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Waveform Design for Wireless Power Transfer with Power Amplifier and Energy Harvester Non-Linearities

Yumeng Zhang and Bruno Clerckx, *fellow, IEEE*

Presenter: Yumeng Zhang

Department of Electrical and Electronic Engineering
Imperial College London

Imperial College London

Outline:

- Motivation
- System Model
- Problem Formulation
- Optimization
- Simulation Results

Far-field wireless power transfer (WPT):

WPT generates and transmits suitable RF signals that propagate over the air before being captured and rectified into DC current via rectenna circuits at the receivers.

Motivation:

- Free of periodic replacement or wires;
- Sustainable power sources for the internet of things (IoT) [1];
- Green technology and reduction in energy consumption [1].

Feasibility:

- Lower power consumption on computing [2];
- Performance enhancement in WPT, i.e., advanced rectenna circuits, higher-efficient waveform design [3].

Object: to boost the power harvesting performance in WPT by designing the waveform of the multi-carrier signals.

[1] Perera, Tharindu D. Ponnimbaduge, et al. "Simultaneous wireless information and power transfer (SWIPT): Recent advances and future challenges." IEEE Communications Surveys & Tutorials 20.1 (2017): 264-302.
[2] B. Clerckx, A. Costanzo, A. Georgiadis, and N. B. Carvalho, "Toward 1G mobile power networks: Rf, signal, and system designs to make smart objects autonomous," IEEE

Motivation

Far-field wireless power transfer (WPT):

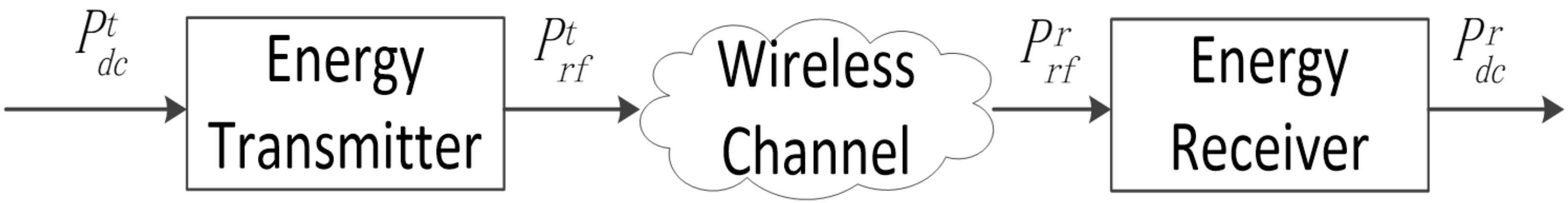

Fig 1. Block diagram of a generic WPT system.

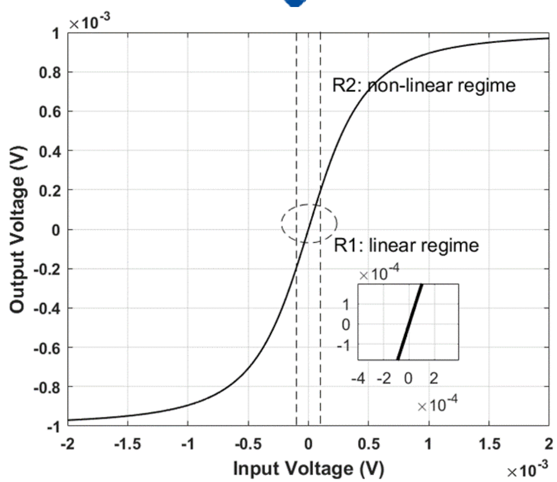

Fig 2. The transfer characteristics of the non-linear high power amplifier (HPA).

