Signal Theory and Design for Wireless Transmission of Information and Power

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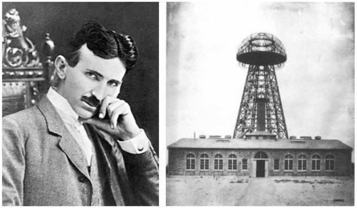
Wireless is More than just Communications

Radio waves carry both energy and information

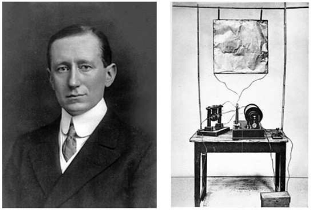
Wireless Power Transmission (WPT)



Tesla 1901

0G

Wireless Information Transmission (WIT)

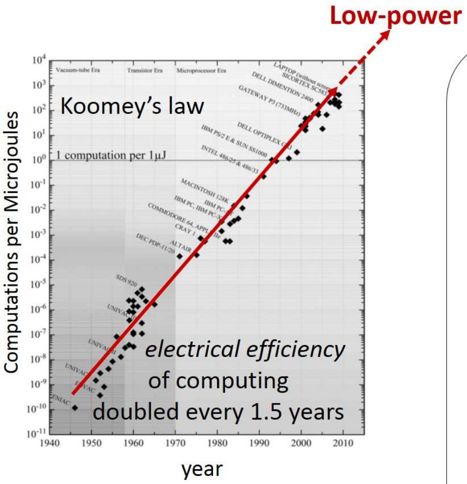


Marconi 1896

5G

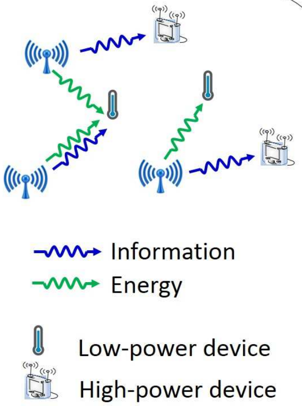
Unified Wireless Information and Power Transmission (WIPT)

In 20 Years from Now ... **Trillions** of **Low-Power** Devices



2017: 5 Billions phones

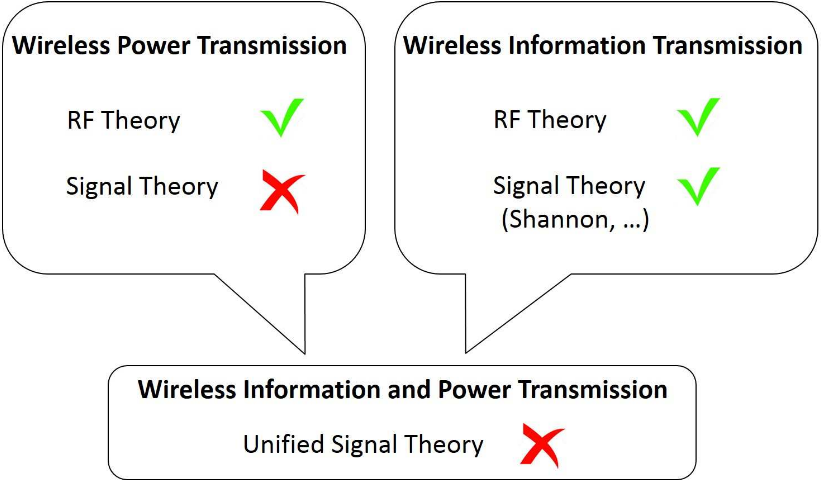
2035: **Trillions** IoT devices



Future of Wireless:

Communicate and Energize

A **Missing** Signal Theory of Wireless Transmission

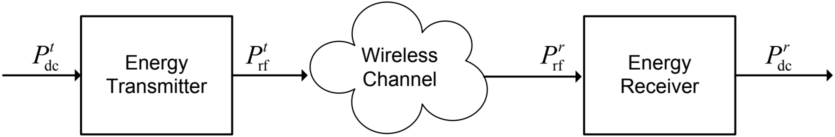


Content

1. Signal Design for Wireless Power Transmission

2. Signal Design for Wireless Information and Power Transmission

A generic architecture

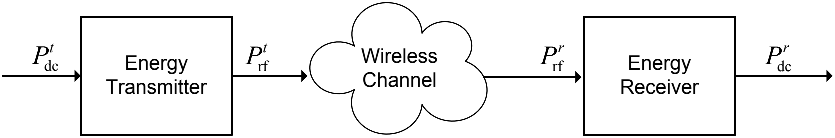


End-to-End Power Transfer Efficiency

$$e = \frac{P^r_{\rm dc}}{P^t_{\rm dc}} = \underbrace{\frac{P^t_{\rm rf}}{P^t_{\rm dc}}}_{e_1} \underbrace{\frac{P^r_{\rm rf}}{P^t_{\rm rf}}}_{e_2} \underbrace{\frac{P^r_{\rm dc}}{P^r_{\rm rf}}}_{e_3}$$

- WEH: no control of e_1 and e_2.
- WPT: more control of the design and room for enhancement of e

WPT Architecture



Careful! Maximizing e not achieved by maximizing e_1, e_2, e_3 independently from each other

- e_1, e_2, e_3 coupled due to **nonlinearity**, especially at $1\mu W$-$1mW$
- e_3(input signal shape and power) $\rightarrow$ e_3(Tx signal, wireless channel state)
- e_2(Tx signal, wireless channel state)
- e_1(Tx signal PAPR)

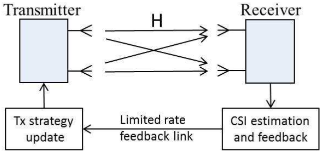
To tackle the listed challenges, we need...

