Effects of Magnitude Dynamic Range Constraints on MIMO Wireless Power Transfer Efficiency

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***Abstract*—This paper studies the effect of magnitude dynamic range constraints on Power Transfer Efficiency (PTE) in MIMO Wireless Power Transfer (WPT) systems. Conventional optimized PTE pattern shows high impractical distributions across transmitter arrays (TXA), with extreme dynamic ranges unsuitable for real power amplifiers (PAs). By assuming an ideal Doherty PA, proposed convex approach demonstrates that even with a tight range (e.g., 3 dB), PTE degradation remains minimal. These findings will enable practical WPT implementations considering PAE using Doherty PA should potentially enhance end-to-end system (DC-DC) efficiency in real-world applications.**

***Keywords*—Power Amplifier, Power Added Efficiency (PAE), Power Transfer Efficiency (PTE), Wireless Power Transfer.**

I. INTRODUCTION

Wireless Power Transfer using Radio Frequency (RF) has emerged as a promising technology to deliver power [1]. The major parameter for determining WPT system performance is PTE, which is defined as the ratio of received RF power to transmitted RF power (Fig. 1 shows the PTE stage in a conventional WPT system). Optimizing this metric has been continuously researched using various techniques [2], [3], [4]. These approaches result in optimal patterns of both magnitude and phase at the TXA.

However, the magnitude results derived from conventional PTE optimizations exhibit impractical dynamic ranges, particularly in MIMO configurations. Fig. 2 shows a certain example of MIMO WPT scenario with a 16×16 TXA and 6×6 RXA, which demonstrates power differences approaching a maximum of 45 dB across the TXA. Such extreme dynamic range requirements cannot be realistically implemented in real-world systems due to the limitations of PAs. Furthermore, these requirements will significantly impact the Power Added Efficiency (PAE) of the amplifiers, which ultimately highly lower the end-to-end DC-DC efficiency of the entire WPT system. This highlights the critical gap between conventional PTE optimization and practical system implementations that must consider PA dynamic ranges.

Therefore, this paper observes the effect of magnitude range limits on PTE optimization, which is especially dramatic in MIMO WPT systems. By mimicking the PA output power dynamic range by constraining the magnitude range, the research explore how it affects the PTE in various scenarios. The results provide important insights for future research expanding toward end-to-end (DC-to-DC) optimized realistic WPT systems with specified PAs.

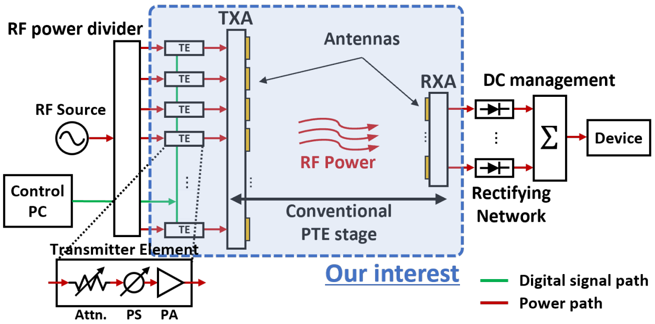

Fig. 1. Conventional WPT system configuration. This paper focuses on the RF-RF stage with PA dynamic range constraints (denoted as 'our interest').

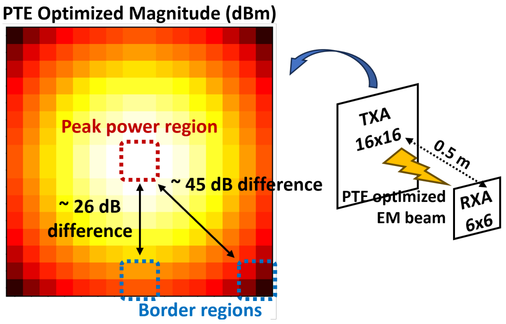

Fig. 2. An example of magnitude pattern (in dBm) from conventional PTE optimization. The total transmitted power was constrained to 30 RF Watts.

II. METHODOLOGY

Consider a MIMO WPT system as shown in Fig. 1 with M-element TXA and N-element RXA. The Channel State Information (CSI) between the TXA and RXA represent $\mathbf{G} \in \mathbb{C}^{N\times M}$ and let $\mathbf{x}_t \in \mathbb{C}^{M\times 1}$ denote the transmit signal. Then the problem can be formulated in convex form as follows:

$$\begin{aligned} \max_{\mathbf{S}} \quad & Q_{RF} := \mathrm{tr}((\mathbf{GSG}^H)/Z) \\ \text{subject to} \quad & \mathrm{tr}(\mathbf{S})/Z \le P_t, \quad \mathbf{S} \succeq 0, \\ & P_{\text{min}} \le \mathrm{diag}(\mathbf{S})/Z \le P_{\text{max}}. \end{aligned} \tag{1}$$

where $\mathbf{S} = \mathcal{E}[\mathbf{x}_t\mathbf{x}_t^H]$ is the covariance matrix, Z is the impedance, and P_t is the total transmit power constraint. Q_{RF} is the sum of received RF power at the N receivers,

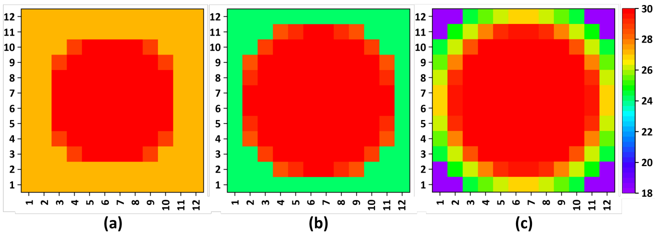

Fig. 3. Heatmap of radiated magnitude patterns in dBm at TXA 12×12 by various dynamic range constraints: (a) 3 dB, (b) 6 dB, and (c) 12 dB.

