1, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}. \tag{43}$$

Note that if $\tilde{\tau}_n < \tau_m$, user n cannot transmit information to the m-th RRH during the interval $(\tilde{\tau}_n, \tau_m)$, since RRH_m is still operating in the energy transferring mode and not in the reception mode. Similarly, when $\tilde{\tau}_n > \tau_m$, user n has been fully charged by RRH_m, but is still harvesting energy from the rest of the operating RRHs, i.e., user n can only transmit information after $\tilde{\tau}_n$. In order to dispose of the "max" operator, we set $\delta_{m,n} = \max(\tau_m, \tilde{\tau}_n)$ and we provide the additional constraints

$$\delta_{m,n} \geq \tau_m, \quad \delta_{m,n} \geq \tilde{\tau}_n, \tag{44}$$

so finally the initial constraint in (43) is transformed to

$$t_{m,n} + \delta_{m,n} \leq 1, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}. \tag{45}$$

Fig. 2 provides insights for the previous analysis and the following statements. The overall transmission time of the n-th user plus the energy harvesting time of the user, cannot exceed the unitary time slot duration. Thus, it must hold that

$$\sum_{m=1}^{M} t_{m,n} + \tilde{\tau}_n \leq 1, \quad \forall n \in \mathcal{N}. \tag{46}$$

In addition, the overall transmission time of all users to the m-th RRH plus the energy transferring time of RRH_m, cannot exceed the unitary time slot duration, i.e.,

$$\sum_{n=1}^{N} t_{m,n} + \tau_m \leq 1, \quad \forall m \in \mathcal{M}. \tag{47}$$

Finally, the constraint for the total transmission time of all users can be formulated as follows

$$\sum_{n=1}^{N}\sum_{m=1}^{M} t_{m,n} + y \leq 1, \tag{48}$$

where $y \geq \min_{n\in\mathcal{N}}(\tilde{\tau}_n)$, since the information transmission begins, when the user with the least energy harvesting duration, i.e., $\min_{n\in\mathcal{N}}(\tilde{\tau}_n)$, terminates the harvesting procedure. In order to handle properly the variable y, the following constraints are introduced

$$y \geq \tilde{\tau}_n - \mathrm{K}b_n, \quad \forall n \in \mathcal{N}, \tag{49}$$

where K is an arbitrary big, positive constant and b_n are binary variables, with $\sum_{n=1}^{N} b_n = N - 1$. This implies that all b_n are equal to 1, apart from one of them, which is equal to 0. The binary variable b_i, which is $b_i = 0$, is associated with the $\tilde{\tau}_i = \min_{n\in\mathcal{N}}(\tilde{\tau}_n)$. Therefore, b_i indicates the i-th user, which presents the least energy harvesting time duration, among all users, while with this approach it is ensured that $y \geq \tilde{\tau}_i = \min_{n\in\mathcal{N}}(\tilde{\tau}_n)$.

Moreover, the energy harvesting time duration $\tilde{\tau}_n$ of each user, should be greater than or equal to the minimum of the RRHs energy transferring time. Thus, it must hold that: $\tilde{\tau}_n \geq \min_{m\in\mathcal{M}}(\tau_m) = \gamma$, $\forall n \in \mathcal{N}$. This constraint should be handled similar to the previous one. It can be written as:

$$\gamma \geq \tau_m - \mathrm{K}a_m, \quad \forall m \in \mathcal{M}, \tag{50}$$

where a_m are binary variables with $\sum_{m=1}^{M} a_m = M - 1$. The binary variable a_i, which is $a_i = 0$, is associated with the $\tau_i = \min_{m\in\mathcal{M}}(\tau_m)$ and indicates the RRH, which presents the smallest energy transferring time.

