Harvest-Use Cooperative Networks with Half/Full-Duplex Relaying

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Abstract—**Harvest-use (HU) is an energy harvesting (EH) architecture where the received energy cannot be stored and immediately must be consumed in order to maintain operability. Due to its current limited application interest, this architecture has not yet been examined in the literature and its deployment to communication system is an open problem. This paper deals with the application of HU architecture to communication systems and investigates cooperative protocols where the relay node has HU capabilities. We show that HU relaying introduces a trade-off between EH time and relaying (data communication) time; this trade-off is discussed for two fundamental relaying policies a) Amplify-and-forward (AF) with half-duplex (HD) relaying and b) AF with full-duplex (FD) relaying. The optimal time split is formulated as an optimization problem and an approximation is given in a closed form. Numerical results show that FD outperforms HD and is introduced as an efficient relaying policy for HU cooperative systems.**

Index Terms—**Energy harvesting, harvest-use architecture, relay channel, full-duplex relaying, fading channel.**

I. Introduction

Conventional battery-power communication systems suffer from a short lifetime and require periodical replacement or recharging in order to maintain network connectivity. Recent advances in microelectronics and materials makes energy harvesting (EH) a feasible technical solution and enables the design of full-autonomous and self-sustained networks without lifetime constraints [1]. EH for wireless communication systems refers to the ability of the wireless nodes to harvest energy from the surrounding (solar, vibration, ambient radio power etc) and convert it to electric power in order to ensure operability. From an architectural standpoint, EH systems are divided into two main categories [2], [3]: (a) *harvest-use (HU)*, where harvested energy cannot be stored and is used immediately and (b) *harvest-store-use (HSU)*, where the harvested energy can be accumulated for future use.

Most work in the literature deals with the HSU architectures due to their significant application/commercial interest. HSU systems assume an energy storage device at the EH nodes and require an appropriate management of the stored energy. Studies such as [4]–[6] model the power battery as an energy buffer and analyze different transmission policies for different communication scenarios and optimization objectives. On the other hand, HU systems do not have mechanism to store harvested energy and refer to applications where nodes exchange/diffuse some bursty short messages (i.e. sensor networks for monitoring etc). The literature related to HU architectures is very limited and mainly concerns some hardware implementations for specific applications [1]; an overview of works related to HU implementations is given in [3] (and references therein). An interesting HU implementation is the shoe-mounted piezoelectric system designed at the MIT Media Lab [7] where energy is harvested through human walking.

On the other hand, relaying cooperation is a promising technique to combat fading and path-loss in wireless networks. Transmission/reception cooperation between nodes of a network provides significant benefits (bandwidth, energy, reliability etc) and has been extensively studied in the literature over the last years [8], [9]. Most of work on cooperative networks assume half-duplex (HD) relaying where the relay nodes are not able to receive and transmit data in the same frequency and time [9]. Recent advances on antenna technology and signal processing allow full-duplex (FD) relaying where the relay nodes can simultaneously receive and transmit but with the cost of a loop interference from the relay output to the relay input [10], [11]. Relaying cooperation ensures a more efficient use of the harvested energy and studies such as [12], [13] investigate its impact on HSU-based networks.

To the best of the authors' knowledge there is not any literature on the protocol (cooperative or non-cooperative protocols) design for HU systems; this remark motivates the work reported in this paper. In our work we focus on a simple 2-hop cooperative scenario (source-relay-destination) [13] where the relay node employs an HU architecture for EH. Given that the relay node requires some time to harvest energy in order to perform relaying, HU introduces a fundamental trade-off between EH time and communication time. We study this trade-off for conventional HD relaying and we derive an approximation of the optimal time split in closed form by using the capacity expression as an objective function. In order to further boost the system performance, an FD relaying is also investigated. An approximation of the optimal power split for an FD relay is given in a closed-form and we show that FD significantly outperforms HD. In addition, a hybrid scheme that dynamically switches between FD/HD is discussed. The main conclusion of this paper is that FD seems to be an attractive and promising technology for HU-based cooperative

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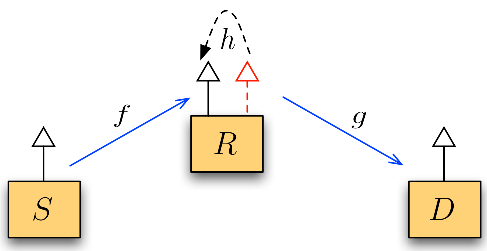

Fig. 1. The system model $S \rightarrow R \rightarrow D$; the relay node employs a HU architecture (the second antenna at the relay node is used for the FD case).

networks.

