Wireless Transmission of Information and Power

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Wireless is More than Just Communications

Wireless communications via radio-frequency (RF) radiation everywhere

Wireless is **More than Just Communications**

- Wireless power via near-field Power Transfer nowadays a reality
- Wireless power via radio-frequency (RF) radiation recognized as feasible
- Wireless power will bring numerous new opportunities

Beyond conventional communication-centric transmission

- 5G mobile communications vs. 0G mobile power

Radio waves carry both energy and information simultaneously

- RF transmissions of energy and information traditionally treated separately
- Imagine information and energy flow together through the wireless medium
- Make the best use of the RF spectrum/radiation to communicate and energize

New challenge and paradigm: **unified wireless network design**

Why Wireless Power?

Wireless Power Transfer (WPT): deliver power wirelessly (without wires)

Benefits

- No wires, no contacts (it travels through walls), no (or at least reduced) batteries
- A perpetual, predictable, dedicated, on-demand and reliable energy supply as opposed to ambient energy-harvesting technologies such as solar, thermal, or vibration
- Smaller, lighter and compact devices
- No production/maintenance/disposal of trillions of batteries
- Prolonged lifetime of devices

Applications

- Networks with ubiquitous/autonomous low-power/energy-limited devices
- Consumer electronics wireless charging
- Biomedical implants wireless charging
- Wireless sensor/IoT devices charging
- Simultaneous wireless information and power transfer (SWIPT)
- Wirelessly powered communication networks (WPCNs)
- Wirelessly powered backscatter communication (WPBC), e.g. RFID

Wireless Power via Coupling

Two **Near-Field WPT** techniques: **Inductive Coupling** and **Magnetic Resonant Coupling**

Benefits: (very) high efficiency (e.g. 90%)

Limitations: Tx/Rx coil alignment, short range ($<$ a few m)

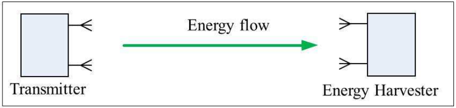
Applications: electric vehicle charging, smart phone charging, RFID, toothbrush, wireless powered medical implants

Industry standard: Qi (Chee), Wireless Power Consortium, Power Matters Alliance, Alliance for Wireless Power, Rezence

Companies: Powermat, Delphi, GetPowerPad, WildCharge, Primove, Intel, PowerbyProxi, WiTricity, WiPower,...

Wireless Power via RF

Via EM/microwave/RF radiation (also called far-field, radiative)



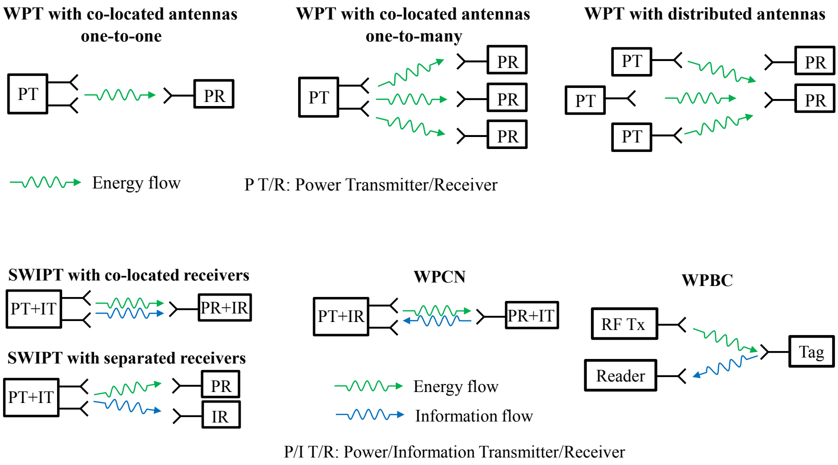
Two **far-field** techniques: **Wireless Power Transfer** (WPT) and **Wireless Energy Harvesting** (WEH)

- WEH: Tx designed for communications, ambient signals harvested
- WPT: Tx are designed exclusively for wireless power delivery

Benefits:

- long range (several meters to 100m/kms)
- small Tx/Rx
- flexible deployment, applicable to LoS and NLoS
- support mobility
- one-to-one (i.e. single-user) and one-to-many (i.e. multi-user) charging
- integration with wireless communication (WPBC, SWIPT, WPCN)

Wireless Power via RF



Wireless Power via RF

Limitations: low efficiency, safety and health issues

- WiFi: 5.18GHz, 36dBm ($4W$) Tx power, 2dBi Rx antenna gain, 58dB path loss (i.e. office) $\rightarrow$ Rx power before conversion of about -20dBm ($10\mu W$)

Applications: Wireless charging for

- low-power devices: RFID tags, wireless sensors/IoT devices,
- consumer electronics: smart phones, laptops, household robots, ...
- high-power: microwave-powered aircrafts, solar power satellite (SPS)

Industry standard: pretty much 0G (RFID only?)

Companies: Intel, Energous, PowerCast, Ossia, Drayson Technologies,...

Wireless Power via Laser Power Beaming

WPT via **highly concentrated laser emission**

Benefits: long range, compact size, high energy concentration, no interference to existing communication systems or electronics

Limitations: laser radiation is hazardous, require LoS link and accurate RX focusing, vulnerable to cloud, fog, and rain

Applications: Laser-powered UAVs, laser-powered solar power satellite,...

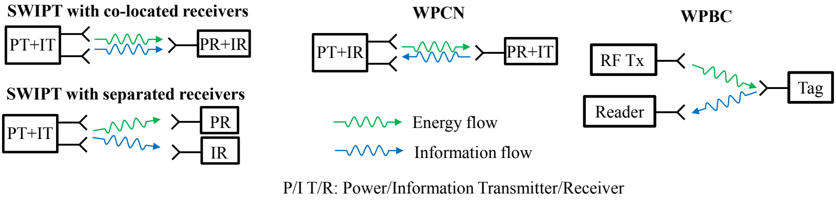
Companies: LaserMotive, ...

Comparison of the main technologies for WPT

Technology	Devices	Range	Frequency	Pros/Cons
Inductive coupling	Wire coils	Millimeters to centimeters	Hz to MHz	High efficiency, require precise tx/rx coil alignment, very short range, single receiver only
Magnetic resonant coupling	Tuned wire coils, lumped element resonators	A few meters, typically 4 to 10 times the coil diameter	kHz to MHz	High efficiency, safe, mid-range, large tx/rx size
EM radiation	Dish antenna, antenna array, rectenna	Several meters to hundreds of kilometers	MHz to dozens of GHz	Long range, small receiver form factors, flexible in deployment and movement, support power multicasting, potential for SWIPT, LoS link is not a must, low efficiency, safety and health issues
Laser power beaming	Laser emitter, photovoltaic receiver	up to kilometers	THz	Compact size, high energy concentration, no interference to existing communication systems or electronics, laser radiation is hazardous, require LoS link and accurate receiver targeting, vulnerable to atmospheric absorption and scattering by clouds, fog, and rain

Focus in this tutorial is on WPT with EM radiation

Wireless Information and Power Transfer



Various forms of Wireless Information and Power Transfer:

- **Simultaneous Wireless Information and Power Transfer** (SWIPT): DL WPT and WIT at the same time
- **Wirelessly Powered Communication Networks** (WPCNs): DL WPT and UL wireless information transmission (WIT)
- **Wirelessly Powered Backscatter Communication** (WPBC): backscattering modulation at the tag to reflect and modulate the incoming RF signal for communication with a reader

... applications in all usual communication channels

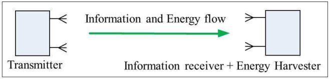


Figure: Point-to-point

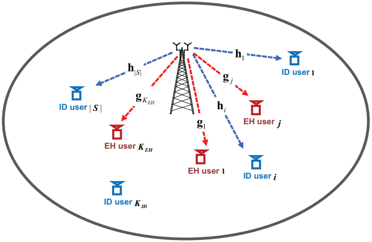


Figure: Broadcast Channel

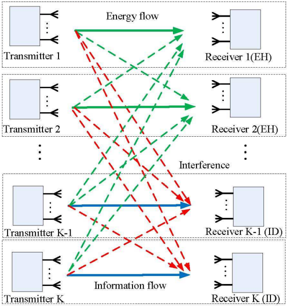


Figure: Interference Channel

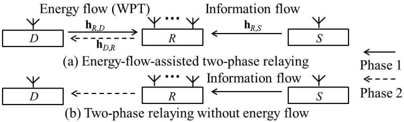


Figure: Relay Channel

Communications and Signals Design for WPT

Main References

1. B. Clerckx and E. Bayguzina, "Waveform Design for Wireless Power Transfer," IEEE Trans on Sig Proc, Vol. 64, No. 23, pp. 6313-6328, Dec 2016.

