Throughput Optimization for Wireless Information and Power Transfer in Communication Network

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Abstract*—*In this paper, a relay-based wireless communication model is studied. Such a model is capable of relaying information and power in either direction. At the relay amplify-then-forward scheme is used. Two relaying protocols viz. time switching-based relaying and power splitting-based relaying is used to facilitate this two-way information and power transfer. A single relay model is considered, an end to end throughput expression for our model is derived mathematically by using both the relaying protocols. Dependence of system throughput on parameters which are time switching ratio and the power splitting ratio is studied. Results show that there exists an optimal value of splitting ratio and switching ratio for a given relay position, to obtain optimal throughput. The simulation shows that relay placement significantly affects the system throughput performance.

Keywords—Information and power transfer; amplify-then-forward; power splitting; time switching; throughput

I. Introduction

In a communication network, nowadays wireless powered communication (WPC) has become an important area of research. As all the devices in any network need some source of energy, thus powered by batteries so the performance of such a network highly depends on these batteries. With the help of WPC, a network can be made more reliable and robust. In [1,2,4] an overview of wireless power transfer technologies and its use in wireless communication system is given highlighting on the important design challenges with proposed solutions. It also provides in detail about the system architecture and various RF energy harvesting techniques. The authors in [3] study a multiple-input-multiple-output (MIMO) wireless broadcast system with multiple nodes, where one of the receiver is harvesting the energy from received signals, whereas another receiver separately decodes the information signal which is coming from the same transmitting node. A new protocol is proposed in [5] named as harvest-then-transmit protocol, where nodes are first harvesting the energy transmitted by a common access point and then transmits their information to the corresponding nodes by using time multiplexing technique. The throughput of all the users is calculated and maximized by optimizing the value of time allocated for the wireless power transfer and information signal transfer. A communication model with a relay is considered [6] where the relay is helping in both information and power relaying coming from the access point (AP). Both relay and the user are power constrained so getting energy for charging by harvesting energy from the received signal. Two relaying protocols viz. power splitting-based technique and time-switching based splitting are proposed for the relay. An expression is derived for the throughput of the system by considering the case of delay-tolerant and delay-tolerant transmission mode. The authors in [7] have followed the work done in [6] and modified the scenario as shown in Figure 1. This model closely resembles the wireless sensor network scenario where power constrained sensor nodes are deployed in far field areas and they can be powered by a central access point using a helping relay. By considering the delay-limited transmission mode, an expression for throughput formulated and is maximized to get optimal values of the power splitting ratio and time switching ratio.

Further, as the single relay model is not very reliable due to the presence of a single path, so the idea of cooperative diversity can be used while deploying multiple relays in the path between AP and user as shown in Figure 4. In [8-10], relay selection schemes are given based on the SNR. To select a relay path, the accumulative sum of SNRs at the receiving end is obtained, and the path with maximum SNR gets selected. Relay selection schemes based on distance are proposed in [11,12], in such schemes relay nearest to the receiving node gets selected. In [13], another scheme known as the best worse channel selection is discussed, in which the relay whose worst channel is the best and is selected. A selection scheme based on the best harmonic mean of the two channels is proposed in [14], in this the relay path having best harmonic mean gets selected. Further, in [15] all these single relay selection schemes are modified in terms of their selection function and apart from single-relay selection schemes; multiple-relay selection schemes are also discussed. So, by following the previous work done, a multi-relay model is best

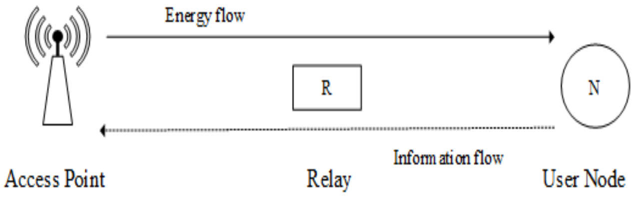

Fig. 1. Information and power transfer in a wireless network.