Systematic signal design for WPT to maximize e

Link and system design for WPT: from a rectenna paradigm to a network paradigm

- Multiple transmitters/receivers, coordination among energy transmitters

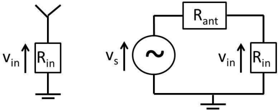
Closed-loop and adaptive WPT

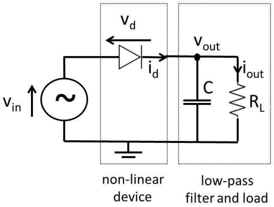


- to support channel feedback/training, energy feedback, charging control
- to flexibly adjust the Tx strategy across space and frequency

Then only, leverage WPT design for SWIPT design (bottom-up approach)

But first, we need a Rectenna Model





Challenge: Relate input signal $y(t)$ to output DC current i_{out}

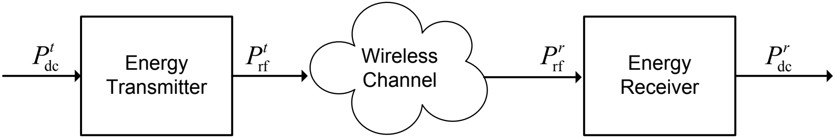
$$y(t) \rightarrow v_s(t) \rightarrow v_{in}(t) \rightarrow i_d(t) \rightarrow i_{out}$$

Needs to be as tractable and accurate as possible

Output DC Current: time average of the diode current $i_d(t)$

$$i_{out} = \mathcal{E}\left\{i_d(t)\right\} \quad \text{proportional to} \quad z_{DC} \approx \sum_{i \, even, i \geq 2}^{n_o} k_i R_{ant}^{i/2} \mathcal{E}\left\{y(t)^i\right\}$$

Linear vs Nonlinear Model



Linear Model: Truncate to order 2

$$z_{DC} = k_2 R_{ant} \underbrace{\mathcal{E}\left\{y(t)^2\right\}}_{P_{\mathrm{rf}}^r}$$

- $\max z_{DC} = \max e_2$ with constant e_3
- Tx strategy that maximizes P_{rf}^r is the same strategy that maximizes P_{dc}^r

Nonlinear Model: Truncate to a higher-order term, e.g. order 4 ($n_o = 4$)

$$z_{DC} = k_2 R_{ant} \underbrace{\mathcal{E}\left\{y(t)^2\right\}}_{P_{\mathrm{rf}}^r} + k_4 R_{ant}^2 \mathcal{E}\left\{y(t)^4\right\}$$

- $\max z_{DC} = \max e_2 e_3 \neq \max e_2$

Waveform Design for WPT

Multi-sine multi-antenna transmit signal (antenna $m = 1, ..., M$ and sinewave $n = 0, ..., N-1$)

$$x_m(t) = \sum_{n=0}^{N-1} s_{n,m} \cos(2\pi f_n t + \phi_{n,m})$$

Received signal after multipath

$$y(t) = \sum_{m=1}^{M} \sum_{n=0}^{N-1} s_{n,m} A_{n,m} \cos(2\pi f_n t + \underbrace{\phi_{n,m} + \bar{\psi}_{n,m}}_{\psi_{n,m}})$$

Frequency response of the channel of antenna m at w_n

$$h_{n,m} = A_{n,m} e^{j\bar{\psi}_{n,m}}$$

Goal: design $\{s_{n,m}, \phi_{n,m}\}_{\forall n,m}$ so as to maximize the DC output power subject to average transmit power constraint

Systematic Waveform Design

Design amplitudes and phases to maximize the DC output power subject to Tx power constraint using the linear and nonlinear models

Assume **Channel State Information CSI** (in the form of frequency response $h_{n,m}$) **known to the Tx**

Problem: Maximize the quantity z_{DC}

$$\max_{\mathbf{S},\mathbf{\Phi}} \quad z_{DC}(\mathbf{S},\mathbf{\Phi}) = \underbrace{k_2 R_{ant} \mathcal{E}\left\{y(t)^2\right\}}_{\text{Linear term}} + \underbrace{k_4 R_{ant}^2 \mathcal{E}\left\{y(t)^4\right\} + \ldots}_{\text{Nonlinear terms}}$$

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

Systematic design? Yes, for any M, N, n_o.

