Waveform Design for WPT and SWIPT

Bruno Clerckx

Communication and Signal Processing Group
Department of Electrical and Electronic Engineering
Imperial College London

WPCNets 2016, IEEE WCNC 2016, 3-6 April 2016, Doha, Qatar
1. Waveform for Wireless Power Transfer and Energy Harvesting

2. Waveform/Transceiver for SWIPT
WPT: Rectifier

- Challenge? Increase the DC power level and range.
- Receiver: Rectifying circuit (a non-linear device + a low-pass filter and load)

Transmitter

- Transmitter: RF-to-DC conversion efficiency function of its input waveform!

![Diagram of transmitter and energy flow](image-url)
WPT: Waveform Design

- Some attempts in the RF literature:

**Observation**

A multisine signal excitation is shown through analysis, simulations and measurements to enhance the DC power and RF-DC conversion efficiency over a single sinewave signal.


**Observation**

Various input waveforms (OFDM, white noise, chaotic) are considered and experiments show that waveforms with high peak to average power ratio (PAPR) increase RF-to-DC conversion efficiency.
... but so many limitations:

- No formal tool
- Multipath fading ignored

- Channel State Information (CSI) unknown to the transmitter

- Transmitter commonly equipped with a single antenna
WPT: Waveform Design

- Problem tackled recently by leveraging communication/signal processing tools
- Multi-sine multi-antenna transmit signal (antenna \( m = 1, \ldots, M \) and sinewave \( n = 0, \ldots, N - 1 \))

\[
x_m(t) = \sum_{n=0}^{N-1} s_{n,m} \cos(w_n t + \phi_{n,m})
\]

- Received signal after multipath

\[
y(t) = \sum_{m=1}^{M} \sum_{n=0}^{N-1} s_{n,m} A_{n,m} \cos(w_n t + \psi_{n,m})
\]

- \( y(t) \) creates an input voltage \( v_{in}(t) \) to the rectifier

The rectifier is nonlinear (use Taylor expansion)!

\[
i_{out} \approx k_0 + \sum_{\text{ieven}, i \geq 2} k_i R_{ant}^{i/2} \mathbb{E}\{y(t)^i\}
\]
WPT: Waveform Design

- Goal: design amplitudes and phases so as to maximize the DC output power
- Assume the rectifier characteristics $k_i$ and the CSI (in the form of frequency response $h_{n,m}$) is known to the transmitter

\[
\max_{S, \Phi} i_{out}(S, \Phi) = k_0 + \sum_{i \text{even}, i \geq 2}^{n_o} k_i R_{ant}^{i/2} \mathcal{E}\{y(t)^i\}
\]

subject to \( \frac{1}{2} \|S\|_F^2 \leq P \).

- Design based on Linear Model:
  - Only accounts for second order term \( \mathcal{E}\{y(t)^2\} \).
  - Classical model used in the SWIPT literature.
  - Adaptive Single Sinewave (ASS) strategy: allocate all power to a single sinewave, the one corresponding to the strongest channel

- Design based on Nonlinear Model:
  - Accounts for any order in the rectifier Taylor expansion
  - Globally optimal phases obtained in closed-form.
  - Locally optimal amplitudes to result from a non-convex posynomial maximization problem. Formulate as a Reverse Geometric Program and solve iteratively.
  - Extendable to account for PAPR constraints and multi-user/rectenna WPT
Assume $N = 2$, $M = 1$, $n_o = 4$ and real frequency domain channel.

\[ z_{DC}(s_0, s_1) = k_2 R_{ant} / 2 \left( s_0^2 A_0^2 + s_1^2 A_1^2 \right) + 3k_4 R_{ant}^2 / 8 \left[ (s_0^2 A_0^2 + s_1^2 A_1^2)^2 + 2s_0^2 s_1^2 A_0^2 A_1^2 \right] \]

Transmit power constraint $s_0^2 + s_1^2 = 2P$.

