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Throughput-Save Ratio Optimization in Wireless Powered Communication Systems

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Abstract—**This paper deals with the idea of wireless energy harvesting and energy transfer used to establish communication between devices in a wireless network. Wireless energy harvesting and transfer has proved to be very advantageous in areas like WSN in which this technique not only improve the nodes lifetime but also makes the communication eco-friendly. A protocol namely save-then-transmit is used to accomplish the communication between the nodes in which some part of the time slot is devoted for energy harvesting and transfer with remaining part used for data transfer. Two models TCM-EH-ET and TRCM-EH-ET have been considered in which the nodes have no source of energy and they only get energy by natural means i.e. they harvest energy for recharging their batteries from the environment. An energy co-operation scheme is given, parameters involved in energy harvesting and transfer, i.e. energy transfer rate and save-ratio are optimized to maximize the overall throughput of the communication network. The proposed scheme is simulated on MATLAB R2013a, simulation results shows that the throughput of system with given energy cooperation scheme are better than the scheme without energy transfer and energy transfer with half save-ratio.**

Keywords—Energy harvesting, Save-then-transmit protocol, Save-ratio, Energy transfer rate, Throughput.

I. INTRODUCTION

As the lifetime of wireless nodes completely depend on their battery life and also in a battery powered node, when battery gets drained, it is required to replace the battery but this will not be practical in many situations, like hard to reach areas. Hence the main challenge, in wireless communication network is to prolong the life time of battery. To counter this challenge concept of energy harvesting can be used. In energy harvesting techniques node or battery recharges by natural means such as solar energy, wind energy, etc. So the energy harvesting not only helps to increase the lifetime of battery but also makes contribution in green communication. Wireless energy transfer can also help in improving the life-time of nodes involved in communication. Electromagnetic radiation-based wireless power transfer technique can be used for transferring energy between far separated nodes [2]. In [3], results show that the throughput of a sparse network increases logarithmically with the energy arrival rate and linearly with the transmitter density. The throughput of the network modelled as a Poisson point process and the energy arrival rate have been derived in simple expressions which shows the trade-off between energy harvesting rate, encoding rate, and density of nodes. In [4], a protocol has been introduced to enhance the performance of system by giving optimum value of save-ratio, in which a fraction of the time is dedicated for energy harvesting and the rest time given for data transmission. In [5], it characterizes how the optimal save-ratio and the maximum throughput that can be achieved vary with energy harvesting rate and also validates the selection of optimal save-ratio. In this, the energy harvesting rate is considered for both deterministic and stochastic case and derivation of the optimal value of save-ratio as the function of energy harvesting rate for both cases is done. In [6,7], simultaneous transmission of energy and information is discussed and optimal transmission strategy is given to obtain the trade-off relation between maximum data rate and energy transfer rate. In [8], throughput optimization of nodes in two-way communication network scenario was considered, in which nodes were harvesting energy and transferring a fraction the of harvested energy to other nodes. In [9], it uses the results of [8] to remodel new network architectures, i.e., multiple access and relay channels.

For optimizing the throughput of network we have combined the two techniques which are energy harvesting at nodes and energy transfer between the nodes and have discussed an energy cooperation scheme. On the basis of save-then-transmit protocol, consider two models: Two node communication model with energy harvesting and energy transfer (TCM-EH- ET), and Three node relay communication

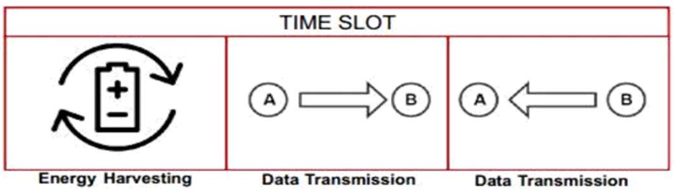

Figure 1: Time slot division in save-then-transmit protocol.

with energy harvesting and energy transfer (TRCM-EH-ET). In the first model, all nodes are harvesting the energy and also transferring it to the other node, whereas in second model there is a relay and the energy harvesting is allowed only at source and relay node. In both the models, throughput of system is completely depending on two parameters namely save-ratio and energy transfer rate. Optimum value of these parameters have been used to maximize the throughput. An assumption is taken that nodes involved in communication have self-dependent external energy arrival process to charge the battery and energy consumed in processing and sensing is also negligible.

