Joint Wireless Information and Energy Transfer in Cache-assisted Relaying Systems

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***Abstract*—We investigate the performance of time switching (TS) based energy harvesting model for cache-assisted simultaneous wireless transmission of information and energy (Wi-TIE). In the considered system, a relay which is equipped with both caching and energy harvesting capabilities helps a source to convey information to a destination. First, we formulate based on the time-switching architecture an optimization problem to maximize the harvested energy, taking into consideration the cache capability and user quality of service requirement. We then solve the formulated problem to obtain closed-form solutions. Finally, we demonstrate the effectiveness of the proposed system via numerical results.**

***Index Terms*—Simultaneous wireless transmission of information and energy, relay systems, caching, energy harvesting.**

I. Introduction

THE exponential increase in the usage of wireless devices like smart-phones, wearable gadgets, or connected vehicles, has not only posed substantial challenges to meet the performance and capacity demands, but also presented some serious environmental concerns with alarming CO_2 emissions [1]. By the end of 2020, this number is expected to grow manifold and is speculated to cross 50 billion [2]. Recent developments in the paradigm of Internet-of-Things (IoT) emphasize on the interconnection between equipments, commodities, functionalities, and customers, with or without slightest human mediation [3]. Since most of these connecting operations involve battery-limited devices that may not be continuously powered, the energy becomes a sparse and pivotal resource and hence management of energy becomes crucial. In order to address these issues, emerging technologies like energy harvesting [4], caching [5], etc., shows great promise.

Increasing number of devices provides an alluring opportunity of relaying the desired signal from the transmitter to the far placed receiver and vice-versa. Nodes facilitating the relay techniques may adopt various methods to expand the network coverage area and diversity gains [6]. In this context, *regenerative* (e.g., decode-and-forward (DF) [7]), and *non-regenerative* (e.g., amplify-and-forward (AF) [8]) protocols are two of the widely adopted relay strategies. Considering the aspect of high secrecy rate [9] and comparison of average performance between the two modes in terms of capacity measure [10], regenerative relaying strategy (i.e., DF protocol) shows great promise with paramount practical interest.

Efficient power management is another key objective of future wireless networks to improve the availability and traffic capacity. Simultaneous wireless transmission of information and energy (Wi-TIE) is a new paradigm for concurrent data reception and energy harvesting from the same Radio Frequency (RF) input signal. It is noteworthy that Wi-TIE has huddled ample attention in the recent years and is expected to serve the emerging technologies at large [11]–[13]. Most researches on Wi-TIE rely on two baseline structure time switching (TS) or power splitting (PS) architectures [14].

Congestion due to the network traffic is often observed during the peak hours whereas most of the resources are in idle state during the off-peak hours [15]. The cause of this network blockage is mainly due to the fact that replicas of a common content may be demanded by various mobile users. Exploiting the plentiful network resources during off-peak hours is one of the ways to mitigate the congestion in the network. Duplication of the content, also termed as content placement or caching, is carried out during the off-peak hours by leveraging the information from the memories distributed across the network. In this vein, a framework for minimization of energy in cache-assisted content delivery networks with wireless backhaul is proposed in [16] while [17] presents the performance analysis and optimization for edge-caching wireless networks.

A generic concept outlining joint energy harvesting (EH) and caching was recently proposed as GreenDelivery Framework in [1] and for the IoT technologies in [3]. An online energy-efficient power control scheme for EH with caching capability was developed by the authors in [18]. However, these works highlight a general overview of EH with caching and does not consider the aspect of Wi-TIE along with caching in RF regime using relay systems. With regards to Wi-TIE, PS scheme cannot be considered as one of the best receiving modes due to complex hardware design challenges of PS [14], [19].

In this paper, we propose a framework to realize the benefit of Wi-TIE combined with caching capability to support future technologies. In particular, we develop a hybrid architecture for a DF relay which is equipped with TS based Wi-TIE and caching capability. To the best of our knowledge, study of Wi-TIE with caching in relaying systems has not been addressed so far in the literature. An optimization problem is formulated to maximize of the energy stored at the relay, taking into account the harvested energy constraint at the relay and quality of service (QoS) requirement at the destination. Due to the non-linearity of the formulate problem, Karush-Kuhn-Tucker (KKT) conditions are used to solved to obtain the closed-form solutions. Finally, we demonstrate the effective of the proposed system via numerical results, which also show the key role of

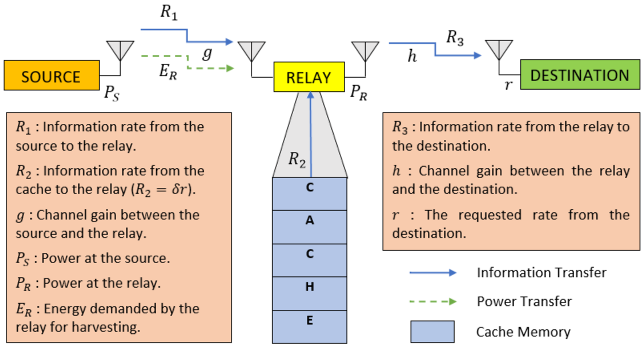

Fig. 1. System model for Wi-TIE with caching at the DF relay.

