

Relay-Centric Two-Hop Networks With Asymmetric Wireless Energy Transfer: Stackelberg Games

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Abstract—This paper studies two-hop networks with wireless energy transfer (WET) consisting of one source and multiple relay–destination pairs. We focus on relays’ primary interest of sending their own messages to the associated destinations. As an incentive for relaying, WET is offered by the source to relays who forward source data as a return. We propose an asymmetric WET (AWET) model, where relays receive source signals one by one but those waiting longer are able to accumulate more energy by harvesting from earlier signals. We also consider symmetric WET, broadcast WET, and independent WET for comparison, where source signals can either be harvested by all relays via time-division, or via broadcasting, or harvested by intended relays exclusively. We adopt the framework of Stackelberg game to capture the self-interest and hierarchically competing nature of nodes. The relay–destination pairs play as leaders and the source–destination pairs as followers. The existence and the uniqueness of the Stackelberg equilibrium (SE) are shown, and a best-response-based algorithm that achieves the SE is provided. Simulation results demonstrate that the AWET protocol outperforms the others.

Index Terms—Wireless energy transfer, two-hop networks, Stackelberg games, Stackelberg equilibrium.

I. INTRODUCTION

IN RECENT years, the pervasive deployment of wireless nodes has highlighted the issue of ever-increasing energy consumption in wireless communication networks. Energy harvesting networks, where wireless nodes can harvest energy from natural sources, such as solar radiation, or dedicated sources, for instance, radio frequency (RF) beams, have garnered interest as a promising solution for perpetual energy self-sufficient operation [2]–[12]. Wireless energy transfer (WET) by RF energy harvesting is accomplished by transferring energy as RF signals from energy-abundant wireless nodes to energy-deprived ones [13]–[15]. In addition to data transmission cooperation in conventional wireless systems, WET can be viewed as a special case of energy cooperation, new dimension for cooperation among wireless nodes in addition to signal relaying [16], [17]. Significant research effort

has focused on WET from different perspectives, for instance, the trade-off between data transmission and energy harvesting in various systems, practical issues in the implementation of WET, see [13]–[15], [18] and references therein.

One such direction focuses on wireless information and power transfer (WIPT) in relay networks. A relay network with WET was proposed in [19], where the relay is energy-constrained and harvests energy from the received RF signals to forward the source’s information. Both power splitting and time switching energy harvesting protocols are investigated. Following this two-hop model, growing research has studied WIPT relay networks in terms of optimal energy harvesting protocol design, full duplex relaying (FD), relay selection, and so on [20]–[23]. Another line of research considers wireless powered communication networks (WPCN), which was proposed in [24]. WPCN refers to the system that a set of users without energy access harvest energy from an access point (AP) or a power beacon in downlink and transmit information to the AP in uplink using the harvested energy. This model has been extended to the setup with full duplex AP in [25]. Based on these models, [26] proposed a relaying cooperative communication network with the destination working as the power beacon.

In wireless sensor networks, energy harvesting sensors could experience energy shortage periods when natural energy sources may be unavailable, rendering communication infeasible even if there are favorable channel conditions to fusion centers (destinations). Conversely, there could be sensors with stable energy supplies but poor channels to destinations. Thus, a viable solution to enable all is *energy and signal* cooperation between these two parties. In this paper, we study a two-hop network with one source and multiple relay–destination pairs, where the source is energy-rich but has poor channels to the destinations and the relays are energy-deficient but have better channels to the destinations. The cooperation between the source and the relays in energy transfer and data transmission is of interest. We consider that the source and the relays belong to different service operators; thus are noncooperative when left to their own devices and need incentives to cooperate. They are selfish in the sense that each node aims to transmit its own data to the associated destination. With the competitive objectives of the source and the relays, we study two-hop systems with relay-centric objectives by Stackelberg games. The framework of Stackelberg game models the hierarchical competition among players. The players with competitive advantage, namely, the leaders, form an upper-level game, and the followers play the lower-level game in response to the leaders’ strategies.

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In related work, a number of papers have investigated two-hop networks with WET from various game-theoretic perspectives [27]–[38]. Reference [27] considers multiple source-destination pairs competing for the assistance of an energy harvesting relay. An auction-based power allocation strategy is derived by solving a Nash game and the properties of the Nash equilibrium are discussed. In [28], a WIPT system with multiple source-destination pairs communicating through their dedicated relays is considered. A Nash game is formulated for the competition among relays whose strategies are the power splitting ratios. In [29], the relay has its own objective of harvesting energy and a Nash bargaining game is proposed to balance the information transmission efficiency of multiple source-destination pairs and the harvested energy of the relay. In [30], the energy trading in a WPCN is modeled as a Stackelberg game between an AP-user pair and multiple power beacons. The AP plays as the leader to determine downlink energy harvesting time and energy price, and power beacons as followers choose transmit powers to maximize the income of WET service. Reference [31] studies similar energy trading problem for a system with a multi-antenna power beacon and multiple energy harvesting users. Reference [32] extends the Stackelberg game with complete information to the scenario, where the AP is not aware of the channel state and the energy cost of power beacons, and expected utility of AP is maximized. Reference [33] considers a robust Stackelberg game in a WPCN with imperfect channel state information (CSI) between the users and the power beacon. Cognitive radio networks with energy harvesting are investigated in [34]–[36] via Stackelberg games. In [37], considering the data transmission objectives of both the source and the relays, a single-leader Stackelberg game is formulated for two-hop networks with WET, and Vickery auction is employed for relay selection. As an extension, [38] considers multi-leader-single-follower Stackelberg games allowing multiple relays to transmit in a multiple access channel (MAC) in the second hop and derives the existence and uniqueness properties of the equilibrium.

This paper considers a WET two-hop system with multiple relay-destination pairs. The source has its data delivered to destinations by a set of relays via decode-and-forward (DF) relaying. WET occurs in the first hop from the source to the relays to supply energy for data transmission in the second hop. Each relay receives information and harvests energy from the source intended signal in a time switching manner [39]. Relays are allowed to harvest energy from signals intended for other relay nodes. By this means, we introduce interactions among relays on wireless energy harvesting. For the second hop, orthogonal channels by time-division are used for multiple relay-destination transmission. Built upon this system model, we highlight the contributions of this paper as follows.

1) We propose an asymmetric wireless energy transfer (AWET) protocol. More specifically, with a time-division transmission protocol in the first hop, each relay, in addition to harvesting energy from its dedicated signal sent by the source, while waiting for its turn to receive source information, it also harvests from previously transmitted signals to other relays. Thus, asymmetry in terms of energy accumulation and wait time arises,

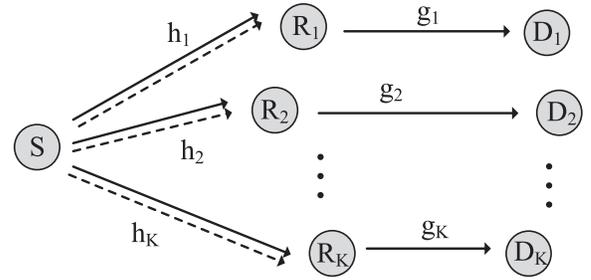


Fig. 1. The two-hop network with wireless energy transfer. Solid lines and dash lines indicate information transmission and energy transfer, respectively.

where relays with longer wait have opportunities to harvest more energy at the expense of delay.¹

- 2) Multi-leader-follower Stackelberg games are formulated to capture the hierarchical competition between the source and relays. We incorporate data rate, energy cost and delay in the utility functions of players. The existence of Stackelberg equilibrium (SE) is shown and a sufficient condition of the uniqueness of SE for AWET is proved.
- 3) We show that the AWET model achieves higher utility and average rate for relays, which implies that the asymmetry of energy accumulation and delay improves the performance of each agent in the network. We also find that the competitive interaction on wireless energy transfer facilitates to save energy and improves energy efficiency in WET.

The remainder of the paper is organized as follows. In Section II, we describe the two-hop network and propose the asymmetric wireless energy transfer model AWET, as well as the models considered for comparison, i.e., symmetric wireless energy transfer (SWET), broadcast wireless energy transfer (BCWET), and independent wireless energy transfer (IWET). In Section III, we introduce the framework of Stackelberg games with multiple leaders and followers. We formulate and solve the multi-leader-follower Stackelberg games for AWET and SWET models. In Section IV, we formulate single-leader-follower Stackelberg games for BCWET and IWET models and derive the optimal strategies. In Section V, we present the simulation results for all proposed models and verify our analytical findings. Section VI concludes the paper.