2. Y. Zeng, B. Clerckx and R. Zhang, "Communications and Signals Design for Wireless Power Transmission," IEEE Trans. on Comm, invited paper, Vol 65, No 5, pp 2264 - 2290, May 2017.

Historical Milestones for Radiative WPT

Year	Main activity and achievement
1888	Heinrich Hertz demonstrated electromagnetic wave propagation in free space.
1899	Nicola Tesla conducted the first experiment on dedicated WPT.
1901	Nicola Tesla started the Wardenclyffe Tower project.
1964	William C. Brown invented rectenna.
1964	William C. Brown successfully demonstrated the wireless-powered tethered helicopter.
1968	William C. Brown demonstrated the beam-positioned helicopter.
1968	Peter Glaser proposed the SPS concept.
1975	An overall DC to DC power transfer efficiency of 54% was achieved in Raytheon Laboratory.
1975	Over 30kW DC power was obtained over 1.54km in the JPL Goldstone demonstration.
1983	Japan launched the MINIX project.
1987	Canada demonstrated the free-flying wireless-powered aircraft 150m above the ground.
1992	Japan conducted the MILAX experiment with the phased array transmitter.
1993	Japan conducted the ISY-METS experiment.
1995	Japan conducted the ETHER experiment for wireless powering the airship.
1997	France conducted the Reunion Island project to transmit 10kW power to a remote village.
2008	Power was successfully transmitted over 148km in Hawaii.
2015	Japan announced successful power beaming to a small device.

Past and Present

Historical WPT:

- Targeting for long distance and high power (e.g., 450kW)
- Mainly driven by the wireless-powered aircraft and SPS applications
- Requires high transmission power, huge Tx/Rx antennas (e.g., 26-m diameter parabolic dish), clear LoS

Modern WPT:

- Low-power (e.g., from μW to a few W) delivery over moderate distances (e.g., from a few m to possibly hundreds of m)
- Need to build reliable and convenient WPT systems for remotely charging various low- to medium-power devices (RFID tags, wireless sensors, smart phones, ...)

Power Requirements and Consumption of Devices

Reductions in power requirements of electronics

- Amount of requested energy falls by 2 every 1.5 year
- Wireless power only became feasible recently

IC industry **paradigm shift**: from computing power towards **power efficiency**

- No need for nm technology with billions of gates for sensors/IoT

Power consumption: **sensor**, **data processing** and **wireless data link**

- Data link more power hungry because of analog RF components
- We can do a lot with **10-100**μW nowadays

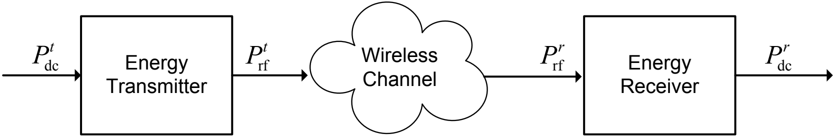
Consumption	Application
14.25μW	CMOS image sensor
17μW	low power microphones
33μW	ADC digitizing the microphone output
35mW	Zigbee and low power Bluetooth transmitters
20μW	WiFi chipset standby mode
600mW	active WiFi transmission
10-100μW	integrated ULP System on Chip (SoC) and duty-cycled radio using custom protocols (10-200kbps)
10-60μW	passive WiFi to generate 802.11b transmission over distances of 10-30m for 1 and 11 Mbps transmissions

New Design Challenges and Requirements

1. Range: Deliver wireless power at distances of 5-100m for indoor/outdoor charging of low-power devices.
2. Efficiency: Boost the end-to-end power transfer efficiency (up to a fraction of percent/a few percent).
3. Non-line of sight (NLoS): Support LoS and NLoS to widen the practical applications of this network.
4. Mobility support: Support mobile receivers, at least for those at pedestrian speed.
5. Ubiquitous accessibility: Support ubiquitous power accessibility within the network coverage area.
6. Seamless integration of wireless communication and wireless power: Interoperate wireless communication and wireless power via a unified wireless information and power transfer (WIPT).
7. Safety and health: Resolve the safety and health issues of RF systems and comply with the regulations.
8. Energy consumption: Limit the energy consumption of the energy-constrained RF powered devices.

WPT Architecture

A generic architecture

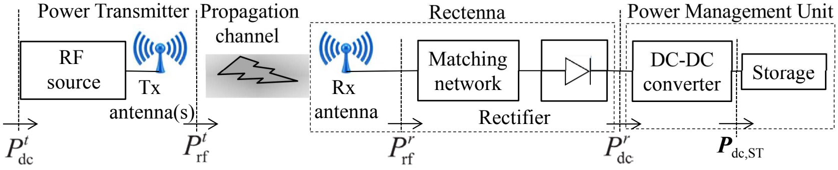


End-to-End Power Transfer Efficiency

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

- WEH: no control of e_1 and e_2. Unlikely sufficient for powering devices with a few cm^2 in size requiring 10-100μW
- WPT: more control of the design and room for enhancement of e

... slightly more detailed



End-to-End Power Transfer Efficiency: $e = \frac{P_{dc,ST}}{P^t_{dc}} = \underbrace{\frac{P^t_{rf}}{P^t_{dc}}}_{e_1} \underbrace{\frac{P^r_{rf}}{P^t_{rf}}}_{e_2} \underbrace{\frac{P^r_{dc}}{P^r_{rf}}}_{e_3} \underbrace{\frac{P_{dc,ST}}{P^r_{dc}}}_{e_4}$

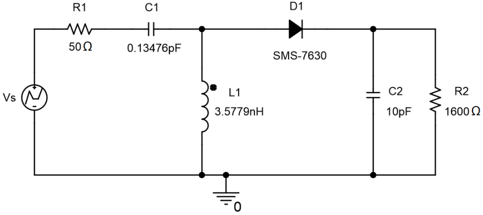
DC-to-RF conversion efficiency e_1: efficient power amplifier (PA) design and transmit signals with constrained PAPR

RF-to-RF conversion efficiency e_2: directional transmission

- RF literature: time-modulated arrays based on localization of the power receivers, phased-arrays, retrodirective arrays
- Comms literature: multi-antenna and accurate channel knowledge at Tx

WPT Architecture

RF-to-DC conversion efficiency e_3: rectenna design

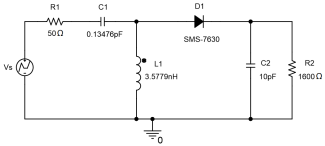


- **Antenna + Rectifier** (a non-linear device + a low-pass filter and load)
- Assuming $P_{\mathrm{rf}}^{t} = 1W$, 5-dBi Tx/Rx antenna gain, a continuous wave (CW) at 915MHz, $e_3 \approx 50\%$ (1m), 25% (10m), 5% (30m)
- With CW, $e_3 \approx 80\%$ (10mW), 40% (100μW), 20% (10μW), 2% (1μW)
- For input power 1μW-1mW, low barrier Schottky diodes preferred
- Single diode at 1-500μW and multiple diodes above 500μW

WPT Architecture

RF-to-DC conversion efficiency e_3: waveform design

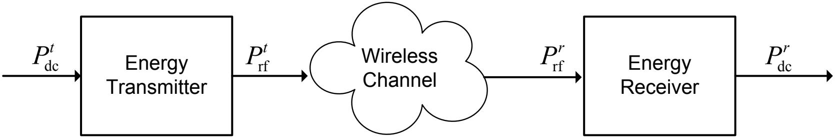
- Due to rectifier nonlinearity, e_3 *influenced by input waveform power and shape* in the low input power regime ($1\mu W$-$1mW$)!



- Measurements have shown that 1) a multisine signal excitation enhances the output DC power and e_3 over a CW signal, 2) OFDM, white noise, chaotic waveforms with high PAPR increase e_3.