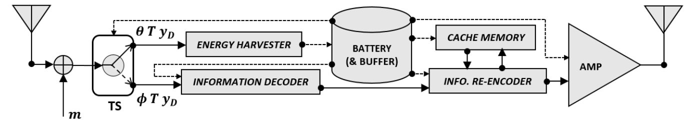

Fig. 2. Proposed DF relay transceiver design for hybrid Wi-TIE and caching with time switching (TS) architecture.

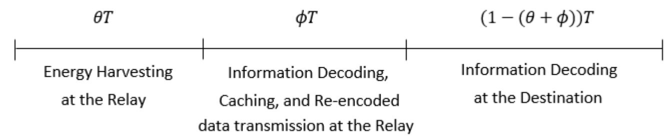

Fig. 3. Time distribution assumed for communication and decoding to investigate the Maximization Problem of Energy stored at the Relay.

caching on the Wi-TIE architecture.

The remainder of this paper is organized as follows. Section II presents the system model and parameters. Section III formulates a maximization problem for energy stored at the relay. Section IV shows numerical results. Finally, Section V concludes the paper.

II. System Model

We consider a generic Wi-TIE system in which a DF relay equipped with caching and Wi-TIE capabilities helps to convey information from one source to a destination, as depicted in Fig. 1. Due to limited coverage, there is not direct connection between the source and the destination. The considered model can find application on the downlink where the base station acts the source's role and sends information to a far user via a small- or femto- cell base station. The relay node is equipped with an information decoder, an energy harvester, and a cache in order to store or exchange information as shown in Fig. 2. At the relay, the time switching (TS) scheme is employed so that the received signal is first provided to the the energy harvester for some fraction of the time allocated for transmitter-relay communication link, and then to information decoder for the remaining fraction. This type of mechanism is also referred in literature as harvest-then-forward protocol [20].

We consider block-based communications in which a transmission section is accomplished within a coherence time T. A coherence time is divided further into periods for energy harvesting, source-relay information, and relay-destination information, as shown in Fig. 3. More specifically, the source-relay link is considered to be active for a fraction of $(\theta+\phi)T$ seconds, while the relay-destination link is active for the remaining $(1-(\theta+\phi))T$, where $0 \leq \theta+\phi \leq 1$. As mentioned earlier, since the relay adopts a TS based scheme for Wi-TIE, we assume that the energy harvesting at the relay takes place for a fraction of θT seconds and the information decoding and re-encoding at the relay takes place for a fraction of ϕT seconds. For simplicity, we assume normalized time to use energy and power interchangeably.

Denote P_S, P_R as the transmit power at the source and at the relay, respectively. In addition, let g and h denote the channel fading coefficients between the source and the relay and the relay and the destination, respectively. The signal received at the relay when the transmitter transmits the symbols $x \in \mathbb{C}$, such that $\mathbb{E}\{|x|^2\} = 1$ where $\mathbb{E}\{\cdot\}$ and $|\cdot|$ denotes the statistical expectation and the norm respectively, is given by

$$y_R = \sqrt{P_S}\ g\ x\ +\ m, \tag{1}$$

where m is the additive white Gaussian noise (AWGN) at the relay which is an independent and identically distributed (i.i.d.) complex Gaussian random variable with zero mean and variance σ_m^2.

Upon receiving y_R, the relay decodes and re-encodes the source signal to obtain the estimate $\tilde{x}$, which is then forwarded to the destination. The signal received at the destination is given by

$$y_D = \sqrt{P_R}\ h\ \tilde{x}\ +\ n, \tag{2}$$

where n is the AWGN at the destination node which is an i.i.d. complex Gaussian random variable with zero mean and variance σ_n^2.

The achievable information rate of the source-relay link is

$$R_1 = B \log_2\left(1 + \frac{P_S\ |g|^2}{\sigma_m^2}\right), \tag{3}$$

and the achievable information rate of the relay-destination link is

$$R_3 = B \log_2\left(1 + \frac{P_R\ |h|^2}{\sigma_n^2}\right), \tag{4}$$

where B is the channel bandwidth.

In addition to the information sent from the source, the relay has access to the information stored in its cache to serve the destination. For robustness, we assume that the relay does not have information about content popularity. Therefore, it will store $0 \leq \delta \leq 1$ parts of every file in its cache [15]. For convenience, we interchangeably refer to δ as the caching gain coefficient or the cache capacity throughout the paper. This caching scheme will serve as the lower bound benchmark since the content popularity in practice might not be uniform but, e.g., Zipf distribution.

When the destination requests a file from the library, δ parts of that file are already available at the relay's cache. In other words, the relay's cache can provide, in addition to the source-relay link, an information rate

$$R_2 = \delta r, \tag{5}$$

where r is the information rate required by the destination.

The harvested energy at the relay is given by

$$E_R = \zeta\theta(P_S|g|^2 + \sigma_m^2), \tag{6}$$

where ζ is the energy conversion efficiency of the receiver.