A Toy Example

Assume $N = 2$, $M = 1$ and real frequency domain channel

$$z_{DC}(s_0, s_1) = \underbrace{k_2 R_{ant}/2 \left(s_0^2 A_0^2 + s_1^2 A_1^2\right)}_{\text{Linear term}} + \underbrace{3k_4 R_{ant}^2/8 \left[\left(s_0^2 A_0^2 + s_1^2 A_1^2\right)^2 + 2 s_0^2 s_1^2 A_0^2 A_1^2\right]}_{\text{Nonlinear term}}$$

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

Lagrangian optimization leads to **3 stationary points**:

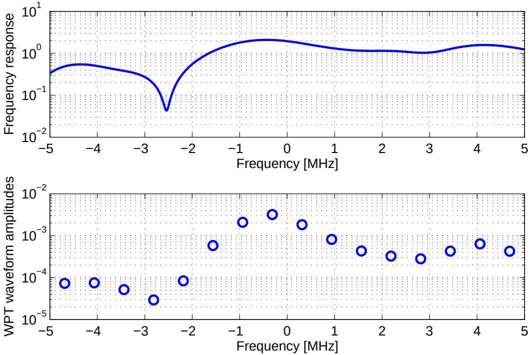
1. $(2P, 0)$: Allocate all power to the first sinewave if $A_0 >> A_1$
2. $(0, 2P)$: Allocate all power to the second sinewave if $A_0 << A_1$
3. $({s_0^\star}^2, {s_1^\star}^2)$: Allocate power to both sinewaves if $A_0 \approx A_1$

The first two points in general suboptimal with the nonlinear model

Benefits of allocating power over multiple sinewaves for some channel states

Nonlinear model-based design backs up the experimental results

Waveform Illustration



Observation

1. *Allocate power over multiple sinewaves with more power to frequencies exhibiting larger channel gains*
2. *Optimally exploits **frequency-diversity gain**, spatial **beamforming gain** and **rectifier nonlinearity***

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

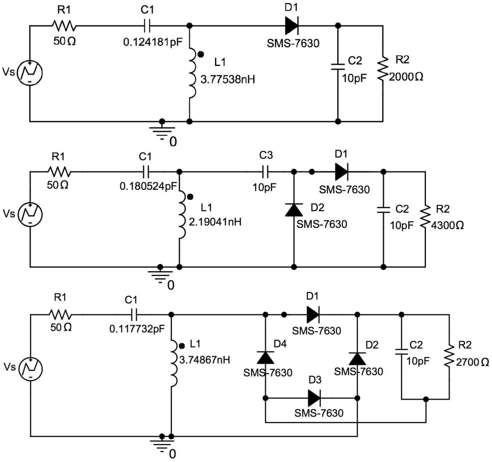
Waveform	Frequency-Flat (FF)	Frequency-Selective (FS)
No CSIT		
z_{DC} NL design	$k_2 R_{ant} P + 2k_4 R_{ant}^2 P^2 N$	$k_2 R_{ant} P + 3k_4 R_{ant}^2 P^2$
CSIT		
z_{DC} L design	$k_2 R_{ant} P + 3k_4 R_{ant}^2 P^2$	$k_2 R_{ant} P \log N + \frac{3}{2} k_4 R_{ant}^2 P^2 \log^2 N$
z_{DC} NL design	$k_2 R_{ant} P + 2k_4 R_{ant}^2 P^2 N$	$k_2 R_{ant} P + k_4 R_{ant}^2 P^2 N$

Observation

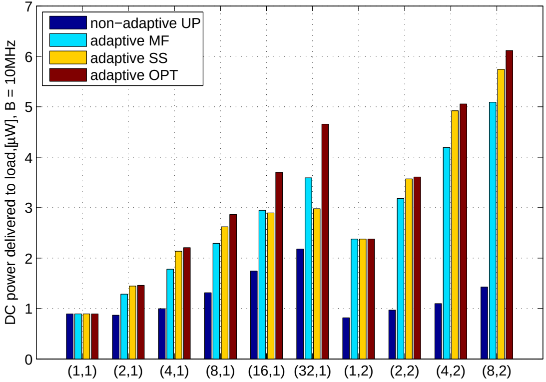
1. *Linear increase with N in FF and FS channels.*
2. *CSIT not needed in FF channels but needed in FS channels.*
3. *linear model-based design leads to significantly lower scaling laws than the non-linear model-based design for FF and FS channels.*
   $\rightarrow$ *increase in* $\log N$ *vs* N.

