A ZERO-FORCING BEAMFORMING BASED TIME SWITCHING PROTOCOL FOR WIRELESS POWERED INTERNET OF THINGS SYSTEM

HANYU CAO¹, MEIYING ZHANG¹, HUANXI CAI¹, WEI GONG¹, MIN SU¹ AND BIN LI*¹,²

¹College of Electrical and Information Technology
Sichuan University, Chengdu, China
²Key Laboratory of Wireless Power Transmission of Ministry of Education
Sichuan University, Chengdu, China

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ABSTRACT. In this paper, a time switching (TS) protocol for the wireless powered communications system with per-antenna power constraints is considered. To eliminate the multi-user interference, we adopt the zero-forcing beamforming scheme to maximize the sum rate performance. A two-step algorithm is proposed to solve the sum rate maximization problem with per-antenna power constraints. More specifically, golden section search method is used to find optimal time switching factor in the first step. For each given TS factor, the sub-problem in the second step is convex, which can be efficiently solved by standard software package. Numerical results are provided to demonstrate the effectiveness of the proposed methods, and some interesting results are also observed.

1. Introduction.

1.1. Background. The number of the Internet of Things (IoT) devices has increased dramatically in recent years [1]. A significant challenge is the energy supply and service life of the IoT devices, as they are powered by batteries in many applications. Although replacing batteries is an option that can prolong service life of IoT devices, a high cost is usually associated. Moreover, in many cases, replacing batteries cannot be easily carried out due to physical or economic limitation. For example, sometimes the devices may be embedded in building structures or even inside human bodies.

Therefore, energy harvesting (EH) in IoT systems become an important area in research [12, 13, 17]. The conventional energy harvesting methods depend on the wind or solar energy, which is limited by the installation environment. Considering on the lack of stability, conventional energy harvesting methods cannot satisfy the
requirements of IoT systems. As a result, researchers are increasingly focusing on emerging technologies that can overcome these problems by using radio frequency signals to deliver energy. Compared with traditional methods, wireless powered transmission is more suitable to solve the energy harvesting problem in IoT systems.

The concept of using radio frequency signals to transmit energy was first proposed by Tesla in the 1880s. However, restricted by the electrical equipment of that time, there were problems of high energy loss and low radio energy conversion efficiency, so it could not be applied at that time. With the development and progress of low power electrical instruments in recent years, the large-scale implementation of energy transmission and harvesting by radio frequency becomes feasible. Using radio frequency signals as both an energy transmission and an information transmission medium, Varshney proposed the concept of Simultaneous Wireless Information Powered Transfer (SWIPT) [20]. Since there is a large amount of information interaction between the sensors of various devices in IoT systems, wireless powered communication has a wide application prospect in it.

Zero-forcing (ZF) beamforming is a common precoding method [2, 21, 11, 7]. It is a suboptimal approach that each user’s information is steered in a particular direction in the signal space without having interferences to the other users. It performs well in the high signal to noise ratio (SINR) regime or when the number of users is sufficiently large, and is known to provide full degrees of freedom [2].

1.2. Literature review. An ideal receiver capable of performing information decoding (ID) and EH simultaneously has been proposed in [20]. The trade-off between the achievable information rate and the harvested energy is also characterized by a capacity-energy function in [20]. However, there are two challenges from practical considerations [24]. Firstly, in practice, the circuits for harvesting energy cannot decode the carried information. To coordinate wireless information transfer (WIT) and wireless energy transfer (WET) at the receiver, a time switching (TS) protocol and a power splitting (PS) protocol have been proposed in [23]. Secondly, since WIT and WET operate with different sensitivity (-10dBm for energy receivers and -60dBm for information receivers), the architecture of traditional ID receiver may not be optimal for EH receiver. To tackle this problem, a separated architecture receiver and an integrated architecture receiver have been developed in [24] for a more general protocol called dynamic PS which includes the TS protocol and the PS protocol as special cases. Waveform design for wireless power transfer has been studied in [3] and [25].