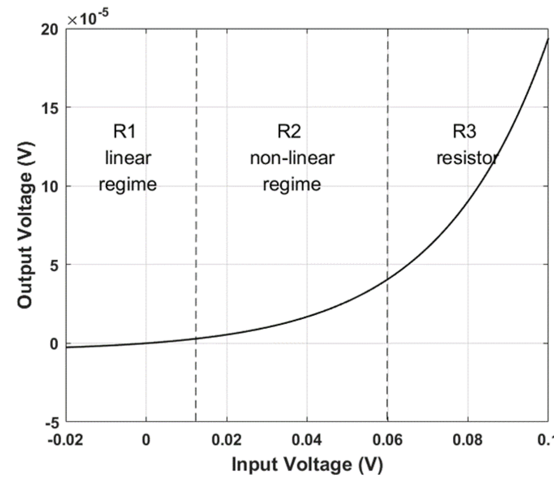

Fig 3. The transfer characteristics of the non-linear rectifier.

Object: designing waveforms considering both HPA's and rectifier's non-linearity.

[3] Clerckx, Bruno, and Ekaterina Bayguzina. "Waveform design for wireless power transfer." IEEE Transactions on Signal Processing 64.23 (2016): 6313-6328.

System Model

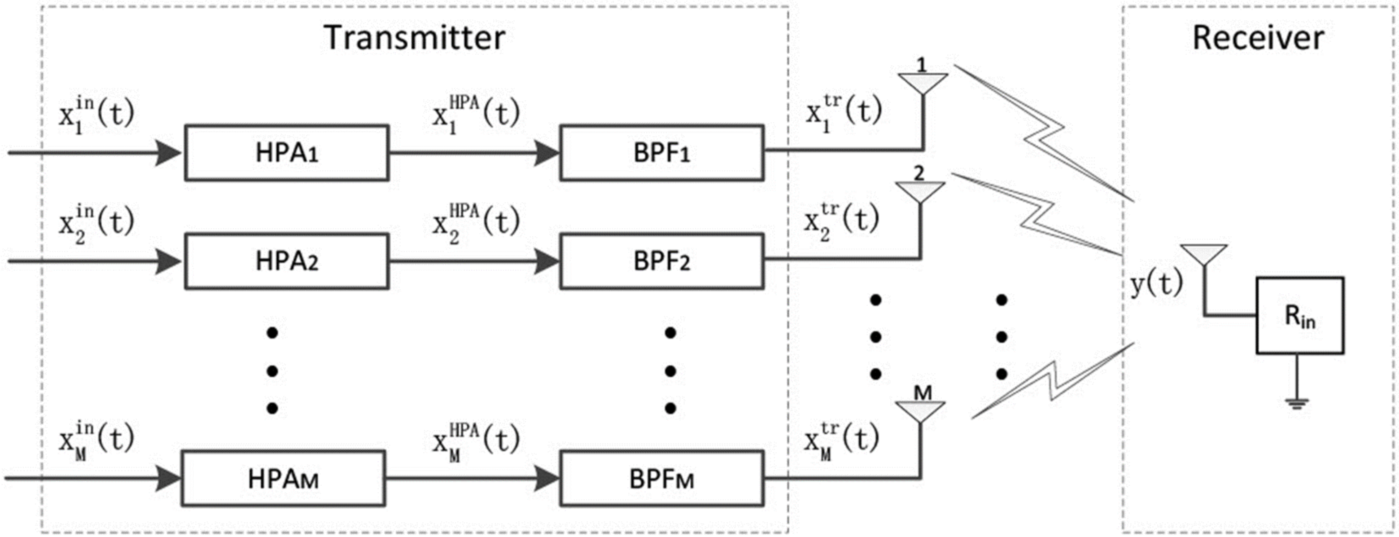

Fig 4. The WPT structure with transmitter's and rectenna's non-linearity. The transmitter is composed of a non-linear HPA and a band pass filter (BPF). The rectenna is composed of a non-linear rectifier and a low pass filter.