Circuit Evaluations

Single series, voltage doubler and diode bridge rectifiers



Circuit Evaluations



Observation

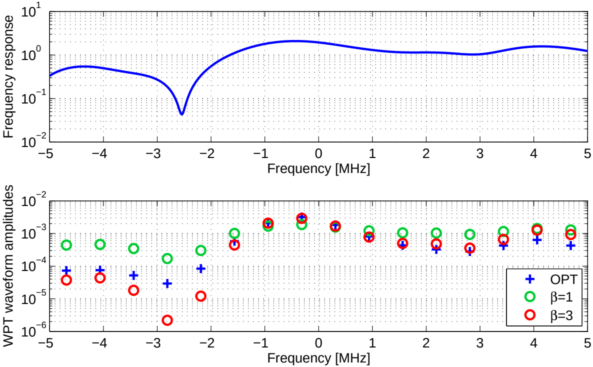
1. *Nonlinearity beneficial and exploitable.*
2. *Systematic designs exploits BF gain + channel FS + rectifier nonlinearity.*

Low-Complexity Waveform Design

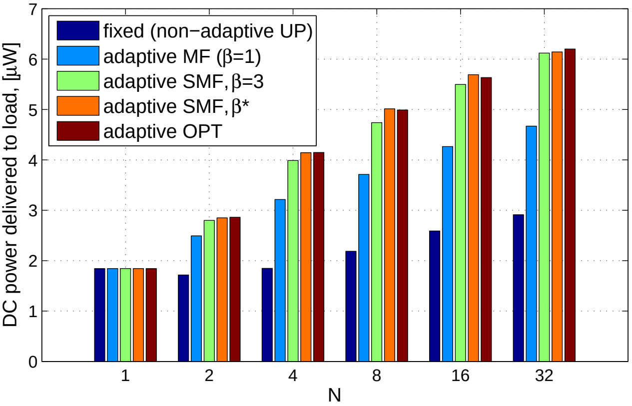
So far, not implementation friendly, difficult to tackle large-scale system

Low-Complexity Adaptive Multisine Waveform

- Idea: allocate more power to frequencies exhibiting larger channel gains
- Scaled Matched Filter (SMF): $s_n = cA_n^\beta$ with c a constant
- A_n^β: amplify strong frequency components and attenuate weak ones



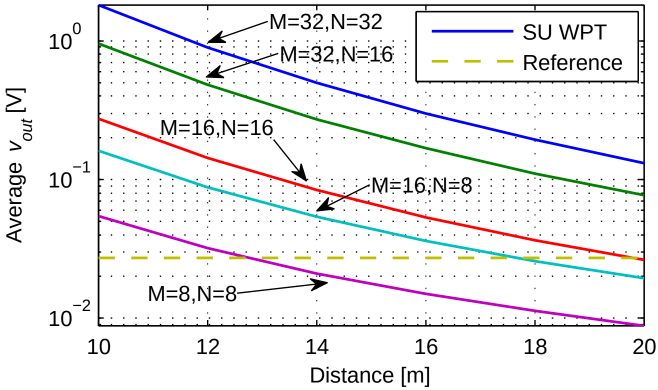
Circuit Evaluations



Observation

1. *SMF very close to OPT despite much lower design complexity*
2. *Waveform design holds for single and multiple-diode rectennas*

Large-Scale WPT Architecture



Observation

1. *Significant benefits of the architecture to* ***boost the end to end power transfer efficiency*** *and the* ***transmission range***

Modulation Design for WPT

Energy modulation in single-carrier/sinewave transmission to **boost** e_3?

Induce fluctuations of the transmit signal

Recall $z_{DC} = k_2 R_{ant} \mathcal{E}\{y(t)^2\} + k_4 R_{ant}^2 \mathcal{E}\{y(t)^4\}$

Design modulation/**input distribution** with **large fourth order moment**!

Flash signaling distribution with following probability mass function (with $l \geq 1$)

$$p_r(r) = \begin{cases} 1 - \frac{1}{l^2}, & r = 0, \\ \frac{1}{l^2}, & r = l\sqrt{P}. \end{cases}$$

Low probability of high amplitude signals

- Average power constant $\mathcal{E}\left\{r^2\right\} = P$
- ... but $\mathbb{E}\left[r^4\right] = l^2 P^2$, i.e. the larger l, the larger the fourth order moment.

Scaling Laws

Modulation	z_{DC}
Continuous wave (CW)	$k_2 R_{ant} P + 3k_4 R_{ant}^2 P^2$
Complex Gaussian (CG)	$k_2 R_{ant} P + 6k_4 R_{ant}^2 P^2$
Real Gaussian (RG)	$k_2 R_{ant} P + 9k_4 R_{ant}^2 P^2$
Flash signaling l	$k_2 R_{ant} P + 3l^2 k_4 R_{ant}^2 P^2$

Observation

1. *From 2nd order term: Modulated/Unmodulated carriers equally suitable.*
2. *From 4th order term: **Modulated better than Unmodulated**.*
3. *Gain of modulation comes from large fourth order moment.*

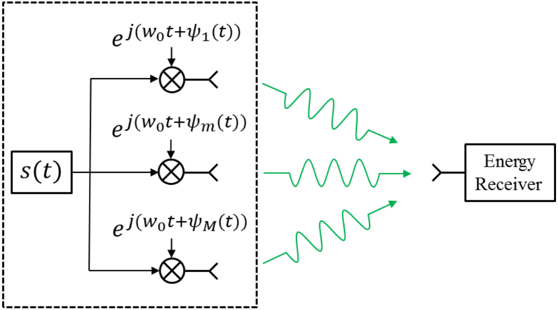
Circuit Evaluations

Transmission type	Delivered DC Power (μW)
Continuous wave (CW)	1.0959
Complex Gaussian (CG)	1.5296
Real Gaussian (RG)	1.7547
Flash signaling $l = 2$	2.6899
Flash signaling $l = 3$	3.4262
Flash signaling $l = 4$	3.4884
Flash signaling $l = 5$	3.2965

Energy modulation gives a 250% gain over CW

Rectenna **nonlinearity favors distributions with a large fourth moment**!