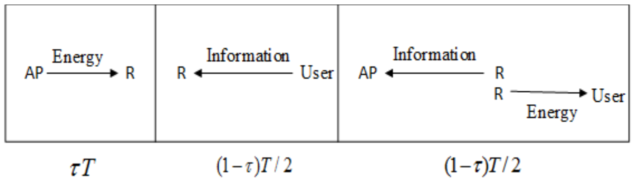

Fig. 2. Time switching-based relaying.

to be considered to facilitate the wireless transfer of information and power by using power splitting and time switching techniques. Relay selection schemes will be used for selecting the best path, and their performance is being studied in terms of system throughput.

The rest of this paper is organized as follows. In section 2, a single-relay model with relaying techniques used for information and power transmission in wireless network are discussed. The throughput expression for single-relay model using both relaying techniques is derived Simulation results with discussion are presented in section 3 and the paper is concluded in section 4, with the future scope.

II. System model

A. Time Switching-based Relaying

A model is represented in Fig. 1 with a helping relay that facilitates the two-way transfer of information and power. Both relay and the user node are energy constrained and getting the energy for charging their batteries from the AP. The user node is transferring information to the AP through the relay. At the relay, some technique must be used to manage this two-way information and power transfer, which are discussed in the later sections.

In a time switched relaying each time frame is divided into three slots as shown in Fig.2. During the first phase of duration τT, the AP transmits power P_a to the relay. In the next slot of duration $(1-\tau)T/2$, user transmits an information signal to relay and finally in the third-time slot of duration $(1-\tau)T/2$, relay forwards the received energy and information signal to the user and AP respectively. It is assumed that the relay node forwards amplified version of the received signal, and this amplification coefficient satisfies the power consumed and energy harvesting balance constraint at the relay.

During the first-time slot of each frame, the AP sends energy to the relay node with power P_a with the duration of the time slot τT. The energy harvested by relay during τT is given by,

$$E_r = \eta\, p_a |h|^2 \tau T \tag{1}$$

where, η is energy conversion efficiency.

In the second-time slot, the user node from other end transmits information signal x_u, to relay with power P_u. x_u is the normalized information signal from the source, i.e. $\mathbb{E}\{|s(t)|^2\} = 1$. The information signal received at relay during second-time slot is thus given as,

$$y_r = \sqrt{P_u}\, g x_u \ + n_r \tag{2}$$

where, n_r is the Narrowband Gaussian Noise at the relay.

The relay amplifies the signal y_r and transmits it to the AP and energy signal to the user node. The information signal send by relay to AP will be,

$$x_r = \sqrt{\beta_{ts}} y_r \tag{3}$$

where, β_{ts} is the amplification coefficient for TSR protocol and satisfies energy consumption and harvesting balance constraint at the relay. i.e.

$$\beta_{ts} \mathbb{E}[|y_r|^2](1-\tau)\frac{T}{2} = E_r \tag{4}$$

From equation (1), (2), and (3) we get

$$\beta_{ts} = \frac{2\tau\eta P_a |h|^2}{(1-\tau)(P_u|g|^2 + \sigma_r^2)} \tag{5}$$

$$x_r = \frac{\sqrt{P_r} y_r}{\sqrt{P_u|g|^2 + \sigma_r^2}} \tag{6}$$

$$y_a = h x_r + n_r + n_a = \frac{h\sqrt{P_r} y_r}{\sqrt{P_u|g|^2 + \sigma_r^2}} + n_r + n_a \tag{7}$$

From equation (2), we can have

$$y_a = \frac{h g x_u \sqrt{P_r P_u}}{\sqrt{P_u|g|^2 + \sigma_r^2}} + \frac{h n_r \sqrt{P_r}}{\sqrt{p_u|g|^2 + \sigma_r^2}} + n_r + n_a \tag{8}$$

Power transmitted by relay node, P_r can be expressed as

$$P_r = \frac{E_r}{(1-\tau)T/2} = \frac{2\eta\tau P_a|h|^2}{(1-\tau)} \tag{9}$$

and the signal received at the AP will be,

$$y_a = \frac{\sqrt{2\eta\tau P_a|h|^2 P_u}\, h g x_u}{\sqrt{(1-\tau)}\sqrt{(P_u|g|^2+\sigma_r^2)}} + \frac{\sqrt{2\eta\tau P_a|h|^2}\, h n_r}{\sqrt{(1-\tau)}\sqrt{(P_u|g|^2+\sigma_r^2)}} + n_{AP} \tag{10}$$

where, n_{AP} denotes the overall noise present at AP.