$$\tilde{x}^{in}_m(t) = \sum_{n=0}^{N-1} \tilde{w}^{in}_{n,m} e^{j2\pi f_n t},$$

After HPA

$$\tilde{x}^{HPA}_m(t) = f_{HPA}(\tilde{x}^{tr}_m(t)) = G\tilde{x}^{tr}_m(t) / \left[1 + \left(\frac{G\tilde{x}^{tr}_m(t)}{A_s}\right)^{2\beta}\right]^{\frac{1}{2\beta}},$$

After BPF

$$\tilde{x}^{tr}_m(t) = \sum_{n=0}^{N-1} \tilde{w}^{tr}_{n,m} e^{j2\pi f_n t},$$

After wireless propagation

$$\tilde{y}(t) = \sum_{m=1}^{M} \sum_{n=0}^{N-1} \tilde{h}^{tr}_{n,m} \tilde{w}^{tr}_{n,m} e^{j2\pi f_n t},$$

We use the solid state power amplifier (SSPA)'s model here. G is the small signal gain of SSPA, A_s is the saturation power of SSPA, and β is the smoothing parameter[4].

[4] Banelli, Paolo, Giuseppe Baruffa, and Saverio Cacopardi. "Effects of HPA nonlinearity on frequency multiplexed OFDM signals." IEEE Transactions on Broadcasting 47.2 (2001): 123-136.

➢ System Model

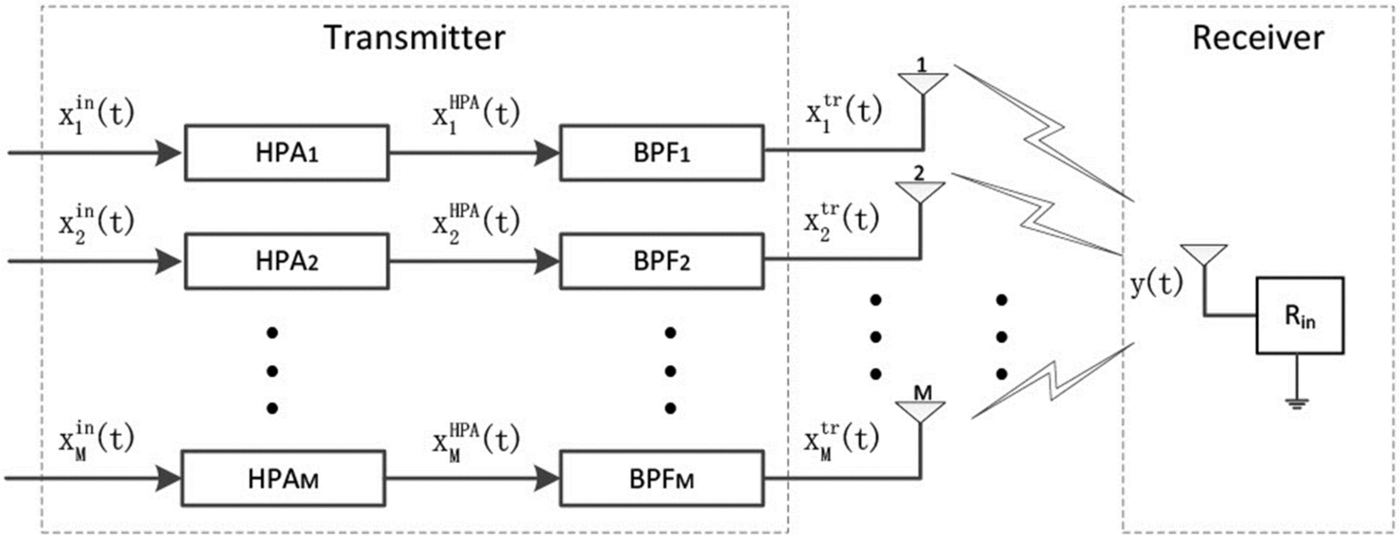

Fig 3. The WPT structure with transmitter's and rectenna's non-linearity. The transmitter is composed of a non-linear HPA and a band pass filter (BPF). The rectenna is composed of a non-linear rectifier and a low pass filter.