Transmit Diversity for WPT



Energy transmitter with transmit diversity

Multiple **dumb antennas** to **induce fast fluctuations of the wireless channel**

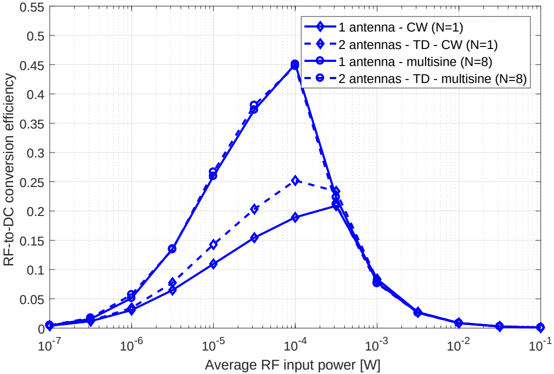
Fluctuations **boost** e_3 thanks to EH nonlinearity

Multiple antenna but **no CSIT** (in contrast to beamforming)

Multiple transmit antennas be useful to WPT in the absence of CSIT!

Circuit Evaluations

Increase in RF-to-DC conversion efficiency



35% **gain with two antennas over one antenna**

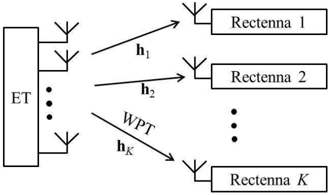
Very **low** implementation **complexity**

Well suited for **massive IoT** for which CSIT acquisition is unpractical

Multi-User WPT Signal Design

Multi-User WPT: WPT to K single-antenna users/rectennas

- Rectennas belong to a single user (i.e. point-to-point MIMO WPT)
- Rectennas spread across multiple users



Trade-off: $z_{DC,q}$ in general depends on $z_{DC,p}$, $p \neq q$

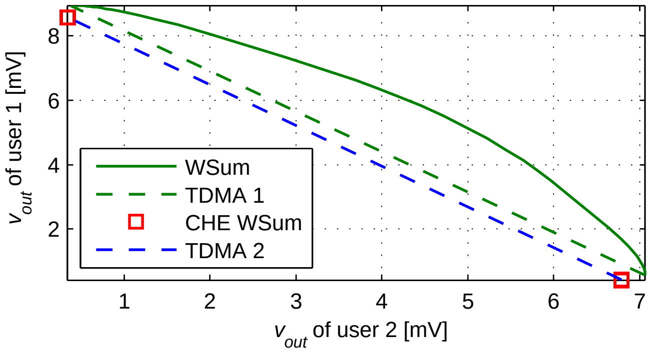
Energy Region $\mathcal{Z}_{DC}$: set of all rectenna harvested energy $(z_{DC,1}, \ldots, z_{DC,K})$ that are simultaneously achievable

Boundary of $\mathcal{Z}_{DC}$: **weighted sum** of $z_{DC,k}$ with weights v_k, $k = 1, \ldots, K$

$$\max_{\mathbf{S},\mathbf{\Phi}} Z_{DC}(\mathbf{S}, \mathbf{\Phi}) = \sum_{k=1}^{K} v_k z_{DC,k}(\mathbf{S}, \mathbf{\Phi}) \;\; \text{s.t.} \;\; \frac{1}{2} \|\mathbf{S}\|_F^2 \leq P$$

Energy region

Energy region: Achievable v_{out} region, with $M = 20$ and $N = 10$



Observation

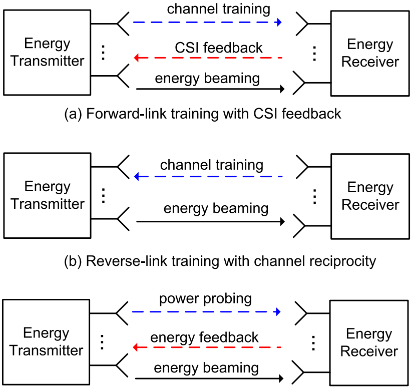
1. *Achievable energy region with WSum larger than that of TDMA*

Channel Acquisition for WPT

Waveform/beamforming requires **Channel State Information** (CSI) at Tx

Unique considerations

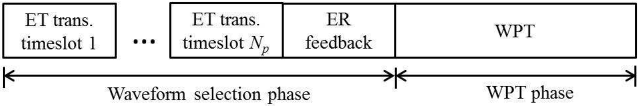
- **CSI at (energy) receiver**: not required for WPT
- **Net energy maximization**: to balance the energy overhead for CSI acquisition and the energy harvested with CSI-based signal design
- **Hardware constraint**: no/low signal processing capability for low-cost ERs