The paper is further organized as follows. In section 2, TCM-EH-ET model is presented and the throughput for this is formulated with optimal values of energy transfer rate and save-ratio. Further in section 3, TRCM-EH-ET model is discussed with their throughput formulation. Simulation parameters and results are given in section 4,5 respectively, followed by concluding remarks in section 6.

II. TCM-EH-ET MODEL

As shown in figure 2, we have considered two nodes say node A and node B with self-energy harvesting capabilities. The energy harvesting rates of the two nodes are denoted by x_1 and x_2 with an assumption that x_1>0, and x_2>0. The energy transfers between the nodes only when there exists a gradient of energy i.e. either $x_1 > x_2$ or $x_1 < x_2$. If no energy gradient between the nodes exist i.e. $x_1 = x_2$ then no transfer of energy will occur between them.

The save-then-transmit protocol is used for energy transfer in which each time slot is divided into three parts as shown in figure 1. In first part of each time-slot, energy harvesting at the nodes takes place and in other two, data transmission between the nodes takes place.

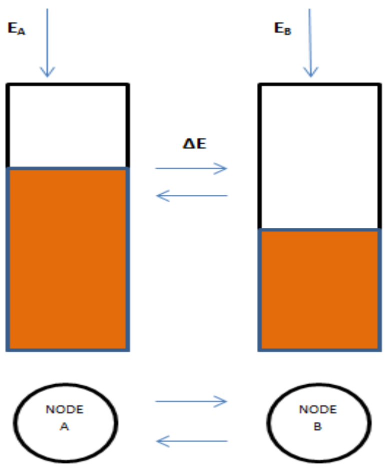

Figure 2: Energy harvesting and energy transfer in two-node communication model.

A. First phase of time slot (Energy harvesting and energy transfer)

The time-slot of duration T in the interval (0, ρT] both the nodes will harvest energy from nature as, $E_a = \rho T x_1$ and $E_b = \rho T x_2$; where ρ represent save ratio (0<ρ< 1).

$$\Delta E = (E_a - E_b) \qquad \textit{assuming } x_1 > x_2 \qquad (1)$$

$$\Delta E = (\rho T x_1 - \rho T x_2)$$

$$\Delta E = \rho T (x_1 - x_2)$$

$$\Delta E = \rho T \delta$$,where δ represents energy transfer rate (2)

With the assumption $x_1 > x_2$ node A will harvest more energy than node B and hence will transfer some part of its harvested energy. After transferring the energy, the remaining energy at node A and node B will be,

$$E_a = \rho T (x_1 - \delta) \qquad (3)$$

$$E_b = \rho T (x_2 + \alpha\delta)$$,where α is energy transfer efficiency (0< α<1)

B. Second phase of time slot (Data transfer)

During the second part of duration (ρT, 0.5(1 + ρ) T), node A transfers data to node B. The corresponding throughput of node A is given by,

$$R_{12}(\rho, \delta) = \frac{0.5(1-\rho)T}{T} \log_2\left[1 + \frac{\rho T h (x_1 - \delta)}{n_1 0.5T(1-\rho)}\right] \qquad (4)$$

$$R_{12}(\rho, \delta) = 0.5(1-\rho) \log_2\left[1 + \frac{\rho h (x_1 - \delta)}{0.5(1-\rho)}\right] \qquad (5)$$

C. Third phase of time slot (Data transfer)

In the third part of duration (0.5(1 + ρ) T, T), node B transfers data to node A. The corresponding throughput of node B is given by

$$R_{21}(\rho, \delta) = \frac{0.5(1-\rho)T}{T} \log_2\left[1 + \frac{\rho T h (x_2 + \alpha\delta)}{n_2 0.5T(1-\rho)}\right]$$

$$R_{21}(\rho, \delta) = 0.5(1-\rho) \log_2\left[1 + \frac{\rho h (x_2 + \alpha\delta)}{0.5(1-\rho)}\right] \qquad (6)$$

Where, h represents the channel coefficient and n_1, n_2 represents noise power having unit value.