III. Maximization of Energy Stored at the Relay

In this section we formulate an optimization problem to maximize the energy stored at the relay, while ensuring that the requested rate between relay-destination is above a given threshold and that the total transmit powers at the transmitter and relay do not exceed a given limit. The corresponding optimization problem (P1) can be expressed as

$$(P1): \max_{\theta,\phi,P_R} \quad [\zeta\theta(P_S|g|^2+\sigma_m^2)-(1-(\theta+\phi))P_R]^+ \quad (7)$$

$$\text{subject to} \quad (C1): \phi(R_1+R_2) \geq (1-(\theta+\phi))R_3, \quad (8)$$

$$(C2): (1-(\theta+\phi))P_R \leq E_R+E_{ext}, \quad (9)$$

$$(C3): (1-(\theta+\phi))R_3 \geq r, \quad (10)$$

$$(C4): 0 < P_S \leq P^\star, \quad (11)$$

$$(C5): 0 \leq \theta+\phi \leq 1. \quad (12)$$

where $(x)^+ = \max(0,x)$, E_{ext} is the external energy from other sources, e.g., power line, and $P^\star$ is the maximum power limit at the transmitter. Here, the objective function of $(P1)$ is the expression of the overall energy stored at the relay, $(C1)$ ensures the request rate fulfillment at the destination, $(C2)$ safeguards the power management at the relay, and $(C3)$ denotes the QoS constraint. Clearly, this is a non-linear programming problem involving joint computations of θ, ϕ, and P_R, which introduces intractability. Therefore, we propose to solve this problem using the Karush-Kuhn-Tucker (KKT) conditions. To proceed, we denote the Lagrangian of $(P1)$ as follows

$$\mathcal{L}(\theta,\phi,P_R;\lambda_1,\lambda_2,\lambda_3,\lambda_4) = F(\theta,\phi,P_R) - \lambda_1\ G(\theta,\phi,P_R) - \lambda_2\ H(\theta,\phi,P_R) - \lambda_3\ I(\theta,\phi,P_R) - \lambda_4\ J(\theta,\phi,P_R), \quad (13)$$

where

$$F(\theta,\phi,P_R) = [\zeta\theta(P_S|g|^2+\sigma_m^2)-(1-(\theta+\phi))P_R]^+, \quad (14)$$

$$G(\theta,\phi,P_R) = (1-(\theta+\phi))B\log_2(1+\gamma_{_{R,D}}) - \phi[B\log_2(1+\gamma_{_{S,R}})+\delta r] \leq 0, \quad (15)$$

$$H(\theta,\phi,P_R) = (1-(\theta+\phi))P_R - \zeta\theta(P_S|g|^2+\sigma_m^2) - E_{ext} \leq 0, \quad (16)$$

$$I(\theta,\phi,P_R) = r-(1-(\theta+\phi))B\log_2(1+\gamma_{_{R,D}}) \leq 0, \quad (17)$$

$$J(\theta,\phi,P_R) = (\theta+\phi)-1 \leq 0, \quad (18)$$

where $\gamma_{_{S,R}} = \frac{P_S\ |g|^2}{\sigma_m^2}$ and $\gamma_{_{R,D}} = \frac{P_R\ |h|^2}{\sigma_n^2}$.

For local optimality, $\nabla\mathcal{L}(\theta,\phi,P_R;\lambda_1,\lambda_2,\lambda_3,\lambda_4)=0$. Thus, we represent the equations satisfying the optimality conditions as

$$\frac{\partial\mathcal{L}(\theta,\phi,P_R;\lambda_1,\lambda_2,\lambda_3,\lambda_4)}{\partial\theta} \implies [\zeta(P_S|g|^2+\sigma_m^2)+P_R] - \lambda_1[-B\log_2(1+\gamma_{_{R,D}})] - \lambda_2[-P_R-\zeta(P_S|g|^2+\sigma_m^2)] - \lambda_3[B\log_2(1+\gamma_{_{R,D}})] - \lambda_4 = 0, \quad (19)$$

$$\frac{\partial\mathcal{L}(\theta,\phi,P_R;\lambda_1,\lambda_2,\lambda_3,\lambda_4)}{\partial\phi} \implies P_R - \lambda_1[-B\log_2(1+\gamma_{_{R,D}}) - (B\log_2(1+\gamma_{_{S,R}})+\delta r)] - \lambda_2[-P_R] - \lambda_3[B\log_2(1+\gamma_{_{R,D}})] - \lambda_4 = 0, \quad (20)$$

$$\frac{\partial\mathcal{L}(\theta,\phi,P_R;\lambda_1,\lambda_2,\lambda_3,\lambda_4)}{\partial P_R} \implies -(1-(\theta+\phi)) - \lambda_1\left[(1-(\theta+\phi))\left(\frac{\ln(2)|h|^2}{\sigma_n^2+P_R|h|^2}\right)\right] - \lambda_2(1-(\theta+\phi)) - \lambda_3\left[-(1-(\theta+\phi))\left(\frac{\ln(2)|h|^2}{\sigma_n^2+P_R|h|^2}\right)\right] = 0. \quad (21)$$

The conditions for feasibility are as expressed in (15), (16), and (17). Complementary slackness expressions can be represented as follows

$$\lambda_1 \cdot G(\theta,\phi,P_R) = 0, \quad (22)$$

$$\lambda_2 \cdot H(\theta,\phi,P_R) = 0, \quad (23)$$

$$\lambda_3 \cdot I(\theta,\phi,P_R) = 0, \quad (24)$$

$$\lambda_4 \cdot J(\theta,\phi,P_R) = 0. \quad (25)$$

The conditions for non-negativity are: $\{\theta,\phi,P_R,\lambda_1,\lambda_2,\lambda_3,\lambda_4\} \geq 0$. It is clear that if $\lambda_4 \neq 0$, then $J(\theta,\phi,P_R)=0$ implying that $\theta+\phi=1$. Since this is not a possible solution, therefore $\lambda_4=0$. Next, we analyze the remaining possibilities in order to obtain a feasible solution. The analysis is as follows