Following this analysis, we will proceed to the problem formulation of the PAT-TDMA protocol. From (37), the minimum rate among users is constrained by

$$R_{\min} \leq \sum_{m=1}^{M} t_{m,n}\log_2\left(1 + \rho g_{m,n}\left(\frac{E_{m,n}}{t_{m,n}} - p_{\mathrm{c}}\right)\right), \quad \forall n \in \mathcal{N}. \tag{51}$$

In the continue, we set

$$\tilde{R} = wR_{\mathrm{sum}} + (1-w)R_{\min}, \tag{52}$$

and we aim to maximize $\tilde{R}$ subject to the constraints, while R_{sum} is given by (38). Equation (52) leads to

$$R_{\min} = \frac{\tilde{R} - wR_{\mathrm{sum}}}{1-w}. \tag{53}$$

From (51),(53), $\tilde{R}$ is constrained by

$$\tilde{R} \leq wR_{\mathrm{sum}} + (1-w)\sum_{m=1}^{M} t_{m,n}\log_2\left(1 + \rho g_{m,n}\left(\frac{E_{m,n}}{t_{m,n}} - p_{\mathrm{c}}\right)\right). \quad \forall n \in \mathcal{N}, \tag{54}$$

Considering the constraints which have been discussed previously, the optimization problem for maximizing $\tilde{R}$ can be formally given as

$$\begin{aligned}
&\max_{\tilde{R},\mathbf{E},\mathbf{t},\boldsymbol{\tau},\tilde{\boldsymbol{\tau}},\mathbf{z},\boldsymbol{\delta},y,\gamma,b_n,a_m} \quad \tilde{R}\\
&\textit{s.t}\\
&\mathrm{C}_1: \tilde{R} \leq wR_{\mathrm{sum}}\\
&\quad + (1-w)\sum_{m=1}^{M} t_{m,n}\log_2\left(1+\rho g_{m,n}\left(\frac{E_{m,n}}{t_{m,n}}-p_{\mathrm{c}}\right)\right),\\
&\quad \forall n\in\mathcal{N},\\
&\mathrm{C}_2: \sum_{m=1}^{M} E_{m,n} \leq \sum_{m=1}^{M} z_{m,n}\Phi_{m,n}, \quad \forall n\in\mathcal{N},\\
&\mathrm{C}_3: t_{m,n}p_{\mathrm{c}} - E_{m,n} \leq 0, \quad \forall m\in\mathcal{M}, n\in\mathcal{N},\\
&\mathrm{C}_4: z_{m,n}\leq \tau_m, \quad z_{m,n}\leq\tilde{\tau}_n,\\
&\qquad \delta_{m,n}\geq\tau_m, \quad \delta_{m,n}\geq\tilde{\tau}_n, \quad \forall m\in\mathcal{M}, n\in\mathcal{N},\\
&\mathrm{C}_5: t_{m,n}+\delta_{m,n}\leq 1, \quad \forall m\in\mathcal{M}, n\in\mathcal{N},\\
&\mathrm{C}_6: \sum_{m=1}^{M} t_{m,n}+\tilde{\tau}_n\leq 1, \quad \forall n\in\mathcal{N},\\
&\mathrm{C}_7: \sum_{n=1}^{N} t_{m,n}+\tau_m\leq 1, \quad \forall m\in\mathcal{M},\\
&\mathrm{C}_8: \sum_{n=1}^{N}\sum_{m=1}^{M} t_{m,n}+y\leq 1,\\
&\mathrm{C}_9: y\geq\tilde{\tau}_n-\mathrm{K}b_n, \quad \forall n\in\mathcal{N}, \quad b_n\in\{0,1\},\\
&\mathrm{C}_{10}: \tilde{\tau}_n\geq\gamma, \quad \forall n\in\mathcal{N},\\
&\mathrm{C}_{11}: \gamma\geq\tau_m-\mathrm{K}a_m, \quad \forall m\in\mathcal{M}, \quad a_m\in\{0,1\}.
\end{aligned} \tag{55}$$

The above optimization problem is a combinatorial one, due to the presence of the binary variables b_n and a_m. However, the problem can be solved for all possibles values of b_n, a_m, in order to find the optimal solution, i.e., a check for each possible value of them should be applied. As it was mentioned previously, among the sets b_n, a_m, only a single variable is equal to zero, for each set of variables separately, while the rest of the binary variables are equal to one. It is noted that the total number of combinations between b_n and a_m is $N\times M$. Following that, for known b_n and a_m, the problem belongs to the category of convex-optimization, since C_1 is convex, while the objective function and the rest of the constraints are linear and affine. As a consequence, standard convex-optimization methods or the dual decomposition, similarly to (24), may be employed, in order to solve the problem in (55).