ZF beamforming scheme can be used to eliminate the multi-user interference [2, 11, 7]. A joint optimization of transmit beamforming and PS ratio under zero-forcing method is developed in [18]. Meanwhile, other researchers focused on energy efficiency optimization [16, 19]. In [16] researchers study on power splitting based MISO system by using Lagrangian relaxation method to optimize the energy efficiency. [15] study a ZF beamforming method of SWIPT MISO full-duplex systems. Moreover, [14] develop a suboptimal algorithm of zero-forcing sum rate optimal problem in TS based SWIPT MISO system.

Per-antenna power constraints (PAPC) are more realistic constraints in real world applications since each transmitted antenna has its own power amplifier and each power amplifier has its own power limit [11, 7]. ZF beamforming under PAPC is a non-trivial optimization problem [21]. In [21], it is shown that ZF pre-coding is closely related to generalized inverses, but it is a difficult optimization problem. Because finding the optimal generalize inverse under PAPC is depending on the
specific performance criterion. In [11, 7], the researchers reduce the computational complexity of normal PAPC zero-forcing problem. In [22], an algorithm is developed to solve MIMO/MISO zero-forcing problem subjects to PAPC by using semi-definite relaxation (SDR), and prove that there is always a rank one solution of the SDR problem.

1.3. Contributions. In this paper, we consider the ZF beamforming problem with PAPC for a TS based WPC IoT system. We investigate the sum rate maximization problem of the system by using SDR technique, and develop a computational method for this problem. Since the sum rate problem is a non-convex problem, we proposed a two-step algorithm to solve the problem efficiently. More specifically, we apply the SDR to the original problem. Then, we show that for the approximated problem the optimal TS factor can be found by a golden section search in the first step. Then, in the second step, the optimization problem is convex for each given TS factor and hence it can be solved by efficiently standard optimization software package such as CVX [6]. In the numerical simulations, we found that the obtained solutions are rank one matrices in most cases.

1.4. Structure. The rest of this paper is organized as follows. Our problem is formulated in Section II. In Section III, the solution method is developed. Section IV presents some simulation results to show the effectiveness of our proposed algorithm. Finally, we conclude this paper in Section V.

2. Problem formulation. We considered a MISO WPC IoT system which consists of a base station equipped with $N_1$ antennas and $M$ users with a single antenna. The wireless channel is a quasi-static fading channel, and the channel state information (CSI) is perfectly known. Under a TS based protocol, each communication cycle is divided into two time intervals.

In the first time interval, the signal sent by the base station is

$$x_k = v_k s_k$$

where $s_k$ and $v_k$ denote the information signal and the beamforming vector for the $k$th user, respectively. The information received by $k$th user can, then, be written as

$$y_{1,k} = h_k^H x_k + \sum_{j \neq k} h_j^H x_j + n_k$$

where $h_k$ denotes to the $N_1 \times 1$ channel gain matrix of user $k$. $n_k$ is the noise which is subject to the Gaussian distribution. Its mean is 0 and its variance is $\sigma^2$.

The signal to interference plus noise ratio (SINR) of each user can be expressed as

$$\text{SINR}_k = \frac{1 + h_k^H v_k v_k^H h_k}{\sum_{j \neq k} h_j^H v_k v_k^H h_j + \sigma^2}$$

According to Shannon theorem, the sum rate in this time interval is

$$R_{\text{sum}}(\alpha, v_k) = \sum_{k=1}^{M} \alpha \log_2 \left( \frac{1 + h_k^H v_k v_k^H h_k}{\sum_{j \neq k} h_j^H v_k v_k^H h_j + \sigma^2} \right)$$

where $\alpha$ is the TS time factor. Without loss of generality, we assume the duration of one communications cycle is $T = 1$. 
After the first time interval, the signal $s_k$ starts to carry energy from the base station to users’ receivers, which is

$$y_{2,k} = h_k H_k x_k + \sum_{j \neq k} h_k^H x_j + n_k$$  \hspace{1cm} (5)

Therefore, during the second time interval the energy received by EH of user $k$ is

$$(1 - \alpha) \zeta_k \left( h_k^H v_k^H h_k + \sum_{j \neq k} h_k^H x_j + \sigma_k^2 \right)$$  \hspace{1cm} (6)

where $\zeta_k$ is the energy conversion efficiency.

