Relay Selection and Transceiver Design for Joint Wireless Information and Energy Transfer in Cooperative Networks

Sumit Gautam[†⋆] and P. Ubaidulla[⋆]
[†]Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg, Kirchberg, LUXEMBOURG.
[⋆]Signal Processing and Communication Research Centre, International Institute of Information Technology, Hyderabad, INDIA.

***Abstract*—In this paper, we consider optimal transceiver design and relay selection for simultaneous transfer of data and energy in a cooperative network consisting of amplify-and-forward (AF) relays. In this context, we address two different problems and propose optimal relay selection and transceiver processing. Furthermore, the problems are formulated for both *time switching* (TS) and *power splitting* (PS) schemes. The first problem is the maximization of overall rate while ensuring a minimum harvested energy at the receiver. For this problem, we perform computations of optimal fractions to distribute the received signal corresponding to TS and PS schemes, the relay weighing coefficients, and optimal relay selection. In the second problem, optimal resource allocation for maximizing the overall harvested energy at the user under constraints on the minimum achievable rate has been formulated. For this problem, we propose a suitable solution to meet the requirements for both TS and PS. For both the problems, we obtain a closed form solution. Finally, the performance of proposed design under various operating conditions and parameter values are illustrated with a comparison between TS and PS schemes.**

I. Introduction

Simultaneous wireless transmission of information and energy (Wi-TIE) has gathered considerable attention over the last few years and is likely to play significant role in emerging technologies [1]–[3]. Applications like wearable devices, wireless sensor nodes etc., are expected to adopt Wi-TIE more rapidly. With the increasing demand for energy to operate the devices, it has almost become a necessity to adopt such techniques to compensate for rapidly draining battery sources. Two of the practical receiver architectures to support Wi-TIE are *time switching (TS)*, where the receiver harvests energy from the received signal for a first few symbol duration in a block, and then performs information decoding for the remaining duration; and *power splitting (PS)*, where a fraction of received signal power is used for energy harvesting and the rest is used for information decoding simultaneously [2]–[4].

Cooperative relay techniques enables expansion of the network coverage area and diversity gains [5], [6] in wireless network. There are different kinds of cooperative strategies that can be used in a cooperative network [7]. The two widely used cooperative strategies are *regenerative* (e.g., decode-and-forward (DF) [8], [9]), and *non-regenerative* (e.g., amplify-and-forward (AF) [10]) relaying. In DF, the received signal is decoded by the relay and the re-encoded message is transmitted. In AF, the received noisy signal is directly amplified by the relay with a suitably selected gain and then re-transmitted to the destination. Due to the ease of implementation and independence of modulation schemes at the source terminal, non-regenerative relaying strategy is of practical interest.

Establishment of Wi-TIE for extended range may be difficult due to constraints like size and cost of devices. In such cases, relaying plays an important role in achieving Wi-TIE over extended range. One of the means to benefit from multiple relays with low complexity and support for Wi-TIE is optimal relay selection [11]. It has been shown in [11] that for the best performance, relays should be placed mid-way between source and the destination, as the channel gains between source-relays, and relays-destination are equally important in conventional relay networks. The relays can be exploited not only as an extra dimension for improving performance, but also to enhance the rate-energy (R-E) trade-off [12]. An overview of simultaneous wireless information and power transmission (SWIPT) systems is provided in [13], particularly focusing on the hardware realization of rectenna circuits and practical techniques which supports SWIPT. But this work does not consider incorporation of SWIPT with cooperative network of relays. The diversities of many single-relay schemes were derived in [14] for relay selection scheme in a wireless relay network. However, additional constraint of energy harvesting is not addressed in [14]. The work in [15] presents the study of Wi-TIE in large-scale networks with or without relaying. The problem of optimal relay selection in the context of Wi-TIE has not been widely studied [15]–[17]. We address this problem and propose optimal solutions in this regard.