The remainder of this paper is organized as follows. Section II introduces the HU-based system model and the basic assumptions. Section III deals with the application of HD and FD relaying to the considered HU system and gives the associated optimal time split. In Section IV, the performance of the investigated schemes is quantified through numerical results and Section V concludes the paper.

II. System model

We assume a simple three-node network topology consisting of one source S, one relay node R and one destination D. Fig. 1 schematically depicts the system mode. A direct link between source-destination is not available and communication can be established only via the relay node. All nodes are equipped with one antenna (in case that the relay operates in FD mode, it is equipped with two antennas, one for transmission and one for reception). The source node has always data to transmit (backlogged) and transmits with a fixed power P_0. The relay node has no energy supply and harvests energy from the surrounding (solar, vibration etc) in order to be able to forward the source's signal. It adopts a HU architecture and therefore it directly converts the harvested energy to electric energy for operating its circuits. Due to hardware/circuit constraints the relay node cannot simultaneously receive/transmit data and harvest energy. Communication is organized in time-frames of duration 1 time unit; each frame is further divided in two variable-size time slots where the first time slot (of duration $\omega[n]$ for the n-th frame with $\omega_0 < \omega[n] < 1$, where $\omega_0 > 0$ denotes the minimum time that can be assigned for EH and is associated to hardware constraints) is used for energy scavenging while the second one (of duration $1-\omega[n]$) for relaying the source signal.

We assume that the surrounding energy is always available with a constant energy profile[1] $E(t) = \delta$ and thus $e = \int_0^{T_1} E(t)dt = \delta T_1$ denotes the energy harvested for an observation time equal to T_1 (scavenging time); this simple energy profile is sufficient for the purpose of this work. We assume that all the harvested energy can be used for transmission (we neglect energy consumption for other operations) and the transmitted power at the relay node depends on the duration of the transmission time i.e. $P = e/T_2$ for a transmission time equal to T_2 (transmission power is limited by the harvested energy and thus further power constraints are not assumed). The relay node employs an Amplify-and-Forward (AF) relaying strategy and can operate either in HD or in FD mode; details related to the relaying operation are given in the following section.

All wireless links exhibit fading and additive white Gaussian noise (AWGN). The fading is assumed to be frequency non-selective Rayleigh block fading. This means that the fading coefficients remain constant during one frame, but change independently from one frame to another; $f[n]$, $g[n]$ and $h[n]$ denotes the exponential channel power gains for the link $S \rightarrow R$, $R \rightarrow D$ and $R \rightarrow R$ (loop interference from the relay output to the relay input for the case of FD operation), respectively, for the n-th time frame; the variance for the link $i \rightarrow j$ is denoted by $\sigma_{i,j}^2$. The variance of the AWGN is assumed to be normalized with zero mean and unit variance. Finally, we assume global channel-state information (CSI) at the relay node; an instantaneous feedback channel supports this CSI assumption [14].

[1] Function of the available surrounding energy with time.

III. HU relaying protocols: Half-duplex Vs Full-duplex

In this section we study the application of HD and FD operation mode for the HU cooperative system considered.

A. Half-duplex relaying

In the HD case the relay node cannot receive and transmit data simultaneously and communication can be performed in two orthogonal and equal time slots. Therefore, the second slot of each time frame is further divided in two orthogonal and equal sub-slots, one sub-slot for source transmission and one sub-slot for relaying AF transmission; based on the system model the duration of each sub-slot is equal to $(1-\omega[n])/2$ for the n-th frame. Fig. 2(a) depicts the frame structure for the HD case. The relay harvests $e[n] = \delta\omega[n]$ (energy units) and transmits with a power $P[n] = 2\delta\omega[n]/(1-\omega[n])$ due to the orthogonal relaying (sub-slot split increases the transmitted power at the relay node). By omitting the frame index, the channel capacity for the n-th transmission is given by [8], [15]

$$C_{\mathrm{HD}}(\omega) = \frac{1-\omega}{2}\log_2\left(1+\frac{P_0 f P g}{P_0 f + P g + 1}\right)$$
$$= \frac{1-\omega}{2}\log_2\left(1+\frac{P_0 f \frac{2\delta\omega}{1-\omega} g}{P_0 f + \frac{2\delta\omega}{1-\omega} g + 1}\right). \quad (1)$$