The harvested power is proportional to the scaling term [3]:

$$z_{DC} = k_2 R_{ant} \varepsilon \left\{ \Re\left\{ \tilde{y}(t) \right\}^2 \right\} + k_4 R_{ant} \varepsilon \left\{ \Re\left\{ \tilde{y}(t) \right\}^4 \right\},$$

where $k_i = i_s / (i!(\eta_0 v_0)^i)$ with i_s being the reverse bias saturation current, η_0 being the ideality factor, v_0 being the thermal voltage of the diode and R_{ant} being the characteristic impedance of the receiving antenna.

[3] Clerckx, Bruno, and Ekaterina Bayguzina. "Waveform design for wireless power transfer." IEEE Transactions on Signal Processing 64.23 (2016): 6313-6328.

Problem Formulation

$$\max_{\{\tilde{w}_{n,m}^{\text{in}}\}} \quad z_{\text{DC}}(\{\tilde{w}_{n,m}^{\text{in}}\})$$

$$\text{s.t.} \quad \frac{1}{2}\sum_{m=1}^{M}\sum_{n=0}^{N-1}\left|\tilde{w}_{n,m}^{\text{in}}\right|^2 \le P_{\text{in}}^{\max},$$

The input power budget

$$\frac{1}{2}\sum_{m=1}^{M}\sum_{n=0}^{N-1}\left|\tilde{w}_{n,m}^{\text{tr}}\left\{\tilde{w}_{n,m}^{\text{in}}\right\}\right|^2 \le P_{\text{in}}^{\text{tr}}.$$

For human safety

For tractability

$$\max_{\{\tilde{w}_{n,m}^{\text{tr}}\}} \quad z_{\text{DC}}(\{\tilde{w}_{n,m}^{\text{tr}}\})$$

A convex function with respect to $\{\tilde{w}_{n,m}^{\text{tr}}\}$

$$\text{s.t.} \quad \frac{1}{2T}\sum_{m=1}^{M}\left\{\frac{\left|\tilde{x}_m^{\text{in}}(t)\right|}{G}\left[1-\left(\frac{\tilde{x}_m^{\text{in}}(t)}{A_s}\right)^{2\beta}\right]^{-\frac{1}{2\beta}}\right\}^2 \le P_{\text{in}}^{\max},$$

Convex with respect to $\{\tilde{w}_{n,m}^{\text{tr}}\}$

$$\frac{1}{2}\sum_{m=1}^{M}\sum_{n=0}^{N-1}\left|\tilde{w}_{n,m}^{\text{tr}}\right|^2 \le P_{\text{tr}}^{\max}.$$

Convex with respect to $\{\tilde{w}_{n,m}^{\text{tr}}\}$

Optimization

$$\max_{\{\tilde{w}_{n,m}^{\mathrm{tr}}\}} \quad z_{\mathrm{DC}}(\{\tilde{w}_{n,m}^{\mathrm{tr}}\})$$

$$\text{s.t.} \quad \frac{1}{2T}\sum_{m=1}^{M}\left\{\frac{\left|\tilde{x}_m^{\mathrm{in}}(t)\right|}{G}\left[1-\left(\frac{\tilde{x}_m^{\mathrm{in}}(t)}{A_s}\right)^{2\beta}\right]^{-\frac{1}{2\beta}}\right\}^2 \le P_{\mathrm{in}}^{\max},$$

$$\frac{1}{2}\sum_{m=1}^{M}\sum_{n=0}^{N-1}\left|\tilde{w}_{n,m}^{\mathrm{tr}}\right|^2 \le P_{\mathrm{tr}}^{\max}.$$

Step 1: successive convex programming (SCP) for the objective function (Algorithm 1)