DC-to-DC conversion efficiency e_4: dynamic tracking of rectifier optimum load

WPT Architecture



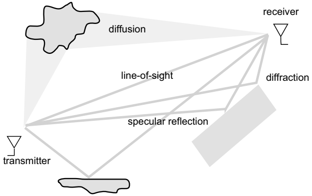
Careful! Maximizing e not achieved by maximizing e_1, e_2, e_3, e_4 independently from each other, and simply concatenating the above techniques

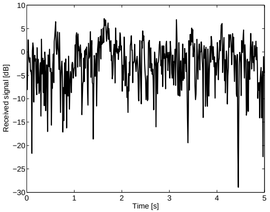
- e_1, e_2, e_3, e_4 coupled due to nonlinearity, especially at $1\mu W$-$1mW$
- e_3(input signal shape and power) $\rightarrow$ e_3(Tx signal,wireless channel state)
- e_2(Tx signal,wireless channel state)
- e_1(Tx signal PAPR)

Notations: P^t_{rf} often simply denoted as P in the sequel for simplicity

Observations from RF literature

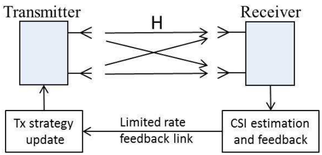
1. Most efforts devoted to rectenna design but less on signals design
2. Emphasis much remained on point-to-point (single user) transmission
3. Rectenna non-linearity known (in RF literature) but design focused on decoupling and optimizing Tx and Rx independently from each other
4. Focus on open-loop approach, i.e. no CSIT-based design
5. No systematic signal design methodology
6. Multipath fading, critical in NLoS, ignored





To tackle the listed challenges, we need...

Closed-loop and adaptive WPT



- to support channel feedback/training, energy feedback, charging control
- to flexibly adjust the Tx strategy across space and frequency
- state-of-the-art MIMO processing an indispensable part of WPT

Systematic signal design approach (as a function of the channel) so as to maximize e

Link and system design approach: from a rectenna paradigm to a network paradigm

- Multiple transmitters/receivers, coordination among energy transmitters

Single-User WPT Signal Design

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

$$x_m(t) = \sum_{n=0}^{N-1} s_{n,m} \cos(2\pi f_n t + \phi_{n,m}) = \Re\left\{ \sum_{n=0}^{N-1} \underbrace{w_{n,m}}_{s_{n,m} e^{j\phi_{n,m}}} e^{j2\pi f_n t} \right\}$$

Received signal after multipath

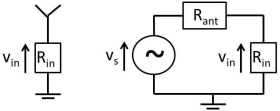
$$y(t) = \sum_{m=1}^{M} \sum_{n=0}^{N-1} s_{n,m} A_{n,m} \cos(2\pi f_n t + \underbrace{\phi_{n,m} + \bar{\psi}_{n,m}}_{\psi_{n,m}}) = \Re\left\{ \sum_{n=0}^{N-1} \mathbf{h}_n \mathbf{w}_n e^{j2\pi f_n t} \right\}$$

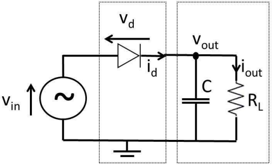
Frequency response of the channel of antenna m at w_n

$$h_{n,m} = A_{n,m} e^{j\bar{\psi}_{n,m}} = \sum_{l=0}^{L-1} \alpha_l e^{j(-2\pi f_n \tau_l + \Delta_{n,m,l} + \xi_l)}$$

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

Rectenna Model





Antenna Equivalent Circuit

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

$$v_s(t) = 2y(t)\sqrt{R_{ant}}, \qquad v_{in}(t) = y(t)\sqrt{R_{ant}}$$

- Antenna noise is too small to be harvested

Rectifier and Diode Non-Linearity

- Ideal diode (neglecting its series resistance): $i_d(t) = i_s\left(e^{\frac{v_d(t)}{n v_t}} - 1\right)$
- Taylor expansion around a fixed operating voltage drop $v_d = a$

$$i_d(t) = \sum_{i=0}^{\infty} k_i'(v_d(t) - a)^i = \sum_{i=0}^{\infty} k_i'(v_{in}(t) - v_{out}(t) - a)^i$$

where $k_0' = i_s\left(e^{\frac{a}{n v_t}} - 1\right)$ and $k_i' = i_s \frac{e^{\frac{a}{n v_t}}}{i!(n v_t)^i}$, $i = 1, \ldots, \infty$.

Rectifier and Diode Non-Linearity

- Assume a steady-state response and an ideal low pass filter such that $v_{out}(t)$ is at constant DC level. Choose $a = \mathcal{E}\{v_d(t)\} = -v_{out}$.

$$i_d(t) = \sum_{i=0}^{\infty} k_i' v_{in}(t)^i = \sum_{i=0}^{\infty} k_i' R_s^{i/2} y(t)^i$$

- Truncating the expansion to order n_o, the DC component of $i_d(t)$ is the time average of the diode current

$$i_{out} = \mathcal{E}\{i_d(t)\} \approx \sum_{i even}^{n_o} k_i' R_{ant}^{i/2} \mathcal{E}\{y(t)^i\}$$

- Make the dependence explicit

$$i_{out} \approx \sum_{i even}^{n_o} k_i'(i_{out}) R_{ant}^{i/2} \mathcal{E}\{y(t)^i\}$$

- Fortunately, maximizing i_{out} is equivalent to maximizing

$$z_{DC}(\mathbf{S}, \mathbf{\Phi}) = \sum_{i \text{ even}, i \geq 2}^{n_o} k_i R_{ant}^{i/2} \mathcal{E}\left\{y(t)^i\right\}$$

where $k_i = \frac{i_s}{i!(n v_t)^i}$

Linear Model

Linear Model: Truncate to order 2

$$z_{DC} = k_2 R_{ant} \mathcal{E}\left\{ y(t)^2 \right\} = \frac{k_2}{2} R_{ant} \left[\sum_{n=0}^{N-1} \left| \mathbf{h}_n \mathbf{w}_n \right|^2 \right]$$

- $\max z_{DC} = \max \mathcal{E}\left\{ y(t)^2 \right\} = \max P_{\mathrm{rf}}^r$
- Assume sufficiently low input RF power such that the higher-order terms would not contribute to z_{DC}
- Maximizing $e_2 \times e_3$ corresponds to maximizing e_2 with constant e_3, i.e. coupling between e_2 and e_3 ignored by assuming e_3 constant
- Tx strategy that maximizes P_{rf}^r is the same strategy that maximizes P_{dc}^r

Nonlinear Model

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

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

- Non-linearity characterized through $\mathcal{E}\left\{y(t)^4\right\}$
- Maximizing z_{DC} or equivalently $e_2 \times e_3$ does not lead to the same solution as maximizing e_2 only
- Assume $M = 1$ and $n_o = 4$

$$z_{DC}(\mathbf{S}, \mathbf{\Phi}) = \frac{k_2}{2} R_{ant} \left[\sum_{n=0}^{N-1} s_n^2 A_n^2\right] + \frac{3k_4}{8} R_{ant}^2 \left[\sum_{\substack{n_0,n_1,n_2,n_3 \\ n_0+n_1=n_2+n_3}} \left[\prod_{j=0}^{3} s_{n_j} A_{n_j}\right] \cos(\psi_{n_0} + \psi_{n_1} - \psi_{n_2} - \psi_{n_3})\right]$$

- Assuming $i_s = 5\mu A$, a diode ideality factor $n = 1.05$ and $v_t = 25.86mV$, typical values are given by $k_2 = 0.0034$ and $k_4 = 0.3829$.

Signal/Waveform Design

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

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

Original problem: Maximize the DC output current i_{out}

$$\max_{\mathbf{S},\mathbf{\Phi}} \quad i_{out}(\mathbf{S},\mathbf{\Phi}) = k_0' + k_2' R_{ant} \mathcal{E}\left\{y(t)^2\right\} + k_4' R_{ant}^2 \mathcal{E}\left\{y(t)^4\right\} + \ldots$$

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

Equivalent problem: Maximize the quantity z_{DC}

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

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

Design based on Linear Model

Problem

$$\max_{\mathbf{w}_n} \sum_{n=0}^{N-1} \left|\mathbf{h}_n \mathbf{w}_n\right|^2 \quad \text{s.t.} \quad \frac{1}{2}\left[\sum_{n=0}^{N-1} \left\|\mathbf{w}_n\right\|^2\right] \leq P$$

Solution: matched (energy) beamformer on a single sinewave, namely the one corresponding to the strongest channel $\bar{n} = \arg\max_i \left\|\mathbf{h}_i\right\|^2$

$$\mathbf{w}_n^{\star} = \begin{cases} \sqrt{2P}\,\mathbf{h}_n^H / \left\|\mathbf{h}_n\right\|, & n = \bar{n}, \\ \mathbf{0}, & n \neq \bar{n}. \end{cases}$$

Adaptive Single Sinewave (ASS) strategy: allocate all power to a single sinewave, the one corresponding to the strongest channel

- A single-sine waveform favoured over a multisine waveform
- Exploits **frequency-diversity gain** and spatial **energy-beamforming gain**

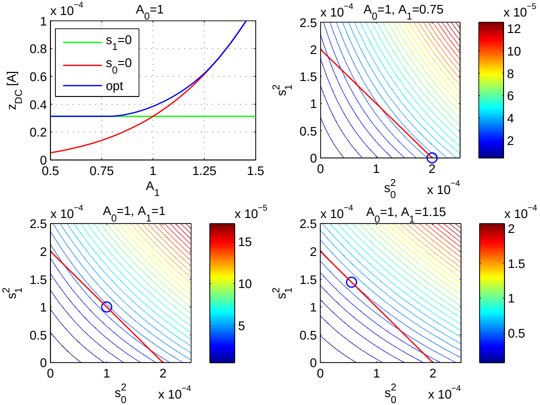
Design based on Nonlinear Model: A Toy Example

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

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

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

Lagrangian optimization: 3 stationary points $(2P, 0)$, $(0, 2P)$ and $(s_0^{\star 2}, s_1^{\star 2})$



Design based on Nonlinear Model: A Toy Example

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 correspond to the ASS strategy $\rightarrow$ ASS is in general suboptimal with the nonlinear model

Benefits of allocating power over multiple sinewaves for some channel states

RF experiments show the benefits of allocating power uniformly across multiple sinewaves

- **Nonlinear model-based design backs up the experimental results**
- Linear model and ASS cannot explain RF experiment results

General approach? for any order n_o in the rectifier Taylor expansion?