(a) Forward-link training with CSI feedback
(b) Reverse-link training with channel reciprocity
(c) Power probing with energy feedback

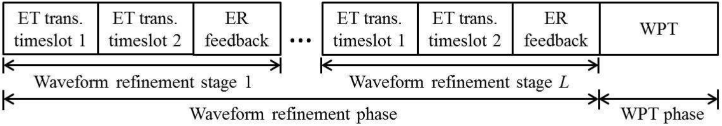
Waveform for WPT with Limited Feedback

Waveform Selection-based WPT



- Waveform precoders: a predesigned N_p-codeword codebook

Waveform Refinement-based WPT



- Waveform precoders: a predesigned tree-structured codebook

Waveform codebook design reminiscent of Lloyd Algorithm.

Challenge: finding the centroid subject to nonlinearity.

Prototyping and Experimentation of Closed-Loop WPT

Demonstrate the first prototype of a closed-loop WPT system with adaptive waveform optimization based on CSI acquisition

Establish an **experimental environment for closed-loop WPT** with waveform optimization

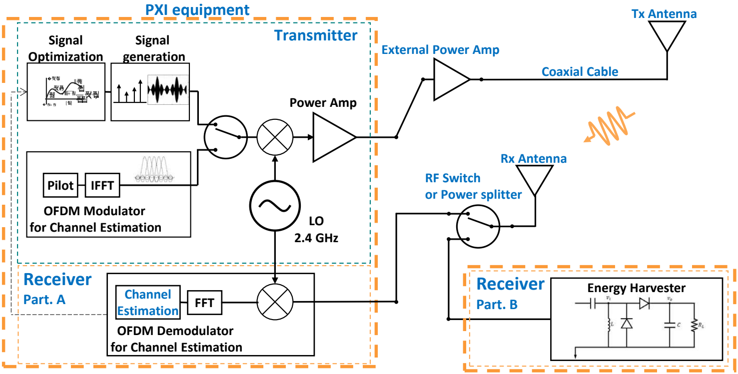
- Design optimized multi-sine RF Tx
- Implement CSI acquisition/channel estimator
- Design efficient rectenna

Verify advantages of systematic signal designs for WPT

- waveform, beamforming, modulation, transmit diversity

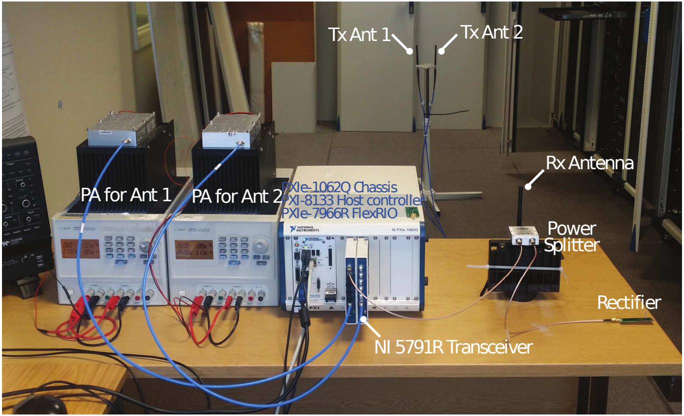
Measurements confirm theory: gains very promising

Prototype Architecture

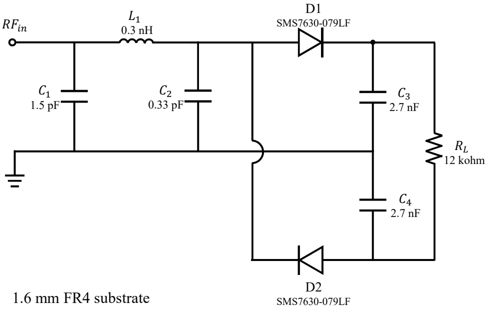


- The system operates in 2.4 GHz ISM band
- Software Defined Radio (SDR) used for transmitter and channel estimator. NI FlexRIO (PXI-7966R) and transceiver module (NI 5791R)
- Channel estimation and waveform design implemented in LabVIEW