From the above expression we can see an interesting trade-off associated with the duration of the EH slot: a longer EH time increases the energy harvested but decreases the available time for communication and vice-versa; in addition, a shorter communication time increases the transmitted power at the relay node and vice-versa. An appropriate system design can optimize the instantaneous capacity by adjusting the parameter ω. More specifically, the optimal frame division is given by solving the following optimization problem

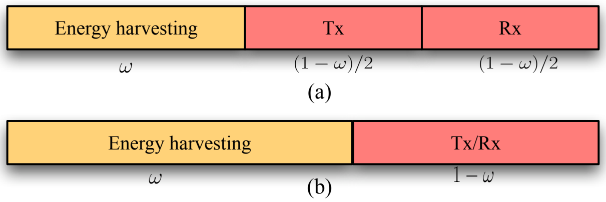

Fig. 2. Frame structure for HU-based AF: (a) HD relaying, (b) FD relaying.

$$\begin{aligned}&\omega^* = \arg\max_{\omega} C_{\text{HD}}(\omega)\\ &\text{subject to } \ \omega_0 \leq \omega \leq 1. \qquad (2)\end{aligned}$$

Given that the function $C_{\text{HD}}(\omega)$ is a concave function of ω, the optimal value ω^* can be given by solving the equation $\frac{\vartheta C_{\text{HD}(\omega)}}{\vartheta \omega} = 0$. However, due to the complexity of the involved expression, a closed-form (and general) solution of the optimization problem is not possible; in this work, the optimal value ω^* is calculated numerically by using standard technical computing tools such as Matlab and Maples.

In order to simplify the optimization problem and be able to provide a closed-form approximation of ω^*, we consider an approximation (tight upper bound) of (1) given by [16, Eq. (6)]

$$C'_{\text{HD}}(\omega) = \frac{1-\omega}{2}\log_2\left(1+\min\left[P_0 f, \frac{2\delta\omega}{1-\omega} g\right]\right). \qquad (3)$$

The above approximation in our optimization problem, allows a closed-form approximation of ω^* given as

$$\begin{aligned}&\frac{\vartheta C'_{\text{HD}(\omega)}}{\vartheta \omega} = 0 \Rightarrow\\ &\omega^*_{\text{HD}} \approx \begin{cases}\max[\omega_1, \omega_0], & \text{If } f \leq \frac{2\delta g - Q(2) - 1}{P_0 Q(2)}\\ \max[\omega_2, \omega_0], & \text{elsewhere}\end{cases}\\ &\qquad \to \max[\omega_2, \omega_0] \ \text{ for } P_0 \to \infty, \qquad (4)\end{aligned}$$

with

$$\begin{aligned}Q(x) &\triangleq W\left((x\delta g - 1)/exp(1)\right),\\ \omega_1 &= \frac{1}{1+\frac{2\delta g}{P_0 f}},\\ \omega_2 &= \frac{1}{2\delta g - 1}\frac{(2\delta g - 1) - Q(2)}{Q(2)+1}, \qquad (5)\end{aligned}$$

where we denoted by W the LambertW function, where $W(x)$ is the solution of $W\exp(W) = x$. Simulation results in Section V validate the efficiency of the proposed approximation.

B. Full-duplex relaying

A disadvantage of the HD relaying (for the specific application) is that the time slot duration assigned for EH is significantly compressed in order to ensure efficient time for the orthogonal relaying. The main motivation for FD relaying is to ensure a better balance for the fundamental trade-off between EH time and communication time. More specifically, in the FD case, the relay node can simultaneously receive and transmit data but with the cost of a loop interference that leaks from the relay output to the relay input. FD relaying provides a compression of the communication time and thus can release some extra time for further EH and potential performance benefits. In this case the second sub-slot is not further divided and simultaneously supports data reception and relaying transmission. Fig. 2(b) depicts the frame structure for the FD case. By extending the expressions in [11], the channel capacity for the n-th transmission is given by [15]

$$\begin{aligned}C_{\text{FD}}(\omega) &= (1-\omega)\log_2\left(1+\frac{\frac{P_0 f}{Ph+1}Pg}{\frac{P_0 f}{Ph+1}+Pg+1}\right)\\ &= (1-\omega)\log_2\left(1+\frac{\frac{P_0 f}{\frac{\delta\omega}{1-\omega}h+1}\frac{\delta\omega}{1-\omega}g}{\frac{P_0 f}{\frac{\delta\omega}{1-\omega}h+1}+\frac{\delta\omega}{1-\omega}g+1}\right). \qquad (6)\end{aligned}$$