II. SYSTEM MODEL

We consider a two-hop relay network consisting of one source, multiple relays, and multiple destinations shown in Fig. 1. The source (S) transmits information to K destinations, D_k , $k = 1, \dots, K$, via K relays, R_k , $k = 1, \dots, K$, that are capable of energy harvesting, i.e., each destination (D) has one subscribed relay (R) to help forward signals in half duplex mode. Decode-and-forward (DF) relaying is adopted. Let $\mathcal{K} = \{1, 2, \dots, K\}$ denote the set of R-D pairs. We consider the setup where direct channels are too weak to be useful and thus only include the channels of S-R and R-D pairs within

¹We note that this is distinct from [40], [41], which also allow nodes to harvest energy from peer nodes' signals or interference signals without this deliberate asymmetry.

the two-hop network. In order to convey messages to destinations, the source provides wireless energy transfer to relays as a trade for relaying service. Each relay has the primary goal of transmitting its own information to the associated destination. The relays, however, do not have power supplies and thus are considered to operate only with the energy harvested from the source's signals to sustain transmission. The source's information is forwarded by the relays as a return for getting wireless energy transfer from the source. Energy is harvested at relays in a time switching manner, i.e., time division, during the first hop transmission.

The two-hop transmission completes in two time slots, where each hop occupies one slot of duration one second. For the k th S-R-D channel, the source transmits to relay k with power p_k in the first hop, and then the relay uses the harvested energy to transmit to destination k subsequently in the second hop. We consider a system with low mobility such that the channels are quasi-static over the two hops. The channel state information (CSI) is known at the respective transmitters and receivers. The source to relay and relay to destination channel gains are denoted by h_k and g_k , respectively, $\forall k \in \mathcal{K}$. We note that the analysis readily extends to fading channels with known CSI, in which case h_k and g_k represent the channel fading level of the corresponding communication time slot. For wireless energy transfer, we consider four different models for the first hop for thorough comparison, namely, asymmetric WET (AWET), symmetric WET (SWET), broadcast WET (BCWET), and independent WET (IWET) as will be described shortly.

In the second hop, we adopt time division transmission, where each relay is assigned a $1/K$ long subslot to transmit to its destination. Note that time division in the second hop of AWET model is due to the asymmetry in the first hop, where the asymmetry is introduced to allow the relays harvest more energy at the cost of waiting, as explained shortly in Section II-A. Consequently, interference from other R-D pairs is avoided. For the sake of a fair comparison, the same type of protocol in the second hop is also deployed in the variants of SWET, BCWET, and IWET, i.e., they only differ from the AWET in the energy transfer scheme in the first hop. We also remark that a K -user interference channel in the second hop could be considered for each protocol. However, this would decidedly complicate the notation and formulation, and would still, in general, be suboptimal since treating interference as noise, or decoding interference (the two known techniques), are only known to be optimal in certain interference regimes. Thus, we opt for a simpler protocol that highlights the impact of energy harvesting protocol in the first hop.

The harvested energy in the first hop is exploited for sending relay's own information and forwarding the source's signals in the second hop. Let $E_{R_k}^M$ denote the available energy for the second-hop transmission obtained from wireless energy transfer for relay k , $M \in \{\text{AWET}, \text{SWET}, \text{BC}, \text{IWET}\}$. The transmit power of relay is $p_{R_k}^M = KE_{R_k}^M, \forall k$. The instantaneous transmission rate of relays is given by

$$R_{R_k}^M = \log \left(1 + \frac{g_k p_{R_k}^M}{\sigma^2} \right), \quad (1)$$

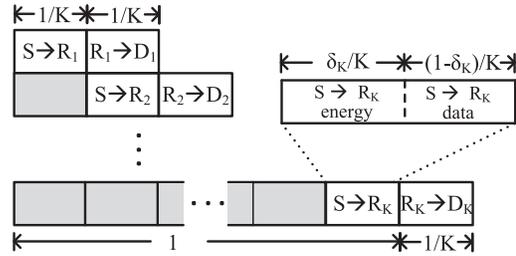


Fig. 2. Two-hop transmission protocol with asymmetric wireless energy transfer.

where σ^2 denotes the variance of Gaussian noise with zero mean at all nodes in the system. Next, we characterize different wireless energy transfer models in the first hop. The first one is our proposed new model, and the others are comparative models described for the sake of completeness.

A. Asymmetric Wireless Energy Transfer (AWET)

As shown in Fig. 2, the source communicates with the K relays one by one by time division. Specifically, the source transmits to relays in a predefined order.² Each relay is assigned a subslot of duration $1/K$ second, which is divided into the energy transfer fraction over time δ_k/K and the information transmission fraction over time $(1-\delta_k)/K$ with $\delta_k \in [0, 1]$. The instantaneous transmission rate of source is given by

$$R_{S_k} = \log \left(1 + \frac{h_k p_k}{\sigma^2} \right). \quad (2)$$

We propose asymmetric wireless energy transfer (AWET), where each relay harvests energy from existing RF signals in the network until it is its turn to receive source's data. After receiving source's data, the relay transmits immediately to its associated destination using the harvested energy. More specifically, when waiting for its turn of source access, relay k harvests from both the source signals intended for previous $k-1$ relays and the transmitted signals of relay $1, 2, \dots, k-2$, one by one over each subslot of duration $1/K$, i.e., over $\frac{k-1}{K}$ seconds in total. During its energy harvesting interval δ_k/K in the k th subslot, it harvests from its dedicated signal with power p_k , as well as the signal transmitted by relay $k-1$.

For RF energy harvesting, the energy conversion efficiency, i.e., the ratio between harvested power and the received power, is, in general, a nonlinear function of the received power [39], [42], [43], where the received power is dominated by the transmit power and the path loss. Specifically, the conversion efficiency is zero when the received power is below the sensitivity threshold and a constant when the received power is above the saturation threshold. Between the sensitivity and saturation thresholds, it can be approximated as a piecewise linear function of the received power. To enable RF energy harvesting, we consider a communication scenario without loss of generality that the range of the transmit power avoids the sensitivity effect. Moreover, in order to simplify the analysis, we assume an empirical constant $\eta_k, \forall k \in \mathcal{K}$, is chosen for relay

²The access order of relays could be determined based on the channel state or the priority of destinations in the system.

k based on measurements so that η_k denotes the portion of the received energy that is available for the second-hop transmission and $1 - \eta_k$ fraction of the energy captures the loss due to energy conversion, circuitual processing, and all relevant signal processing. Thus, the harvested energy that is available for the transmission to destination k is

$$E_{R_k}^{\text{AWET}} = \frac{\eta_k}{K} \left[\sum_{i=1}^{k-1} h_k p_i + \sum_{i=1}^{k-2} l_{i,k} p_{R_i}^{\text{AWET}} + \delta_k \left(h_k p_k + l_{k-1,k} p_{R_{k-1}}^{\text{AWET}} \right) \right], \quad (3)$$

where $l_{i,k}$ is the channel gain between relay i and relay k . In particular, the first two terms represent the harvested energy from the source and previous relays in the first $k-1$ subslots and the last term is the harvested energy in the k -th subslot. In this proposed protocol, relays can harvest more energy at the cost of delay. There are multiple routes for one energy beam to be harvested at relay k . For instance, p_1 can be harvested via routes $1-k$, $1-2-k$, $1-3-k$, $1-2-3-k$, and so on, where $1-j-k$ means p_1 is first harvested by relay j , then, relay k harvests from relay j 's signal. Due to the large attenuation caused by the product of channel coefficients, in the sequel, we only take into account harvesting energy beams that are attenuated by at most two channel coefficients.³ That is, the routes in the form of $i-k$ and $i-j-k$, $\forall i, j \in \mathcal{K}$, are counted for energy harvesting at relay k , $\forall k \in \mathcal{K}$. After some arrangement, $E_{R_k}^{\text{AWET}}$ can be expressed as

$$E_{R_k}^{\text{AWET}} = \frac{1}{K} \left[p_k h_{k,k} \delta_k + p_{k-1} (h_{k,k} + h_{k-1,k} \delta_{k-1} \delta_k) + \sum_{i=1}^{k-2} p_i \left(h_{k,k} + h_{k-1,k} \delta_k + h_{i,k} \delta_i + \sum_{j=i+1}^{k-2} h_{j,k} \right) \right], \quad (4)$$

where $h_{k,k} \triangleq \eta_k h_k$ and $h_{i,k} \triangleq \eta_i h_i \eta_k l_{i,k}$ for $i \neq k$.