Case I: $\lambda_1=0 \implies G(\theta,\phi,P_R)\neq 0$; $\lambda_2=0 \implies H(\theta,\phi,P_R)\neq 0$; $\lambda_3=0 \implies I(\theta,\phi,P_R)\neq 0$

From (19) and (20), we find that $P_R=-\zeta(P_S|g|^2+\sigma_m^2)$ or $P_R=0$ respectively. Since both these solutions cannot be accepted, therefore this case is not possible.

Case II: $\lambda_1=0 \implies G(\theta,\phi,P_R)\neq 0$; $\lambda_2=0 \implies H(\theta,\phi,P_R)\neq 0$; $\lambda_3\neq 0 \implies I(\theta,\phi,P_R)=0$

This case again leads us to the unacceptable solution as in the previous case, therefore this case can be excluded.

Case III: $\lambda_1=0 \implies G(\theta,\phi,P_R)\neq 0$; $\lambda_2\neq 0 \implies H(\theta,\phi,P_R)=0$; $\lambda_3=0 \implies I(\theta,\phi,P_R)\neq 0$

From the optimality conditions, we deduce that $\lambda_2=1$ with no solutions for θ, ϕ, and P_R. Hence, this case is not admissible.

Case IV: $\lambda_1\neq 0 \implies G(\theta,\phi,P_R)=0$; $\lambda_2=0 \implies H(\theta,\phi,P_R)\neq 0$; $\lambda_3=0 \implies I(\theta,\phi,P_R)\neq 0$

Herein, we find that $\lambda_1<0$; which violates the non-negativity condition. Thus, this case is infeasible.

Case V: $\lambda_1=0 \implies G(\theta,\phi,P_R)\neq 0$; $\lambda_2\neq 0 \implies H(\theta,\phi,P_R)=0$; $\lambda_3\neq 0 \implies I(\theta,\phi,P_R)=0$

Solving the corresponding equations, we obtain the following

$$P_R = \max\Big(\exp\big(\mathcal{W}(\exp(-\log^2(2))+\log(2))+\log^2(2)\big), \exp\big(\mathcal{W}_{-1}(\exp(-\log^2(2))+\log(2))+\log^2(2)\big)\Big), \quad (26)$$

where $\mathcal{W}(\cdot)$ is the LambertW function or the product log function and $\mathcal{W}_k(\cdot)$ is the analytic continuation of the product log function [21]. As the solution is independent of P_S, it is reasonable to discard this solution.

Case VI: $\lambda_1\neq 0 \implies G(\theta,\phi,P_R)=0$; $\lambda_2=0 \implies H(\theta,\phi,P_R)\neq 0$; $\lambda_3\neq 0 \implies I(\theta,\phi,P_R)=0$

From (19) and (20), we obtain

$$\lambda_1 = \frac{\zeta(P_S|g|^2+\sigma_m^2)}{B\log_2(1+\gamma_{_{S,R}})+\delta r}. \quad (27)$$

Substituting (27) in (21), we find the following

$$\lambda_3 = \left(\frac{\sigma_n^2 + P_R|h|^2}{\ln(2)|h|^2}\right) + \left(\frac{\zeta(P_S|g|^2 + \sigma_m^2)}{B\log_2(1+\gamma_{S,R}) + \delta r}\right). \quad (28)$$

Next, substituting (27) and (28) in (20), and assuming $\nu = 1 + \gamma_{R,D}$, we obtain the following equation

$$\nu[B\log_2(\nu) - \ln(2)] + \mathcal{A} = 0, \quad (29)$$

where $\mathcal{A} = \ln(2) - \left(\frac{\zeta}{\sigma_n^2}\right)(\ln(2)|h|^2)(P_S|g|^2 + \sigma_m^2)$.

The solution of the above expression can be expressed as

$$\nu = \exp\left(\mathcal{W}(-\mathcal{A}\exp(-\log^2(2)) + \log(2)) + \log^2(2)\right). \quad (30)$$

Consequently, we obtain the following solution

$$P_R^\dagger = (\nu - 1)\frac{\sigma_n^2}{|h|^2}, \quad (31)$$

From (15) and (17), and using (30), it yields

$$\phi^\dagger = \frac{r}{B\log_2(1+\gamma_{S,R}) + \delta r}. \quad (32)$$

Finally, by substituting (32) in (17), we find that

$$\theta^\dagger = 1 - r\left(\frac{1}{B\log_2(1+\gamma_{S,R}) + \delta r} + \frac{1}{B\log_2\left(1 + \frac{P_R^\dagger|h|^2}{\sigma_n^2}\right)}\right), \quad (33)$$

where $P_R^\dagger$, $\phi^\dagger$, and $\theta^\dagger$ are the optimal values obtained for P_R, ϕ, and θ.