Considering of the power limits on each of the antennas, we have the PAPC as

$$\sum_{k=1}^{M} Tr(B_i v_k v_k^H) \leq P$$  \hspace{1cm} (7)

where $P$ denotes to the max transmit power on each antenna, and $B_i$ has such structure as follow:

$$B_i = \text{diag}[0, \ldots, 0, 1, 0, \ldots, 0] \in \mathbb{R}^{M \times M}$$  \hspace{1cm} (8)

The $i$th element of $B_i$ is 1 and all the other elements are 0.

Thus, the sum rate maximization problem can be written as

$$\max_{\alpha, v_k} \sum_{k=1}^{M} \alpha \log_2 \left( \frac{1 + h_k^H v_k v_k^H h_k + \sum_{j \neq k} h_j^H x_j + \sigma_k^2}{\sum_{j \neq k} h_j^H v_k v_k^H h_j + \sigma^2} \right)$$  \hspace{1cm} (9)

s.t. \hspace{1cm}$1 + h_k^H v_k v_k^H h_k \geq \gamma_k, \forall k$  \hspace{1cm} (10)

$$1 - \alpha) \zeta_k \left( h_k^H v_k v_k^H h_k + \sum_{j \neq k} h_k^H x_j + \sigma_k^2 \right) \geq \epsilon_k, \forall k$$  \hspace{1cm} (11)

$$\sum_{k=1}^{M} Tr(B_i v_k v_k^H) \leq P$$  \hspace{1cm} (12)

$$h_j^H v_k = 0, \forall j \neq k$$  \hspace{1cm} (13)

$$0 \leq \alpha \leq 1$$  \hspace{1cm} (14)

where (11) and (12) are the SINR constraints and energy harvesting constraint for each user, respectively. The two constraints guarantee every user to receive acceptable SINR and energy during each time cycle.

In order to eliminate the interference between users and to realize errorless information transmission, we introduce the ZF constraint as follow

$$h_j^H v_k = 0, \forall j \neq k$$  \hspace{1cm} (15)

From (15), the SINR of information receiver can be rewritten as

$$\text{SINR}_k = \frac{h_k^H v_k v_k^H h_k}{\sigma_k^2}$$  \hspace{1cm} (16)

and the sum rate of whole system in a time cycle is changed into

$$R_{\text{sum}}(\alpha, v_k) = \sum_{k=1}^{M} \alpha \log_2 \left( 1 + \frac{h_k^H v_k v_k^H h_k}{\sigma_k^2} \right)$$  \hspace{1cm} (17)
By substituting (15) into (6), the energy received by kth user with ZF scheme is

\[(1 - \alpha)\zeta_k (h_k^H v_k v_k^H h_k + \sigma_k^2)\]  (18)

Now we formally state our problem as

\[
\max_{v_k, \alpha} \sum_{k=1}^{M} \alpha \log_2 (1 + h_k^H v_k v_k^H h_k / \sigma_k^2) \quad (19)
\]

s.t. \(h_k^H v_k v_k^H h_k / \sigma_k^2 \geq \gamma_k, \forall k\) \quad (20)

\[(1 - \alpha)\zeta_k (h_k^H v_k v_k^H h_k + \sigma_k^2) \geq e_k, \forall k\]  (21)

\[
\sum_{k=1}^{M} \text{Tr}(B_i v_k v_k^H) \leq P \quad (22)
\]

\(h_k^H v_k = 0, \forall j \neq k\) \quad (23)

\[0 \leq \alpha \leq 1\]  (24)

Notice here problem (19) - (24) is a non-convex problem which is difficult to solve, and we shall develop an efficient two-step algorithm in the next section.

3. A solution method. In this section, we shall develop an efficient solution method to solve (19) - (24). Towards this goal, we first apply the SDR scheme to problem (19) - (24).