Remark 1: We consider equal-length subslots for all relays in the two hops. The slot-duration and the scheduling for the relays could be optimized to further improve the system performance, which are interesting future directions.

B. Symmetric Wireless Energy Transfer (SWET)

For symmetric wireless energy transfer (SWET), see Fig. 3, relays receive their dedicated signals from the source one by one as in AWET model in a predefined order. δ_k is dedicated for energy transfer to relay k in each subslot. The instantaneous source rate R_{S_k} is given in (2). Each relay, while being idle, can also harvest energy by listening to the signals intended for all other relays throughout the entire remaining duration of the first hop transmission. Thus, energy harvesting proceeds in a symmetric manner throughout the first hop session, and the second hop starts after all relays receive source's information.

³This simplification does not change the form of energy harvesting expression or problem formulation in the paper.

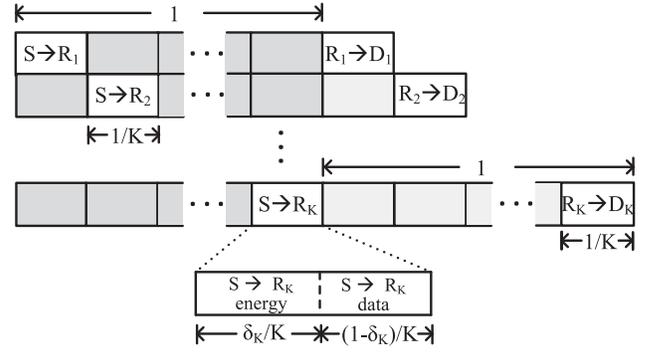


Fig. 3. Two-hop transmission protocol with symmetric wireless energy transfer.

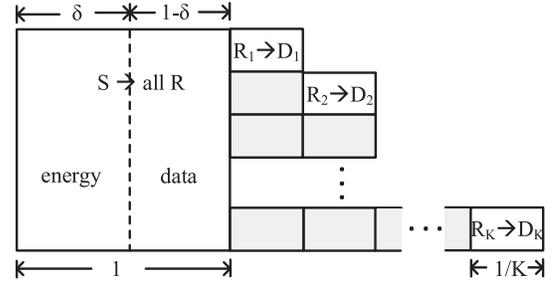


Fig. 4. Two-hop transmission protocol with broadcast wireless energy transfer.

In the second hop, relay k keeps harvesting energy from the earlier $k-1$ transmitted signals, then uses all harvested energy for transmission to the associated destination. The harvested energy is expressed by

$$E_{R_k}^{\text{SWET}} = \frac{1}{K} \sum_{i=1}^k h_{i,k} \left(p_i \delta_i + \sum_{j=1, j \neq i}^K p_j \right), \quad (5)$$

where $h_{i,k}$ is defined in (4).

C. Broadcast Wireless Energy Transfer (BCWET)

In the broadcast wireless energy transfer (BCWET) model, see Fig. 4, the source broadcasts to all relays with power p_k for all k throughout the first hop. Energy and information transfer proceed at all relays for time δ and $1-\delta$ seconds, respectively. Independent messages are sent to relays using superposition coding. Each relay decodes its dedicated information by decoding and canceling the signals intended for the relays with degraded channels before decoding its own. The rate at each relay is

$$R_{S_k}^{\text{BC}} = \log \left(1 + \frac{h_k p_k}{\sigma^2 + h_k \sum_{i: h_i \geq h_k} p_i} \right). \quad (6)$$

In the second hop, time-division multiple access is used, same as in Section II-B. Relays harvest energy until it is their turn to transmit. The harvested energy for second-hop transmission at each relay is given by

$$E_{R_k}^{\text{BC}} = \delta \left(\sum_{i=1}^K p_i \right) \left(\sum_{i=1}^k h_{i,k} \right), \quad (7)$$

where $h_{i,k}$ is defined in (4). Noting that successive inference cancellation (SIC) at the relays may require extra energy for signal processing, here, for comparison we consider the best case scenario for BCWET that the relays can use all available energy for second-hop transmission.

D. Independent Wireless Energy Transfer (IWET)

Independent wireless energy harvesting model (IWET) is the baseline model, where each relay only harvests energy from the source signal intended for itself. In other words, the relays are only active in energy harvesting over time δ_k/K , $\forall k$, in their assigned subslots. Using the harvested energy $E_{R_k}^{\text{IWET}}$, relay k transmits to its paired destination immediately after receiving source's data. The source rate is given as (2). $E_{R_k}^{\text{IWET}}$ is characterized by

$$E_{R_k}^{\text{IWET}} = \frac{1}{K} h_{k,k} p_k \delta_k. \quad (8)$$

In the next section, we formulate and solve multi-leader-follower Stackelberg games for two-hop networks with AWET and SWET. Then, we will extend the formulations and solutions for single-leader-follower Stackelberg games of other models in Section IV.

III. MULTI-LEADER-FOLLOWER STACKELBERG GAMES FOR TWO-HOP NETWORKS

In the two-hop network under consideration, the source and the relays are primarily interested in transmitting their individual information to the corresponding destination. To capture the selfish nature of each node and the hierarchical competition between the source and relays, we adopt the framework of Stackelberg games. In general, a multi-leader-follower Stackelberg game consists of multiple upper-level players, the leaders, and a group of lower-level players, the followers. Each leader has the advantage of being able to choose its strategy by anticipating the followers' strategies and compete with the other leaders. The followers compete with each other and choose their strategies in response to the leaders' strategies [44]. Thus, an outer game among the leaders and an inner game among the followers are played. We consider static games with a group of rational players. Each player knows the complete and perfect information of the set of players, the set of strategies and the utility functions of all players, and does best response [45].

In our relay-centric system with AWET and SWET, we have the R-D pairs as leaders and the S-D pairs as followers. The leader k , i.e., the R-D pair k , determines the strategy, δ_k that maximizes its utility U_{R-D_k} . The follower k , i.e., the S-D pair k , maximizes its utility U_{S-D_k} by choosing its strategy, the transmit power p_k . We denote $\boldsymbol{\delta} \triangleq (\delta_1, \dots, \delta_K)$ the strategies of leaders, $\boldsymbol{\delta}_{-k} \triangleq (\delta_1, \dots, \delta_{k-1}, \delta_{k+1}, \dots, \delta_K)$ the strategies of leaders except leader k , $\mathbf{p} \triangleq (p_1, \dots, p_K)$ the strategies of followers, and $\mathbf{p}_{-k} \triangleq (p_1, \dots, p_{k-1}, p_{k+1}, \dots, p_K)$ the strategies of followers except follower k . The Stackelberg equilibrium (SE) is defined as follows [44].

Definition 1: Let δ_k^* and p_k^* , $\forall k$, be the optimal strategies for leaders and followers, respectively. $(\boldsymbol{\delta}^*, \mathbf{p}^*)$ is a SE for

the multi-leader-follower Stackelberg game if for any feasible strategy $(\boldsymbol{\delta}, \mathbf{p})$

$$U_{R-D_k}(\delta_k^*, \boldsymbol{\delta}_{-k}^*, \mathbf{p}^*) \geq U_{R-D_k}(\delta_k, \boldsymbol{\delta}_{-k}^*, \mathbf{p}^*), \quad \forall k \in \mathcal{K}, \quad (9)$$

$$U_{S-D_k}(\mathbf{p}_k^*, \mathbf{p}_{-k}^*, \boldsymbol{\delta}^*) \geq U_{S-D_k}(p_k, \mathbf{p}_{-k}^*, \boldsymbol{\delta}^*), \quad \forall k \in \mathcal{K}. \quad (10)$$

Next, we define the utility functions and solve for SE of the multi-leader-follower Stackelberg game for AWET and SWET models.