4) Fully AT-TDMA: In the case of FAT-TDMA, the total transmission time of all users should be less than or equal to the unitary time-slot. Therefore, we introduce the following constraint

$$\sum_{m=1}^{M}\sum_{n=1}^{N} t_{m,n}\leq 1. \tag{56}$$

Following that, the optimization problem for maximizing $\tilde{R}$ can be formulated similarly to the PAT-TDMA protocol as

$$\begin{aligned}
&\max_{\tilde{R},\mathbf{E},\mathbf{t}} \quad \tilde{R}\\
&\textit{s.t}\\
&\mathrm{C}_1: \tilde{R} \leq wR_{\mathrm{sum}}\\
&\quad + (1-w)\sum_{m=1}^{M} t_{m,n}\log_2\left(1+\rho g_{m,n}\left(\frac{E_{m,n}}{t_{m,n}}-p_{\mathrm{c}}\right)\right),\\
&\quad \forall n\in\mathcal{N},\\
&\mathrm{C}_2: \sum_{m=1}^{M} E_{m,n} \leq \sum_{m=1}^{M}\Phi_{m,n} - \sum_{m=1}^{M}\sum_{j=1}^{N} t_{m,j}\Phi_{m,n},\\
&\qquad \forall n\in\mathcal{N},\\
&\mathrm{C}_3: t_{m,n}p_{\mathrm{c}} - E_{m,n} \leq 0, \quad \forall m\in\mathcal{M}, n\in\mathcal{N}\\
&\mathrm{C}_4: \sum_{m=1}^{M}\sum_{n=1}^{N} t_{m,n}\leq 1.
\end{aligned} \tag{57}$$

where C_2 is related with (39). It's easy to verify that the optimization problem in (57) is convex and can be solved via the dual decomposition, similarly to (24).

V. Extension to a non-linear EH model

Apart from linear EH models in WPNs, non-linear models have been also proposed in the literature, which can capture more accurately the limitations of the devices and are considered to be more practical [30]. In the aforementioned work, authors proposed a non-linear EH model, where the n-th user's harvested power, for a single BS case is given by

$$\Phi_{\mathrm{EH},n} = \mathrm{A}\frac{1-e^{-\alpha g_n P_0}}{1+e^{-\alpha(g_n P_0-\beta)}}, \tag{58}$$

where A denotes the maximum power that receiver can harvest, while α and β, express physical harvest phenomena. Thus, indeed is possible to introduce a non-linear energy harvesting model, for the centralized implementation. In addition to this, in multi-RRH TDMA and NOMA protocols, the extension to non-linear model is also possible, since users are harvesting energy by all RRHs for equal time intervals. More, specifically in this case the total harvested power of n-th user, by all RRHs can be written as

$$\Phi_{\mathrm{EH},n} = \mathrm{A}\frac{1-e^{-\alpha\sum_{m=1}^{M}\tilde{P}_0 g_{m,n}}}{1+e^{-\alpha(\sum_{m=1}^{M}\tilde{P}_0 g_{m,n}-\beta)}}, \tag{59}$$

where $\tilde{P}_0 = P_0/M$, while the total harvested energy is given by $E_{H,n} = (1-T)\Phi_{\mathrm{EH},n}$.