In this paper, we consider Wi-TIE in a cooperative network where half-duplex relays employing non-regenerative relay protocol assist a source node and a destination node to simultaneously transfer both data and energy to the destination node. It is assumed that the destination node is capable of harvesting energy and decoding information from the same received signal. Optimal selection of a relay as well as optimal allocation of resources is a challenging problem when additional requirement of energy harvesting is taken into account. We address the problem of optimal selection of relays and optimal receive processing to maximize the rate and total harvested energy. We propose suitable solutions for optimal

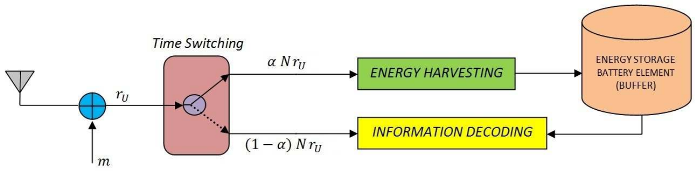

Fig. 1. Receiver architecture for time switching (TS) scheme.

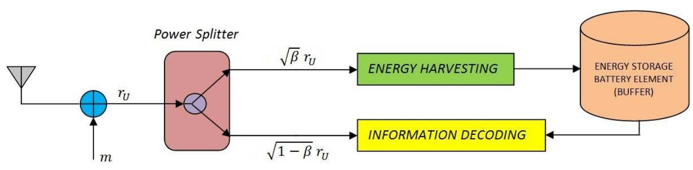

Fig. 2. Receiver architecture for power splitting (PS) scheme.

relay selection and transceiver processing for maximization of rate under a constraint on minimum harvested energy as well as for maximization of total harvested energy under constraint on minimum rate. In this process, computations of optimal TS and PS ratios are also addressed.

This paper is organized as follows. The next section introduces the system model. Section III describes the problem of overall rate maximization and its solution. Section IV addresses the problem of maximization of the total harvested energy and its solution. Section V comprises of simulation results for the proposed algorithms. Finally, section VI provides the conclusion of this paper.

II. System Model

The system considered in this paper consists of a cooperative half-duplex multi-relay network, wherein the source node transfers both information and energy to a single destination node with the help of a relay chosen from a set of L relays. Each relay operates according to the AF protocol. The receiver is capable of decoding information and harvesting energy simultaneously. The overall energy and information transfer takes place in two phases. In the first phase, transmitter transmits symbol $s \in \mathbb{C}$, with $\mathbb{E}\{|s|^2\} = 1$ where $\mathbb{E}[\cdot]$ and $|\cdot|$ denotes the statistical expectation and the absolute value, respectively. The corresponding signal received by the ith relay, denoted by r_i, can be written as

$$r_i = \sqrt{P_T} g_i s + n_i, \qquad 1 \le i \le L, \tag{1}$$

where P_T is the total power transmitted by the transmitter, g_i denotes the channel gain between transmitter and the ith relay, n_i is the additive white Gaussian noise (AWGN) at the ith relay, and L is the total number of relays. The noise samples $\{n_i\}$ are assumed to be independent and identically distributed (i.i.d.) complex Gaussian random variables (RVs) with zero mean and variance $\sigma^2_{n_i}$.

In the second phase, the optimally selected relay re-transmits the received signal after scaling it by a complex number, and the destination node then receives the desired signal from that relay node. Assuming that ith relay is selected, the signal received at the destination node can be written as

$$r_U = w_i h_i r_i + m, \tag{2}$$

where $w_i \in \mathbb{C}$ is the amplification or weighing coefficient at the ith relay, h_i denotes the channel gain between ith relay and the destination node, and m is the additive white Gaussian noise (AWGN) with $m \in \mathbb{CN}(0, \sigma^2_m)$. The total relay transmit power is upper bounded by

$$|w_i|^2 (P_T |g_i|^2 + \sigma^2_{n_i}) \le \overline{P}_R, \tag{3}$$

where $\overline{P}_R$ is the maximum available power for the relay transmission.

We consider optimal processing for both TS and PS receiver architectures. The receiver architecture for TS scheme is shown in Fig. 1. We consider block transmission of duration T seconds with $T = NT_s$, where N denotes the number of transmitted symbols per block and T_s denotes the symbol period. At the time switcher, a time switching ratio, α, where $0 \le \alpha \le 1$, is computed such that for the first $\alpha N T_s$ seconds, all the received signal power is used for harvesting energy, whereas during the remaining $(1-\alpha)NT_s$ seconds, information decoding from the received signal takes place.

In case of the PS receiver depicted in Fig. 2, a power splitter is employed so that a fraction β of the received signal power, where $0 \le \beta \le 1$, is provided to the energy harvester and the remaining part is provided to the information decoder.