A. AWET

We first focus on the Stackelberg game for AWET. The utility of the follower S-D pair is defined as the net revenue of sending data with the consideration of energy cost, which is averaged over transmission completion time $(k+1)/K$ for $k = 1, \dots, K$.

$$\begin{aligned} U_{S-D_k}^{\text{AWET}} &= \frac{1}{k+1} [(1-\delta_k)R_{S_k} - \mu p_k] \\ &= \frac{1}{k+1} \left[(1-\delta_k) \log \left(1 + \frac{h_k p_k}{\sigma^2} \right) - \mu p_k \right], \end{aligned} \quad (11)$$

where $\mu \geq 0$ denotes the cost per energy unit, which is fixed for all k . The principal purpose of each relay is to convey its own message to the corresponding destination. Thus, the leader utility is defined as the time-averaged transmission rate of relay's data, and is given by

$$\begin{aligned} U_{R-D_k}^{\text{AWET}} &= \frac{1}{k+1} \left[R_{R_k}^{\text{AWET}} - (1-\delta_k)R_{S_k} \right] \\ &= \frac{1}{k+1} \left[\log \left(1 + \frac{g_k p_{R_k}^{\text{AWET}}}{\sigma^2} \right) - (1-\delta_k) \log \left(1 + \frac{h_k p_k}{\sigma^2} \right) \right], \end{aligned} \quad (12)$$

where

$$\begin{aligned} p_{R_k}^{\text{AWET}} &= p_k h_{k,k} \delta_k + p_{k-1} (h_{k,k} + h_{k-1,k} \delta_{k-1} \delta_k) \\ &\quad + \sum_{i=1}^{k-2} p_i \left(h_{k,k} + h_{k-1,k} \delta_k + h_{i,k} \delta_i + \sum_{j=i+1}^{k-2} h_{j,k} \right). \end{aligned} \quad (13)$$

The game is formulated as that the followers determine their strategy p_k , $\forall k$, by solving

$$\max_{p_k \in [0, P]} U_{S-D_k}^{\text{AWET}}, \quad (14)$$

where P is the maximum transmit power. Each leader solves the following optimization problem to choose its strategy δ_k , $\forall k$.

$$\max_{\delta_k \in [0, 1]} U_{R-D_k}^{\text{AWET}} \quad (15)$$

The SE of the proposed game can be solved by backward induction. In particular, the source's strategy is analytically solved in the first step and substituted into each leader's optimization problem, then the SE can be found by solving the Nash equilibrium (NE) of the leaders' noncooperative game.

In the followers' game, problem (14) is convex with respect to p_k for given δ_k and independent of \mathbf{p}_{-k} . Applying the first-order optimality condition on the objective function yields

$$\frac{\partial U_{S-D_k}^{\text{AWET}}}{\partial p_k} = \frac{1}{k+1} \left[(1-\delta_k) \frac{h_k}{\sigma^2 + h_k p_k} - \mu \right] = 0. \quad (16)$$

Solving p_k and projecting to $[0, P]$ yields the follower strategy

$$p_k = \begin{cases} 0, & \text{if } \delta_k \in [\bar{\delta}_k, 1], \\ \frac{1-\delta_k}{\mu} - \frac{\sigma^2}{h_k}, & \text{if } \delta_k \in [\underline{\delta}_k, \bar{\delta}_k], \\ P, & \text{if } \delta_k \in [0, \underline{\delta}_k], \end{cases} \quad (17)$$

where $\bar{\delta}_k \triangleq 1 - \min\{1, \mu \frac{\sigma^2}{h_k}\}$ and $\underline{\delta}_k \triangleq 1 - \min\{1, \mu(\frac{\sigma^2}{h_k} + P)\}$. Note that p_k is nonincreasing in δ_k . As δ_k increases, $U_{S-D_k}^{\text{AWET}}$ decreases due to a shorter transmission phase. As a response, the source has to lower its transmission power to reduce the energy cost so as to maintain a positive utility. Furthermore, p_k is also nonincreasing in μ and nondecreasing in h_k , which implies p_k equals zero if μ is too large and/or h_k is too small. In this case, $U_{S-D_k}^{\text{AWET}}$ is zero due to zero transmit power. Without harvesting from p_k , relay k is still able to harvest energy from the other signals. However, since relay k does not receive data from the source, it becomes a free rider in the sense that it can transmit its own information by the harvested energy without forwarding source's data.

Now consider the leaders' game (15) only for $\delta_k \in [0, \bar{\delta}_k]$. When $\delta_k \in [0, \underline{\delta}_k]$, by plugging $p_k = P$ into (12), the leader utility $U_{R-D_k}^{\text{AWET}}$ increases on δ_k given δ_{-k} . This implies that the optimal δ_k that maximizes $U_{R-D_k}^{\text{AWET}}$ falls into the interval $[\underline{\delta}_k, \bar{\delta}_k]$. Thus, it suffices to focus on $\delta_k \in [\underline{\delta}_k, \bar{\delta}_k]$. By substituting $p_k = \frac{1-\delta_k}{\mu} - \frac{\sigma^2}{h_k}$ into (15), the leader's optimization problem can be rewritten as follows.

$$\begin{aligned} \max_{\delta_k \in [\underline{\delta}_k, \bar{\delta}_k]} U_{R-D_k}^{\text{AWET}} &= \frac{1}{k+1} \left[\log(A_k \delta_k^2 + B_k \delta_k + C_k) \right. \\ &\quad \left. - (1-\delta_k) \log\left(\frac{h_k}{\sigma^2 \mu} (1-\delta_k)\right) \right], \quad (18) \end{aligned}$$

where $A_k \triangleq -\frac{g_k h_{k,k}}{\sigma^2 \mu}$, $B_k \triangleq \frac{g_k}{\sigma^2} [h_{k,k} (\frac{1}{\mu} - \frac{\sigma^2}{h_k}) + h_{k-1,k} \delta_{k-1} (\frac{1-\delta_{k-1}}{\mu} - \frac{\sigma^2}{h_{k-1}}) + \sum_{i=1}^{k-2} h_{k-1,k} (\frac{1-\delta_i}{\mu} - \frac{\sigma^2}{h_i})]$, and $C_k \triangleq 1 + \frac{g_k}{\sigma^2} [h_{k,k} (\frac{1-\delta_{k-1}}{\mu} - \frac{\sigma^2}{h_{k-1}}) + \sum_{i=1}^{k-2} (\frac{1-\delta_i}{\mu} - \frac{\sigma^2}{h_i}) (h_{k,k} + h_{i,k} \delta_i + \sum_{j=i+1}^{k-2} h_{j,k})]$.

The following lemma states the concavity of the objective function.

Lemma 1: In the maximization problem (18), the objective function $U_{R-D_k}^{\text{AWET}}$ is a concave function with respect to δ_k for given δ_{-k} , $\forall k$.

Proof: We first show that $f_1(\delta_k) = \log(A_k \delta_k^2 + B_k \delta_k + C_k)$ is concave on δ_k . $f_1(\delta_k)$ can be viewed as a function composed by a logarithm function $h(g(x)) = \log(x)$ with a quadratic function $g(x) = A_k x^2 + B_k x + C_k$. We know h is concave and nondecreasing and g is concave due to $A_k < 0$. Then, f_1 is concave [46]. Furthermore, $f_2(\delta_k) = (1-\delta_k) \log(\frac{h_k}{\sigma^2 \mu} (1-\delta_k))$ is convex since the negative entropy function $x \log(x)$

is convex and composition with an affine mapping preserves convexity. Thus, $U_{R-D_k}^{\text{AWET}} = \frac{1}{k+1} (f_1 - f_2)$ is concave. ■

We now investigate the existence and the uniqueness of the SE. We denote the utilities of all leaders by $\mathbf{U}^{\text{AWET}} \triangleq (U_{R-D_1}^{\text{AWET}}, \dots, U_{R-D_K}^{\text{AWET}})$, and denote the strategy set of the leader game by $\mathcal{Q} \triangleq Q_1 \times \dots \times Q_K$, where $Q_k \triangleq [\underline{\delta}_k, \bar{\delta}_k]$ and \times denotes Cartesian product. Then, the leader game $\mathcal{G}^{\text{AWET}}$ is given by the triple $(\mathcal{K}, \mathcal{Q}, \mathbf{U}^{\text{AWET}})$, which is a noncooperative game. The SE of the multi-leader-follower Stackelberg game can be obtained by solving the Nash equilibrium (NE) of the noncooperative game $\mathcal{G}^{\text{AWET}}$. The existence of pure strategy NE can be guaranteed since $U_{R-D_k}^{\text{AWET}}$ is continuous and concave with respect to δ_k for given δ_{-k} , and the strategy set Q_k is nonempty, convex, and compact [47]. Furthermore, we derive a sufficient condition for the uniqueness of NE.