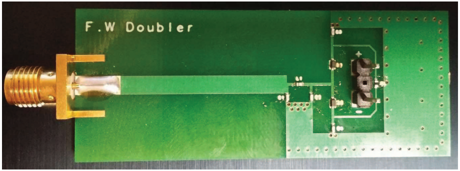
Actual Prototype



Rectifier

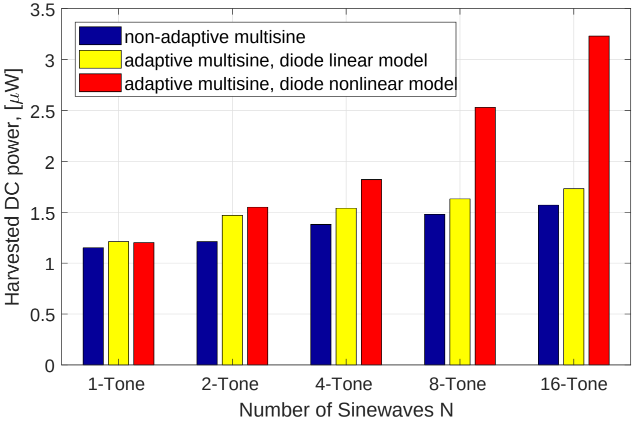


1.6 mm FR4 substrate



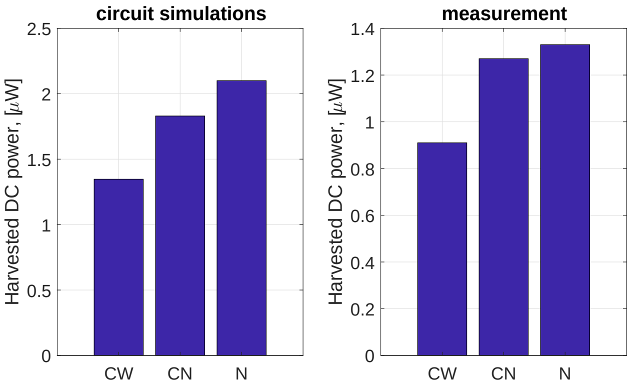
Measurement Results: Waveform

Received DC power as a function of N with 10 MHz bandwidth in NLoS



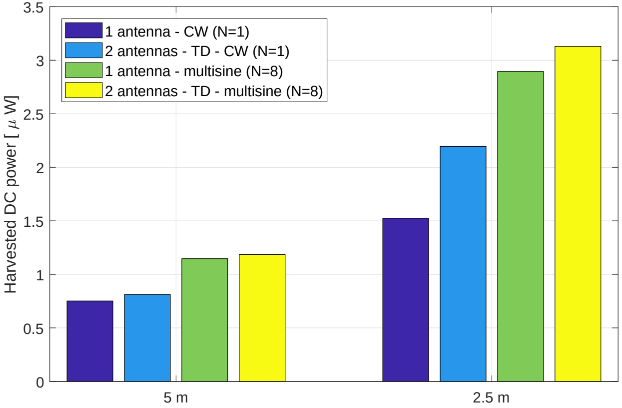
Measurement Results: Modulation

Received DC power as a function of modulation (CW refers to continuous wave, CN to CSCG input, and N to real Gaussian input).

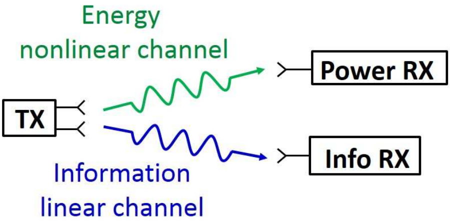


Measurement Results: Transmit Diversity

Received DC power with a continuous wave (CW), transmit diversity ($M = 2$) with continuous wave, multisine ($N = 8$) and transmit diversity with multisine ($N = 8$)



Wireless Information and Power Transmission

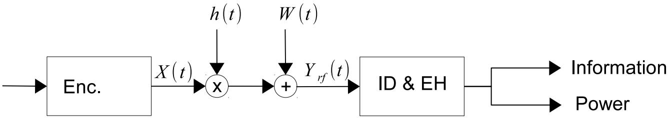


Fundamental tradeoff between rate and harvested DC power?

Unified signal theory and design for WIPT?

Characterizing Fundamental Limits of SWIPT

... in single-carrier frequency-flat AWGN channel with Nonlinear EH



Rate-Energy Region: Maximize information rate and delivered power

- Information rate (R): (Mutual information)

$$R = I(X;Y)$$

- Delivered power (P_{del}): (Nonlinear approximation)

$$P_{\text{del}}(X) = \mathcal{E}[k_2 Y_{\text{rf}}(t)^2 + k_4 Y_{\text{rf}}(t)^4]$$

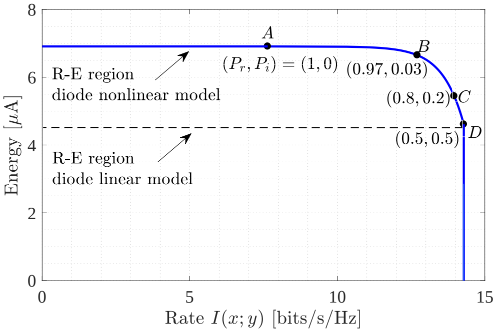
- Problem

$$\sup_{p_X(x)} \quad I(X;Y)$$

$$\text{s.t.} \quad \begin{cases} E[|X|^2] \le P_{\text{rf}}^t \\ P_{\text{del}}(X) \ge P_d \end{cases}$$

Characterizing Fundamental Limits of SWIPT

Gaussian inputs: $\Re\{X\} \sim \mathcal{N}(0, P_r)$, $\Im\{X\} \sim \mathcal{N}(0, P_i)$ with $P = P_r + P_i$.