The proposed transceiver design aims at computing the optimal PS and TS ratios, and optimal relay weight at the source node, selection of the best relay out of L available relays in order to amplify the transmit signal, and to perform optimal receive processing at the destination node. Perfect channel state information (CSI) and the information about harvested energy and rate demanded by the destination node are assumed to be available. The amplified signal transmitted by the relay is used for information decoding and energy extraction at the destination according to TS or PS scheme.

The signal-to-noise ratio (SNR) between the source node and ith relay is given by

$$\gamma_{T,R_i} = \frac{P_T |g_i|^2}{\sigma^2_{n_i}}. \tag{4}$$

In the case of TS, the destination node harvests energy from the received signal for αT seconds and then performs information decoding for the remaining block duration. Correspondingly, the effective SNR between ith relay and the destination node for TS receiver is given by

$$\gamma^{TS}_{R_i,U} = \frac{|w_i|^2 |g_i|^2 |h_i|^2 P_T}{|w_i|^2 |h_i|^2 \sigma^2_{n_i} + \sigma^2_m}. \tag{5}$$

The overall rate of the TS receiver can be expressed as

$$R^{TS}_{eff} = \left(\frac{1-\alpha}{2}\right) \log_2 \left(1 + \gamma^{TS}_{R_i,U}\right). \tag{6}$$

The energy harvested by the receiver implementing TS scheme is given by

$$E^{TS}_h = \zeta(\alpha N T_s)\big(|w_i|^2 |h_i|^2 (P_T |g_i|^2 + \sigma^2_{n_i}) + \sigma^2_m\big), \tag{7}$$

where ζ is the energy conversion efficiency of the receiver.

Similarly, in case of PS, a fraction β of received signal power is used for energy harvesting and the rest is used for information decoding simultaneously. The effective SNR between ith relay and the destination node for PS receiver is given by

$$\gamma^{PS}_{R_i,U} = \frac{(1-\beta)|w_i|^2 |g_i|^2 |h_i|^2 P_T}{(1-\beta)|w_i|^2 |h_i|^2 \sigma^2_{n_i} + \sigma^2_m}. \tag{8}$$

The overall rate of the PS receiver can be expressed as

$$R_{eff}^{PS} = \frac{1}{2}\log_2\Big(1 \ + \ \gamma_{R_i,U}^{PS}\Big). \tag{9}$$

The energy harvested by the PS receiver is given by

$$E_h^{PS} = \zeta(\beta T)\big(|w_i|^2|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_m^2\big), \tag{10}$$

where T denotes the time duration of block of symbols received at the PS receiver. Two times slots required for the relaying process account for the pre-log factor of $\frac{1}{2}$ in the rate equations (6) and (9) given above.

We define the following triplet to simplify the notation:

$$\big(R; E_h; \phi\big) = \begin{cases} \big(R_{eff}^{TS}; E_h^{TS}; \alpha\big), \\ \big(R_{eff}^{PS}; E_h^{PS}; \beta\big), \end{cases} \tag{11}$$

corresponding to TS and PS schemes, respectively.

III. Optimal Relay Selection and Transceiver Design to Maximize Rate

We consider the problem of selection of relay that maximizes the effective source-destination rate, while ensuring that the harvested energy at the destination node is above a given threshold and that the total transmit power does not exceed a given limit. Mathematically, we can represent the overall optimization problem as

$$(P1) : \max_{i\in\mathcal{I},\phi,\{w_i\}} \quad R \tag{12}$$

$$\text{subject to} : \quad E_h \geq \eta, \tag{13}$$

$$0 < |w_i|^2 \leq P_R, \tag{14}$$

$$0 \leq \phi \leq 1, \tag{15}$$

where i is the relay index, $\mathcal{I} = \{1, 2, \cdots, L\}$ is the set of relay indices, P_R is the upper limit on relay power such that $P_R < \overline{P}_R$, and η is the minimum harvested energy demanded by the user. However, it is difficult to solve this problem, since it is a non-linear mixed-integer optimization problem. So, we recast $(P1)$ into a pair of coupled optimization problems for performing outer optimization involving relay selection, and inner optimization involving computations of optimal fractions, α or β, and optimal weighing coefficients of each relay. In the following two subsections, we address the optimal solutions to the inner optimization of this problem considering both TS and PS schemes separately. In the final subsection, we address the solution to outer optimization of the problem $(P1)$ where the index of optimally selected relay is computed that maximizes the rate.