Theorem 1: The game $\mathcal{G}^{\text{AWET}}$ has a unique NE if $C_k > B_k$, $\forall k$.

Proof: Define matrix \mathbf{G} such that the k -jth entry is $[\mathbf{G}]_{kj} = \frac{\partial^2 U_{R-D_k}^{\text{AWET}}}{\partial \delta_k \partial \delta_j}$, $k, j = 1, 2, \dots, K$. Then, for the game $\mathcal{G}^{\text{AWET}}$ with Q_k convex and compact and $U_{R-D_k}^{\text{AWET}}$ continuous and concave with respect to δ_k , a sufficient condition for the uniqueness of NE is that $\mathbf{G} + \mathbf{G}^T$ is negative definite [48]. Note that \mathbf{G} is a lower triangular matrix since the k -jth element $[\mathbf{G}]_{kj} = 0$ for $j > k$. The diagonal element $[\mathbf{G}]_{kk}$ is calculated as

$$[\mathbf{G}]_{kk} = \frac{1}{k+1} \left[\frac{-2A_k^2 \delta_k^2 + 2A_k(C_k - B_k \delta_k) - B_k^2}{(A_k \delta_k^2 + B_k \delta_k + C_k)^2} - \frac{1}{1-\delta_k} \right]. \quad (19)$$

As $C_k > B_k$ and $0 \leq \delta_k \leq 1$, $C_k > B_k \delta_k$. Due to $A_k < 0$, we have $[\mathbf{G}]_{kk} < 0$. The eigenvalues of \mathbf{G} are its diagonal elements. This implies that \mathbf{G} is negative definite. So is \mathbf{G}^T . Hence, $\mathbf{G} + \mathbf{G}^T$ is indeed negative definite. This completes the proof. ■

The uniqueness of the NE implies the uniqueness of the SE of the proposed multi-leader-follower Stackelberg game for the AWET model. We apply Gauss-Seidel best-response-based algorithm to achieve the equilibrium [49]. Each leader, given the strategies of other leaders, plays its best response δ_k^* iteratively by solving problem (18). Due to the convexity of (18), δ_k^* can be obtained by solving the first-order optimality condition and projecting to the feasible interval. Taking the derivative of the objective function with respect to δ_k and equating to zero gives

$$\begin{aligned} \frac{\partial U_{R-D_k}^{\text{AWET}}}{\partial \delta_k} &= \frac{1}{k+1} \left[\frac{2A_k \delta_k + B_k}{A_k \delta_k^2 + B_k \delta_k + C_k} \right. \\ &\quad \left. + \log\left(\frac{h_k}{\sigma^2 \mu} (1-\delta_k)\right) + 1 \right] = 0. \quad (20) \end{aligned}$$

Let δ_k' denote the solution of (20). Then, the optimal leader strategy is given by

$$\delta_k^* = \min\{\bar{\delta}_k, \max\{\underline{\delta}_k, \delta_k'\}\}, \quad \forall k. \quad (21)$$

Algorithm 1 Gauss-Seidel Best-Response-Based Algorithm

-
- 1: Choose an initial strategy $\delta^{(0)} = (\delta_k^{(0)})_{k=1}^K$, set $n = 0$.
 - 2: **repeat**
 - 3: **for** $k = 1, \dots, K$ **do**
 - 4: compute $\delta_k^{(n+1)}$ by (21) for given $(\delta_1^{(n+1)}, \dots, \delta_{k-1}^{(n+1)}, \delta_{k+1}^{(n)}, \dots, \delta_K^{(n)})$.
 - 5: **end for**
 - 6: set $\delta^{(n+1)} = (\delta_k^{(n+1)})_{k=1}^K$ and $n \leftarrow n + 1$.
 - 7: **until** $\delta^{(n+1)}$ satisfies a suitable termination criterion.
 - 8: Compute the strategies of S-D pairs \mathbf{p} as in (17).
-

The Gauss-Seidel best-response-based algorithm is summarized in Algorithm 1. Note that the objective monotonically increases in each iteration and the algorithm is guaranteed to converge to the optimum [50].

We further observe that the optimal objective $U_{\text{R-D}_k}^{\text{AWET}}(\delta_k^*, \delta_{-k})$ is nonnegative.

Lemma 2: At the optimal solution δ_k^* , the leader utility $U_{\text{R-D}_k}^{\text{AWET}}$ is nonnegative.

Proof: As mentioned before, at the lower bound $\delta_k = \underline{\delta}_k$, the objective function $U_{\text{R-D}_k}^{\text{AWET}}$ is increasing in δ_k . Then, due to the concavity, $U_{\text{R-D}_k}^{\text{AWET}}$ achieves the maximum either at a unique point on the open interval $(\underline{\delta}_k, \bar{\delta}_k)$ or at the upper bound $\bar{\delta}_k$. This leads to the optimal value $U_{\text{R-D}_k}^{\text{AWET}}(\delta_k^*) \geq U_{\text{R-D}_k}^{\text{AWET}}(\bar{\delta}_k)$. When $\delta_k = \bar{\delta}_k$, $U_{\text{R-D}_k}^{\text{AWET}}(\bar{\delta}_k) > 0$ since $R_{\text{R}_k}^{\text{AWET}} \geq 0$ and $R_{\text{S}_k} = 0$ by letting $p_k = 0$ in (12). Therefore, the optimal utility is nonnegative. ■

Lemma 2 implies the nonnegativity of leader utility at the equilibrium. Therefore, the proposed multi-leader-follower Stackelberg game guarantees to relay all of the source's data.

To compute the optimal strategy, CSI needs to be exchanged between the relays for distributed implementation. Alternatively, for a centralized setup, a control center with CSI can compute the strategy (possibly offline) and communicate to the terminals. Regarding the implementation of AWET, each relay only needs to know the start of the frame of the two-hop transmission and in which slot it is going to receive the source's information signal, so that it can harvest energy from other signals while waiting for its intended information signal, then transmit to the associated destination after receiving the source's data. In other words, the system only requires the overhead for CSI and transmission order at the beginning of the two-hop transmission.

B. SWET

For SWET, the utility functions of follower k and leader k , $U_{\text{S-D}_k}^{\text{SWET}}$ and $U_{\text{R-D}_k}^{\text{SWET}}$, are defined similarly as in (11) and (12) respectively, except averaging over transmission completion time $1 + k/K$, $\forall k$. The energy harvesting strategy $\delta_k \in [0, 1]$ is chosen by leader k . Accordingly, the follower adjusts its transmit power p_k satisfying $p_k \in [0, P]$. Specifically, each follower's problem is given by

$$\max_{p_k \in [0, P]} U_{\text{S-D}_k}^{\text{SWET}} = \frac{1}{K+k} \left[(1 - \delta_k) \log \left(1 + \frac{h_k p_k}{\sigma^2} \right) - \mu p_k \right], \quad (22)$$

whose solution is given by (17). The leaders' game is to solve the following problem for all k .

$$\max_{\delta_k \in [0, 1]} U_{\text{R-D}_k}^{\text{SWET}} = \frac{1}{K+k} \left[\log \left(1 + \frac{g_k P_{\text{R}_k}^{\text{SWET}}}{\sigma^2} \right) - (1 - \delta_k) \log \left(1 + \frac{h_k p_k}{\sigma^2} \right) \right], \quad (23)$$

where

$$P_{\text{R}_k}^{\text{SWET}} = \sum_{i=1}^k h_{i,k} \left(p_i \delta_i + \sum_{j=1, j \neq i}^K p_j \right). \quad (24)$$