Design based on Nonlinear Model: General Approach

Globally optimal phases in closed-form: $\phi^\star_{n,m} = -\bar{\psi}_{n,m}$ so as $\psi_{n,m} = 0 \ \forall n, m$.

$z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star)$ is a **posynomial**

- Monomial $g : \mathbb{R}^N_{++} \rightarrow \mathbb{R} : g(\mathbf{x}) = c x_1^{a_1} x_2^{a_2} \ldots x_N^{a_N}$ where $c > 0$ and $a_i \in \mathbb{R}$.
- Posynomial $f(\mathbf{x}) = \sum_{k=1}^K g_k(\mathbf{x})$, $g_k(\mathbf{x}) = c_k x_1^{a_{1k}} x_2^{a_{2k}} \ldots x_N^{a_{Nk}}$, $c_k > 0$.

Amplitudes: Non-convex Posynomial Maximization Problem

$$\begin{aligned} \max_{\mathbf{S}} \quad & z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star) \\ \text{subject to} \quad & \frac{1}{2} \|\mathbf{S}\|_F^2 \leq P. \end{aligned}$$

$$\begin{aligned} \min_{\mathbf{S}, t_0} \quad & 1/t_0 \\ \text{subject to} \quad & \frac{1}{2} \|\mathbf{S}\|_F^2 \leq P, \\ & t_0 / z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star) \leq 1. \end{aligned}$$

Formulate as a **Reversed Geometric Program** and solve iteratively

- lower bound $z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star)$ by a monomial $\bar{z}_{DC}(\mathbf{S})$, i.e. upper bound $1/z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star)$ by the monomial $1/\bar{z}_{DC}(\mathbf{S})$
- Form of successive convex approximation or inner approximation method

Design based on Nonlinear Model: General Approach

AM-GM inequality: Arithmetic M $\geq$ Geometric M ($\gamma_k \geq 0$, $\sum_{k=1}^{K} \gamma_k = 1$)

$$z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star) = \sum_{k=1}^{K} g_k(\mathbf{S}, \mathbf{\Phi}^\star) \geq \prod_{k=1}^{K} \left(g_k(\mathbf{S}, \mathbf{\Phi}^\star)/\gamma_k\right)^{\gamma_k} = \bar{z}_{DC}(\mathbf{S})$$

Tightness of the upper bound heavily depends on the choice of $\{\gamma_k\}$

(Local) Optimal WPT Waveform

Problem 1: **Standard GP**

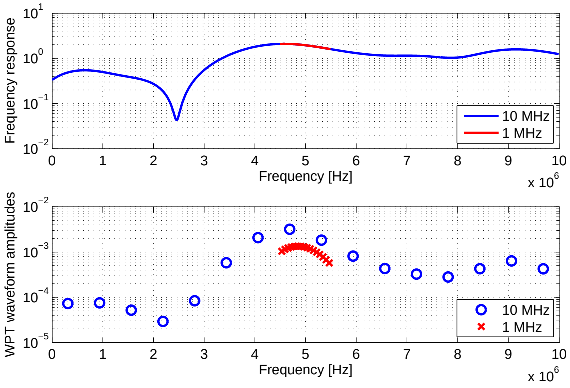
$$\begin{aligned} \min_{\mathbf{S}, t_0} \quad & 1/t_0 \\ \text{s.t.} \quad & \frac{1}{2}\|\mathbf{S}\|_F^2 \leq P, \\ & t_0 \prod_{k=1}^{K} \left(\frac{g_k(\mathbf{S}, \mathbf{\Phi}^\star)}{\gamma_k}\right)^{-\gamma_k} \leq 1, \end{aligned}$$

Algorithm

1: **Initialize**: $i \leftarrow 0$, $\mathbf{\Phi}^\star$, $\mathbf{S}$, $z_{DC}^{(0)} = 0$
2: **repeat**
3: $i \leftarrow i + 1$, $\ddot{\mathbf{S}} \leftarrow \mathbf{S}$
4: $\gamma_k \leftarrow g_k(\ddot{\mathbf{S}}, \mathbf{\Phi}^\star)/z_{DC}(\ddot{\mathbf{S}}, \mathbf{\Phi}^\star)$, $\forall k$
5: $\mathbf{S} \leftarrow \arg\min$ Problem 1
6: $z_{DC}^{(i)} \leftarrow z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star)$
7: **until** $\left| z_{DC}^{(i)} - z_{DC}^{(i-1)} \right| < \epsilon$ or $i = i_{\max}$

Convergence to a **KKT** point guaranteed, not a global optimum

Waveform Illustration



Observation

1. *Allocate more power to frequencies exhibiting larger channel gains*
2. *Optimally exploits **frequency-diversity gain** and **rectifier nonlinearity***

Decoupling Space and Frequency Domains

Decoupling Space and Frequency Domains without impacting performance

1. **Matched (energy) beamformer**

$$\mathbf{w}_n = s_n \mathbf{h}_n^H / \|\mathbf{h}_n\|$$

   Multi-antenna multi-sine WPT weight optimization converted into an effective single antenna multi-sine WPT weight optimization

2. **Optimize magnitude** s_n based on effective channel gain $\|\mathbf{h}_n\|$ subject to $\sum_{n=0}^{N-1} s_n^2 = 2P$. Use Reversed GP.

Same performance as the joint space-frequency design but **lower computational** complexity

Exploits **frequency-diversity gain**, spatial **energy-beamforming gain** and **rectifier nonlinearity**

Decoupling only optimal in **SU WPT**

PAPR Constraints

PAPR on antenna m defined as

$$PAPR_m = \frac{\max_t |x_m(t)|^2}{\mathcal{E}\{|x_m(t)|^2\}} = \frac{\max_t |x_m(t)|^2}{\frac{1}{2}\|\mathbf{s}_m\|^2}$$

Waveform design subject to **PAPR constraints**

$$\begin{aligned} \max_{\mathbf{S},\mathbf{\Phi}} \quad & i_{out}(\mathbf{S},\mathbf{\Phi}) \\ \text{subject to} \quad & \frac{1}{2}\|\mathbf{S}\|_F^2 \leq P, \\ & PAPR_m \leq \eta, \forall m. \end{aligned}$$

PAPR constraints leads to **signomials**. Solved using Reversed GP as well.

Decoupling the space and frequency domains leads to a **suboptimal** design compared to the joint space-frequency design in the presence of PAPR constraints.

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.*
   $\rightarrow$ *increase in* $\log N$ *vs* N.