The overall throughput of two-node communication model will be

$$R_{sum}(\rho, \delta) = R_{12}(\rho, \delta) + R_{21}(\rho, \delta)$$

$$\max R_{sum}(\rho, \delta) = 0.5(1-\rho) \log_2\left[1 + \frac{\rho h (x_1 - \delta)}{0.5(1-\rho)}\right] + 0.5(1-\rho) \log_2\left[1 + \frac{\rho h (x_2 + \alpha\delta)}{0.5(1-\rho)}\right] \qquad (7)$$

such that, 0<ρ<1 and 0< δ<1

Solving for max $R_{sum}(\rho, \delta)$ we get optimal ρ, δ values as,

when $x_1 > x_2$,

$$\delta_{\circ} = \frac{x_2(Y-\alpha) + x_1(1-Y)}{Y(1+\alpha) - 2\alpha} \qquad (8)$$

$$\rho_\circ = \frac{0.5(1-Y)}{h(x_1-\delta_\circ)Y-0.5Y+0.5} \quad (9)$$

where,

$$Y = \frac{W[\left(hx_1 + \frac{1}{a}hx_2 - 0.5 - \frac{1}{2a}\right).\frac{\sqrt{\alpha}}{e}]}{hx_1 + \frac{1}{a}hx_2 - 0.5 - \frac{1}{2a}} \quad (10)$$

when $x_1 < x_2$,

$$\delta_\circ = \frac{x_2(Y-\alpha)+x_1(1-Y)}{Y(1+\alpha)-2\alpha} \quad (11)$$

$$\rho_\circ = \frac{0.5(1-Y)}{h(x_2-\delta_\circ)Y-0.5Y+0.5} \quad (12)$$

where,

$$Y = \frac{W[\left(hx_2 + \frac{1}{a}hx_1 - 0.5 - \frac{1}{2a}\right).\frac{\sqrt{\alpha}}{e}]}{hx_2 + \frac{1}{a}hx_1 - 0.5 - \frac{1}{2a}} \quad (13)$$

when x_1=x_2, no energy transfer takes place so energy transfer rate comes out to be 0.

$$\delta_\circ = 0 \quad (14)$$

$$\rho_\circ = \frac{2x_1h-1-W(\frac{2x_1h-1}{e})}{(2x_1h-1)[W(\frac{2x_1h-1}{e})+1]} \quad (15)$$

III. TRCM-EH-ET MODEL

In this model as shown in figure3, the source and destination nodes are not in line-of-sight so the communication between them takes place through a relay node. The energy harvesting takes place only at source and relay node. The harvesting rate of energy for node A and B are y_1, y_2 respectively. Our aim is to maximize the throughput of relay node since it cannot be greater than the throughput of node A.

A. First phase of time slot (Energy Harvesting and transfer)

In duration of (0, ρT] both the source node(S) and the relay node(R) harvest the energy and also during this time some part of the harvested energy gets transferred between both the nodes.

$$\Delta E = \rho T\delta$$

The energy stored at both the nodes are as

$$E_s = \rho T(y_1 - \delta) \quad (16)$$

$$E_r = \rho T(y_2 + \alpha\delta) \quad (17)$$

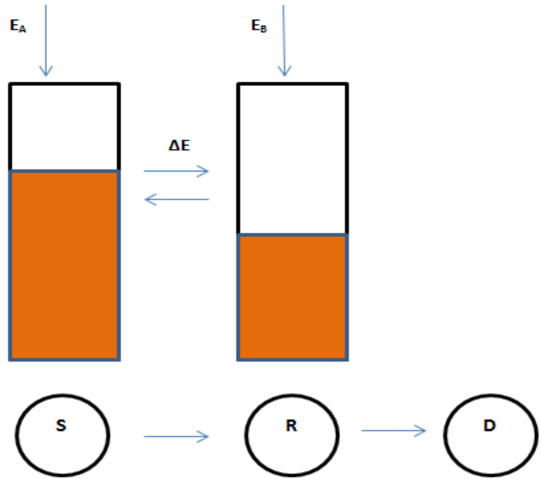

Figure 3: Energy harvesting and energy transfer in Three-node relay communication model.

B. Second phase of time slot (Data Transmission)

In this duration (ρT, 0.5(1 + ρ) T), node S transfers its data to R and the corresponding throughput is given as

$$R_{sr}(\rho, \delta) = 0.5(1-\rho).\log_2\left[1 + \frac{\rho h_1(y_1-\delta)}{0.5(1-\rho)}\right] \quad (18)$$

C. Third phase of time slot (Data Transmission)

In this duration (0.5(1 + ρ) T, T), node R transfers its data to S and the corresponding throughput is given as

$$R_{rd}(\rho, \delta) = 0.5(1-\rho).\log_2\left[1 + \frac{\rho h_2(y_2+\alpha\delta)}{0.5(1-\rho)}\right] \quad (19)$$

The aim is to maximize throughput, R_{rd}

$$\max R_{rd}(\rho, \delta) = 0.5(1-\rho).\log_2\left[1 + \frac{\rho h_2(y_2+\alpha\delta)}{0.5(1-\rho)}\right]$$

such that $0 < \rho < 1$ and $0 \le \delta < y1$

$$R_{rd}(\rho, \delta) = R_{sr}(\rho, \delta) \quad (20)$$

Solving for this we get the following optimal values of ρ, δ.

