Boosting the Efficiency of WPT and SWIPT through Waveform Design and Optimization

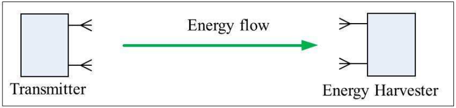
Bruno Clerckx

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

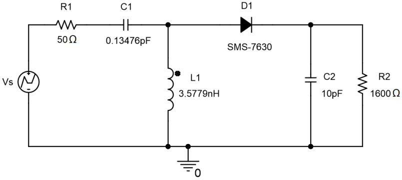
2016 Tyrrhenian International Workshop on Digital Communications,
Livorno, Italy

Content

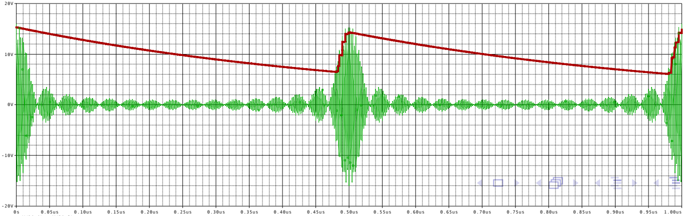
WPT: Rectifier



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



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



WPT: Waveform Design

- Some attempts in the RF literature:

M.S. Trotter, J.D. Griffin and G.D. Durgin, *Power-Optimized Waveforms for Improving the Range and Relibaility of RFID Systems*, 2009 IEEE International Conference on RFID.
A. S. Boaventura and N. B. Carvalho, *Maximizing DC Power in Energy Harvesting Circuits Using Multisine Excitation*, 2011 IEEE MTT-S International Microwave Symposium Digest (MTT).

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.

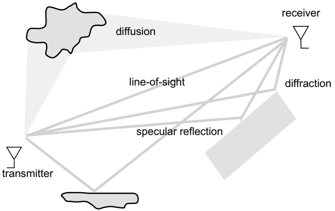
A. Collado and A. Georgiadis, *Optimal Waveforms for Efficient Wireless Power Transmission*, IEEE Microwave and Wireless Components Letters, vol. 24, no.5, May 2014.

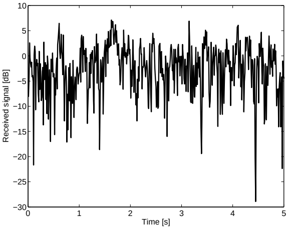
Observation

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.

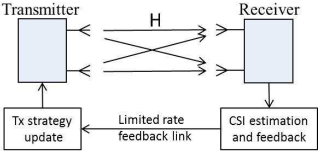
WPT: Waveform Design

- ... but so many limitations:
  - No formal tool
  - Multipath fading ignored





  - Channel State Information (CSI) unknown to the transmitter



Tx strategy update

Limited rate feedback link

CSI estimation and feedback

  - 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 $m = 1, ..., M$ and sinewave $n = 0, ..., N-1$)

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

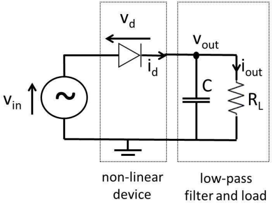
- Received signal after multipath

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

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

  The rectifier is nonlinear (use Taylor expansion)!

$$i_{out} \approx \underbrace{k_0 + \sum_{i even, i \geq 2}^{n_o} k_i R_{ant}^{i/2} \mathcal{E}\{y(t)^i\}}_{z_{DC}}$$



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

$$\max_{\mathbf{S},\mathbf{\Phi}} \quad i_{out}(\mathbf{S},\mathbf{\Phi}) = k_0 + k_2 R_{ant}\mathcal{E}\left\{y(t)^2\right\} + k_4 R_{ant}^2\mathcal{E}\left\{y(t)^4\right\} + \dots$$

$$\text{subject to} \quad \frac{1}{2}\left\|\mathbf{S}\right\|_F^2 \leq P.$$

- Design based on Linear Model:
  - Only accounts for second order term $\mathcal{E}\left\{y(t)^2\right\}$.
  - 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

WPT: Waveform Illustration

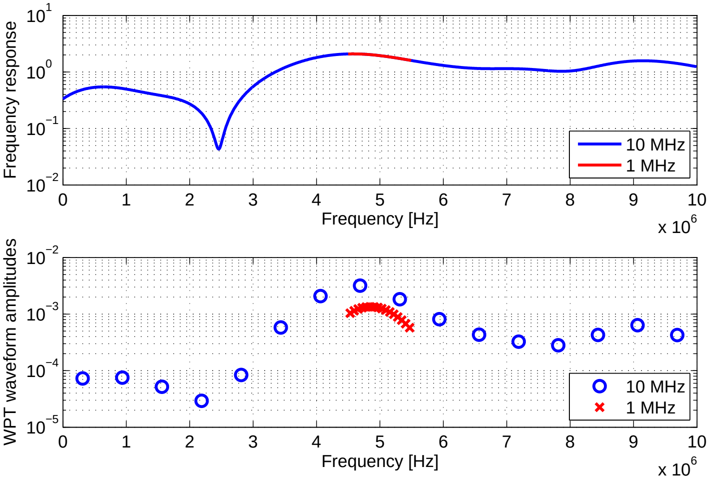


Figure: Frequency response of the wireless channel over 1MHz and 10 MHz and WPT waveform magnitudes for $N = 16$ over 1MHz and 10 MHz. Average input power of -50dBm.