For this, we define \(S_k = v_k v_k^H\) and \(\text{rank}(S_k) \leq 1\). Then, we have the SDR form of (19) - (24) as

\[
\max_{S_k, \alpha} \sum_{k=1}^{M} \alpha \log_2 (1 + h_k^H S_k h_k / \sigma_k^2) \quad (25)
\]

s.t. \(h_k^H S_k h_k / \sigma_k^2 \geq \gamma_k, \forall k\) \quad (26)

\[(1 - \alpha)\zeta_k (h_k^H S_k h_k + \sigma_k^2) \geq e_k, \forall k\]  (27)

\[
\sum_{k=1}^{M} \text{Tr}(B_i S_k) \leq P \quad (28)
\]

\(h_j^H S_k h_j = 0, \forall j \neq k\) \quad (29)

\[0 \leq \alpha \leq 1\]  (30)

\[\text{Rank}(S_k) \leq 1, \forall k\]  (31)

Notice here the problem (25) - (31) is still non-convex because of the constraint (30) and \(\alpha\). According to [22], we drop the rank constraint and assume \(S_k \succeq 0\) for each \(k\). Then, the problem (25) - (31) becomes
Interestingly, we observe that problem (32) - (38) is convex optimization problem when \( \alpha \) is fixed. If the functions of (32) - (38) are monotonic unimodal with respect to \( \alpha \), searching the optimal \( \alpha \) can cost lots of computation effort. Fortunately, we can prove that the (32) - (38) is a monotonic unimodal function to \( \alpha \).

Firstly, we can easily find that the object function (32) is a monotonic unimodal function to \( \alpha \). So we only need to study on variation of the feasible region while \( \alpha \) changes. When \( \alpha \) is increasing, to satisfy the constraint (34), the value of \( h_h^H S_k h_k / \sigma^2_k \) must be increasing too. And this makes the value of object function (32) increasing too. Therefore, we can prove that the solution of (32) - (38) is a monotonic unimodal function to \( \alpha \).

Based on this fact, we develop a two-step algorithm to solve the problem (32) - (38) which is summarized in Algorithm 1. For a given \( \alpha \), we optimize \( S_k \) by solving the subproblem (32) - (38). And then a simple one dimensional search (such as the golden section search method) can be applied to obtain the optimal \( \alpha \). The procedure of the proposed two-step algorithm is summarized in Algorithm 1, where \( \epsilon \) is a positive constant close to 0, and \( \delta > 0 \) is the reduction factor. It has been shown in [6] that the optimal \( \delta = 1.618 \), also known as the golden ratio.

\textbf{Algorithm 1} Solving the Problem (32)-(38)

\textbf{Input:} \( h_k, \sigma^2_k, P \).
\textbf{Output:} \( S^*_k, \alpha^* \).

\begin{verbatim}
Initialization: \( \alpha_l = 0 \) and \( \alpha_u = 0 \).
1: \textbf{while} \( |\alpha_u - \alpha_l| > \epsilon \) \textbf{do}
2: \hspace{1em} Define \( d_1 = (\delta - 1)\alpha_l + (2 - \delta)\alpha_u \) and \( d_2 = (\delta - 1)\alpha_u + (2 - \delta)\alpha_l \).
3: \hspace{1em} Solve the problem (32) - (38) for \( \alpha = d_1 \); Compute \( R_{\text{sum}}(d_1) \) for \( \alpha = d_1 \).
4: \hspace{1em} Repeat Step 3 for \( \alpha = d_2 \).
5: \hspace{1em} if \( R_{\text{sum}}(d_1) < R_{\text{sum}}(d_2) \) \textbf{then}
6: \hspace{2em} Assign \( \alpha_l = d_1 \).
7: \hspace{1em} else
8: \hspace{2em} Set \( \alpha_u = d_2 \).
9: \hspace{1em} end if
10: \textbf{end while}
11: \( \alpha^* = (\alpha_u + \alpha_l)/2 \)
\end{verbatim}

\textbf{Remark 1} We need to emphasize that the solution we obtained here is not the exact optimal solution since we have dropped the rank constraint. If \( \text{rank}(S_k) \leq 1 \),
then the solution is an optimal solution. However, in the numerical simulations, we found that the solution we obtained is usually a rank one matrix.