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

Large-Scale Multi-Sine Multi-Antenna WPT

$$z_{DC} \overset{N,M\nearrow}{\approx} k_2 R_{ant} P M + k_4 R_{ant}^2 P^2 N M^2$$

for both FF and FS channels

Easily achieved by **matched energy beamforming** and **uniform power allocation** for N, M very large

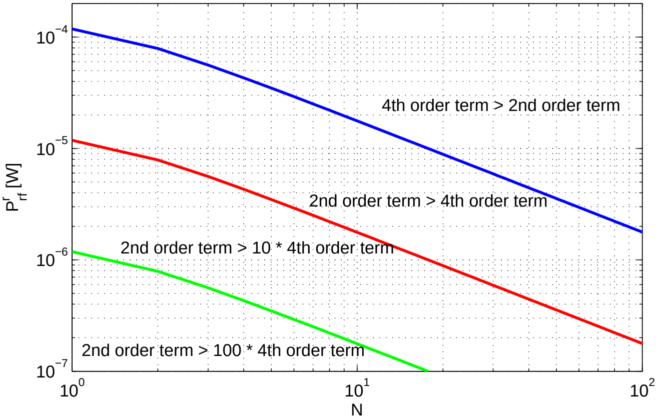
The **large dimension** enables to significantly **simplify the waveform design**

Reminiscent of **Massive MIMO** in communication

Linear vs Non-linear Regime

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

$$P^r_{\mathrm{rf}} \leq \frac{k_2}{k_4} \frac{1}{R_{ant}} \frac{1}{N} \frac{1}{G}$$



Performance Evaluations

WiFi-like environment

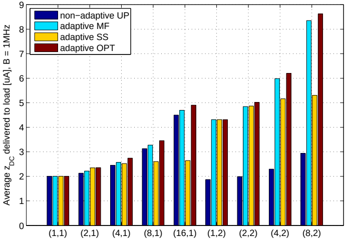
- 5.18GHz, 36dBm Tx power, 2dBi Rx antenna gain, 58dB path loss, office.
- Average received power of about -20dBm.
- Frequency gap fixed as $\Delta_w = 2\pi\Delta_f$ with $\Delta_f = B/N$.

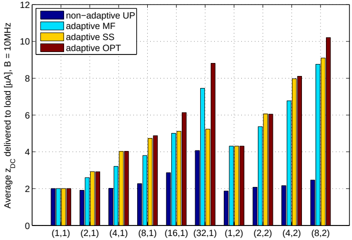
Metric: $z_{DC} = k_2 R_{ant} \mathcal{E}\left\{y(t)^2\right\} + k_4 R_{ant}^2 \mathcal{E}\left\{y(t)^4\right\}$

- $k_2 = 0.0034,\ k_4 = 0.3829,\ R_{ant} = 50\Omega.$

Performance Evaluations

B=1MHz (left) and **B=10MHz** (right)



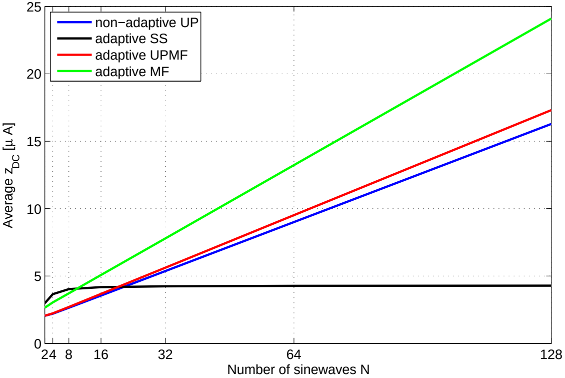


Observation

1. *Nonlinear model-based design outperforms the linear model-based design*
2. *Nonlinearity non-negligible at low input power, e.g. -20dBm ($10\mu W$)*
3. *OPT waveforms jointly exploit beamforming gain, channel frequency-selectivity and rectifier nonlinearity*
4. *ASS (optimal linear model-based design) worse than non-adaptive UP!*

Performance Evaluations

Large-scale multisine waveforms - B=5MHz - $M = 1$

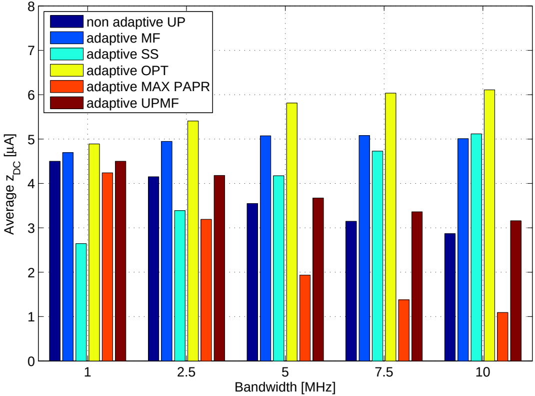


Observation

1. *Significant loss of linear model-based waveform design for* $N \geq 8$

Performance Evaluations

Effect of Bandwidth B on z_{DC} for $N = 16$ and $M = 1$.

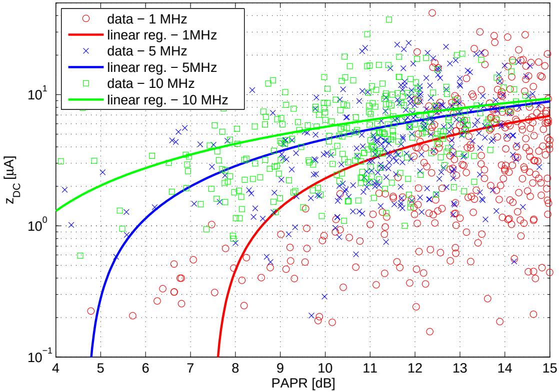


Observation

1. *Importance of non-uniform power allocation as Bandwidth increases*
2. *MAX PAPR waveform not a suitable approach!*

Performance Evaluations

z_{DC} of OPT waveform versus **transmit PAPR** for $N = 16$ and $M = 1$.

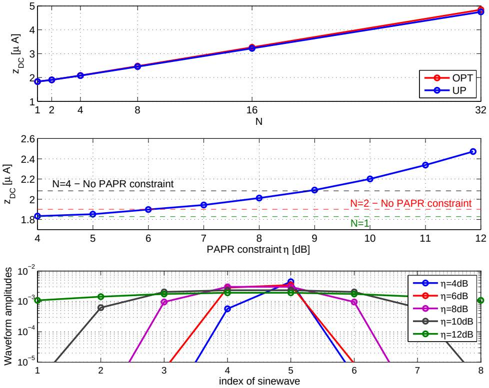


Observation

1. *As bandwidth increases, correlation between DC current and PAPR reduces*
2. *Careful with the use of PAPR as a measure of waveform performance!*

Performance Evaluations

z_{DC} versus **transmit PAPR constraint** for $N = 8$ and $M = 1$.



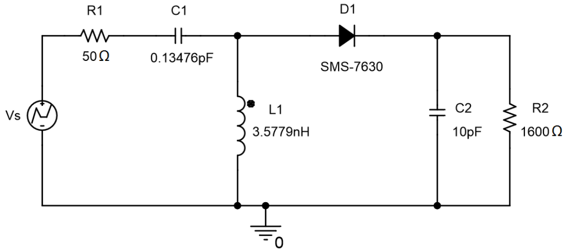
Observation

1. *In frequency flat channel, UP close to optimal*
2. *As η decreases, less power on the side and more on the center frequencies*

Circuit Evaluations

Rectenna with a single diode and a L-matching network used for PSpice evaluations with $B = 10\text{MHz}$.

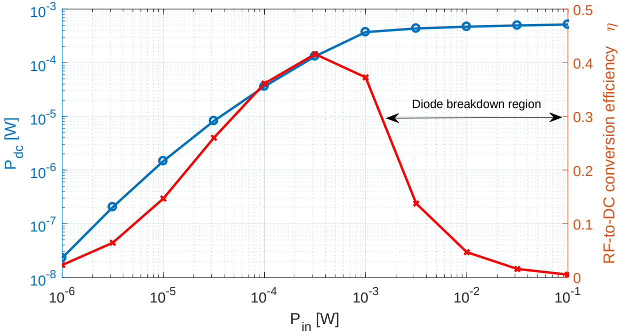
- Designed for an input power of -20 dBm
- Good matching between the rectifier and the antenna and minimize impedance mismatch due to variations in frequency and input power level
- C1 and L1 optimized to match the antenna impedance to the average input impedance of the rectifier resulting from an input signal composed of 4 sinewaves and spread across B = 10 MHz



The output capacitor chosen as C2 $= C_{out} = 100\text{pF}$ for $B = 1\text{MHz}$

Circuit Evaluations

Output DC power versus input RF power with a continuous wave.

