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

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- Basic Schema
- Transceiver Architecture
- Definitions

Maximization of Energy stored at the Relay
- Problem Formulation
- Solution
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Introduction

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Summary

- The exponential increase in the usage of wireless devices 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**.
- By the end of **2020**, this number is expected to cross **50 billion**.
- Recent developments in **IoTs** emphasize on the interconnection between the devices, with or without slightest human mediation.
- Most of these connecting operations involve battery-limited devices that may not be continuously powered $\Longrightarrow$ **management of energy becomes crucial**.
- **In this work, we propose a novel framework to realize the benefit of Wi-TIE combined with caching capability to support future technologies.**

System Model

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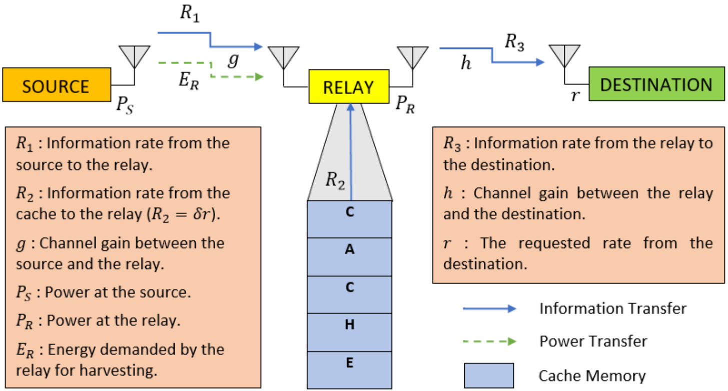
SYSTEM MODEL

System Model

Wi-TIE with Caching at the DF Relay



R_1 : Information rate from the source to the relay.

R_2 : Information rate from the cache to the relay ($R_2 = \delta r$).

g : Channel gain between the source and the relay.

P_S : Power at the source.

P_R : Power at the relay.

E_R : Energy demanded by the relay for harvesting.

R_3 : Information rate from the relay to the destination.

h : Channel gain between the relay and the destination.

r : The requested rate from the destination.

Figure: 1. 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. Due to limited coverage, there is not direct connection between the source and the destination. This model can find application on the downlink where the base station plays the source's role and sends information to a far user via a small- or femto- cell base station.

System Model

Proposed DF Relay Transceiver Design

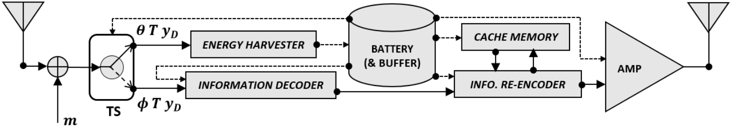


Figure: 2. Proposed DF relay transceiver design for hybrid Wi-TIE and Caching with Time Switching (TS) architecture.

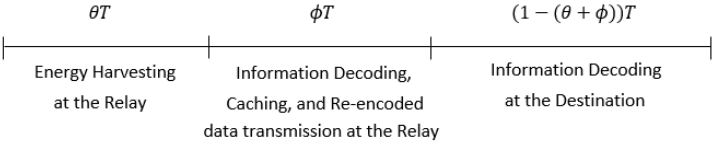


Figure: 3. Convention assumed for distribution of time to investigate the Maximization Problem of Energy stored at the Relay.

System Model

Definitions

- Denote P_S and P_R as the transmit power at the source and at the relay, respectively.
- In addition, let g and h denote the channel gain 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

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

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

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

System Model

Definitions

- The achievable information rate of the source-relay link is

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

where B is the channel bandwidth.