Case VII: $\lambda_1 \neq 0 \implies G(\theta,\phi,P_R) = 0$; $\lambda_2 \neq 0 \implies H(\theta,\phi,P_R) = 0$; $\lambda_3 = 0 \implies I(\theta,\phi,P_R) \neq 0$

From (20) and (21), and assuming $\mu = 1 + \gamma_{R,D}$, we obtain the following equation

$$\mu(B\log_2(\mu) + B\log_2(1+\gamma_{S,R}) + \delta r - \ln(2)) + \ln(2) = 0. \quad (34)$$

Since the solution of (34) is composed of complex values, therefore this case is not acceptable.

Case VIII: $\lambda_1 \neq 0 \implies G(\theta,\phi,P_R) = 0$; $\lambda_2 \neq 0 \implies H(\theta,\phi,P_R) = 0$; $\lambda_3 \neq 0 \implies I(\theta,\phi,P_R) = 0$

The equations to be used for computation of θ, ϕ, and P_R in this case can be re-written in their simplified forms as

$$\left(\zeta(P_S|g|^2 + \sigma_m^2) + P_R\right) + \lambda_1\left(B\log_2(1+\gamma_{R,D})\right) + \lambda_2\left(P_R + \zeta(P_S|g|^2 + \sigma_m^2)\right) - \lambda_3\left(B\log_2(1+\gamma_{R,D})\right) = 0, \quad (35)$$

$$P_R + \lambda_1\left(B\log_2(1+\gamma_{R,D}) + (B\log_2(1+\gamma_{S,R}) + \delta r)\right) + \lambda_2(P_R) - \lambda_3\left(B\log_2(1+\gamma_{R,D})\right) = 0, \quad (36)$$

$$1 + \lambda_1\left(\frac{\ln(2)|h|^2}{\sigma_n^2 + P_R|h|^2}\right) + \lambda_2 - \lambda_3\left(\frac{\ln(2)|h|^2}{\sigma_n^2 + P_R|h|^2}\right) = 0, \quad (37)$$

$$(1 - (\theta+\phi))B\log_2(1+\gamma_{R,D}) - \phi\left(B\log_2(1+\gamma_{S,R}) + \delta r\right) = 0, \quad (38)$$

$$(1 - (\theta+\phi))P_R - \zeta\theta(P_S|g|^2 + \sigma_m^2) - E_{ext} = 0, \quad (39)$$

$$r - (1 - (\theta+\phi))B\log_2(1+\gamma_{R,D}) = 0. \quad (40)$$

From (38) and (40), we obtain

$$\phi = \frac{r}{B\log_2(1+\gamma_{S,R}) + \delta r}. \quad (41)$$

Similarly, from (39) and (40), we find

$$\theta = \frac{rP_R - E_{ext}B\log_2(1+\gamma_{R,D})}{\zeta(P_S|g|^2 + \sigma_m^2)}. \quad (42)$$

Substituting (41) and (42) in (40), and assuming $\eta = 1 + \gamma_{R,D}$, we arrive to the following equation

$$\mathcal{A} + B\log_2(\eta)[\mathcal{B} + \mathcal{C}\eta + \mathcal{D}B\log_2(\eta)] = 0, \quad (43)$$

where $\mathcal{A} = a \cdot b \cdot r$, $\mathcal{B} = -a \cdot b - b \cdot r \cdot \left(\frac{\sigma_n^2}{|h|^2}\right) + a \cdot r$, $\mathcal{C} = b \cdot r \cdot \left(\frac{\sigma_n^2}{|h|^2}\right)$, and $\mathcal{D} = -b \cdot E_{ext}$, with $a = \zeta(P_S|g|^2 + \sigma_m^2)$, and $b = B\log_2(1+\gamma_{S,R}) + \delta r$.

Considering $\mathcal{F}(\eta) = \mathcal{A} + B\log_2(\eta)[\mathcal{B} + \mathcal{C}\eta + \mathcal{D}B\log_2(\eta)]$, we have a non-linear equation of the type

$$\mathcal{F}(\eta) = 0. \quad (44)$$

Let us assume that η is a simple or one of the multiple roots of (44), and η_0 is an initial point prediction sufficiently near to η. Using the Taylor's series expansion [22], we can express the following

$$\mathcal{F}(\eta_0) + (\eta - \eta_0)\mathcal{F}'(\eta_0) + \frac{1}{2}(\eta - \eta_0)^2\mathcal{F}''(\eta_0) = 0. \quad (45)$$

In order to solve the nonlinear equation in (44), an alternative equivalence formulation is used to develop a class of iterative methods. Simplified form of (45) can be re-written as

$$\mathcal{F}''(\eta_0)(\eta - \eta_0)^2 + 2\mathcal{F}'(\eta_0)(\eta - \eta_0) + 2\mathcal{F}(\eta_0) = 0. \quad (46)$$

It is clear that the equation in (46) is of the quadratic form. Hence, the corresponding roots can be expressed as

$$\eta - \eta_0 = \frac{-\mathcal{F}'(\eta_0) \pm \sqrt{[\mathcal{F}'(\eta_0)]^2 - 2\mathcal{F}''(\eta_0)\mathcal{F}(\eta_0)}}{\mathcal{F}''(\eta_0)}. \quad (47)$$