When $\delta_k \in [\bar{\delta}_k, 1]$, $p_k = 0$ and utility $U_{\text{R-D}_k}^{\text{SWET}}$ is invariant to δ_k . When $\delta_k \in [0, \underline{\delta}_k]$, $p_k = P$ and $U_{\text{R-D}_k}^{\text{SWET}}$ increasing in δ_k . Thus, we only focus on $\delta_k \in [\underline{\delta}_k, \bar{\delta}_k]$, where $p_k = \frac{1 - \delta_k}{\mu} - \frac{\sigma^2}{h_k}$. Each leader's problem is rewritten as

$$\max_{\delta_k \in [\underline{\delta}_k, \bar{\delta}_k]} U_{\text{R-D}_k}^{\text{SWET}} = \frac{1}{K+k} \left[\log \left(A_k \delta_k^2 + B_k \delta_k + C_k \right) - (1 - \delta_k) \log \left(\frac{h_k}{\sigma^2 \mu} (1 - \delta_k) \right) \right] \quad (25)$$

with $A_k \triangleq -\frac{g_k h_{k,k}}{\sigma^2 \mu}$, $B_k \triangleq \frac{g_k}{\sigma^2} [h_{k,k} (\frac{1 - \sigma^2}{\mu} - \sum_{i=1}^{k-1} \frac{h_{i,k}}{\mu})]$, and $C_k \triangleq 1 + \frac{g_k}{\sigma^2} [h_{k,k} \sum_{i=1, i \neq k}^K (\frac{1 - \delta_i}{\mu} - \frac{\sigma^2}{h_i}) + \sum_{i=1}^{k-1} h_{i,k} ((\frac{1 - \sigma^2}{\mu} - \frac{\sigma^2}{h_k}) + \delta_i (\frac{1 - \delta_i}{\mu} - \frac{\sigma^2}{h_i}) + \sum_{j \neq i, j \neq k}^K (\frac{1 - \delta_j}{\mu} - \frac{\sigma^2}{h_j}))]$.

The problem in (25) is convex, which can be proven by similar steps as in Lemma 1. Also, by the same argument for AWET, there exists a pure strategy NE for noncooperative game $\mathcal{G}^{\text{SWET}} = (\mathcal{K}, \mathcal{Q}, \mathbf{U}^{\text{SWET}})$, where $\mathbf{U}^{\text{SWET}} = (U_{\text{R-D}_k}^{\text{SWET}})_{k=1}^K$. Thus, the existence of SE is guaranteed. The optimal leader strategy δ_k^* is given in (21), where δ_k^* is the solution of $\frac{\partial U_{\text{R-D}_k}^{\text{SWET}}}{\partial \delta_k} = 0$. We apply the Gauss-Seidel best-response-based algorithm in Algorithm 1 to obtain the SE. Furthermore, the nonnegativity of leaders' optimal utilities hold by the same argument in Lemma 2.

IV. SINGLE-LEADER-FOLLOWER STACKELBERG GAMES FOR TWO-HOP NETWORKS

In this section, we exploit single-leader-follower Stackelberg game to formulate the interaction of nodes in the two-hop network with BCWET and IWET. A single-leader-follower Stackelberg game consists of a leader in the upper-level problem and a follower who solves the lower-level problem. The leader chooses its strategy by taking advantage of anticipating the follower's response, while the follower makes its decision after observing the leader's action. In the sequel, we formulate and solve the games for BCWET and IWET models.

A. BCWET

We consider two-hop networks with cooperative relays for BCWET, where all relays share a common energy harvesting fraction δ . We model the interaction between the source

and relays as a single-leader-follower Stackelberg game in the sense that the relays cooperate with each other to play as a single leader and determine strategy δ that maximizes their common objective. The follower, the source, chooses its strategy, the transmit power $\mathbf{p} = (p_1, p_2, \dots, p_K)$, as a response accordingly. Taking into account the energy cost, the source utility is defined as the net revenue of overall information transmission averaged over the two hop session of 2 seconds.

$$U_S^{\text{BC}} = \frac{1}{2} \sum_{k=1}^K \left[(1-\delta) R_{S_k}^{\text{BC}} - \mu p_k \right], \quad (26)$$

where $R_{S_k}^{\text{BC}}$ is given in (6). Considering the common objective of relays, the leader utility is defined as the average sum rate of transmitting relays' data.

$$U_R^{\text{BC}} = \frac{1}{2} \sum_{k=1}^K \left[\frac{1}{K} R_{R_k}^{\text{BC}} - (1-\delta) R_{S_k}^{\text{BC}} \right]. \quad (27)$$

In particular, $R_{R_k}^{\text{BC}}$ is given in (1) with $p_{R_k}^{\text{BC}} = K E_{R_k}^{\text{BC}}$ and $E_{R_k}^{\text{BC}}$ given in (7). The optimization problem for the follower is formulated as follows.

$$\max_{p_k \geq 0} U_S^{\text{BC}} = \frac{1}{2} \sum_{k=1}^K \left[(1-\delta) \log \left(1 + \frac{h_k p_k}{\sigma^2 + h_k \sum_{i: h_i \geq h_k} p_i} \right) - \mu p_k \right] \quad (28a)$$

$$\text{s.t.} \sum_{k=1}^K p_k \leq P, \quad (28b)$$

where (28b) is the power constraint of the transmitter. The leader problem is

$$\max_{\delta \in [0,1]} U_R^{\text{BC}} = \frac{1}{2} \sum_{k=1}^K \left[\frac{1}{K} \log \left(1 + \frac{g_k p_{R_k}^{\text{BC}}}{\sigma^2} \right) - (1-\delta) \log \left(1 + \frac{h_k p_k}{\sigma^2 + h_k \sum_{i: h_i \geq h_k} p_i} \right) \right], \quad (29)$$

where

$$p_{R_k}^{\text{BC}} = K \delta \left(\sum_{i=1}^K p_i \right) \left(\sum_{i=1}^k h_{i,k} \right), \quad \forall k. \quad (30)$$

We start with the follower problem (28). It can be observed that for any given leader strategy δ , the source will allocate all power to the relay with the best channel gain for utility maximization. Let k^* denote the index of this relay. Then, the source's signal only includes data for relay k^* and its paired destination. The other relays receive no data from the source and can only harvest energy from the signal for relay k^* . Thus, the follower problem is simplified to

$$\max_{p_{k^*} \in [0,P]} U_S^{\text{BC}} = \frac{1}{2} \left[(1-\delta) \log \left(1 + \frac{h_{k^*} p_{k^*}}{\sigma^2} \right) - \mu p_{k^*} \right]. \quad (31)$$

The transmit power p_{k^*} is solved as in (17) with index k^* . Accordingly, the leader utility can be rewritten as

$$U_R^{\text{BC}} = \frac{1}{2} \left[\sum_{k=1}^K \frac{1}{K} \log \left(1 + \frac{g_k}{\sigma^2} K \delta p_{k^*} \left(\sum_{i=1}^k h_{i,k} \right) \right) - (1-\delta) \log \left(1 + \frac{h_{k^*} p_{k^*}}{\sigma^2} \right) \right]. \quad (32)$$

When $p_{k^*} = 0$, both leader and follower have zero utility. When $p_{k^*} = P$, U_R^{BC} increases in δ , which leads to optimal δ lying in interval $[\underline{\delta}_{k^*}, \bar{\delta}_{k^*}]$. Consequently, we only need to focus on leader's problem with $p_{k^*} = \frac{1-\delta}{\mu} - \frac{\sigma^2}{h_{k^*}}$, which is given by

$$\max_{\delta \in [\underline{\delta}_{k^*}, \bar{\delta}_{k^*}]} U_R^{\text{BC}} = \frac{1}{2} \left[\sum_{k=1}^K \frac{1}{K} \log \left(A_k \delta^2 + B_k \delta + C_k \right) - (1-\delta) \log \left(\frac{h_{k^*}}{\sigma^2 \mu} (1-\delta) \right) \right], \quad (33)$$

where $A_k \triangleq -\frac{K g_k}{\sigma^2 \mu} (\sum_{i=1}^k h_{i,k})$, $B_k \triangleq \frac{K g_k}{\sigma^2} (\frac{1}{\mu} - \frac{\sigma^2}{h_{k^*}}) (\sum_{i=1}^k h_{i,k})$, and $C_k \triangleq 1$. It is easy to verify that U_R^{BC} is concave in δ by Lemma 1. Let δ' be the solution of equation

$$\frac{dU_R^{\text{BC}}}{d\delta} = \frac{1}{2} \left[\sum_{k=1}^K \frac{1}{K} \frac{2A_k \delta + B_k}{A_k \delta^2 + B_k \delta + C_k} + \log \left(\frac{h_{k^*}}{\sigma^2 \mu} (1-\delta) \right) + 1 \right] = 0. \quad (34)$$

The optimal strategy δ^* can be obtained by projecting to the feasible interval, that is

$$\delta^* = \min \{ \bar{\delta}_{k^*}, \max \{ \underline{\delta}_{k^*}, \delta' \} \}. \quad (35)$$