4. Numerical simulations. In this section, we test the performance of our proposed algorithm through some numerical examples. For simplicity, we assume that the parameters of each user are the same. We set $\sigma^2 = -50 dBm$, $\gamma_k = 10 dB$, $\zeta_k = 0.5$, $e_k = -20 dBm$, $N_1 = M = 3$ and the distance between users and base station are 20m. All the simulation results are averaged over 1000 independent channel realizations. For comparison purposes, we present the simulation of two situations (under per-antenna power constraints and total power constraints). Though the performance of total power constraints is better because of its larger feasible area, per-antenna power constraints is closer to the real world situations.

4.1. Example 1: Time switching factor versus harvest energy. In the first example, we set $P = 1$ and plot the optimal TS factor $\alpha$ versus the minimum harvest energy of ER. From Fig. 1, it shows that when we increase the energy constraints, the optimal $\alpha$ decreases. The reason is that the system needs more time $(1 - \alpha)$ to charge the ER so that the EH constraints (34) can be met.

4.2. Example 2: Sum rate versus harvest energy. In the second example, we set $P = 1$ and plot the sum rate versus the minimum harvest energy of ER. From Fig. 2, we can find that the sum rate performance of the system decreases as harvest energy is increasing. This is because of trade-off between the sum rate performance and energy requirement.

![Figure 1. Sum Rate versus P](image-url)
4.3. Example 3: Sum rate versus $P$. In the last example, we set $e_k = -20 dBm$ and plot sum rate versus $P$ in Fig. 3. As expected, the sum rate performance increases as the transmit power $P$ increases as shown in Fig. 3. The results of numerical simulation can prove that the more power antennas gain the better performance system has.
5. Conclusions. In this paper, we proposed a TS based protocol for WPC IoT system with per-antenna power constraints. The joint optimization of beamforming matrices and TS factor is studied to maximize the sum rate of system. Comparing with the normal sum antenna power constraint, we consider a more general constraint - the per-antenna power constraint. Based on the SDR, a two-step algorithm was developed to solve the optimization problem. The optimal time switching factor was obtained by the golden section search method in the first step. In the second step, the sub-problem is a convex optimization problem and hence it can be efficiently solved by standard software package. The effectiveness has been demonstrated by the simulation results. However, according to existing works, researchers use Lagrangian relaxation (LR) method to solve the similar problem (without PAPC) [19, 14]. LR method is an efficient technique to solve the complicated non-convex optimization problem, which can provide approximate suboptimal solutions. The proposed algorithm can provide the optimal solutions in mostly cases \( \text{Rank}(S_k) \leq 1 \), which can obtain better performance in contrast with LR method.