At the l-th iteration, the objective function is approximated as:

$$z_{\mathrm{DC}}^{(l)} = \sum_{m=1}^{m=M}\sum_{n=0}^{n=N-1} \bar{a}_{n,m}^{(l)}\bar{w}_{n,m}^{\mathrm{tr}} + \hat{a}_{n,m}^{(l)}\hat{w}_{n,m}^{\mathrm{tr}}$$

Step 2: interior-point (IP) method (Algorithm 2)

Algorithm 1: Successive convex programming (SCP)

Input: $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(0)}, \epsilon_0>0, l\leftarrow 1$;
Output: $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{\star}$;
Repeat:
1: Compute $(\{\overline{\alpha}\},\{\widehat{\alpha}\})^{(l)}$ at the operating point $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(l-1)}$ using Taylor expansion;
2: Compute $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(l)}$ using Algorithm 2;
3: Update $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{\star}\leftarrow(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(l)}$;
4: Quit if $|(\{\overline{\mathbf{w}}_n^{\mathrm{tr}}\},\{\widehat{\mathbf{w}}_n^{\mathrm{tr}}\})^{(l)}-(\{\overline{\mathbf{w}}_n^{\mathrm{tr}}\},\{\widehat{\mathbf{w}}_n^{\mathrm{tr}}\})^{(l-1)}|<\epsilon_0$;
5: $l\leftarrow l+1$;

Algorithm 2: Interior-point

Input: $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(B_0)}\leftarrow(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(l-1)}, t>0, \mu_B>0, \epsilon_B>0$;
Output: $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(l)}$;
Repeat:
1: Compute $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})$ by minimizing problem (16) using Newton's Method with initialised point $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(B_0)}$;
2: Update $(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(l)}\leftarrow(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})$;
3: Quit if $2/t<\epsilon_B$;
4: $t\leftarrow\mu_B t, (\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(B_0)}\leftarrow(\{\overline{w}_n^{\mathrm{tr}}\},\{\widehat{w}_n^{\mathrm{tr}}\})^{(l)}$;

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➢ Simulation results

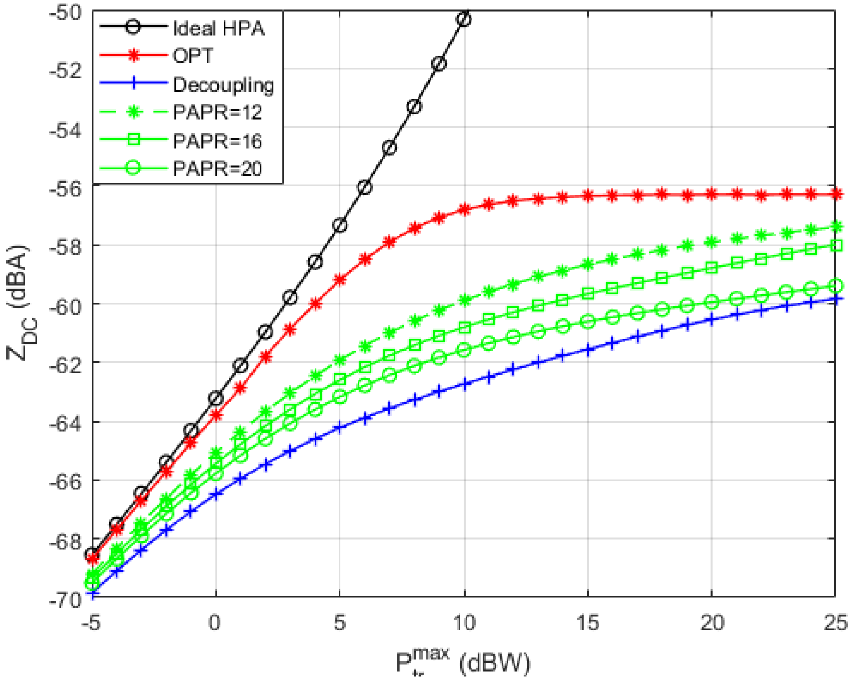

Fig.5 Power harvesting performance with G=1, As=10 dBV, P_{in}^{max} =25 dBW, N=8, M=1.