A. Optimization of TS Ratio and Relay Coefficients for Rate Maximization in TS Scheme

In this subsection, we address the inner optimization problem of $(P1)$ involving the computations of optimal relay weighing coefficients and the TS ratio (α) in TS scheme. This sub-problem $(P2)$ can be formulated as follows:

$$(P2) : \max_{\alpha,w_i} \quad R_{eff}^{TS} \tag{16}$$

$$\text{subject to} : \quad \zeta(\alpha N T_s)E' \geq \eta, \tag{17}$$

$$0 < |w_i|^2 \leq P_R, \tag{18}$$

$$0 \leq \alpha \leq 1, \tag{19}$$

where $E' = |w_i|^2|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_m^2$. Computation of optimal solution for this problem involves joint computation of $\{\alpha\}$ and $\{w_i\}$. R_{eff}^{TS} is an increasing function of $\{w_i\}$. On the other hand, R_{eff}^{TS} decreases linearly within the constraint limits of α in (19). Therefore, the objective function achieves maximum at:

$$|w_i|^2 = P_R, \tag{20}$$

and

$$\alpha = \frac{\eta(\zeta N T_s)^{-1}}{P_R|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_m^2}. \tag{21}$$

B. Optimization of PS Ratio and Relay Coefficients for Rate Maximization in PS Scheme

In this subsection, we find the optimal weighing coefficients of the relays and an optimal PS ratio (β) for the PS scheme. Mathematically, corresponding sub-problem (P3) considering inner optimization of $(P1)$ can be expressed as

$$(P3) : \max_{\{\beta\},\{w_i\}} \quad R_{eff}^{PS} \tag{22}$$

$$\text{subject to} : \quad \zeta(\beta T)E' \geq \eta, \tag{23}$$

$$0 < |w_i|^2 \leq P_R, \tag{24}$$

$$0 \leq \beta \leq 1. \tag{25}$$

R_{eff}^{PS} is an increasing logarithmic function of $|w_i|^2$. From our analysis in the previous subsection, we observe that $(P3)$ shares common characteristics with $(P2)$ when considered with respect to w_i. Therefore, the optimal value of w_i that maximizes the objective in (22) is given by:

$$|w_i|^2 = P_R. \tag{26}$$

Next, it is seen that R_{eff}^{PS} is a decreasing function of β, with maximum at $\beta = 0$. In order to satisfy the constraint in (23), we set an upper bound on $\{\beta\}$ by letting the equality hold. Hence, the optimal value of β is given by:

$$\beta = \frac{\eta(\zeta T)^{-1}}{P_R|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_m^2}. \tag{27}$$

The objective in (22) obtains the maximum value by using the solutions provided in (26) and (27).

C. Optimal Relay Selection to Maximize Rate

In this subsection, we consider optimal selection of relay to address the solution of outer optimization of $(P1)$. Based on the above developments, we find the best relay which provides maximum throughput for both TS and PS schemes corresponding to (16) and (22), respectively. The index of the selected relay can be expressed as $j^\star = \text{argmax}_{j\in\{1,2,\cdots,L\}} R_j^\star$, where $R_j^\star$ is the rate achieved by the jth relay with optimal weighing coefficient. It should be noted that in case of both TS and PS schemes, all of the relay power is used to amplify the signal received by the relay.

IV. Optimal Relay Selection and Transceiver Design for Total Harvested Energy Maximization

In this section, the problem of relay selection that maximizes the overall harvested energy at the destination node is considered while ensuring that the rate is above a given threshold.

Mathematically, the overall optimization problem $(P4)$ can be formulated as

$$(P4): \max_{i\in\mathcal{I},\phi,w_i} \quad E_h \tag{28}$$
$$\text{subject to}: \quad R \geq \rho, \tag{29}$$
$$0 < |w_i|^2 \leq P_R, \tag{30}$$
$$0 \leq \phi \leq 1, \tag{31}$$

where i is the relay index, and ρ is the lower bound on the overall rate. Since this problem is not tractable in its present form, we propose to recast $(P4)$ into two separate optimization problems by performing the outer and inner optimizations respectively, as in the previous case. The sub-problem involving outer optimization addresses the computation of the index of optimally selected relay, while the other sub-problem with inner optimization addresses the computations of TS or PS ratios, and the weighing coefficient of each relay. In the following two subsections, we address the optimal solutions to the inner optimization of this problem for both TS and PS schemes. In the final subsection, outer optimization of the problem is performed where index of the best relay is selected.