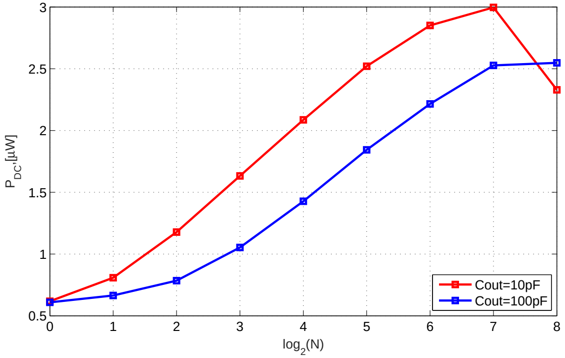


Observation

1. *We do not want to operate in the diode breakdown region*
2. *Saturation can be avoided by proper design of the rectifier*

Circuit Evaluations

DC power versus N for B=10 MHz $(P = -20\text{dBm},\ 10\mu W)$

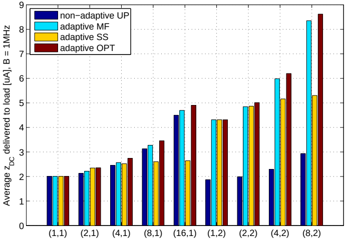


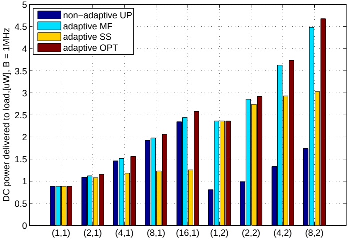
Observation

1. *DC power indeed increases with* N
2. *For* N *larger, circuit (Cout, load and matching network) to be adjusted*
3. *Saturation will occur due to diode breakdown voltage (2Vfor SMS7630)*

Circuit Evaluations

Matlab/CVX (left) and **PSpice** (right) - **B=1MHz**



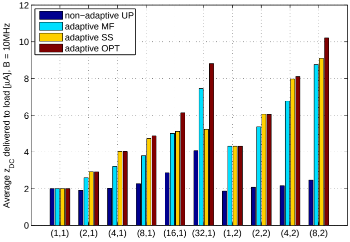


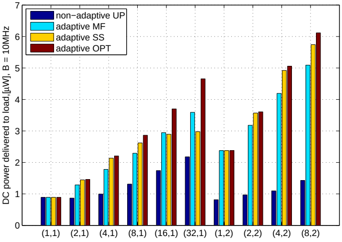
Observation

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

Circuit Evaluations

Matlab/CVX (left) and **PSpice** (right) - **B=10MHz**





Observation

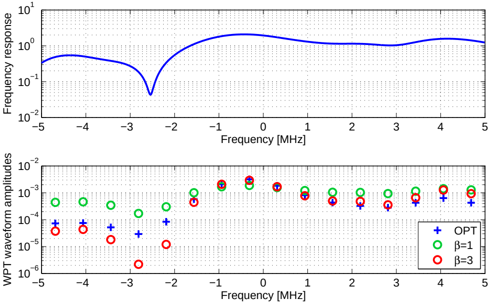
1. *Promising architecture: large-scale multisine multiantenna waveforms.*
2. *Sensors need 10 μW DC (see PsiKick's Fully Integrated Wireless SoC sensors)*
3. *Think big: up to 2048 subcarriers in LTE! 100s antennas/Tx in 5G (Massive MIMO)!*

Low-Complexity Signal Design

Reversed GP: a general approach applicable to any order n_o but **exponential complexity**, not implementation friendly, difficult to tackle large-scale system

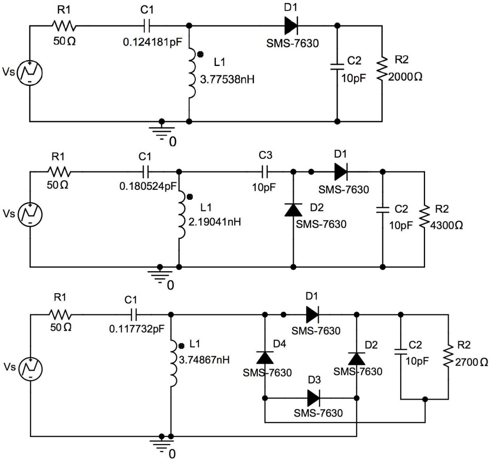
Low-Complexity Adaptive Multisine Waveform

- Idea: allocate more power to frequencies exhibiting larger channel gains
- Scaled Matched Filter (SMF): $s_n = cA_n^{\beta}$ with c a constant
- $\beta = 1$ leads to a matched filter-like behaviour, i.e. MRT
- Scaling A_n using an exponent $\beta > 1$, we further amplify the strong frequency components and attenuate the weak ones

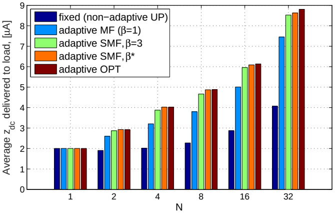


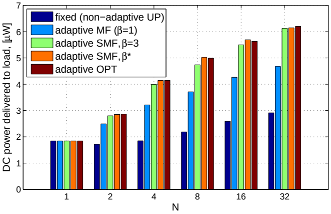
Circuit Evaluations

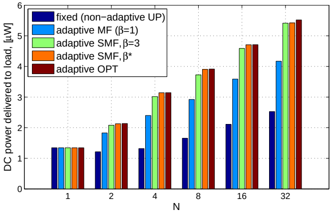
Single series, voltage doubler and diode bridge rectifiers

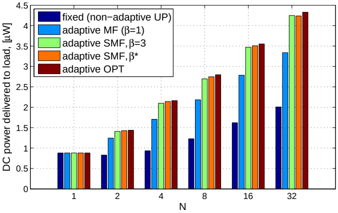


Average z_{DC} and DC power with single series, voltage doubler and diode bridge









Observation

1. *Waveform design holds for single and multiple-diode rectennas*
2. *SMF very close to OPT despite much lower design complexity*
3. *At low input power, single series rectifier preferred*

Large-Scale WPT Architecture

Computationally efficient optimization framework:

- Reformulate the optimization problem by expressing the RF signal model in a compact form using a real-valued function of complex vector variables
- Limited to 4^{th} order ($n_o = 4$)

Wireless channel $\mathbf{h} = [\mathbf{h}_1^T, \ldots, \mathbf{h}_N^T]^T \in \mathbb{C}^{MN\times 1}$

Waveform precoder $\mathbf{s} = [\mathbf{s}_1^T, \ldots, \mathbf{s}_N^T]^T \in \mathbb{C}^{MN\times 1}$

Rectenna output DC voltage ($z_{DC} = v_{\text{out}}\, i_s/(nv_t)$)

$$v_{\text{out}} = \beta_2 \sum_{n=1}^{N} \mathbf{s}_n^H \mathbf{h}_n^* \mathbf{h}_n^T \mathbf{s}_n + \frac{3}{2}\beta_4 \sum_{\substack{n_1,n_2,n_3,n_4 \\ n_1-n_3=-(n_2-n_4)}} \mathbf{s}_{n_3}^H \mathbf{h}_{n_3}^* \mathbf{h}_{n_1}^T \mathbf{s}_{n_1} \cdot \mathbf{s}_{n_4}^H \mathbf{h}_{n_4}^* \mathbf{h}_{n_2}^T \mathbf{s}_{n_2}$$

Computational efficiency: SU WPT vs. Reversed GP

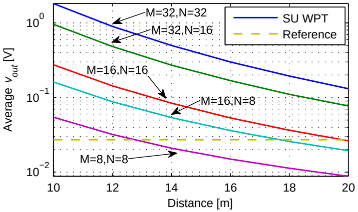
Algorithms	Average v_{out} [V]	Average elapsed time [s]	Average convergence time
SU WPT	9.532×10^{-2}	1.752×10^{-3}	4.18 iterations
Reversed GP	8.417×10^{-2}	99.04	17.16 iterations

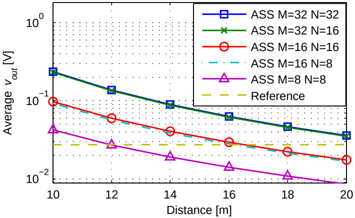
- $M = 1$, $N = 8$, $P = 3.98107\,\text{W}$ and a distance of $10\,\text{m}$
- Stopping criteria: $(v_{\text{out}}^{(l)} - v_{\text{out}}^{(l-1)})/v_{\text{out}}^{(l)} \leq 10^{-3}$

Large-Scale WPT Architecture

Average v_{out} achieved by SU WPT (left) and ASS (right) vs. distance ($P = 0.5\,$W)

- SU WPT: computationally efficient optimal nonlinear model-based waveform design
- ASS: optimal linear model-based waveform design





Observation

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

Unmodulated vs Modulated Signals

Multisine waveform is **deterministic** while modulated waveform exhibits **randomness** due to information symbols

Randomness has an impact on the amount of harvested energy and needs to be captured in the rectenna model

Proposed model for the DC current with a **multi-carrier modulated waveform**

$$y_I(t) = \Re\left\{\sum_{n=0}^{N-1} \mathbf{h}_n \mathbf{w}_{I,n} \tilde{x}_n e^{j2\pi f_n t}\right\},$$

$$z_{DC} = \sum_{i \text{ even}, i\geq 2}^{n_o} k_i R_{ant}^{i/2} \mathcal{E}_{\{\tilde{x}_n\}}\left\{\mathcal{A}\left\{y_I(t)^i\right\}\right\},$$

by averaging out over the distribution of the input symbols $\{\tilde{x}_n\}$

Scaling Laws - Single-Carrier

Waveform	Frequency-Flat (FF)
Modulated	
z_{DC}	$k_2 R_{ant} P + 6 k_4 R_{ant}^2 P^2$
Unmodulated	
z_{DC}	$k_2 R_{ant} P + 3 k_4 R_{ant}^2 P^2$