From the above expression we can see that FD does not suffer from the pre-log factor $1/2$ related to the HD transmission but is affected by a loop interference that is a function of the transmitted power at the relay node. Equivalently to the discussion in Section III-A, an appropriate design splits the frame structure in a way that maximizes the instantaneous channel capacity. The optimization problem is expressed as

$$\begin{aligned}&\omega^*_{\text{FD}} = \arg\max_{\omega} C_{\text{FD}}(\omega)\\ &\text{subject to } \ \omega_0 \leq \omega \leq 1. \qquad (7)\end{aligned}$$

The optimal solution is provided by solving the equation $\frac{\vartheta C_{\text{FD}(\omega)}}{\vartheta \omega} = 0$; a closed-form expression is not possible and the optimal value is calculated numerically. In order to have a closed-form approximation of the optimal time split, we approximate the capacity expression in (6) as follows (tight upper-bound) [16, Eq. (6)]

$$C'_{\text{FD}}(\omega) = (1-\omega)\log_2\left(1+\min\left[q_1(\omega), q_2(\omega)\right]\right), \qquad (8)$$

where $q_1(\omega) \triangleq \frac{P_0 f}{\frac{\delta\omega}{1-\omega}h+1}$ and $q_2(\omega) \triangleq \frac{\delta\omega}{1-\omega}g$. By using the above approximation, the optimization problem gives

$$\begin{aligned}&\omega^*_{\text{FD}} \approx \begin{cases}\max[\omega_1, \omega_0] \text{ If } (1+q_1(\omega_1))^{1-\omega_1} > (1+q_2(\omega_2))^{1-\omega_2}\\ \max[\omega_2, \omega_0] \text{ elsewhere}\end{cases}\\ &\qquad \to \max[\omega_2, \omega_0] \ \text{ for } P_0 \to \infty, \qquad (9)\end{aligned}$$

with

$$\begin{aligned}\omega_1 &= \frac{1}{1+\sqrt{\frac{\delta^2 gh}{P_0 f}}},\\ \omega_2 &= \frac{1}{\delta g - 1}\frac{(\delta g - 1) - Q(1)}{Q(1)+1}. \qquad (10)\end{aligned}$$

Simulation results in Section IV validate the accuracy of the proposed approximation.

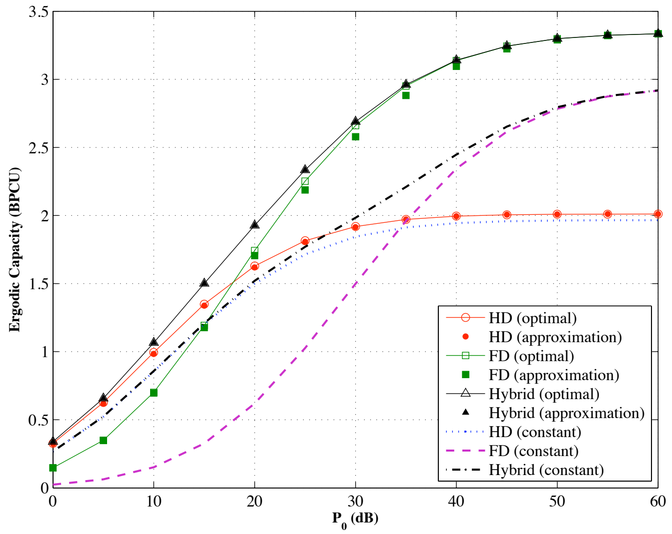

Fig. 3. Ergodic capacity versus P_0 for optimal and approximated time split; $\omega^*_{\text{HD}} = 1/3$ and $\omega^*_{\text{FD}} = 1/2$ for constant time split, $\sigma^2_{S,R} = \sigma^2_{R,D} = \sigma^2_{R,R} = 1$, $\omega_0 = 0.1$, $\delta = 20$ dB.