The signal-to-noise ratio (SNR) can be defined as,

$$\gamma_a = \frac{\mathbb{E}\{|signal\ part|^2\}}{\mathbb{E}\{|noise\ part|^2\}} \tag{11}$$

$$\gamma_a = \frac{2\eta\tau P_a P_u |h|^4 |g|^2}{(2\eta\tau P_a|h|^4\sigma_r^2) + P_u|g|^2\sigma_n^2(1-\tau) + \sigma_r^2\sigma_n^2(1-\tau)} \tag{12}$$

For delay tolerant transmission mode [6], the throughput will be given by,

$$R = \frac{(1-\tau)}{2}\log_2(1+\gamma_a) \quad (13)$$

Energy signal received at user node to harvest energy will be,

$$y_u = g\sqrt{\beta_{ts}}y_r \quad (14)$$

Energy harvested by user node will be given as,

$$E_u = \frac{\eta|g|^2\beta_{ts}\mathbb{E}[|y_r|^2](1-\tau)T}{2} = \tau\eta^2 P_a|h|^2|g|^2 T \quad (15)$$

$$P_u = \frac{E_u}{(1-\tau)T/2} = \frac{2\tau\eta^2 P_a|h|^2|g|^2}{(1-\tau)} \quad (16)$$

$$\gamma_a = \frac{\frac{\tau}{(1-\tau)}2\eta^2 P_a|h|^4|g|^4}{(|h|^2\sigma_r^2 + |g|^4\eta\sigma_n^2) + \left(\frac{1-\tau}{\tau}\right)\left[\frac{\sigma_r^2\sigma_n^2}{2\eta P_a|h|^2}\right]}$$

$$= \frac{\tau/(1-\tau)}{d_1 + d_2(1-\tau)/\tau} \quad (17)$$

where, $d_1 = \frac{|h|^2\sigma_r^2 + \eta|g|^4\sigma_n^2}{2\eta^2 P_a|h|^4|g|^4}$ and $d_2 = \frac{\sigma_r^2\sigma_n^2}{4\eta^3 P_a^2|h|^6|g|^4}$

Therefore,

$$R = \left(\frac{1-\tau}{2}\right)\log_2\left(1 + \frac{\frac{\tau}{1-\tau}}{d_1 + \frac{d_2(1-\tau)}{\tau}}\right) \quad (18)$$

For very large value of P_a, d_2 is dominated by d_1, so we could neglect d_2. Thus

$$R = \left(\frac{1-\tau}{2}\right)\log_2\left(1 + \frac{\tau}{d_1(1-\tau)}\right) \quad (19)$$

For the maximum value of R, $\frac{\partial R}{\partial \tau} = 0$

Hence, $\frac{1}{d_1(1-\tau)+\tau} = \ln\left(1 + \frac{\tau}{d_1(1-\tau)}\right)$ (20)

changing equation (20) into the form

$$q\exp(q) = c$$

where,

, $q = \frac{(1-d_1)(1-\tau)}{\tau + d_1(1-\tau)}$ and $c = \left(\frac{1}{d_1} - 1\right)\exp(-1)$

from above we get,

$$\tau^* = \frac{1 - d_1(q+1)}{1 - d_1(q+1) + q} \quad (21)$$

where, τ^* is optimal time switching ratio, $q = W(c)$, $W(\,)$ is lambert function.