Observation

1. *From 2nd order term: Modulated and Unmodulated waveforms are equally suitable.*
2. *From 4th order term: **Modulated better than Unmodulated**.*
3. *Gain of modulation comes from large fourth order moment with CSCG inputs.*

Scaling Laws - Multi-Carrier

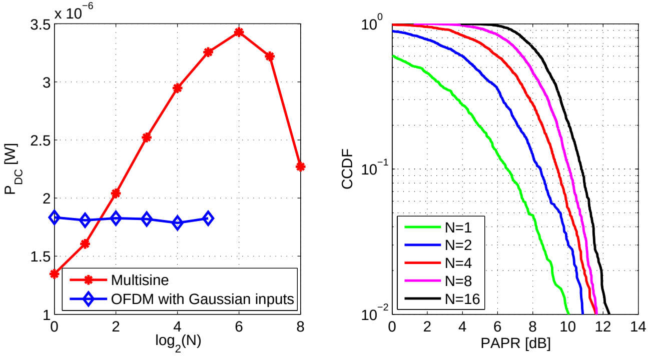
Waveform	Frequency-Flat (FF)	Frequency-Selective (FS)
Modulated		
z_{DC}	$k_2 R_{ant} P + 6k_4 R_{ant}^2 P^2$	$k_2 R_{ant} P \log N + 3k_4 R_{ant}^2 P^2 \log^2 N$
Unmodulated		
z_{DC}	$k_2 R_{ant} P + 2k_4 R_{ant}^2 P^2 N$	$k_2 R_{ant} P + k_4 R_{ant}^2 P^2 N$

Observation

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

Unmodulated vs Modulated Signals

DC power vs N (left) and **CCDF of PAPR with OFDM vs N** (right)

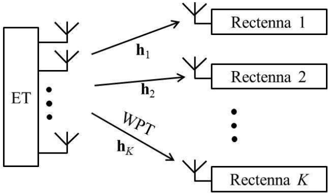


Observation

1. ***Random fluctuation of OFDM*** *waveform vs* ***periodic behavior of multisine*** *waveform (more suitable to turn on and off the rectifier periodically)*
2. *DC power of OFDM insensitive to N despite PAPR increase with N*
3. *Careful again with PAPR metric!*

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, $k = 1, \ldots, K$

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

Design based on Linear Model

Problem

$$\max_{\mathbf{w}_n} \quad \sum_{n=0}^{N-1} \left\|\tilde{\mathbf{H}}_n \mathbf{w}_n\right\|^2 \quad \text{s.t.} \quad \frac{1}{2}\left[\sum_{n=0}^{N-1} \left\|\mathbf{w}_n\right\|^2\right] \leq P$$

with $\tilde{\mathbf{H}}_n = \left[\begin{array}{ccc} \tilde{\mathbf{h}}_{n,1}^T & \ldots & \tilde{\mathbf{h}}_{n,K}^T \end{array}\right]^T$ and $\tilde{\mathbf{h}}_{n,k} = \sqrt{k_2 v_k}\mathbf{h}_{n,k}$

Solution: transmit on a single sinewave $\bar{n} = \arg\max_i \lambda_{max}\left(\tilde{\mathbf{H}}_i^H \tilde{\mathbf{H}}_i\right)$ along the dominant right singular vector of $\tilde{\mathbf{H}}_{\bar{n}}$

$$\mathbf{w}_n^\star = \begin{cases} \sqrt{2P}\,\mathbf{v}_{max,n}, & n = \bar{n}, \\ \mathbf{0}, \quad n \neq \bar{n}, \end{cases}$$

where $\mathbf{v}_{max,n}$ is the dominant right singular vector of $\tilde{\mathbf{H}}_n$

Generalized **ASS strategy**

Design based on Nonlinear Model

Phase and magnitude are **coupled** in MU WPT

- Formulate as a signomial maximization problem requires an initial choice for the phase before the magnitudes can be optimized
- No guarantee of optimality

Optimum solution using complex vector variables problem formulation

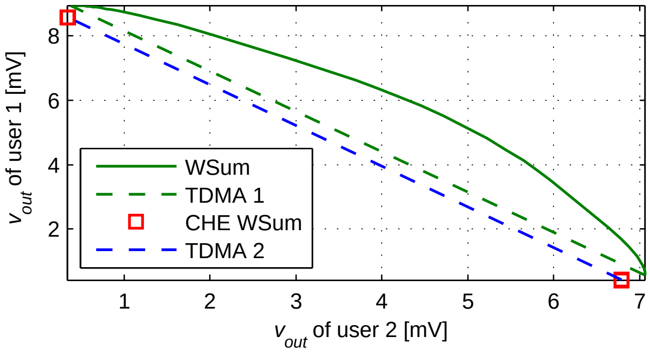
- Generalize the SU WPT algorithm to MU WPT
- Quartic function that leads to NP-hard problems
- Auxiliary variables and convex relaxations used: quartic objective reduced to a non-convex quadratic constraint in equivalent problem
- Non-convex constraint linearized, equivalent problem iteratively approximated
- Convex optimization techniques (e.g., successive convex approximation (SCA), rank reduction) used to solve the approximate problem
- Converge to a KKT point

Joint optimization in the frequency domain and the spatial domain

- **Decoupling** space and frequency design is **suboptimal**

Design based on Nonlinear Model

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



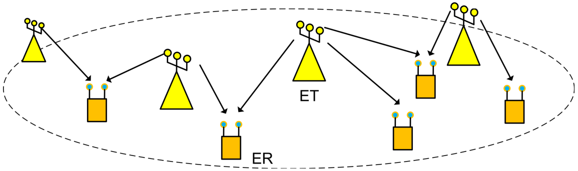
Observation

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

Design extendable to **max-min problem**: $\max \min_{k \in \{1,\ldots,K\}} z_{DC,k}$

Multi-User WPT: Network Architecture

J distributed ETs simultaneously serve K ERs each having multiple antennas



Three **main networking architectures** (with complexity from high to low):

CoMP(Coordinated Multi-Point) WPT

- All ETs jointly design energy signals to the K ERs based on global CSI
- Only requires exchange of CSI and waveform parameters among ETs, as opposed to message exchange in CoMP communications

Locally-coordinated WPT

- Each ER is served by a subset of ETs
- *ET-oriented association*:group the ETs into clusters, with each cluster ETs cooperatively serving a subset of ERs
- *ER-oriented association*:each ER is freely associated with a subset of ETs

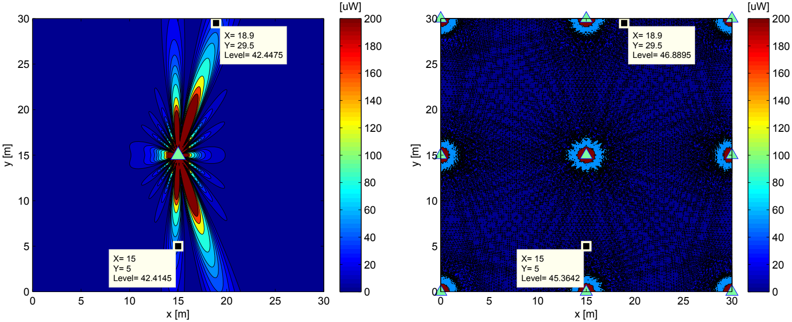
Single-ET WPT: Each ER served by exactly one ET

Co-located Antenna System vs Distributed Antenna System

Simulation assumptions:

- A WPT system that serves a square area of 30m x 30m with **co-located versus distributed** antennas
- **Co-located antennas**: a single ET with 9-element uniform linear array (ULA) at the center of the serving area
- **Distributed antennas**: 9 ETs each with single antenna equally spaced in the area
- Two single-antenna ERs at (15m, 5m) and (18.88m, 29.49m), which are 10m and 15m away from the area center, respectively
- Total transmit power of the system is 2W
- Maximize the minimum (max-min) harvested power by the two ERs

Co-located Antenna System vs Distributed Antenna System



Observation

1. *Power beamed towards the ERs in co-located antenna system*
2. *More even spatial power distribution for distributed antenna system*

Channel Acquisition for WPT

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

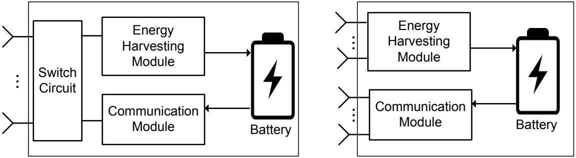
Unique considerations for CSI acquisition in WPT in contrast to conventional wireless communication