Setup: a Wi-Fi-like scenario with $f_0 = 5.18$ GHz.
HPA: $\beta = 1$, $G = 1$.
Rectenna: $i_s = 5\mu A$, $\eta = 1.05$, $v_0 = 25.86mV$, $R_{ant} = 50\Omega$
Path loss: 58 dBi; **Antenna gain**: 2 dBi.

- HPA's non-linearity degrades the power harvesting performance.
- HPA's saturation power limits the power harvesting performance.
- The proposed waveform (red) outperforms the waveform considering rectenna's non-linearity only (blue).

Name (color)	Definition
'Ideal HPA' (black)	Assume an ideal linear HPA (benchmark)
'OPT' (red)	The proposed waveform
'Decoupling' (blue)	Waveform in [3] only considering rectenna's non-linearity
'PAPR'（green)	Add PAPR constraints compared with 'Decoupling'

- Low-PAPR signals suffer less HPA's degradation.

[3] Clerckx, Bruno, and Ekaterina Bayguzina. "Waveform design for wireless power transfer." IEEE Transactions on Signal Processing 64.23 (2016): 6313-6328.

➢ Simulation results

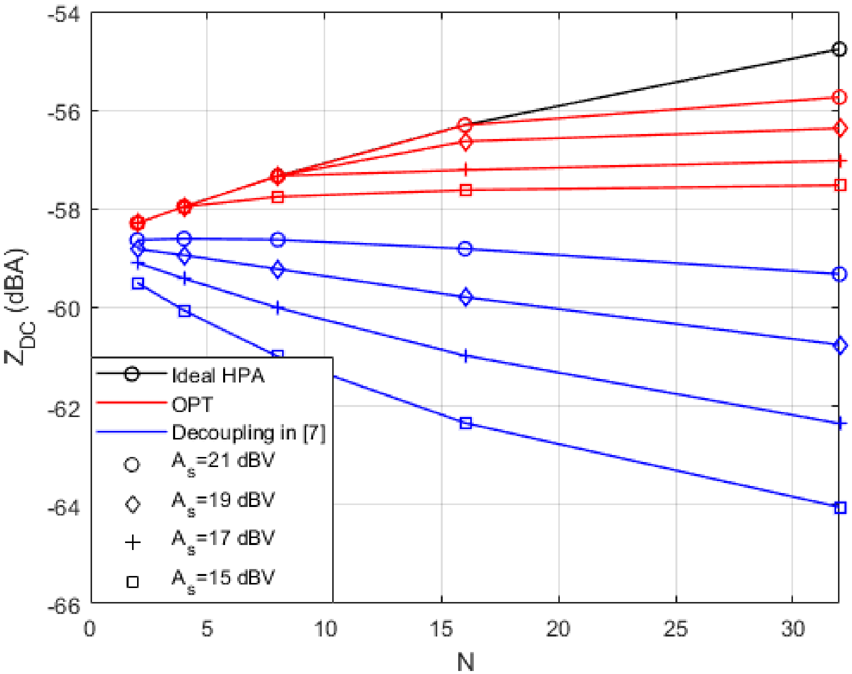

Fig.6 Power harvesting performance as a function of N with different A_s, G=1, P_{in}^{max}=25 dBW, P_{tr}^{max} = 25dBW, M=1.

- Larger HPA's saturation power, larger harvested power.
- For the saturation power large enough, the proposed waveform achieves the largest harvested power as with an ideal HPA.
- A larger N does not necessarily benefit the power harvesting performance.

↓

(Larger N gives larger PAPR)

- The harvested power saturates with increasing N.

↓

(In contrast with [3], where the harvested power is proportionally to N.)

[3] Clerckx, Bruno, and Ekaterina Bayguzina. "Waveform design for wireless power transfer." IEEE Transactions on Signal Processing 64.23 (2016): 6313-6328.

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Thank you