Next, we will proceed to the derivation of users' total harvested energy, in the case of PAT-TDMA. Without loss of generality, we consider that $\tau_1 < \tau_2 < \ldots < \tau_M$. According to the non-linear EH model, the total harvested energy of the n-th user can be written as follows

$$E_{H,n} = \sum_{k=1}^{M}(z_{k,n}-z_{k-1,n})\Phi_{\mathrm{EH,k,n}} \quad ,\forall n\in\mathcal{N}, \tag{60}$$

TABLE I
PROTOCOLS DESCRIPTION

Protocol	Network Architecture	Description
NOMA	Centralized	Users harvest energy for equal time intervals and transmit information via NOMA.
TDMA	Centralized	Users harvest energy for equal time intervals and transmit information via TDMA.
Multi-RRH NOMA	Decentralized	Users harvest energy by all RRHs for equal time intervals, while they select the "best" RRH, which maximizes the objective, to transmit information via NOMA.
Multi-RRH TDMA	Decentralized	Users harvest energy by all RRHs for equal time intervals, while each user select the "best" RRH, according to his channel gains, to transmit information via TDMA.
PAT-TDMA	Decentralized	Different time intervals for energy transferring are assigned to each RRH, while this happens in a successive manner in the beginning of the time slot. Also, for each user, the time instant that his energy harvesting procedure terminates, is specified. The information transmission follows, through TDMA.
FAT-TDMA	Decentralized	For each user, different information transmission time intervals are assigned to each RRH, while TDMA is utilized. Unless an RRH is receiving information messages, is able to transfer energy to the users, while users are constantly harvesting energy, unless they transmit information signals.

where $\Phi_{\mathrm{EH,k,n}}$ is given by

$$\Phi_{\mathrm{EH,k,n}} = A\frac{1-\exp(-\alpha\sum_{i=k}^{M}\tilde{P}_0 g_{i,n})}{1+\exp(-\alpha(\sum_{i=k}^{M}\tilde{P}_0 g_{i,n}-\beta))}, \quad \forall n\in\mathcal{N}, \tag{61}$$

while we define $z_{0,n}\triangleq 0$, for the notational consistency of the formulas. In the continue, we will provide an example according to Fig. 2, in order to verify the formulated expressions. From Fig. 2, we get $z_{1,n}=\tau_1$, $z_{2,n}=\tau_2$ and $z_{3,n}=\tilde{\tau}_n$. Thus, the total harvested energy of user n, according to (60), is given by

$$\begin{aligned} E_{H,n} = \tau_1 &\left(A\tfrac{1-\exp(-\alpha\tilde{P}_0(g_{1,n}+g_{2,n}+g_{3,n}))}{1+\exp(-\alpha(\tilde{P}_0(g_{1,n}+g_{2,n}+g_{3,n})-\beta))}\right) \\ &+(\tau_2-\tau_1)\left(A\tfrac{1-\exp(-\alpha\tilde{P}_0(g_{2,n}+g_{3,n}))}{1+\exp(-\alpha(\tilde{P}_0(g_{2,n}+g_{3,n})-\beta))}\right) \\ &+(\tilde{\tau}_n-\tau_2)\left(A\tfrac{1-\exp(-\alpha\tilde{P}_0 g_{3,n})}{1+\exp(-\alpha(\tilde{P}_0 g_{3,n}-\beta))}\right). \end{aligned} \tag{62}$$

The insights of this expression is that for τ_1 duration, the n-th user is harvesting energy by all RRHs, for $(\tau_2-\tau_1)$ by the 2^{nd} and 3^{rd} RRH, while for $(\tilde{\tau}_n-\tau_2)$ only by the 3^{rd} RRH. This observation can be also verified by Fig. 2. Following this analysis and by observing that $E_{H,n}$ in (60), is a linear function with respect to $\mathbf{z}$, it is evident that the linear EH model can be extended to a non-linear one, since the convexity of the corresponding optimization problem will be preserved.

Finally, analyzing the case of FAT-TDMA with a non-linear model cannot offer any further insights, due to the structure of the considered protocol that in combination with the non-linear model makes the corresponding expressions intractable.