B. IWET

In the IWET model, there is no interaction among relays since each relay harvests energy only from its exclusive source signal. This leads to a single-leader-follower Stackelberg game for each S-R-D link. We consider K parallel single-leader-follower Stackelberg games, in each of which R-D pair k plays as the leader and the S-D pair k acts as the follower. The utility function of follower $U_{S-D_k}^{\text{IWET}}$ is defined as in (11) by replacing the superscript by IWET. The leader utility $U_{R-D_k}^{\text{IWET}}$ is in the form of (12) by plugging in $R_{R_k}^{\text{IWET}}$. In each game, the follower chooses strategy p_k by solving

$$\max_{p_k \in [0,P]} U_{S-D_k}^{\text{IWET}} = \frac{1}{k+1} \left[(1-\delta_k) \log \left(1 + \frac{h_k p_k}{\sigma^2} \right) - \mu p_k \right]. \quad (36)$$

The solution is given in (17). The leader determines strategy δ_k in the problem below.

$$\max_{\delta_k \in [0,1]} U_{R-D_k}^{\text{IWET}} = \frac{1}{k+1} \left[\log \left(1 + \frac{g_k h_{k,k} \delta_k p_k}{\sigma^2} \right) - (1-\delta_k) \log \left(1 + \frac{h_k p_k}{\sigma^2} \right) \right] \quad (37)$$

As we can see, zero utilities for the leader and the follower occur when $p_k = 0$ and $U_{R-D_k}^{\text{IWET}}$ increases monotonically on δ_k if $p_k = P$. Thus, we simplify the leader problem as follows by considering $\delta_k \in [\underline{\delta}_k, \bar{\delta}_k]$.

$$\begin{aligned} & \max_{\delta_k \in [\underline{\delta}_k, \bar{\delta}_k]} U_{R-D_k}^{\text{IWET}} \\ &= \frac{1}{k+1} \left[\log \left(A_k \delta_k^2 + B_k \delta_k + C_k \right) \right. \\ & \quad \left. - (1 - \delta_k) \log \left(\frac{h_k}{\sigma^2 \mu} (1 - \delta_k) \right) \right], \quad (38) \end{aligned}$$

where $A_k \triangleq -\frac{g_k h_{k,k}}{\sigma^2 \mu}$, $B_k \triangleq \frac{g_k h_{k,k}}{\sigma^2 \mu} \left(\frac{1}{\mu} - \frac{\sigma^2}{h_k} \right)$, and $C_k \triangleq 1$. Once again the problem remains convex. Thus, the optimal strategy can be obtained the same way as the other models.

δ_k^* is given by (21), where δ' is the solution of $\frac{dU_{R-D_k}^{\text{IWET}}}{d\delta_k} = 0$, $\forall k$. In particular, the nonnegative property of each leader's utility holds as well for IWET, which can be verified by the argument in Lemma 2.

V. NUMERICAL RESULTS

We present simulation results for the proposed models in this section. We set the carrier frequency to be 900 MHz and the bandwidth is 1 MHz. The noise power spectrum density is -174 dBm/Hz. The channel power gain is modeled as the product of short-term fading gain α^2 and path loss coefficient β , where α is Rician distributed with Rician factor 3 dB for S-R channels and 0 dB (Rayleigh fading) for R-D and R-R channels. For large-scale fading, we use free space path loss model for β with path loss exponent 3 and reference distance 1 meter. The antenna gain is given as 6 dBi. The destinations are located randomly and uniformly 50-100 meters away from the source at the origin, and each relay is located between the source and its paired destination with a uniformly distributed distance away from the source, in [2, 25] meters. We set $\eta_k = 0.5$, $\forall k$, and $P = 1$ W. μ is chosen uniformly from [0, 0.1] bits/Hz/J. In the following figures, we present the results averaged over ten thousand of path loss, channel realizations and μ values.

Our overarching conclusion is that AWET provides the best performance in terms of a number of metrics including those favoring individual agents' interests. Note also that Algorithm 1 is implemented to find the best responses. In all our simulations, we observe that the algorithm converges very fast, for example on an average of fewer than two iterations for a 10-relay system [1]. Next, we compare the results of all models on different performance metrics. In Fig. 5, we show the utility of individual relays for $K = 5$, where the relay index indicates the transmission order. AWET achieves a much better performance than other models in terms of individual relay's data transmission rate. For AWET, SWET, and IWET, the relay that transmits earlier has a higher utility due to a shorter waiting time. In particular, IWET model shows the most drastic decline since relays harvest no extra energy from others' signals. Harvesting extra energy from ambient signals facilitates to mitigate the difference of average rate of relays. The BCWET model gives the fairest but relatively low

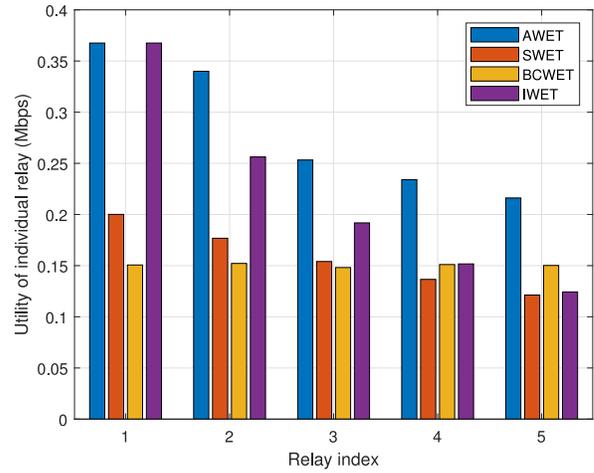


Fig. 5. Utility of individual relay for $K = 5$.

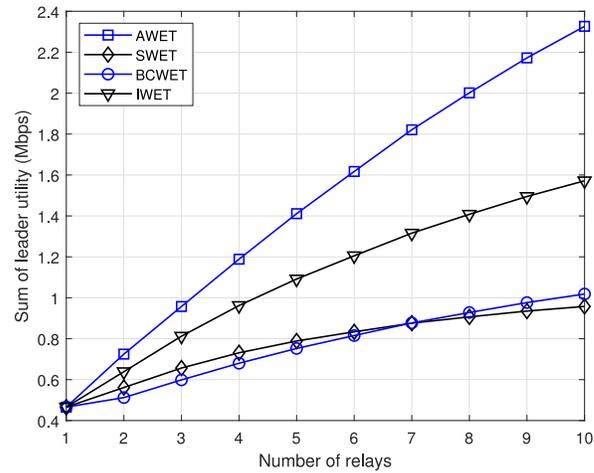


Fig. 6. Sum of leader utility versus number of relays.

utilities among relays because cooperative relays perform as one node in the system.

Fig. 6 shows the sum of leader utility versus the number of relays, where the sum of leader utility increases on the number of relays. We observe that AWET significantly outperforms the other models and the performance gap increases as the number of relays increases. The reason is two-fold. The relays that transmit earlier complete transmission sooner and those who wait longer can harvest more energy and can have higher utility. For BCWET and SWET in Fig. 6, as K gets larger, the relays that transmit later have a lower utility in SWET than in BCWET due to a longer waiting time, causing the sum utility curves to intersect.

We plot the system energy consumption in Fig. 7 versus the number of relays. The energy consumption is increasing in the number of relays for BCWET, and decreasing for AWET and SWET. This is because in AWET and SWET, the competition among R-D pairs, caused by ambient harvested energy, enables the source to transfer less energy for each relay as more relays appear. In other words, competitive interaction during wireless energy transfer saves energy. For BCWET, it is more probable that the best relay has a larger channel power gain when there are more relays, which leads to a larger power allocation.

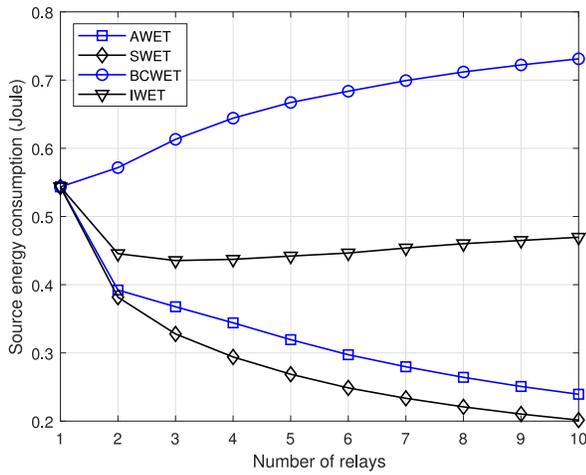


Fig. 7. System energy consumption versus number of relays.