When , $h_1\, y_1 > h_2\, y_2$,

$$\delta_0 = \frac{h_1\, y_1 - h_2\, y_2}{h_1 + \alpha h_2} \quad (21)$$

$$\rho_\circ = \frac{h_2\,(y_2 + \alpha\delta_\circ) - 0.5 - 0.5W[(2h_2\,(y_2 + \alpha\delta_\circ) - 1)e^{-1}]}{[h_2\,(y_2 + \alpha\delta_\circ) - 0.5].\{W[(2h_2\,(y_2 + \alpha\delta_\circ) - 1)e^{-1}] + 1\}} \quad (22)$$

When , $h_1\, y_1 < h_2\, y_2$,

$$\delta_0 = \frac{h_2\, y_2 - h_1\, y_1}{\alpha h_1 + h_2} \quad (23)$$

$$\rho_\circ = \frac{h_2\,(y_2 - \delta_\circ) - 0.5 - 0.5W[(2h_2\,(y_2 - \delta_\circ) - 1)e^{-1}]}{[h_2\,(y_2 - \delta_\circ) - 0.5].\{W[(2h_2\,(y_2 - \delta_\circ) - 1)e^{-1}] + 1\}} \quad (24)$$

When, $h_1\,y_1 = h_2\,y_2$,

$$\delta_0 = 0 \quad (25)$$

$$\rho_\circ = \frac{h_2 y_2 - 0.5 - 0.5W[(2h_2 y_2 - 1)e^{-1}]}{(h_2 y_2 - 0.5) - 0.5].\{W[(2h_2 y_2 - 1)e^{-1}] + 1\}} \quad (26)$$

IV. SIMULATION PARAMETERS

h is the channel coefficient which is Rayleigh distributed and is considered to remain same during the timeslot. x and y are the energy harvesting rates and are assumed to be gamma distributed. It is also assumed to be remain same during the timeslot. PDF for gamma function is given as

$$f(x) = \frac{x^{k-1} e^{-(\frac{x}{\theta})}}{\theta^k\ \Gamma(k)} \quad (27)$$

where, k (k > 0) is shape parameter, θ(θ > 0) is scale parameter, they can have any positive integer value and Γ(.) denotes the gamma function in above given PDF.

Table 1: Simulation parameters

Parameter	Symbol	Value
Energy transfer efficiency	α	0.8
Noise power at node A	n_1	1
Noise power at node B	n_2	1
Energy harvesting rate	x, y	Gamma distributed
Channel coefficient	h	Rayleigh distributed

V. RESULT ANALYSIS

In both models, three schemes have been analyzed i.e. TCM-EH-ET, TCM-half-EH-ET and TCM-EH. In TCM-EH-ET, optimized values of both δ and ρ have been used. In TCM-half-EH-ET ρ is fixed at 0.5 whereas in TCM-EH only energy harvesting occurs without any energy transfer.

In figure 4 and figure 5, the harvesting rates at both the nodes are same represented by same value of parameters k, θ, generated by Γ(5,5) and Γ(5,5). It shows that throughput corresponding to TCM-EH-ET, TCM-EH is nearly same since no energy transfer takes place but it is more than the TCM-half-EH-ET scheme which has not used the optimal value of save-ratio(ρ). Although, the system throughput in each time slot is

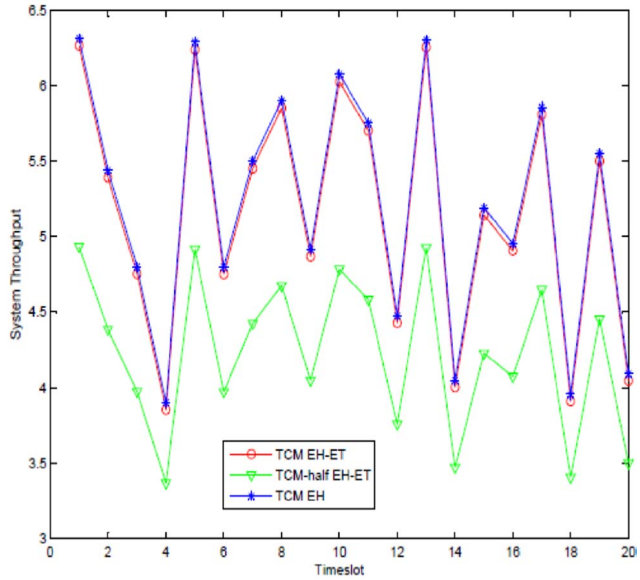

Figure 4: System throughput with same harvesting rate (x_1=x_2)generated by Γ(5,5) and Γ(5,5).