B. Power Splitting-based Relaying

In PSR protocol as shown in Fig. 3, each time frame of length T is divided into two phases, during the first phase of length

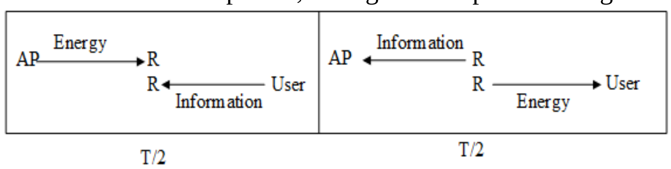

Fig. 3. Power splitting-based relaying.

T/2, AP transmits energy and from another end, the user transmits information to the relay simultaneously. In the second phase, the relay node forwards the received energy and information signal to the user and AP respectively. During the first half of the time slot, at relay received power from AP splits into two parts, ρP is used by relay for charging its battery, $(1-\rho)P$ for the information and energy relaying in the second phase, where ρ is the splitting ratio satisfies the range $0 \leq \rho \leq 1$. A power splitter is used at the relay for this purpose that splits the received energy signal in $\rho : 1-\rho$. One part of received signal power goes to the energy harvesting receiver and another to the information receiver.

In the first phase, the signal received at the relay node will be given by

$$y_r = \sqrt{P_a}hx_a + \sqrt{P_u}gx_u + n_r \quad (22)$$

The energy harvested at the relay will be given as,

$$E_r = \eta\rho\mathbb{E}[|y_r|^2]\left(\frac{T}{2}\right) \approx \eta\rho P_a|h|^2(T/2) \quad (23)$$

The other part of splitted signal at R can be given as,

$$y_r' = \sqrt{(1-\rho)}(\sqrt{P_a}hx_a + \sqrt{P_u}gx_u + n_r) \quad (24)$$

It is assumed that at relay, it has the perfect knowledge on h and x_a so that the energy bearing signal x_a in the equation above will be pre-cancelled at R before relaying of information or energy to the user node, in order to ensure that more power will be used for the information relaying. The signal forwarded by the relay in the second phase will be given as,

$$x_r = \sqrt{\beta_{sr}}(\sqrt{1-\rho}(\sqrt{P_u}gx_u + n_r) + n_r') \quad (25)$$

where, β_{sr} is amplification coefficient for PSR protocol.

As with equation (4), we have

$$\left(\frac{T}{2}\right)\mathbb{E}[|x_r|^2] = E_r \quad (26)$$

From equation (26), we get

$$\beta_{sr} = \frac{\eta\rho P_a|h|^2}{(1-\rho)P_u|g|^2 + \sigma_r^2} \quad (27)$$

$$x_r = \sqrt{\beta_{sr}}(\sqrt{1-\rho}\sqrt{P_u}gx_u + n_r') \quad (28)$$

The signal received by the antenna at the AP will be,

$$y_a = h\sqrt{\beta_{sr}}(\sqrt{1-\rho}\sqrt{P_u}gx_u + n_r') + n_a \quad (29)$$

From equation (27) by substituting the value of β_{sr} in (29) gives,

$$y_a = \left(\sqrt{\frac{\eta\rho P_a P_u |h|^2(1-\rho)}{(1-\rho)P_u|g|^2+\sigma_r^2}}\, hgx_u\right) + \left(\sqrt{\frac{\eta\rho P_a |h|^2}{(1-\rho)P_u|g|^2+\sigma_r^2}}\, hn_r^{'} + n_a\right) \quad (30)$$

In equation (30), first part represents the signal and second is corresponding to the noise present at the AP. By using equation (11), the SNR at AP can be expressed as

$$\gamma_a = \frac{(1-\rho)|h|^2|g|^2 P_u}{|h|^2\sigma_r^2 + \sigma_r^2\left(\frac{(1-\rho)P_u|g|^2+\sigma_r^2}{\eta\rho P_a|h|^2}\right)} \quad (31)$$