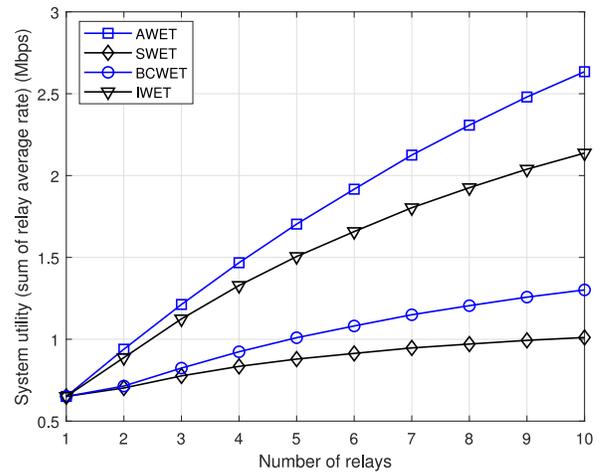


Fig. 9. System utility versus number of relays.

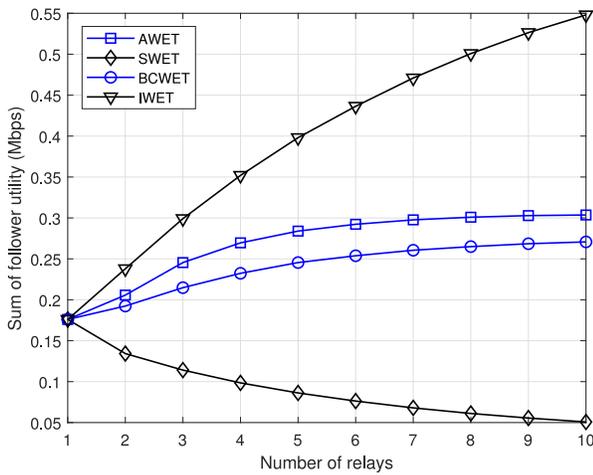


Fig. 8. Sum of follower utility versus number of relays.

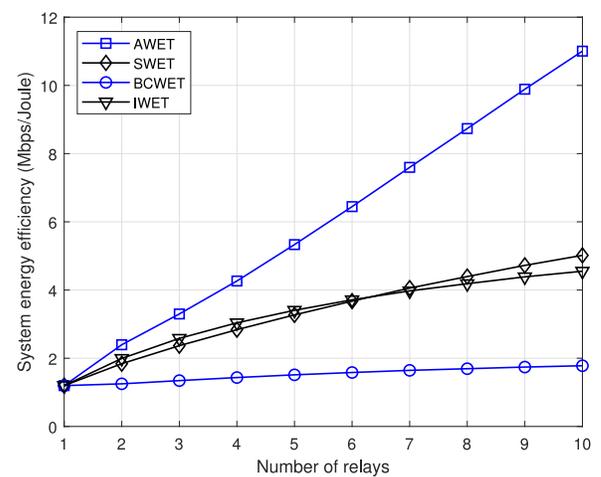
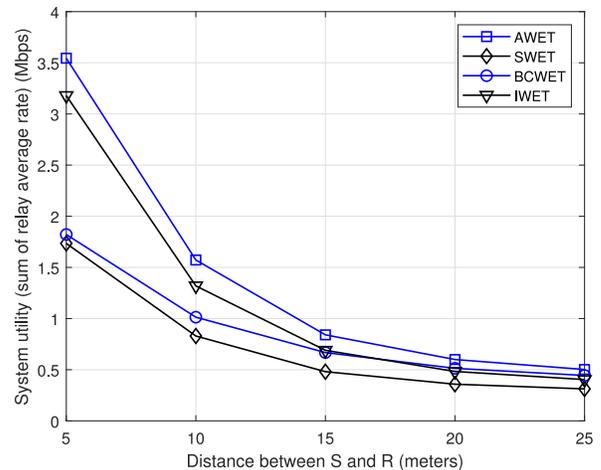


Fig. 10. System energy efficiency versus number of relays.

In IWET, relays cannot depend on harvesting energy from others' signals, thus, the source transmits to each relay with almost the same power, which results in much higher energy consumption than AWET.

Fig. 8 shows the sum of follower utility versus the number of relays. IWET performs the best in terms of follower utility since the source allocates more energy to relays. Some of the relays further take advantage of completing transmission in a shorter time. Sum follower utility for SWET decreases due to less energy being used when K increases as shown in Fig. 7. As a comparison, AWET and BCWET perform in between the two with the utility increasing on the number of relays, and AWET provides larger follower utilities than BCWET.

Fig. 9 illustrates the system utility, our main metric, which is defined as the sum of relay average rate that includes the data of both the source and relays. All WET models have increasing system utility in the number of relays. Our proposed, asymmetric wireless energy harvesting model, i.e., AWET, provides the best performance among all models. The results reflect the impact of energy harvesting from ambient signals, energy consumption, and transmission completion time. We further demonstrate the system energy efficiency in Fig. 10, which is defined as the ratio of system utility to system energy

Fig. 11. System utility versus distance between S and R for $K = 5$.

consumption. All models show increasing efficiency on the number of relays. Our proposed AWET again shows the highest efficiency due to the best performance on system utility and relatively low energy consumption. SWET achieves the second best energy efficiency as the lowest energy is consumed

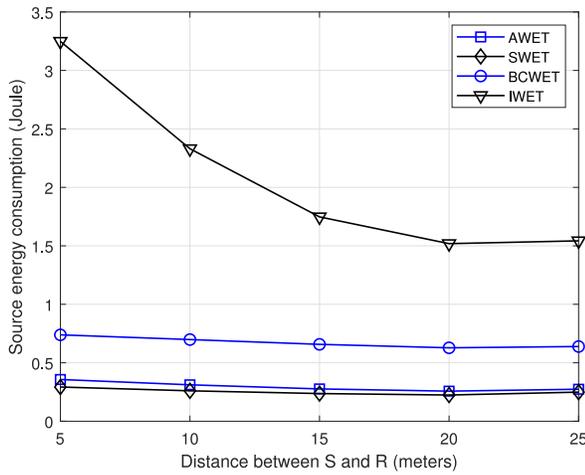


Fig. 12. System energy consumption versus distance between S and R for $K = 5$.

for overall transmissions. BCWET, as expected, performs the worst by this metric since it needs the largest energy allocation.

Fig. 11 and Fig. 12 illustrate the effect of the source-to-relay distance on the system performance. As relays locate farther from the source, the path loss of source to relay channels is larger which leads to less harvested energy at relays. Thus, the system utility in Fig. 11 decreases since less energy can be utilized for the second-hop transmission. The system energy consumption shown in Fig. 12 also decreases as the distance becomes larger. This is because relays have to lengthen the energy harvesting duration to make sure sufficient energy is harvested. As the energy harvesting fraction δ_k increases, the source transmit power p_k decreases, see (17).

VI. CONCLUSION

In this paper, we have studied a relay-centric two-hop network with signal and energy cooperation. Considering the primary objective of transmitting relays' data to destinations, we have adopted the framework of Stackelberg game to model the competition between the R-D pairs, i.e., the leaders, and the S-D pairs, i.e., the followers. We have considered, analyzed and compared different wireless energy transfer models in the first hop. In particular, we have proposed an asymmetric wireless energy transfer model (AWET). In AWET, the source transmits information and energy to the relays, focusing on each relay one by one. The relays are able to harvest energy from the signals intended for previous relays while waiting for their turns. This trading delay for harvesting more energy allows for better system performance. We have also considered SWET, BCWET, and IWET models that allow wireless energy transfer in either a time-division, broadcast, or independent fashion as comparative models. The data rate, energy cost, and delay are taken into account in the utility functions. We have formulated and solved multi-leader-follower Stackelberg games for AWET (and SWET), and single-leader-follower Stackelberg games for BCWET and IWET considering the properties of each game. It has been confirmed by the simulation results that by taking advantage of the asymmetry of energy accumulation and transmission completion time,

AWET outperforms the other models significantly in terms of relay-centric utility. We have further observed that the asymmetric competitive interaction among energy harvesting relays achieves better system utility and energy efficiency.

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