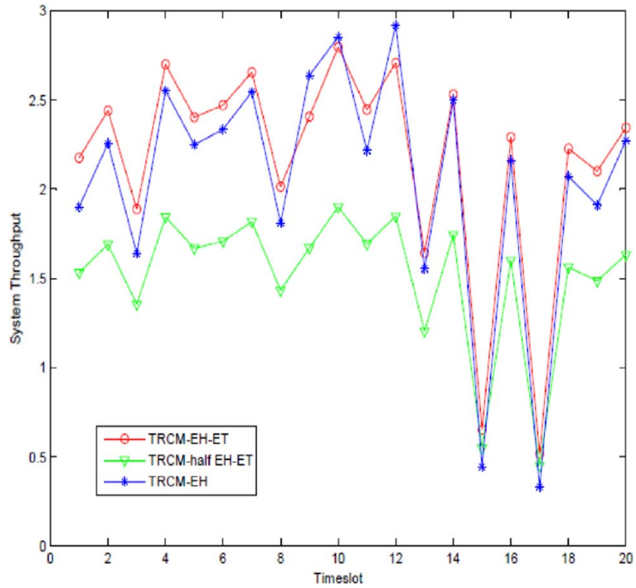

Figure 5: System throughput with same harvesting rate (y_1= y_2) generated by Γ(5,5) and Γ(5,5).

maximum for the TCM-EH-ET scheme which uses the optimal values of energy transfer rate(δ) and save-ratio(ρ).

In figure 6 and figure 7 the harvesting rates at the nodes are different which are shown by different values of parameters k, θ Γ(8,8) and Γ(3,3), i.e., gradient of energy exists and as a result there will be an energy transfer between the nodes. Also in each timeslot the maximum throughput is corresponding to the TCM-EH-ET scheme which uses the optimal values of energy transfer rate(δ) and save-ratio(ρ).

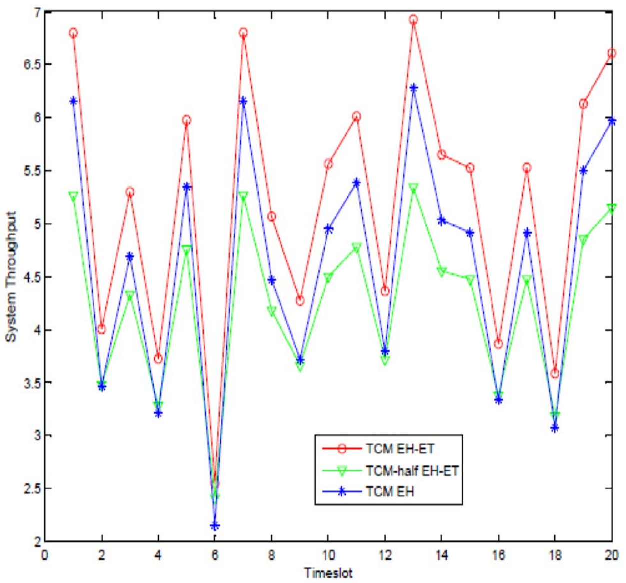

Figure 6: System Throughput with unequal harvesting rate ($x_1 > x_2$)generated by Γ(8,8) and Γ(3,3).

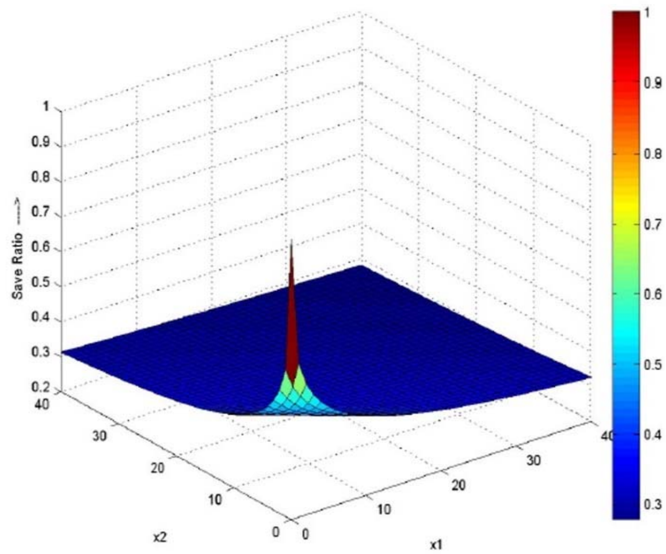

Figure 8: Save-ratio (ρ) variation with energy harvesting rates.