VI. PERFORMANCE EVALUATION AND DISCUSSION

The proposed protocols for both centralized and decentralized network implementation are summarized in Table I. In the continue, we assume that users are uniformly distributed in a disk with radius $r=20\,\mathrm{m}$ [30]. In the case of the centralized network architecture, the BS is located at the center of the disk, i.e., at the position $(0,0)$. On the other hand, in the case of decentralized implementation, when the number of RRHs is $M=2$, the RRHs are situated in the positions $(-10,0)$ and $(10,0)$. In addition, when the number of RRHs is $M=3$, we assume that the RRHs are located in the circumference of a circle with radius $r'=10\,\mathrm{m}$, while they form the vertices of a equilateral triangle. The directional antenna gains of all nodes are 7.5 dBi. Furthermore, we assume that in multiple-RRH case, the RRHs' transmit power is $\tilde{P}_0=P_0/M$, where $P_0(\mathrm{Watt})$ is the transmit power of the BS in the single-BS case. Thus, the total transmit power is equal for both network implementations and the comparison is considered to be fair. In addition, the noise power spectral density is $N_{\mathrm{o}}=-174$ dBm/Hz. The available bandwidth is 1 MHz at a carrier center frequency of 470MHz. The TGn path loss model is adopted, with the breakpoint distance being 5 m. We assume the free space loss with slopes of 2 and 3.5 before and after the breakpoint, respectively [31]. Finally, the energy harvesting efficiency has been set $\eta=0.6$.

In Fig. 5, the average Pareto Front between sum throughput and minimum throughput is illustrated, via Monte Carlo simulations. The circuit power consumption is considered to be negligible i.e., $p_c=0$, the transmit power has been set $P_0=40\,\mathrm{dBm}$, while the total number of users is $N=2$. Finally, each point of the Pareto Front corresponds to a specific value selection of the weighting factor $w\in[0,1]$.

For the single-BS case, NOMA totally dominates TDMA, since for equal sum throughput values, NOMA always presents higher minimum throughput. Note that in this case, both multiple access schemes, achieve the same maximum sum-throughput, as was concluded in [11], while NOMA provides more fairness. Following that, the use of the decentralized architecture, i.e., multiple-RRH protocols, significantly improve the performance in terms of achievable data rate. This result, lies to the fact that in the case of distributed implementation, users' average distance from the RRHs is smaller, while this can lead in obtaining better channel gains. It should be highlighted that, this was the main motive for introducing the decentralized architecture in WPNs. Hence, it is reasonable that users can enhance their performance compared to the centralized network. Finally, the FAT-TDMA scheme exhibits the best performance among all protocols, while PAT-TDMA

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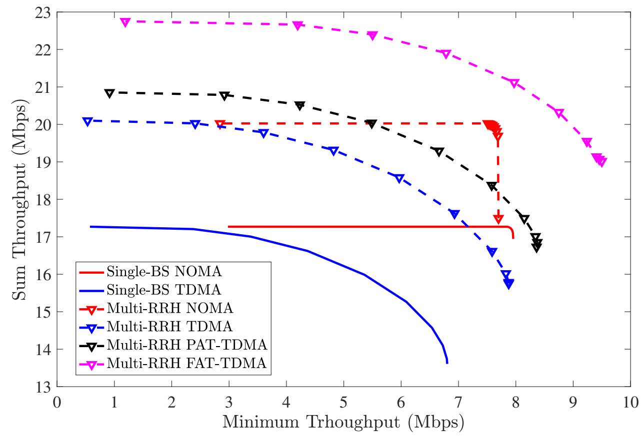

Fig. 5. Average Pareto Front for $N = 2$ users, $M = 2$ RRHs and $p_c = 0$.