WPT: Scaling Laws $(N >> 1, M = 1, n_o = 4)$

Waveform	**Frequency-Flat (FF)**	**Frequency-Selective (FS)**
No CSIT		
$z_{DC,UP}$	$k_2 R_{ant} P + 2k_4 R_{ant}^2 P^2 N$	$k_2 R_{ant} P + 3k_4 R_{ant}^2 P^2$
CSIT		
$z_{DC,ASS}$	$k_2 R_{ant} P + 3k_4 R_{ant}^2 P^2$	$k_2 R_{ant} P \log N + \frac{3}{2} k_4 R_{ant}^2 P^2 \log^2 N$
$z_{DC,UPMF}$	$k_2 R_{ant} P + 2k_4 R_{ant}^2 P^2 N$	$k_2 R_{ant} P + k_4 R_{ant}^2 P^2 N$

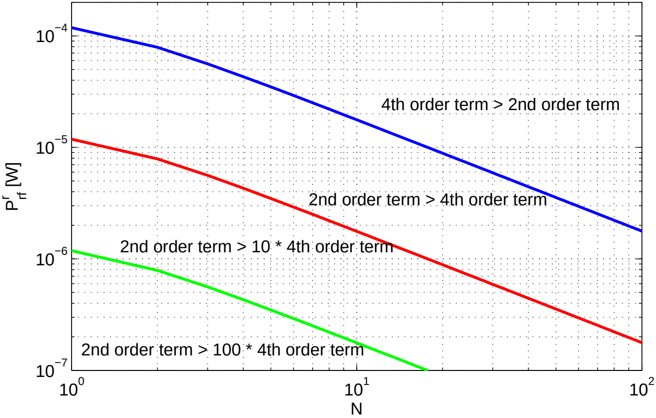
Observation

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: Linear vs Non-linear Regime

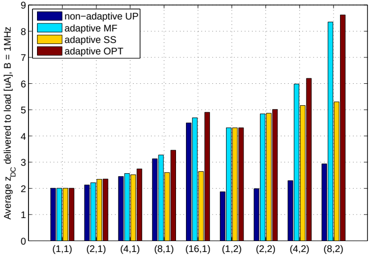
- The 2nd order term is G times larger than the 4th order term if

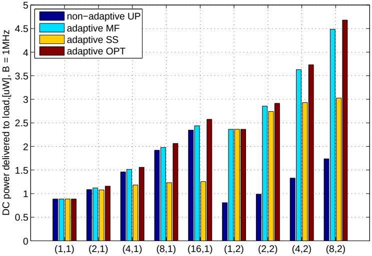
$$P_{in,av} \leq \frac{k_2}{k_4} \frac{1}{R_{ant}} \frac{1}{N} \frac{1}{G}.$$



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: $z_{DC} = k_2 R_{ant}\mathcal{E}\left\{y(t)^2\right\} + k_4 R_{ant}^2\mathcal{E}\left\{y(t)^4\right\}$
- Waveform optimization on matlab/CVX (left) and PSpice (right) - **B=1MHz**



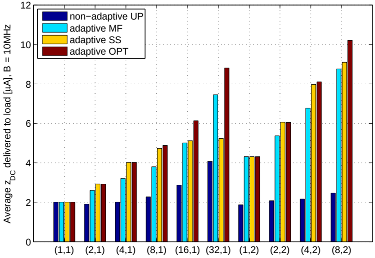


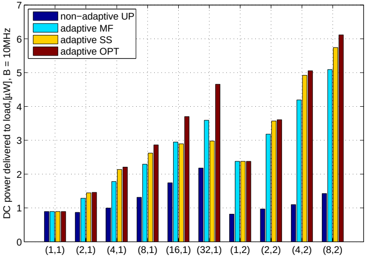
Observation

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=10MHz**





Observation

1. *Promising architecture: large-scale multisine multiantenna waveforms.*
2. *Sensors need 10 μW 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: Modulated Waveforms?