Depending on the sign of the proceeding radical term, the formula in (47) provides the following two possibilities

$$\eta = \eta_0 - \frac{\mathcal{F}'(\eta_0) + \sqrt{[\mathcal{F}'(\eta_0)]^2 - 2\mathcal{F}''(\eta_0)\mathcal{F}(\eta_0)}}{\mathcal{F}''(\eta_0)}. \quad (48)$$

$$\eta = \eta_0 - \frac{\mathcal{F}'(\eta_0) - \sqrt{[\mathcal{F}'(\eta_0)]^2 - 2\mathcal{F}''(\eta_0)\mathcal{F}(\eta_0)}}{\mathcal{F}''(\eta_0)}. \quad (49)$$

Using the fixed point formulations in (48) and (49), and in order to maximize the objective in (7), the following formula for an approximate solution η_{k+1} can be used to find the larger root iteratively [23]

$$\eta_{k+1} = \eta_k - \frac{\mathcal{F}'(\eta_k) - \sqrt{[\mathcal{F}'(\eta_k)]^2 - 2\mathcal{F}''(\eta_k)\mathcal{F}(\eta_k)}}{\mathcal{F}''(\eta_k)}. \quad (50)$$

It should be noted that the denominator of (50) is independent of $\mathcal{F}'(\eta_k)$ which makes it specially fit to find the largest root of the (44).

Since the non-linear equation in (43) involves the logarithmic terms, the number of iterations required to find the optimal largest root may be higher for the chosen value of η_0. In that case, Halley's method (2) or the modified Chebyshev's method (39) in [24] may also be used to reduce the number of iterations.

Finally, we obtain the following solutions for this case

$$P_R^* = (\eta - 1)\frac{\sigma_n^2}{|h|^2}, \quad (51)$$

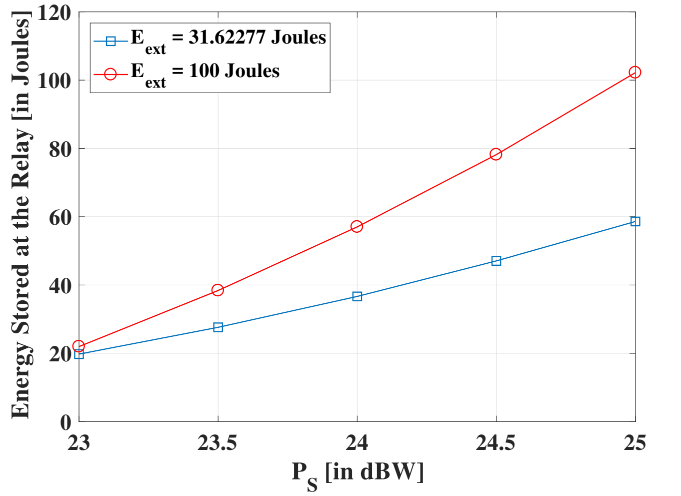

Fig. 4. Energy stored at the relay versus total transmit power at the source (P_S) for various values of E_{ext} with $\delta = 0.9$ and $r = 2.5$ Mbps

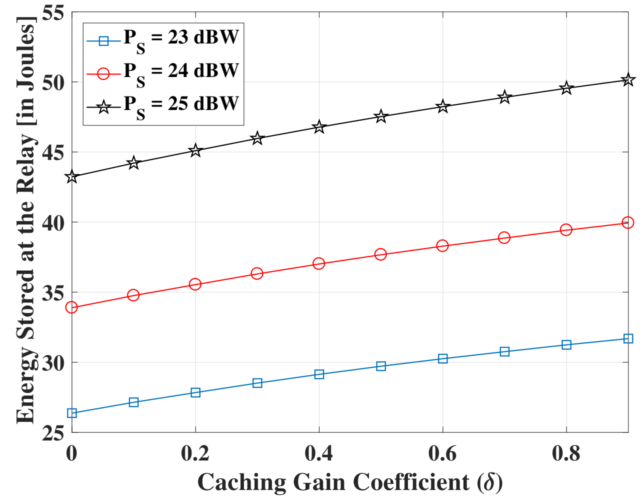

Fig. 5. Energy stored at the relay versus the caching gain (δ) for different values of P_S assuming $E_{ext} = 31.62277$ Joules and $r = 2.5$ Mbps.

$$\phi^* = \frac{r}{B\log_2(1+\gamma_{S,R}) + \delta r}, \quad (52)$$

$$\theta^* = \frac{rP_R^* - E_{ext}B\log_2\left(1+\frac{P_R^*|h|^2}{\sigma_n^2}\right)}{\zeta(P_S|g|^2+\sigma_m^2)}, \quad (53)$$

where P_R^*, ϕ^*, and θ^* are the optimal values obtained for P_R, ϕ, and θ.

The proposed solution is summarized in the algorithm which maximizes the stored energy in the relay supporting Wi-TIE - caching system (MSE-WC Algorithm)

Algorithm. *MSE-WC Algorithm*

Input: The parameters g, h, δ, r, and E_{ext}.
Output: Maximized energy stored at the relay: $\{E_S\}$.