A. Optimization of TS Ratio and Relay Coefficients for Maximization of Harvested Energy in TS Scheme

Here, we consider the inner optimization problem of $(P4)$ for the TS scheme. We determine the optimal weighing coefficients of the relay nodes, and optimal TS ratio (α) for maximizing the total energy harvested at the destination node under constraints on the minimum achievable rate, and limitation on the relay power. Mathematically, the sub-problem (P5) can be formulated as follows:

$$(P5): \max_{\alpha,w_i} \ \zeta(\alpha NT)\big[|w_i|^2|h_i|^2(P_T|g_i|^2+\sigma_{n_i}^2)+\sigma_m^2\big] \tag{32}$$
$$\text{subject to}: \ R_{eff}^{TS} \geq \rho, \tag{33}$$
$$0 < |w_i|^2 \leq P_R, \tag{34}$$
$$0 \leq \alpha \leq 1, \tag{35}$$

for $i \in \mathcal{I}$. The solution of sub-problem $(P5)$ involves joint computations of $\{\alpha\}$ and $\{w_i\}$. In this context, we present analytical solutions for the optimization sub-problem $(P5)$ following the approach in section III.A. To proceed, note that E_h^{TS} is an increasing logarithmic function of $|w_i|^2$. We find that at the maximum of the objective function in (32), the following holds:

$$|w_i|^2 = P_R. \tag{36}$$

On the other hand, it is seen that E_h^{TS} has a linearly decreasing function of $\{\alpha\}$. Therefore, the following holds true at the optimum:

$$\alpha = 1 - \frac{2\rho}{\log_2\left(1+\frac{P_R|g_i|^2|h_i|^2P_T}{|w_i|^2|h_i|^2\sigma_{n_i}^2+\sigma_m^2}\right)}. \tag{37}$$

The solution above is found by letting equality hold for (33). In other words, both the constraints are active at the optimal solution.

B. Optimization of PS Ratio and Relay Coefficients for Maximization of Harvested Energy in PS Scheme

In this subsection, we consider the problem of optimization of β and w_i for maximizing the harvested energy using the PS scheme. Mathematically, the sub-problem (P6) can be formulated as follows:

$$(P6): \max_{\beta,w_i} \ \zeta(\beta T_p)\big[|w_i|^2|h_i|^2(P_T|g_i|^2+\sigma_{n_i}^2)+\sigma_m^2\big] \tag{38}$$
$$\text{subject to}: \ R_{eff}^{PS} \geq \rho, \tag{39}$$
$$0 < |w_i|^2 \leq P_R, \tag{40}$$
$$0 \leq \beta \leq 1, \tag{41}$$

for $i \in \mathcal{I}$. We address the solution of this problem by optimizing β and w_i jointly to obtain a closed form solution. E_h^{PS} is an increasing function of w_i. As in the previous analysis, the following holds true at the optimal point:

$$|w_i|^2 = P_R. \tag{42}$$

E_h^{PS} is a linearly decreasing function of β. It can be observed that the following solution of β is optimal:

$$\beta = 1 - \frac{(2^{2^{\rho}}-1)\sigma_m^2}{P_R|h_i|^2\big(P_T|g_i|^2\sigma_{n_i}^2-(2^{2\rho}-1)\big)}. \tag{43}$$

C. Optimal Relay Selection to Maximize Harvested Energy

From the methods proposed above, optimal weighing coefficients for all the relays can been computed easily. We propose to find the best relay which provides maximized harvested energy for both TS and PS schemes corresponding to (32) and (38) respectively. In this context, the index of optimally selected relay can be expressed as $j^\star = \text{argmax}_{j\in\{1,2,\cdots,L\}} E_j^\star$, where $E_j^\star$ is the energy harvested by the destination node considering jth relay with corresponding optimal weighing coefficient.