Lagrangian optimization leads to 3 stationary points:

1. $\{(2P, 0)\}$: Allocate all power to the first sinewave if $A_0 \gg A_1$
2. $\{(0, 2P)\}$: Allocate all power to the second sinewave if $A_0 \ll A_1$
3. $\{(s_0^*, s_1^*)\}$: Allocate power to both sinewaves if $A_0 \approx A_1$

The first two points correspond to the ASS strategy $\rightarrow$ ASS is in general suboptimal.
Figure: Frequency response of the wireless channel over 1MHz and 10 MHz and WPT waveform magnitudes for $N = 16$ over 1MHz and 10 MHz. Average input power of -50dBm.
### WPT: Scaling Laws \((N \gg 1, M = 1, n_o = 4)\)

<table>
<thead>
<tr>
<th>Waveform</th>
<th>Frequency-Flat (FF)</th>
<th>Frequency-Selective (FS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No CSIT</td>
<td>(k_2 R_{\text{ant}} P + 2k_4 R_{\text{ant}}^2 P^2 N)</td>
<td>(k_2 R_{\text{ant}} P + 3k_4 R_{\text{ant}}^2 P^2)</td>
</tr>
<tr>
<td>(z_{\text{DC,UP}})</td>
<td>(k_2 R_{\text{ant}} P + 2k_4 R_{\text{ant}}^2 P^2 N)</td>
<td>(k_2 R_{\text{ant}} P + 3k_4 R_{\text{ant}}^2 P^2)</td>
</tr>
<tr>
<td>CSIT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(z_{\text{DC,ASS}})</td>
<td>(k_2 R_{\text{ant}} P + 3k_4 R_{\text{ant}}^2 P^2)</td>
<td>(k_2 R_{\text{ant}} P \log N + \frac{3}{2} k_4 R_{\text{ant}}^2 P^2 \log^2 N)</td>
</tr>
<tr>
<td>(z_{\text{DC,UPMF}})</td>
<td>(k_2 R_{\text{ant}} P + 2k_4 R_{\text{ant}}^2 P^2 N)</td>
<td>(k_2 R_{\text{ant}} P + k_4 R_{\text{ant}}^2 P^2 N)</td>
</tr>
</tbody>
</table>

#### Observation

1. Linear increase with \(N\) in FF and FS channels.
2. CSIT not needed in FF channels but needed in FS channels.
3. Linear model-based design (ASS) leads to significantly lower scaling laws than the non-linear model-based design for FF and FS channels.
   → increase in \(\log N\) vs \(N\).
WPT: Evaluations

- WiFi-like environment
  - 5.18GHz, 36dBm Tx power, 2dBi Rx antenna gain, 58dB path loss, office.
  - Average received power of about -20dBm.
  - The frequency gap is fixed as $\Delta_w = 2\pi \Delta f$ with $\Delta f = B/N$.
- Metric: $z_{DC} = k_2 R_{ant} E\{y(t)^2\} + k_4 R_{ant}^2 E\{y(t)^4\}$
- Waveform optimization on matlab/CVX (left) and PSpice (right) - $B=1MHz$

Observation

1. Good match between the analytical nonlinear model and the PSpice evaluations.
2. Nonlinear model-based design outperforms the linear model-based design.
3. Linear model does not characterize correctly the rectenna behavior.
WPT: Evaluations

- Waveform optimization on matlab/CVX (left) and PSpice (right) - $B=10\text{MHz}$

**Observation**

1. **Promising architecture:** large-scale multisine multiantenna waveforms.
2. **Sensors need** $10\ \mu\text{W} \ \text{DC}$ (see PsiKick’s Fully Integrated Wireless SoC sensors)
3. **Think big:** up to 2048 subcarriers in LTE! 100s antennas/Tx in 5G (Massive MIMO)!
WPT: Evaluations

- Large-scale multisine waveforms - $B=5$ MHz

---

**Average $z_{DC}$ [μ A]**

- Non-adaptive UP
- Adaptive SS
- Adaptive UPMF
- Adaptive MF

**Number of sinewaves $N$**

- 24
- 32
- 64
- 128
Harvested energy versus transmit PAPR for $N = 16$ and $M = 1$.
• Time-domain evolution of the input voltage $v_s(t)$ and output voltage $v_{out}(t)$ ($N = 16$, $B = 10$ MHz).
SWIPT: Transceiver Architecture