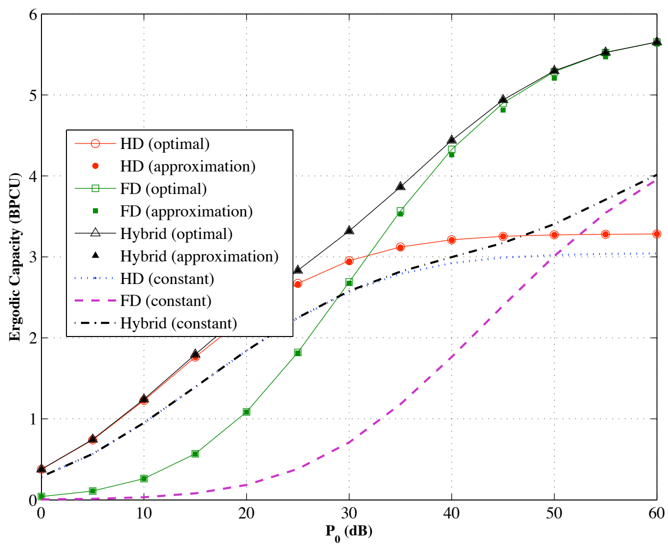

Fig. 4. Ergodic capacity versus P_0 for optimal and approximated time split; $\omega^*_{\text{HD}} = 1/3$ and $\omega^*_{\text{FD}} = 1/2$ for constant time split, $\sigma^2_{S,R} = \sigma^2_{R,D} = \sigma^2_{R,R} = 1$, $\delta = 30$ dB and $\omega_0 = 0.1$.

C. A hybrid scheme

The hybrid scheme dynamically switches between the HD and FD relaying in order to use the optimal mode at each time frame. Based on the available CSI, the relay node decides about the optimal operation mode based on a simple parameter comparison. The hybrid scheme can be expressed as

$$m^* = \arg \max_{m \in \{\text{HD,FD}\}} \left[C_m(\omega^*_m) \right] \tag{11}$$

where m^* denotes the optimal operation mode; the above expression can be applied for both the exact and the approximated values of ω^*.

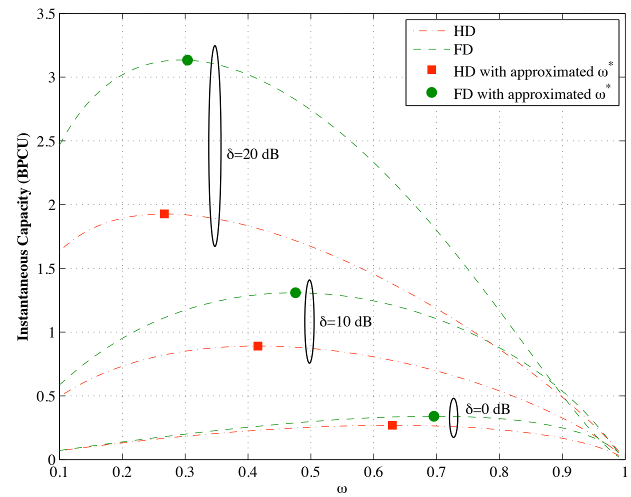

Fig. 5. Instantaneous capacity versus ω; $f = 2.83$, $g = 0.5122$, $h = 0.91$, $\delta = \{0,\ 10,\ 20\}$ dB, $P_0 = 40$ dB and $\omega_0 = 0.1$.

IV. Numerical Results

Monte Carlo simulations are carried out in order to evaluate the performance of the investigated schemes. The simulation environment follows the description in Section II. The performance criterion adopted is the ergodic capacity (in bits per channel use (BPCU)) which is defined as the average channel capacity over large number of channel realizations.

Figs 3 and 4 plot the ergodic capacity versus the source's transmitted power P_0 for the investigated relaying schemes (AF-HD scheme with optimal/approximated time split, AF-FD scheme with optimal/approximated time split and hybrid AF-HD/FD scheme). The simulation set-up consists of $\sigma^2_{S,R} = \sigma^2_{R,D} = \sigma^2_{R,R} = 1$, $\omega_0 = 0.1$ and an EH profile with $\delta = 20$ dB and $\delta = 30$ dB, respectively. The performance for a constant and symmetric time split with $\omega^*_{\text{HD}} = 1/3$ and $\omega^*_{\text{FD}} = 1/2$ is used for comparison. The first main observation is that all the protocols converge to a capacity floor due to the EH-based transmitted power at the relay node; the signal-to-noise ratio (SNR) of the second hop is strongly related with δ and thus remains constant as $P_0 \to \infty$. As it can be seen from the curves, AF-FD with optimal time split outperforms AF-HD scheme and achieves a higher ergodic capacity performance (higher capacity floor). The FD duplex mode provides a better balance between EH and transmission time and is introduced as an efficient solution for HU cooperative systems. A closer observation of the curves shows that AF-HD outperforms AF-FD for low P_0 and this remark motivates the hybrid scheme that dynamically switches between HD and FD operation mode; the hybrid scheme combines the benefits from both duplex modes and achieves the best performance for all cases (it coincides with AF-FD at high P_0). On the other hand, we can see that the performance achieved by the approximated time split efficiency approximates the performance given by the exact solution of the optimization problem in (2) and (7); these observations validate our analysis for the optimal