1) : Initialize: $\zeta \in (0, 1]$, $P_T \in (0, \varepsilon P_{Max}]$, $0.5 < \varepsilon < 1$, $\sigma_m^2 = 1$, and $\sigma_n^2 = 1$.
2) : Compute $P_R^\dagger$, $\phi^\dagger$, and $\theta^\dagger$ using (31), (32), and (33) respectively.
3) : Define: $E_S^\dagger = \zeta\theta^\dagger(P_S|g|^2 + \sigma_m^2) - (1 - (\theta^\dagger + \phi^\dagger))P_R^\dagger$.
4) : Compute P_R^*, ϕ^*, and θ^* using (51), (52), and (53) respectively.
5) : Define: $E_S^* = \zeta\theta^*(P_S|g|^2 + \sigma_m^2) - (1 - (\theta^* + \phi^*))P_R^*$.
6) : $E_S = \max(E_S^\dagger, E_S^*)$.
7) : **return** E_S.

The proposed algorithm returns the maximized value of the objective function as its output. First, we initialize all the necessary values as indicated in 1). Then, we compute the optimal values of $P_R^\dagger$, $\phi^\dagger$, and $\theta^\dagger$ in 2), and define the energy stored at the relay in 3). 2) and 3) correspond to the solutions obtained for Case VI during the analysis. Similarly, we find the optimal values of P_R^*, ϕ^*, and θ^* in 4), and define the energy stored at the relay in 5) accordingly. 4) and 5) correspond to the solutions obtained for Case VIII during the analysis. Next, we find the maximum of the two computed local optimal solutions for the energy stored at the relay, which in turn maximizes the objective function. It should also be noted that the solutions proposed in (P2) for maximizing the energy stored at the relay are not necessarily globally optimal, as the problem is non-linear in nature. However, the KKT conditions guarantees the local optimal solutions.

IV. Simulation Results

In this section, we evaluate the performance of the proposed system for the solutions presented in this paper. We consider a total bandwidth of $B = 1$ MHz, $\zeta = 0.80$, $\sigma_m^2 = 0$ dBW, and $\sigma_n^2 = 0$ dBW. Throughout the simulations, we assume that the channel coefficients are i.i.d. and follow Rayleigh distribution. For each channel realization, we calculate the stored energy at the relay based on the solution of Section III. All the results are evaluated and averaged over 500 Monte-Carlo random channel conditions considering a path loss of 3 dB in both hops.

Fig. 4 presents the stored energy at the relay as a function of the source's transmit power and different external energy values. It is shown from the results that the source transmit power has large impacts on the stored energy at the relay. In particular, increasing the source's transmit power by 2 dBW will double the stored energy at the relay. It is also observed that increasing the external energy can significantly improve the stored energy at high P_S values. However, when P_S is small, increasing E_{ext} does not bring considerable improvement because at low P_S values, most of the time is used for information transfer from the source to the relay.

Fig. 5 depicts the energy stored at the relay as a function of the cache capacity δ, with $E_{ext} = 31.6$ Joules and $r = 2.5$ Mbps. The case with $\delta = 0$ implies that there is no caching at the relay. It is shown that caching helps to increase the saved energy at the relay for all P_S values. And the increased stored energy are almost similar for different P_S. This is because of the linear model of the caching system in (5).

Fig. 6 presents the energy stored at the relay against P_S. It is shown that the energy stored at the relay keeps increasing with increasing transmit power values at the source (P_S), for $\delta = 0.2$ and $E_{ext} = 31.6$ Joules. On the other hand, it is clear that with

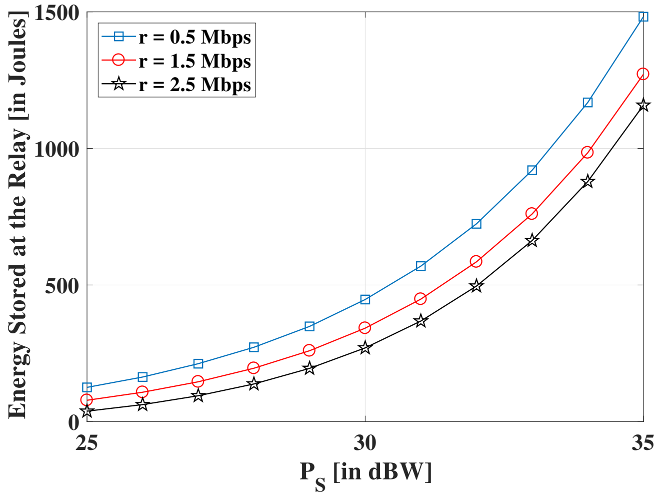

Fig. 6. Energy stored at the relay versus the total transmit power at the source (P_S) for different values of r with $\delta = 0.2$ and $E_{ext} = 31.62277$ Joules.

increasing values of r, the energy stored at the relay decreases non-linearly. This is due to the fact that in order to meet the demand of requested rate at the destination, more energy would be required for resource allocation at the relay which utilizes the harvested energy.

V. Conclusion

In this paper, we investigated a novel time switching based hybrid Wi-TIE and caching communication system. We maximized the energy stored at the relay under constraints on minimum link rate between the relay and the destination, and on minimum harvested energy at the relay. Besides, we presented closed-form solutions for the proposed relay system to enable Wi-TIE with caching in practice. We illustrated via numerical results the effectiveness of the proposed system. This work can be further extended to many promising directions such as selection of the best relay out of given multiple relays, multiuser and multicarrier scenario.