V. Simulation Results

In this section, we evaluate the performance of the proposed solutions using simulations. We consider $L = 6$ relay nodes with overall bandwidth of $B = 1$MHz. We assume that the channel coefficients are i.i.d. and follow Rayleigh distribution throughout the simulations. For simplicity, we set $\zeta = 1$, and $\sigma_{n_i}^2 = \sigma_m^2 = 1$.

Fig. 3 illustrates the decrease in spectral efficiency with demand for harvested energy. It is observed from Fig. 3 that the spectral efficiency of the system increases appreciably with increase in total transmit power with $P_R = 0$ dBW. Moreover, it is seen that PS scheme performs better than TS for the same conditions with slight advantage in terms of demand for harvested energy. Fig. 4 shows decreasing values of harvested energy over demanded rate for different values of P_T with $P_R = 3$ dBW. It is noticed that harvested energy increases considerably on increasing P_T. Interestingly, it is seen that there is very less flexibility in terms of demand for more rate in both TS and PS schemes as both the values converges to zero almost simultaneously. However, it is noted from the results that PS scheme performs better that TS in terms of energy harvesting.

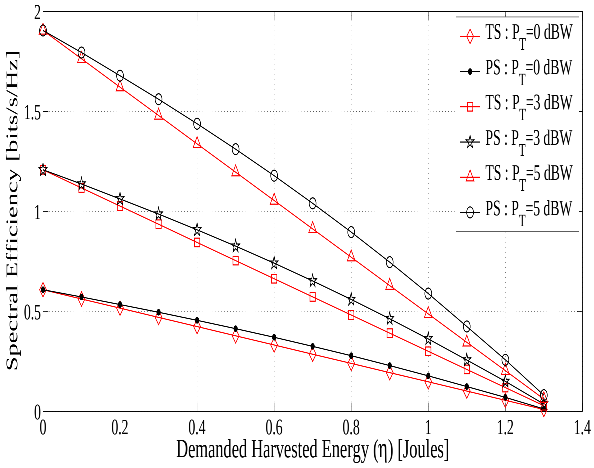

Fig. 3. Spectral efficiency versus minimum demanded harvested energy (η) for different values of P_T and $P_R = 0$ dBW.

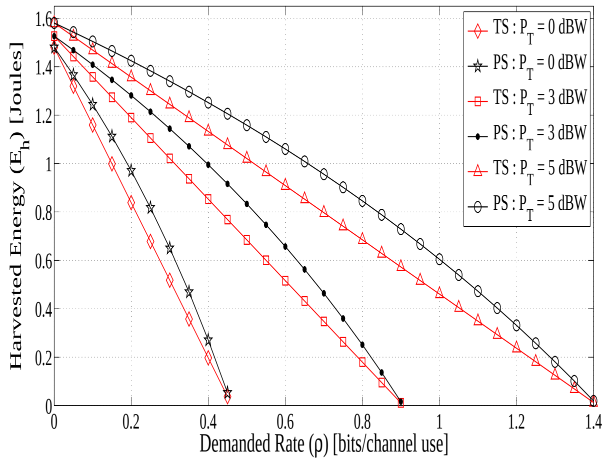

Fig. 4. Harvested energy (in Joules) versus demanded rate (ρ) for different values of P_T and $P_R = 3$ dBW.

It is observed from both Fig. 3 and Fig. 4 that PS scheme always achieves larger gains over TS scheme for increasing values of P_T. Moreover as P_T increases, the gap between the curves increases with increment in the parameter values of PS. It is noteworthy that the same relay is selected for both TS and PS schemes in the algorithm proposed for the first problem, provided that the channel conditions are same for both the cases. The same holds true in case of the algorithm proposed for second problem as well.

VI. Conclusion

In this paper, we investigated the Wi-TIE in a cooperative network of half duplex AF relays, assuming that the channel conditions are perfectly known. We addressed the problem of optimal relay selection for maximizing the rate under constraint on minimum harvested energy, and for maximizing the total harvested energy under constraints on minimum rate. Furthermore, this scenario was studied for both TS and PS schemes. We presented closed-form solutions for the proposed transceiver design problems. With the help of simulations, we demonstrated a comparative study between TS and PS schemes for the aforementioned cases. The results show that PS scheme performs better in comparison to TS for same set of conditions.

VII. Acknowledgement

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