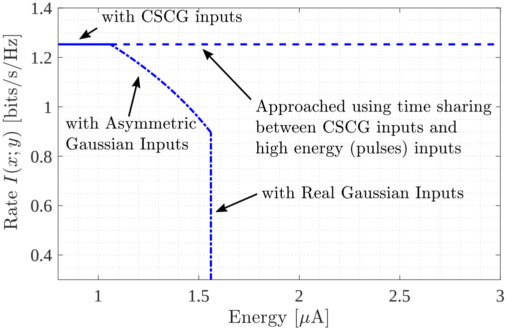


Observation

1. *As a consequence of the nonlinearity, there exists a* ***non-trivial tradeoff*** *between rate and energy even in frequency-flat AWGN channel*
2. *Tradeoff-characterizing input distribution is* ***Gaussian with mean zero*** *and with* ***asymmetric power allocations to the real and imaginary dimensions***

Characterizing Fundamental Limits of SWIPT

Optimal inputs:



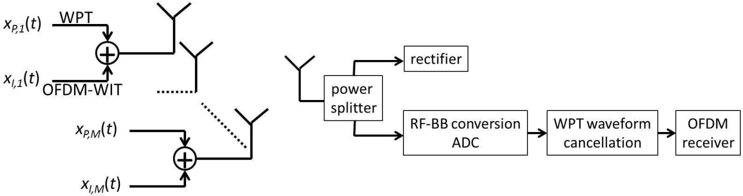
Observation

1. *Due to the nonlinearity, R-E tradeoff is an unbounded rectangle!*
2. *The capacity can be achieved/approached with simple time sharing between CSCG and flash signaling!*
3. *Radically different from the linear model*

Characterizing Fundamental Limits of SWIPT

... in a multicarrier system over frequency-selective channel with Nonlinear EH

- **Key idea**: superimposed deterministic and modulated (CSCG) waveforms



- Energy is harvested from the information and the power waveform
- How to design WIPT waveform?

Rate-Energy Region and Waveform Design

SWIPT Waveform Parameters: $\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho$

Rate-Energy region

$$C_{R-I_{DC}}(P) \triangleq \Big\{(R, I_{DC}) : R \leq I(\mathbf{S}_I, \mathbf{\Phi}_I, \rho), \\ I_{DC} \leq i_{out}(\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho), \frac{1}{2}\big[\, \|\mathbf{S}_I\|_F^2 + \|\mathbf{S}_P\|_F^2 \,\big] \leq P\Big\}.$$

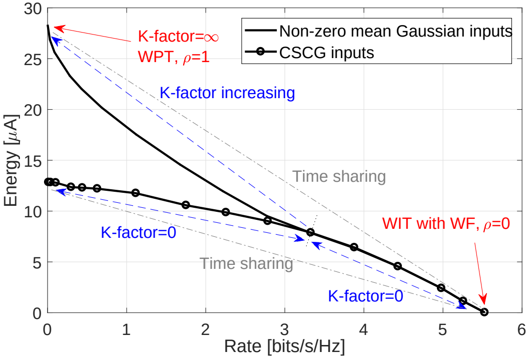
$\rightarrow$ Find optimal values $\mathbf{S}_P^\star$,$\mathbf{S}_I^\star$,$\mathbf{\Phi}_P^\star$,$\mathbf{\Phi}_I^\star$, $\rho^\star$ so as to enlarge $C_{R-I_{DC}}$

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

$$\begin{aligned} \max_{\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho} \quad & i_{out}(\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho) \\ \text{subject to} \quad & \frac{1}{2}\big[\, \|\mathbf{S}_I\|_F^2 + \|\mathbf{S}_P\|_F^2 \,\big] \leq P, \\ & I(\mathbf{S}_I, \mathbf{\Phi}_I, \rho) \geq \bar{R}. \end{aligned}$$

Nonlinearity Changes The Whole Signal Design

Average Rx power of -20dBm. 20dB SNR. $B = 1$MHz. $N = 16$, $M = 1$.



Observation

1. *Superposition of power and communication waveforms beneficial*
2. *A combination of PS and TS in general the best strategy*
3. ***Non-zero mean Gaussian input** distribution outperforms zero-mean Gaussian input distribution!*

Conclusions

Communications and signals for WPT/WIPT systems

- Lay the foundations and tackle the challenges of the envisioned network
- Establish a link and system-level design inspired by communication theoretic ideas
- Develop a signal theory for transmission over the nonlinear wireless power channel and the linear wireless communication channel
- Identify the fundamental tradeoff between conveying information and power wirelessly

Nonlinearity is a fundamental property of the rectifier and is beneficial

- The wireless power channel is nonlinear
- Do not compensate the nonlinearity but exploit it
- Importance of accounting for the nonlinearity in any design involving wireless power
- Leads to fundamental changes to WIPT design (PHY and MAC layers)

Need for **bridging RF and comms/signal processing**

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