Finally, for the delay tolerant transmission, we can express the end to end throughput in terms of SNR at the AP as,

$$R = \frac{1}{2}\log_2(1+\gamma_a) \quad (32)$$

The signal received at the user node will be given as,

$$y_u = gx_r \quad (33)$$

So, the energy harvested by user node can be expressed as,

$$E_u = \eta|g|^2\mathbb{E}[|x_r|^2] = P_a\eta^2\rho|h|^2|g|^2(\tfrac{T}{2}) \quad (34)$$

From equation (31), it is seen that the SNR is a function of P_u, monotonically increases with transmitting power. Maximum value of P_u can be given as,

$$P_u = \frac{E_u}{T/2} = P_a(\eta^2\rho|h|^2|g|^2) \quad (35)$$

Substituting equation (35) into (31), SNR can be expressed as a function of ρ as

$$\gamma_a = \frac{\rho(1-\rho)\eta^2|h|^4|g|^4P_a}{|h|^2\sigma_r^2 + \sigma_a^2(\eta|g|^4(1-\rho) + \sigma_r^2/(\eta\rho P_a|h|^2))} \quad (36)$$

In equation (36), the signal to noise ratio γ_a is a function of splitting ratio ρ. So, by finding optimal value of splitting ratio, we can achieve the max SNR. By solving equation (36), optimal value of splitting ratio ρ^* can be given as

$$\rho^* \approx 1-(\sqrt{1+c}-1)/c \quad (37)$$

where, $c = (\sigma_a^2\eta|g|^4)/(\sigma_r^2|h|^2)$

III. Simulation and Results Analysis

This section comprises of the simulation results obtained for our system model. It is assumed that AP and data transmitting user node are in line-of -sight and separated by a distance, $\boldsymbol{d_{au}}$ which is taken as 10 meters, position of the relay is variable and is on the line connecting the AP and user for the single-relay model. Channel coefficients, h and g characterize the channel between the nodes are assumed to be randomly distributed and follow the Rayleigh distribution. We have considered channel reciprocity so that the forward and reverse links between AP and R have the same channel coefficient h and same is true for link between relay-user. Energy conversion efficiency at the R is assumed to be 0.8. Noise power value at AP and relay is taken as -124 dBm with AP transmitted power equal to 1 watt.

In Fig. 5 and Fig. 6, throughput variation with distance, time switching ratio, and power splitting ratio is shown. Both results show that throughput for both protocols increases, then decrease with time switching ratio, whereas decreases then increase with an increase in the relay distance from the AP.

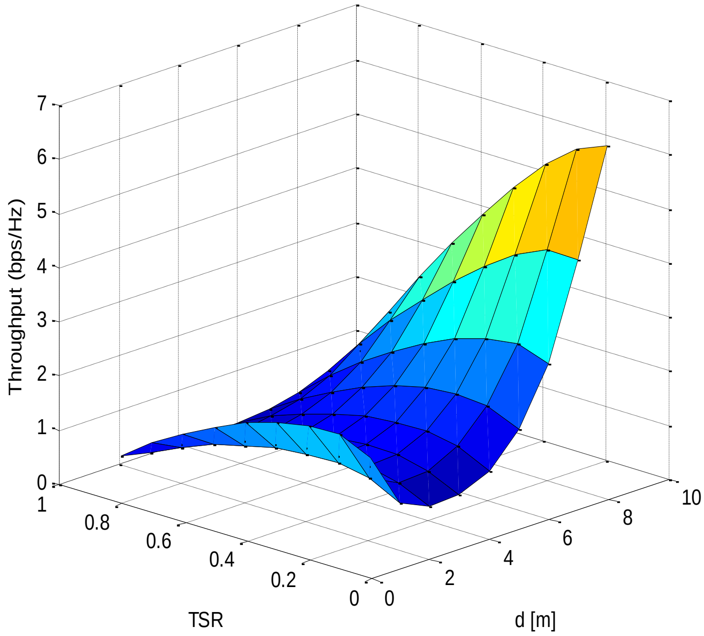

Fig. 5. Throughput variation with time switching ratio (τ) and distance($\boldsymbol{d_{ar}}$).