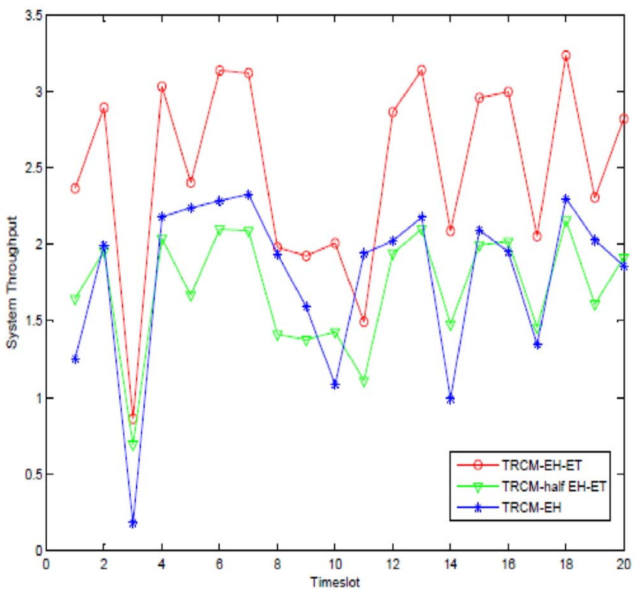

Figure 7: System throughput with unequal harvesting rate ($y_1 > y_2$) generated by Γ(8,8) and Γ(3,3).

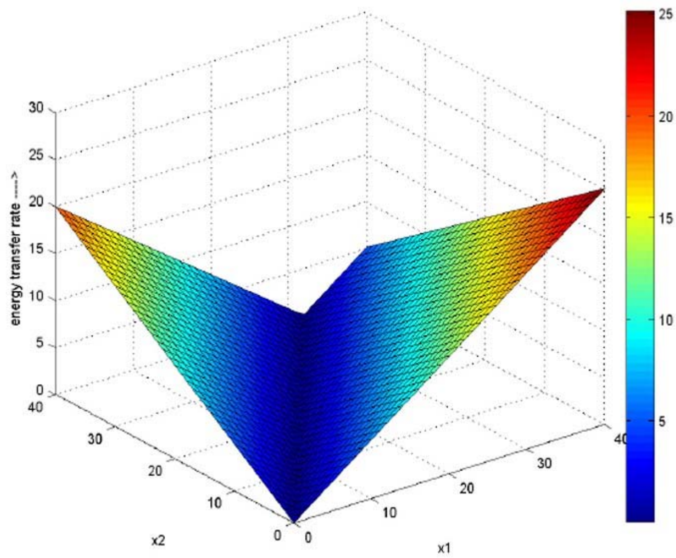

Figure 9: Energy transfer rate(δ) variation with energy harvesting rates.

In figure 8, variation in save-ratio is shown with the variation of energy harvesting rates. We see that save-ratio is reducing with increase in energy harvesting rate. It shows that with larger value of harvesting rate, the nodes prefer to allocate smaller duration of time for harvesting and transmission of energy but the time allocated for transfer of data will be more. For low energy harvesting rate nodes will not be able to harvest enough energy so, more time will be devoted for energy harvesting and energy transmission meaning larger save-ratio. In figure 9, the energy transfer rate d will increase as the difference between energy harvesting rates x_1 and x_2 increases.

When both become equal; that means both the nodes are harvesting.

VI. Conclusion

In this paper, we studied energy cooperation schemes using save-then-transmit protocol in a wireless powered communication systems. The nodes in this system have no fix source of energy, so they harvest energy from the nature. Two models viz. TCM-EH-ET and TRCM-EH-ET are analyzed to maximize overall throughput of the system. It is shown that the how the throughput of network changes with harvesting rate of the nodes. Dependence of throughput on parameters viz. save-ratio and energy transfer rate is shown and optimal values of these parameters are derived by maximizing the throughput of network.

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