- When the destination request a file from the library, δ part of that file is already available at the relay's cache.
- In other words, the relay's cache can provide, in addition to the source-relay link, a cache rate

$$R_2 = \delta r. \tag{4}$$

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

$$R_3 = B\log_2\left(1 + \frac{P_R\,|h|^2}{\sigma_n^2}\right). \tag{5}$$

- The harvested energy at the relay is given by

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

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MAXIMIZATION OF ENERGY STORED AT THE RELAY

Problem Formulation for Maximization of the Energy stored at the Relay (P1)

- **PROBLEM**: We represent the overall optimization problem as

$$
\begin{aligned}
(P1):\ \max_{\theta,\phi,P_R}\quad & [\zeta\theta(P_S|g|^2+\sigma_m^2)-(1-(\theta+\phi))P_R]^+ && (7)\\
\text{subject to}\quad & (C1): \phi(R_1+R_2)\geq(1-(\theta+\phi))R_3, && (8)\\
& (C2): (1-(\theta+\phi))P_R\leq E_R+E_{ext}, && (9)\\
& (C3): (1-(\theta+\phi))R_3\geq r, && (10)\\
& (C4): 0<P_S\leq P^\star, && (11)\\
& (C5): 0\leq\theta+\phi\leq 1. && (12)
\end{aligned}
$$

- Here, the objective function of (P1) is the expression of the overall energy stored at the relay, (C1) ensures the requested data 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.

Solution obtained using the KKT

- We denote the Lagrangian of (P1) as follows

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

where

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

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

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

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

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

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

Solution obtained using the KKT

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

$$P_R^{\dagger} = (\nu - 1)\frac{\sigma_n^2}{|h|^2} \tag{19}$$

$$\phi^{\dagger} = \frac{r}{\log_2(1 + \gamma_{S,R}) + \delta r} \tag{20}$$

$$\theta^{\dagger} = 1 - r\left(\frac{1}{\log_2(1 + \gamma_{S,R}) + \delta r} + \frac{1}{\log_2\left(1 + \frac{P_R^{\dagger}|h|^2}{\sigma_n^2}\right)}\right) \tag{21}$$

where

$$\nu = \exp\left(\mathcal{W}(-\mathcal{A}\exp(-\log^2(2)) + \log(2)) + \log^2(2)\right) \tag{22}$$

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

Solution obtained using the KKT

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

$$P_R^* = (\eta - 1)\frac{\sigma_n^2}{|h|^2}, \tag{23}$$

$$\phi^* = \frac{r}{\log_2(1 + \gamma_{S,R}) + \delta r}, \tag{24}$$

$$\theta^* = \frac{rP_R^* - E_{ext}\log_2\left(1 + \frac{P_R^*|h|^2}{\sigma_n^2}\right)}{\zeta(P_S|g|^2 + \sigma_m^2)}, \tag{25}$$

where

$\eta =$ Largest Root of$[\mathcal{A} + \log_2(\eta)(\mathcal{B} + \mathcal{C}\eta + \mathcal{D}\log_2(\eta)) = 0]$,

with $\mathcal{A} = a \cdot b \cdot r$, $\mathcal{B} = -a \cdot b - b \cdot r \cdot \left(\frac{\sigma_n^2}{|h|^2}\right) + a \cdot r$,

$\mathcal{C} = b \cdot r \cdot \left(\frac{\sigma_n^2}{|h|^2}\right)$, and $\mathcal{D} = -b \cdot E_{ext}$, where

$a = \zeta(P_S|g|^2 + \sigma_m^2)$, and $b = \log_2(1 + \gamma_{S,R}) + \delta r$.