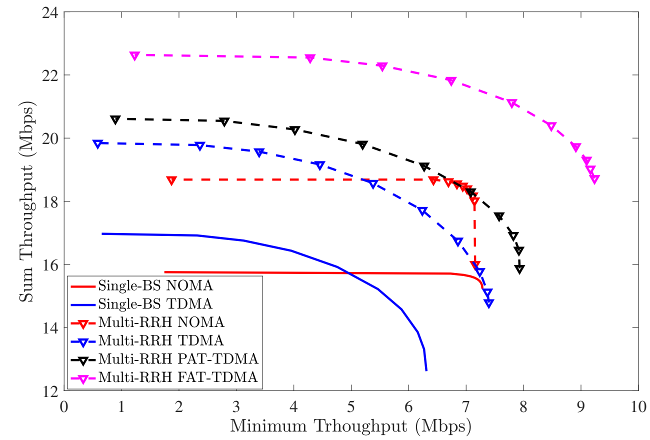

Fig. 7. Average Pareto Front for $N = 2$ users, $M = 2$ RRHs and $p_c = 0.1$mW.

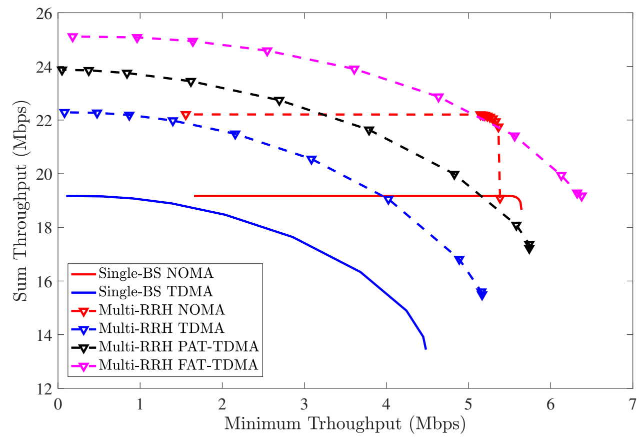

Fig. 6. Average Pareto Front for $N = 3$ users, $M = 2$ RRHs and $p_c = 0$.

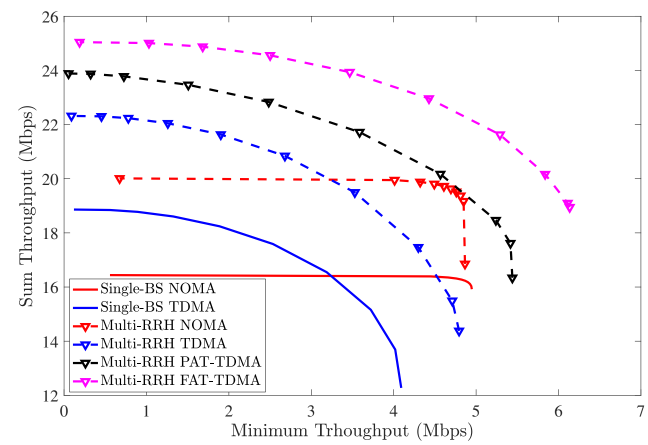

Fig. 8. Average Pareto Front for $N = 3$ users, $M = 2$ RRHs and $p_c = 0.1$mW.

and multiple-RRH NOMA follow. Similar observations can be seen in Fig. 6, where the average Pareto front for $N = 3$ users is demonstrated.

In Fig. 7 and Fig. 8 the circuit consumption is considered to be non-negligible and has been set $p_c = 0.1$mW [32]. The presence of circuit power consumption degrades the performance of all protocols and specially the minimum throughput. We further observe that NOMA performance in sum throughput, is degraded for both single-BS and multiple-RRH case. This is reasonable, since NOMA is more prone to the effects of circuit consumption, when the aim is to achieve high sum throughput [15]. On the other hand, partially and fully AT-TDMA preserve their efficiency, compared to the considered protocols. Finally, in Fig. 9, the number of RRHs has been set as $M = 3$. It is observed that the inclusion of an additional RRH into the network, enhances the users' performance in terms of achievable data rate, in comparison with the case of $M = 2$ RRHs, in Fig. 6. Thus, the significance of the decentralized network architecture, as a measure for mitigating the doubly near-far effect in WPNs, is being once again corroborated.