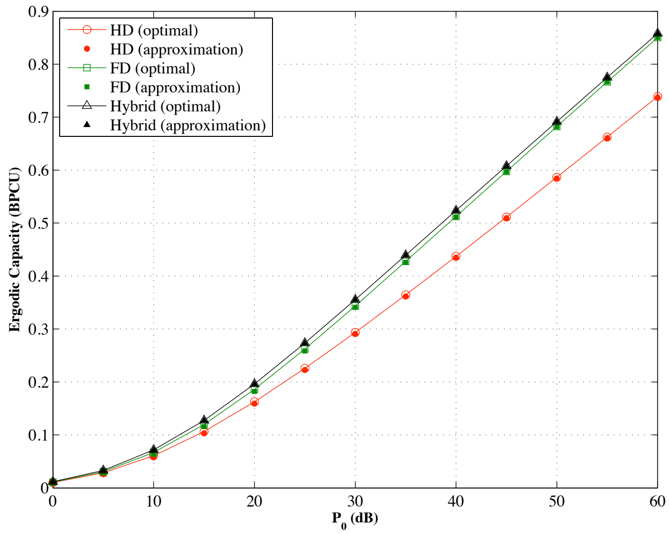

Fig. 6. Ergodic capacity versus P_0; $\sigma^2_{S,R} = \sigma^2_{R,D} = \sigma^2_{R,R} = 1$ and $\delta = P_0$ dB.

time split. In addition, we can see that a suboptimal time split significantly degrades the performance of the system and therefore its optimization is a critical issue for the considered system. Finally, a comparison of the two figures shows that as δ increases the performance of the protocols significantly improved because more energy can be harvested.

Fig. 5 deals with the impact of the time split ω on the achieved performance; we focus on a single time frame with a settings $f = 2.83$, $g = 0.5122$, $h = 0.91$, $\delta = \{0,\ 10,\ 20\}$ dB, $P_0 = 40$ dB, $\omega_0 = 0.1$ and we plot the instantaneous channel capacity versus ω. As it can be seen, the capacity expression is a concave function of ω and its optimal value is of significant interest in order to maximize the system performance; the approximated optimal time split given in (2) and (7) efficiently approximates the optimal value (i.e., the approximated values are very close to the maximum of the curves). In addition, it can be seen that $\omega^*_{\text{FD}} > \omega^*_{\text{HD}}$ for all cases, because HD mode needs to allocate less time for EH due to the associated orthogonal relaying transmission. Finally, Fig. 6 plots the ergodic capacity versus P_0 for a simulation set-up without any constraint on ω (i.e. $\omega_0 = 0$) and an energy profile with $\delta = P_0$ (the other simulation parameters are the same with the ones in Fig. 3). It can be seen that for this case FD outperforms HD without suffering from a capacity floor into the SNR range of interest. It is worth noting that as $P_0 \to \infty$, we have $\omega^* \to 0$ for both duplex modes and therefore this result serves only as a useful theoretical bound.

V. Conclusion

This paper has dealt with the design of cooperative protocols for EH systems where the relay nodes deploy a HU architecture. Based on a fundamental three-node topology we investigated the optimal time split (between EH and relaying transmission) for both AF with HD and AF with FD by using the channel capacity as an objective function. The optimal instantaneous time division has been approximated in closed-form and a hybrid scheme that dynamically selects the duplex mode has been also discussed. We have shown that FD operation mode provides an efficient balance between EH and relaying time and is an attractive solution for HU-based cooperative systems. The investigation of more sophisticated protocols for communication systems with HU characteristics is a promising new research area with several potential battery-less applications.

Acknowledgements

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