Solution obtained using the KKT

- Remaining cases yields unacceptable solutions.
- To summarize the overall solutions, we propose the following algorithm to maximize 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: The maximized value of energy stored at the relay: $\{E_S\}$.

```
: Initialize: $\zeta \in (0,1]$, $P_T \in (0, \varepsilon P_{Max}]$, $0.5 < \varepsilon < 1$, $\sigma_m^2 = 1$, and $\sigma_n^2 = 1$.
: Compute $P_R^\dagger$, $\phi^\dagger$, and $\theta^\dagger$ using (19), (20), and (21) respectively.
: Define: $E_S^\dagger = \zeta\theta^\dagger(P_S|g|^2 + \sigma_m^2) - (1 - (\theta^\dagger + \phi^\dagger))P_R^\dagger$.
: Compute $P_R^*$, $\phi^*$, and $\theta^*$ using (23), (24), and (25) respectively.
: Define: $E_S^* = \zeta\theta^*(P_S|g|^2 + \sigma_m^2) - (1 - (\theta^* + \phi^*))P_R^*$.
: $E_S = \max(E_S^\dagger, E_S^*)$.
: **return** $E_S$.
```

Simulation Result : Energy stored at the relay versus total transmit power

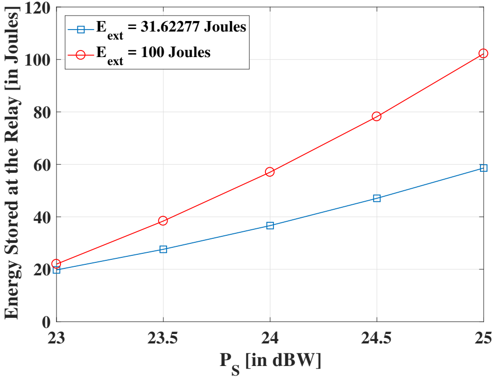

Figure: 4. Energy stored at the relay versus total transmit power at the source (P_S) for various values of E_{ext} with $\delta = 0.9$ and $r = 2$ Mbps.

- ⋆ The results show that the source transmit power has large impacts on the stored energy at the relay.
- ⋆ Increasing the source's transmit power by 2 dBW will double the stored energy at the relay.
- ⋆ 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.

Simulation Result : Energy stored at the relay versus cache gain coefficient

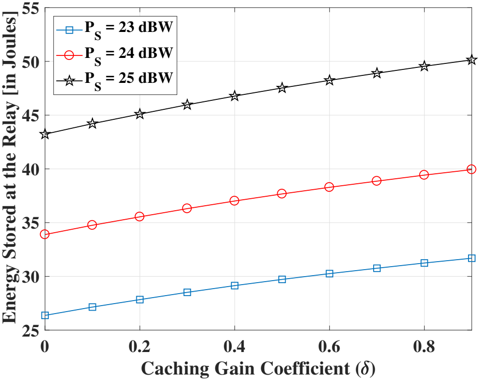

Figure: 5. Energy stored at the relay versus the caching gain (δ) for different values of P_S assuming $E_{ext} = 31.62277$ Joules and $r = 2$ Mbps.

- ⋆ 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 due to the linear model of the caching system.

Simulation Result : Energy stored at the relay versus total transmit power

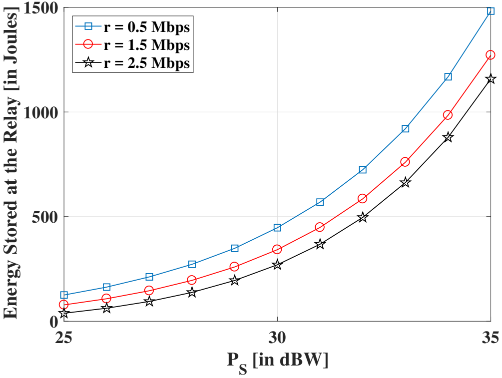

Figure: 6. Energy stored at the relay versus the total transmit power at the source (P_S) for different values of r with $\delta = 0.2$ and $E_{ext} = 31.62277$ Joules.

⋆ It is seen that the energy stored at the relay keeps increasing with increasing transmit power values at the source.
⋆ On the other hand, it is clear that with 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.

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- We investigated a novel time switching based hybrid Wi-TIE and caching communication system.
- We addressed the problem of maximizing the energy stored at the relay under constraints on minimum link throughput 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.

Any Questions...
Just Ask!


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