At this point, some significant observations concerning the multi-RRH protocols will be discussed. Firstly, it can be

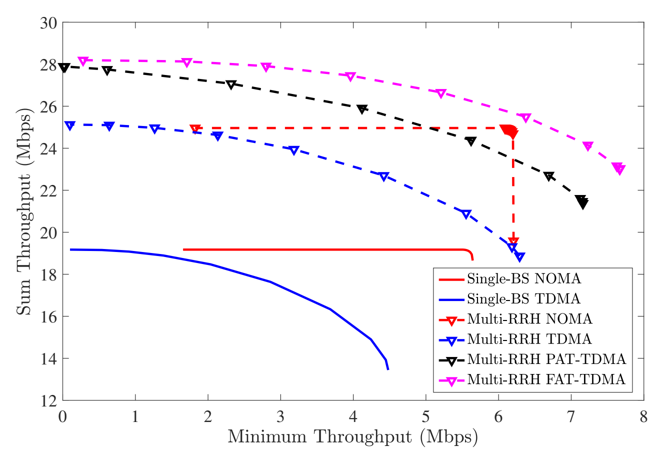

Fig. 9. Average Pareto Front for $N = 3$ users, $M = 3$ RRHs and $p_c = 0$.

easily verified that PAT-TDMA always outperforms the multi-RRH TDMA scheme. Notice that by setting $\tau_m = \tilde{\tau}_n = 1 - T, \quad \forall m \in \mathcal{M}, n \in \mathcal{N}$, PAT-TDMA is reduced to the multi-RRH TDMA. The insight for this observation lies to the

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fact that, by enforcing all RRHs to transfer energy for equal time intervals, while all users harvest energy for the same intervals i.e., $1-T$, the multi-RRH TDMA protocol is being enforced. Secondly, FAT-TDMA always outperforms PAT-TDMA. Recall that FAT-TDMA enables a flexible scheduling of the intervals, where the RRHs operate in energy transferring or information reception mode, while users operate in energy harvesting or information transmission mode, respectively. Thus, FAT-TDMA encourages users to never be idle, i.e., during a time slot users are capable of constantly harvesting energy or transmitting information messages. In opposition to this, in PAT-TDMA, RRHs terminate the energy transferring procedure in a successive manner (Fig. 2 and Fig. 3, provide insights for this statement). Therefore, FAT-TDMA is able to schedule the RRHs' and users' operating mode intervals, similarly to the PAT-TDMA protocol, i.e., be reduced to PAT-TDMA. As a consequence, the performance of FAT-TDMA will be equal or better to the PAT-TDMA one. Finally, the aforementioned observations are clearly verified in all figures, which are entailed in the performance evaluation section.

As discussed previously FAT-TDMA outperforms PAT-TDMA. However, the requirements of continuous synchronization between users and RRHs, in order to ensure the rapid transition among operational states, i.e., from energy harvesting to information transmission and from information reception to energy transferring, may lead to increased overhead and complex implementation of the FAT-TDMA protocol. Therefore, PAT-TDMA could be an alternative option for a more realistic and less complex implementation, even if it's performance is decreased compared to the FAT-TDMA.

VII. Conclusion

In this paper we have proposed and investigated the use of a decentralized network architecture in WPNs, in order to alleviate the doubly near-far problem. We jointly maximized the sum and minimum throughput among users, firstly for the single-BS and then for the multiple-RRH case, i.e., decentralized implementation. Through this analysis, the Pareto Front of the considered objectives was obtained and the trade-off between system throughput and minimum data rate was evaluated. Furthermore, the utilization of NOMA and TDMA protocols was investigated. Finally, we proposed two protocols, the partially and fully asynchronous transmission TDMA, where users are harvesting energy in different time intervals and transmit information messages in different time instants. An interesting conclusion of this work, is that decentralized network architecture can enhance the spectral efficiency, compared to the traditional single-BS case in WPNs. In addition, the proposed AT-TDMA protocols can offer substantial improvement in terms of achievable data rate. At last, the consideration of RRHs' cooperation during the SIC process of NOMA protocol, is an interesting topic for future work.

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