REFERENCES

[1] Internet of Things in 2020 - A Road Map in the Future, 2008. Available from: http://www.smart_systems_integration.org/public/documents/publications/Internet_of_Things_in_2020_EC-EPoSS_Workshop_Report_2008_v3.pdf.
[2] G. Caire and S. Shamai, On the achievable throughput of multiantenna Gaussian broadcast channel, IEEE Trans. Inf. Theory, 49 (2003), 1691–1706.
[3] B. Clerckx and E. Bayguzina, Waveform design for wireless power transfer, IEEE Trans. Signal Process, 64 (2016), 6313–6328.
[4] Z. G. Feng, K. F. C. Yiu and S. E. Nordholm, A two-stage method for the design of near-field broadband beamformer, IEEE Transactions on Signal Processing, 59 (2011), 3647–3656.
[5] Z. G. Feng, K. F. C. Yiu and S. E. Nordholm, Placement design of microphone arrays in near-field broadband beamformers, IEEE Transactions on Signal Processing, 60 (2012), 1195–1204.
[6] M. Grant, S. Boyd, L. Liberti and N. Maculan, Disciplined convex programming in global optimization: From theory to implementation, Nonconvex Optimization and Its Applications, 84 (2006), 155–210.
[7] B. Li, H. H. Dam, A. Cantoni and K. L. Teo, A first-order optimal zero-forcing beamformer design for multiuser MIMO systems via a regularized dual accelerated gradient method, IEEE Commun. Lett., 19 (2015), 195–198.
[8] B. Li, H. H. Dam, A. Cantoni and K. L. Teo, A global optimal zero-forcing beamformer design with signed power-of-two coefficients, Journal of Industrial and Management Optimization, 12 (2016), 595–607.
[9] B. Li and Y. Rong, Joint transceiver optimization for wireless information and energy transfer in nonregenerative MIMO relay systems, IEEE Transactions on Vehicular Technology, 67 (2018), 8348–8362.
[10] B. Li and Y. Rong, AF MIMO relay systems with wireless powered relay node and direct link, IEEE Transactions on Communications, 66 (2018), 1508–1519.
[11] B. Li, C. Z. Wu, H. H. Dam, A. Cantoni and K. L. Teo, A parallel low complexity zero-forcing beamformer design for multiuser MIMO systems via a regularized dual decomposition method, IEEE Trans. Signal Process, 63 (2015), 4179–4190.
[12] X. Lu, P. Wang, D. Niyato, D. I. Kim and Z. Han, Wireless networks with RF energy harvesting: A contemporary survey, IEEE Communications Surveys & Tutorials, 17 (2015), 757–789.
[13] X. Lu, P. Wang, D. Niyato, D. I. Kim and Z. Han, Wireless charging technologies: fundamentals, standards, and network applications, IEEE Communications Surveys & Tutorials, 18 (2016), 1413–1452.
[14] L. Ma, Y. Wang and Y. Xu, Sum rate optimization for SWIPT system based on zero-forcing beamforming and time switching, 2017 13th International Wireless Communications and Mobile Computing Conference (IWCMC), (2017), 351–356.
[15] A. A. Okandeji, et al., SWIPT in MISO full-duplex systems, Journal of Communications and Networks, 19 (2017), 470–480.
[16] C. Peng, Q. Shi, W. Xu and M. Hong, Energy efficiency optimization for multi-user MISO swipt systems, 2015 IEEE China Summit and International Conference on Signal and Information Processing (ChinaSIP), (2015), 772–776.
[17] T. D. Ponnimbaduge Perera, D. N. K. Jayakody, S. K. Sharma, S. Chatzinotas and J. Li, Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges, IEEE Communications Surveys & Tutorials, 20 (2018), 264–302.
[18] Q. Shi, L. Liu, W. Xu and R. Zhang, Joint transmit beamforming and receive power splitting for MISO SWIPT systems, IEEE Transactions on Wireless Communications, 13 (2014), 3269–3280.
[19] Q. Shi, C. Peng, W. Xu, M. Hong and Y. Cai, Energy efficiency optimization for MISO SWIPT systems with zero-forcing beamforming, IEEE Transactions on Signal Processing, 64 (2016), 842–854.
[20] L. R. Varshney, Transporting information and energy simultaneously, IEEE Int. Symp. Inf. Theory (ISIT), 6 (2008), 1612–1616.
[21] A. Wiesel, Y. C. Eldar and S. Shamai, Zero-Forcing precoding and generalized inverses, IEEE Transactions on Signal Processing, 56 (2008), 4409–4418.
[22] R. Zhang, Cooperative multi-cell block diagonalization with per-base-station power constraints, IEEE Journal on Selected Areas in Communications, 28 (2010), 1435–1445.
[23] R. Zhang, R. G. Maunder and L. Hanzo, Wireless information and power transfer: From scientific hypothesis to engineering practice, IEEE Communications Magazine, 53 (2015), 99–105.
[24] R. Zhang and C. K. Ho, MIMO broadcasting for simultaneous wireless information and power transfer, IEEE Trans. Wireless Commun., 12 (2013), 1989–2001.
[25] Y. Zeng, B. Clerckx, and R. Zhang, Communications and signals design for wireless power transmission, IEEE Trans. Commun., 65 (2017), 2264–2290.

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E-mail address: jasontsow@gmail.com
E-mail address: mei.ying.zhang@hotmail.com
E-mail address: huanxi_cai@163.com
E-mail address: gwei349@163.com
E-mail address: sumin@scu.edu.cn
E-mail address: bin.li@scu.edu.cn