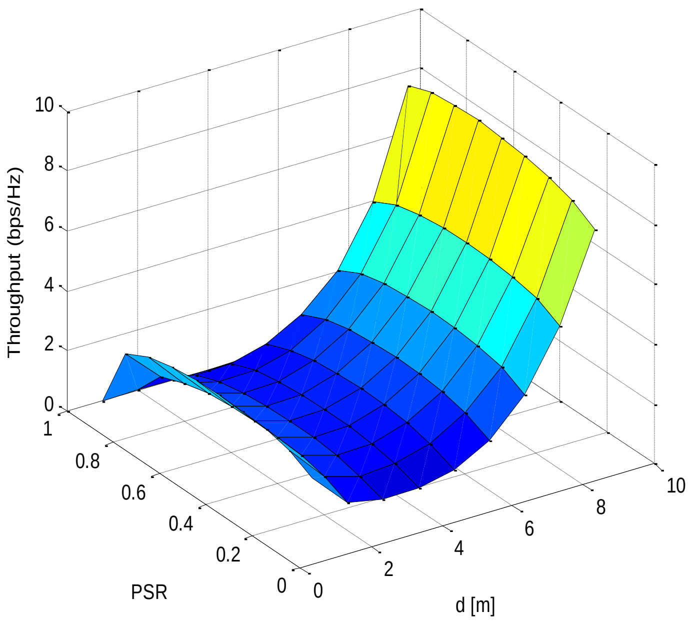

Fig. 6. Throughput variation with power splitting ratio ($\boldsymbol{\rho}$) and distance.

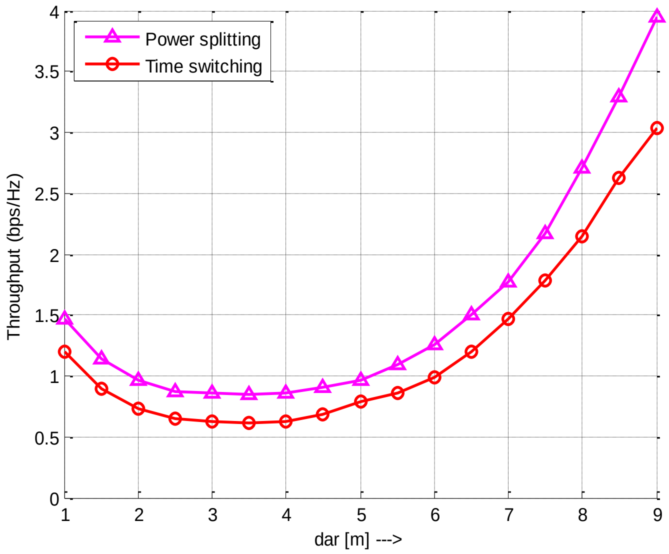

Fig. 7. Optimal throughput versus d_{ar} for PSR and TSR using single relay.

There exists an optimal value of time switching ratio and power splitting ratio for a given distance specified by equation (21), (37) respectively, at which throughput maximizes. In Fig. 7, the variation of optimal throughput is plotted against d_{ar} for the both relaying techniques i.e. PSR and TSR. For both the techniques, it is found that the throughput value calculated at the AP is first slightly decreasing upto some distance and then starts increasing with d_{ar}. As it means the relay is moving away from the AP and towards the user, throughput increases and hence for maximizing the throughput relay must be placed close to the user. It is also observed that throughput performance for PSR is better than TSR.

IV. Conclusions

In this paper, we have studied a communication system model with a relay that is helping in both energy and information transmission. Two techniques, power splitting-based relaying and time switching-based relaying are used at the relay. Throughput performances of the system using both the techniques are studied and among the two techniques, PSR shows better results. It is found that relay placement significantly affects the throughput performance of the system. For future work, instead of using single relay we could make use of multiple relay in the path and cooperative diversity selection schemes can be used for selection of relay path for further throughput enhancement.

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