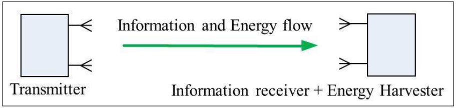
Waveform	**Frequency-Flat (FF)**	**Frequency-Selective (FS)**
OFDM		
z_{DC}	$k_2 R_{ant} P + 6 k_4 R_{ant}^2 P^2$	$k_2 R_{ant} P \log N + 3 k_4 R_{ant}^2 P^2 \log^2 N$
Multisine		
z_{DC}	$k_2 R_{ant} P + 2 k_4 R_{ant}^2 P^2 N$	$k_2 R_{ant} P + k_4 R_{ant}^2 P^2 N$

Observation

1. *From 2nd order term: OFDM and multisine waveforms are equally suitable.*
2. *From 4th order term: multisine much better than OFDM.*
3. *Loss in scaling law is inherently due to the randomness of information symbols.*

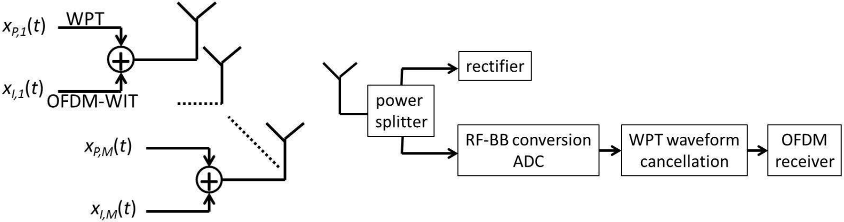
SWIPT: Transceiver Architecture

- Energy flow and Information flow



R. Zhang and C. K. Ho, IEEE TWC, May 2013.

- 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: $\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho$
- Achievable rate-harvested energy (or more accurately rate-DC current) region as

$$C_{R-I_{DC}}(P) \triangleq \Big\{(R, I_{DC}) : R \leq I(\mathbf{S}_I, \mathbf{\Phi}_I, \rho),$$

$$I_{DC} \leq i_{out}(\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho), \frac{1}{2}\left[\, \|\mathbf{S}_I\|_F^2 + \|\mathbf{S}_P\|_F^2 \,\right] \leq P\Big\}.$$

  Optimal values $\mathbf{S}_P^\star$,$\mathbf{S}_I^\star$,$\mathbf{\Phi}_P^\star$,$\mathbf{\Phi}_I^\star, \rho^\star$ 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 $\bar{R}$

$$\max_{\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho} \quad i_{out}(\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho)$$

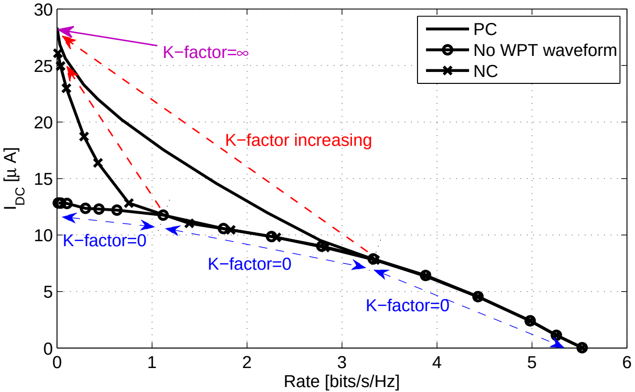
$$\text{subject to} \quad \frac{1}{2}\left[\, \|\mathbf{S}_I\|_F^2 + \|\mathbf{S}_P\|_F^2 \,\right] \leq P,$$

$$I(\mathbf{S}_I, \mathbf{\Phi}_I, \rho) \geq \bar{R}.$$

- 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. $B = 1\text{MHz}$. $N = 16$, $M = 1$.



Observation

A non-zero mean Gaussian input distribution outperforms the conventional capacity-achieving zero-mean Gaussian input distribution!

Conclusions

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

References

Fundamentals

B. Clerckx, E. Bayguzina, D. Yates, and P.D. Mitcheson, "Waveform Optimization for Wireless Power Transfer with Nonlinear Energy Harvester Modeling," IEEE ISWCS 2015, August 2015, Brussels.

- B. Clerckx and E. Bayguzina, "Waveform Design for Wireless Power Transfer," IEEE Trans on Sig Proc, in press.

Low-complexity design

- B. Clerckx and E. Bayguzina, "A Low-Complexity Multisine Waveform Design for Wireless Power Transfer," submitted for publication.

Large scale design

- Y. Huang and B. Clerckx, "Waveform Optimization for Large-Scale Multi-Antenna Multi-Sine Wireless Power Transfer," IEEE SPAWC 2016, arXiv:1605.01191.
- Y. Huang and B. Clerckx, "Large-Scale Multi-Antenna Multi-Sine Wireless Power Transfer," arXiv:1609.02440.

SWIPT

- B. Clerckx, "Waveform Optimization for SWIPT with Nonlinear Energy Harvester Modeling," ITG 20th International ITG Workshop on Smart Antennas (WSA 2016), arXiv:1602.01061.
- B. Clerckx, "Waveform and Transceiver Design for Simultaneous Wireless Information and Power Transfer," arXiv:1607.05602.