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References

[1] S. Zhou, J. Gong, Z. Zhou, W. Chen, and Z. Niu, “GreenDelivery: proactive content caching and push with energy-harvesting-based small cells,” *IEEE Communications Magazine*, vol. 53, no. 4, pp. 142–149, April 2015.

[2] E. white paper, “More than 50 Billion Connected Devices ,” https://www.ericsson.com/openarticle/mwc-connected-devices_1686565587_c, 2011, [Online].

[3] D. Niyato, D. I. Kim, P. Wang, and L. Song, “A novel caching mechanism for Internet of Things (IoT) sensing service with energy harvesting,” in *2016 IEEE International Conference on Communications (ICC)*, May 2016, pp. 1–6.

[4] D. Gunduz, K. Stamatiou, N. Michelusi, and M. Zorzi, “Designing intelligent energy harvesting communication systems,” *IEEE Communications Magazine*, vol. 52, no. 1, pp. 210–216, January 2014.

[5] M. Tao, E. Chen, H. Zhou, and W. Yu, “Content-Centric Sparse Multicast Beamforming for Cache-Enabled Cloud RAN,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6118–6131, Sept 2016.

[6] S. S. Ikki, P. Ubaidulla, and S. Aissa, “Performance Study and Optimization of Cooperative Diversity Networks with Co-Channel Interference,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 14–23, January 2014.

[7] T. Cover and A. E. Gamal, “Capacity theorems for the relay channel,” *IEEE Transactions on Information Theory*, vol. 25, no. 5, pp. 572–584, September 1979.

[8] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, December 2004.

[9] P. Zhang, J. Yuan, J. Chen, J. Wang, and J. Yang, “Analyzing Amplify-and-Forward and Decode-and-Forward Cooperative Strategies in Wyner’s Channel Model,” in *2009 IEEE Wireless Communications and Networking Conference*, April 2009, pp. 1–5.

[10] M. Yu and J. Li, “Is amplify-and-forward practically better than decode-and-forward or vice versa?” in *Proceedings. (ICASSP ’05). IEEE International Conference on Acoustics, Speech, and Signal Processing, 2005.*, vol. 3, March 2005, pp. iii/365–iii/368 Vol. 3.

[11] K. Huang and E. Larsson, “Simultaneous Information and Power Transfer for Broadband Wireless Systems,” *IEEE Transactions on Signal Processing*, vol. 61, no. 23, pp. 5972–5986, December 2013.

[12] S. Gautam and P. Ubaidulla, “Relay Selection and Transceiver Design for Joint Wireless Information and Energy Transfer in Cooperative Networks,” in *Proc. 85th Vehicular Technology Conference (VTC), 2017-Spring*, June 2017.

[13] S. Gautam, E. Lagunas, S. Sharma, S. Chatzinotas, and B. Ottersten, “Relay Selection Strategies for SWIPT-Enabled Cooperative Wireless Systems,” *in Proc. 28th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, October 2017.

[14] X. Zhou, R. Zhang, and C. K. Ho, “Wireless Information and Power Transfer: Architecture Design and Rate-Energy Tradeoff,” *IEEE Transactions on Communications*, vol. 61, no. 11, pp. 4754–4767, November 2013.

[15] M. A. Maddah-Ali and U. Niesen, “Fundamental Limits of Caching,” *IEEE Transactions on Information Theory*, vol. 60, no. 5, pp. 2856–2867, May 2014.

[16] T. X. Vu, S. Chatzinotas, B. Ottersten, and T. Q. Duong, “Energy Minimization for Cache-assisted Content Delivery Networks with Wireless Backhaul,” *IEEE Wireless Communications Letters*, vol. PP, no. 99, pp. 1–1, 2018.

[17] T. X. Vu, S. Chatzinotas, and B. Ottersten, “Edge-Caching Wireless Networks: Performance analysis and Optimization,” *IEEE Transactions on Wireless Communications*, to appear.

[18] A. Kumar and W. Saad, “On the tradeoff between energy harvesting and caching in wireless networks,” in *2015 IEEE International Conference on Communication Workshop (ICCW)*, June 2015, pp. 1976–1981.

[19] L. Ma, Y. Wang, and Y. Xu, “Sum rate optimization for SWIPT system based on zero-forcing beamforming and time switching,” in *2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC)*, June 2017, pp. 351–356.

[20] S. Lohani, R. A. Loodaricheh, E. Hossain, and V. K. Bhargava, “On multiuser resource allocation in relay-based wireless-powered uplink cellular networks,” *IEEE Transactions on Wireless Communications*, vol. 15, no. 3, pp. 1851–1865, March 2016.

[21] R. M. Corless, G. H. Gonnet, D. E. Hare, D. J. Jeffrey, and D. E. Knuth, “On the LambertW function,” *Advances in Computational mathematics*, vol. 5, no. 1, pp. 329–359, 1996.

[22] E. W. Weisstein, “Taylor series,” 2004.

[23] Z. Hong-bin, “A Novel Method Finding Multiple Roots of Nonlinear Equations,” in *2009 Fifth International Conference on Natural Computation*, vol. 6, Aug 2009, pp. 299–302.

[24] B. Neta, “New third order nonlinear solvers for multiple roots,” *Applied Mathematics and Computation*, vol. 202, no. 1, pp. 162–170, 2008.