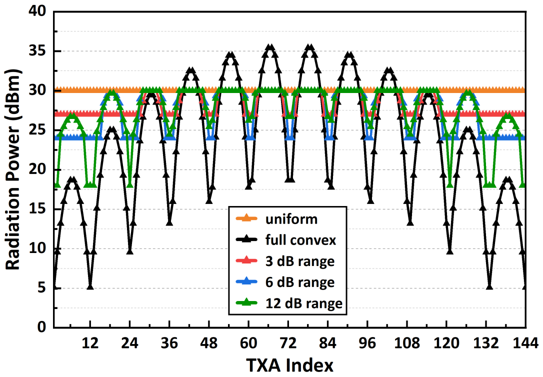

Fig. 4. TXA magnitude patterns in 1D by various dynamic range constraints.

diag($\mathbf{S}$) represents the transmitted power at each TXA element, and $P_{\min}$, $P_{\max}$ constrain its power range. Therefore, this convex problem directly optimizes PTE with integrated range constraints, *not just simply truncating min/max* from a conventionally optimized PTE pattern.

III. SIMULATION RESULTS

The simulation was conducted at 5.8 GHz using MATLAB to simulate free space WPT [3]. For a more in-depth analysis, a specific MIMO scenario with a 12×12 TXA and 6×6 RXA was selected. Then, the power range ($P_{\min}$, $P_{\max}$) was determined by assuming an ideal Doherty PA, as it maintains peak efficiency as much as possible through power back-off, which is commonly 3, 6, or 12 dB depending on the common design. $P_{\max}$ was set at 30 dBm, and P_t was fixed at 100 W.

Fig. 3 shows the heatmap of TXA power pattern with various ranges ($P_{\max} - P_{\min}$), and Fig. 4 presents its 1D pattern by TXA element index. The conventional approach (full convex opt.) is shown without any constraints, while the others implement specified constraints. The results clearly demonstrate that the power levels remain within the designated ranges, verifying the algorithm.

Fig. 5 displays the PTE versus distance across various power configurations: full convex, uniform (all elements are 30 dBm), and constrained ranges of 3, 6, and 12 dB. While the full convex approach achieves maximum PTE, the uniform pattern yields the lowest efficiency, confirming the necessity of magnitude tapering for PTE enhancement. The range-constrained cases result in only minimal PTE differences. Using the full convex optimization as a baseline, the 3, 6, and 12 dB constraints demonstrated only 13.1%, 10.4%, and 10.0% relative PTE degradation at 0.5 m, respectively. These results highlight the effectiveness of power limit settings, where constraining the power range preserves nearly the same level of PTE. Although the PTE decreases more significantly with more tight ranges (e.g., 3 dB), since low back-off Doherty PAs are easier to design, this approach may still be effective from a system-level perspective. Additionally, it is notable that all PTE converges near 1.5 m, where the system enters the far-field region and the power distribution becomes uniform.

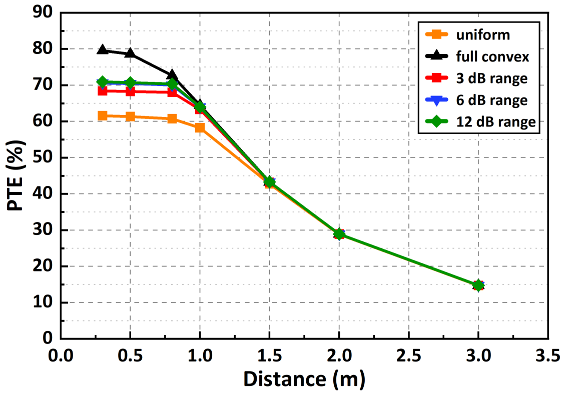

Fig. 5. Distance to PTE plot by varying the power range.

IV. CONCLUSION AND FUTURE EXTENSIONS

This study reveals the necessity of magnitude tapering for PTE enhancement while demonstrating that magnitude constraints minimally impact PTE in MIMO WPT systems. By simulating various back-off power scenarios with Doherty PA characteristics, it showed that even with tight power ranges, PTE degradation remains low. These findings enable future high WPT end-to-end efficiency by allowing tighter power distribution that can significantly improve PAE, particularly when implementing such high-efficiency Doherty PAs.

ACKNOWLEDGMENT

This work was supported by Institute of Information & Communications Technology Planning & Evaluation (IITP) grant funded by the Korea government (MSIT) (No. 2019-0-00098, Advanced and integrated software development for electromagnetic analysis).

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