- Energy flow and Information flow

![Diagram of SWIPT transceiver architecture](image)


- A novel transceiver architecture for SWIPT

- Energy is harvested from the information and the power waveform
- SWIPT waveform design?
- Account for non-linearity and leverage our previous WPT waveform design!
- Deterministic (power) plus randomized (information) waveform
**SWIPT: Waveform Design**

- Joint Information and Power Transfer Waveform Design: $S_P, S_I, \Phi_P, \Phi_I, \rho$
- Achievable rate-harvested energy (or more accurately rate-DC current) region as

  \[
  C_{R-I_{DC}}(P) \triangleq \left\{ (R, I_{DC}) : R \leq I(S_I, \Phi_I, \rho), \right. \\
  I_{DC} \leq i_{out}(S_P, S_I, \Phi_P, \Phi_I, \rho), \frac{1}{2} \left[ \|S_I\|_F^2 + \|S_P\|_F^2 \right] \leq P \left. \right\}.
  \]

  Optimal values $S_P^*, S_I^*, \Phi_P^*, \Phi_I^*, \rho^*$ are to be found in order to enlarge as much as possible the rate-harvested energy region.

- Energy maximization problem subject to the transmit power constraint and the rate being larger than a certain threshold $\bar{R}$

  \[
  \max_{S_P, S_I, \Phi_P, \Phi_I, \rho} \quad i_{out}(S_P, S_I, \Phi_P, \Phi_I, \rho) \\
  \text{subject to} \quad \frac{1}{2} \left[ \|S_I\|_F^2 + \|S_P\|_F^2 \right] \leq P, \\
  I(S_I, \Phi_I, \rho) \geq \bar{R}.
  \]

- Globally optimal phases obtained in closed-form. Locally optimal amplitudes to result from a non-convex posynomial maximization problem can be formulated as a Reverse Geometric Programming and solved iteratively.
SWIPT: Evaluations

- Average received power of about -20dBm. 20dB SNR. Frequency flat channel.

Figure: $C_R - I_{DC}$ as a function of $N$ for $M = 1$. 
SWIPT: Evaluations

- Average received power of about -20dBm. 20dB SNR. Frequency flat channel.

![Graph showing water-filling solution and WPT with and without WIT waveforms](image)

**Figure**: $C_{R-I_{DC}} N = 16$ and $M = 1$. 
Conclusions

• Derive a methodology to design and optimize multisine waveforms for multi-antenna WPT and SWIPT.

• Contrary to existing designs, the waveforms are adaptive to the CSI (assumed available to the transmitter), therefore making them more suitable to “exploit” the non-linearity of the rectifier.

• Provide significant gains (in terms of harvested DC power) over state-of-the-art waveforms under a fixed transmit power constraint.

• Non-linearity is a fundamental property of the rectifier and cannot be ignored.
  – The wireless power channel is non-linear.
  – This contrasts with the wireless communication channel ... commonly assumed linear.

• Importance of accounting for the non-linearity of the rectifier in any design involving wireless power: WPT, SWIPT, WPCN, backscattering communication.

• Need for bridging RF and comms/signal processing
Future Works/Open Problems

- The nonlinear wireless power channel plus the linear wireless communication channel

**Figure:** Point-to-point

**Figure:** Broadcast Channel

**Figure:** Interference Channel

**Figure:** Relay Channel

(a) Energy-flow-assisted two-phase relaying

(b) Two-phase relaying without energy flow
Future Works/Open Problems

- Thinking wireless power in light of the state-of-the-art signal processing and communication theoretic tools.

- Derive a novel mathematical framework of energy transmission over the non-linear wireless power channel.

- Establish a wireless power link and system level design and optimization.

- Better understand the wireless power channel before jumping into SWIPT/WPCN/backscattering/...
This work has been partially supported by the EPSRC of the UK under grant EP/M008193/1.


More to come