- **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 energy beamforming
- **Hardware constraint**: no/low signal processing capability for low-cost ERs

Candidate solutions depending on the **antenna architecture** at Rx

- Forward-link training with CSI feedback
- Reverse-link training via channel reciprocity
- Power probing with limited energy feedback

Antenna Architecture at Rx



(a) Shared-antenna architecture (b) Separate-antenna architecture

For enabling CSI acquisition, each ER must have a **communication module**, in addition to the **energy harvesting module**

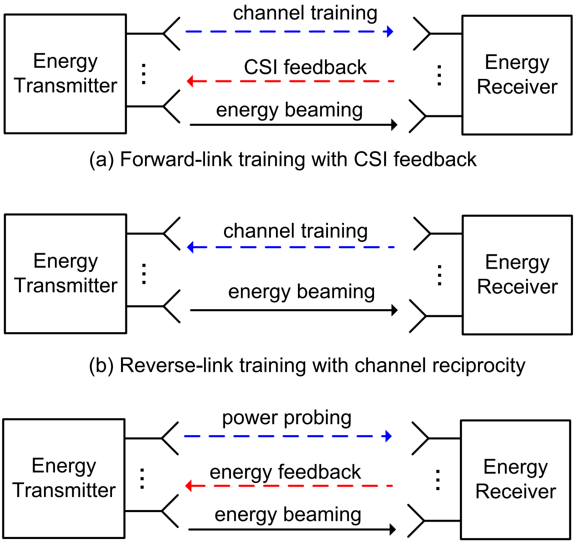
Shared-antenna architecture

- Same set of antennas used for energy harvesting and communication
- Energy harvesting and communication take place in a time-division manner
- Compact receiver form factor, easy channel estimation
- But require communication and energy harvesting at the same frequency, and new frontend design of Rx

Separate-antenna architecture

- Different antennas for energy harvesting and communication, independent and concurrent operations, and commercial off-the-shelf hardware available

Channel Acquisition Schemes for WPT



(a) Forward-link training with CSI feedback

(b) Reverse-link training with channel reciprocity

(c) Power probing with energy feedback

Forward-Link Training with CSI Feedback

Applicable for **shared-antenna** architecture **only**

Similar to conventional wireless communications, pilot signals sent by the ET to the ER for channel estimation

ER then **feeds back the estimated channel** to ET

Limitations:

- Training overhead scales with the number of antennas/frequencies at ET, not suitable for large-scale/massive MIMO WPT
- Requires channel estimation and/or feedback by ER, though it does not require CSI for energy harvesting

Reverse-Link Training via Channel Reciprocity

Applicable for **shared-antenna** architecture **only**

Exploits **channel reciprocity**: ER sends pilots to ET for channel estimation

Advantages:

- **No channel estimation or feedback** required at **ER**
- Time/energy **training overhead independent** of number of ET antennas, suitable for large-scale/massive MIMO WPT

Limitations: Critically depends on channel reciprocity

New design trade-offs:

- **Too little training**: coarsely estimated channel, reduced beamforming gain
- **Too much training**: consumes excessive energy at ER, less time for WPT

Maximize **net energy** at ER: harvested energy − energy consumed for training

Power-Probing with Energy Feedback

Applicable for **separate-antenna** and **shared-antenna** architecture

- ET sends energy signals with online designed transmit covariance matrices
- ER measures the amount of harvested energy during each interval
- ER sends a finite-bit feedback based on its present and past energy measurements
- ET obtains refined CSI estimation based on the feedback bits

Advantages:

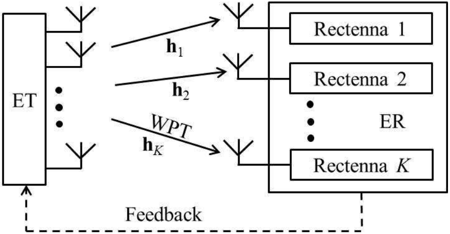
- Low signal processing requirement at the ER, no need for hardware change
- Simultaneous energy harvesting not interrupted

Limitations:

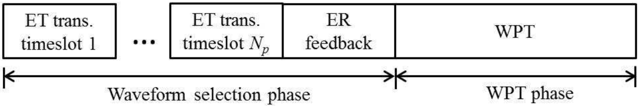
- Training overhead increases with the number of ET antennas

Multi-Antenna Multi-Sine WPT with Limited Feedback

ET: M Tx antennas and N frequencies; ER: K rectennas

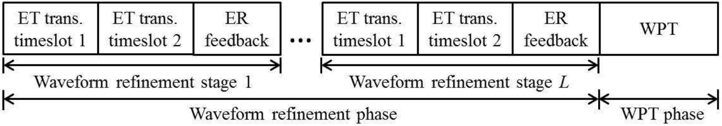


Waveform Selection-based WPT

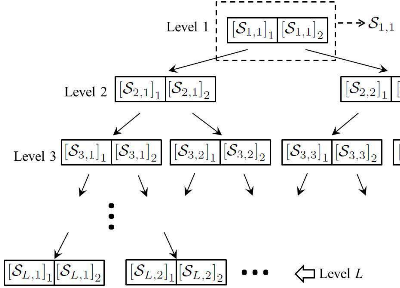


- Waveform precoders: a predesigned N_p-codeword codebook
- ER feedback: $n_p^\star = \arg\max_{n_p \in \{1,\ldots,N_p\}} Z_{DC}([\mathcal{S}]_{n_p})$
- $\log_2 N_p$ feedback bits and N_p energy signals transmitted in the WS phase

Waveform Refinement-based WPT



- Waveform precoders: a predesigned tree-structured codebook

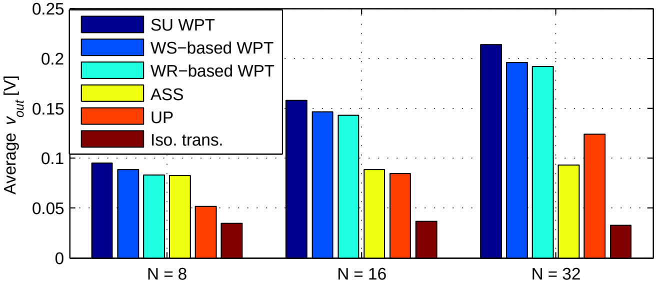


- ER: $f_b = 1$, for $Z_{DC,q}([\mathcal{S}_{l,n_s}]_1) > Z_{DC,q}([\mathcal{S}_{l,n_s}]_2)$; otherwise, $f_b = 0$.
- $\log_2 N_p$ feedback bits and $2\log_2 N_p$ energy signals sent in WR phase

Multi-Antenna Multi-Sine WPT with Limited Feedback

Average v_{out} in the WPT phase as a function of N, with $M = 1$ and $K = 1$ ($P = 36\text{dBm}$)

- In the WS-based WPT, the codebook size $N_p = 2N$.
- In the WR-based WPT, the TS codebook has $L = \log_2 2N$ levels.



Observation

1. *Proposed waveform strategies, based on limited feedback, outperform the linear model-based waveform design relying on perfect CSIT*

Prototyping and Experimentation of Closed-Loop WPT

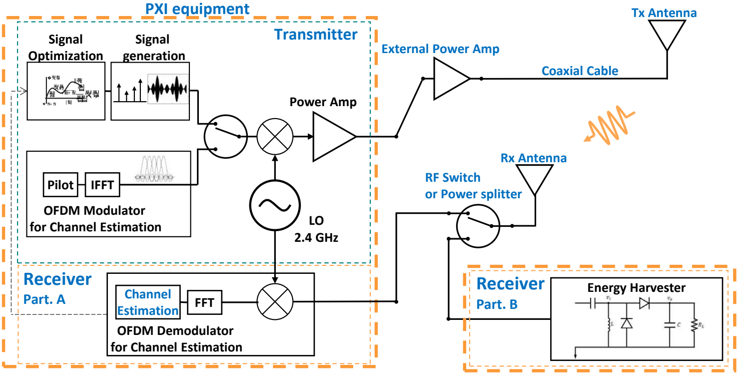
Demonstrate the first prototype of a closed-loop WPT system with adaptive waveform optimization based on CSI acquisition

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 CSI-based optimized signal for WPT

Actual Prototype Architecture

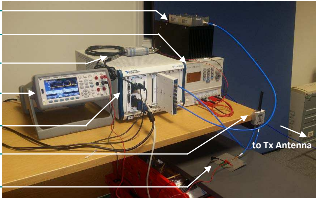


- The system operates in 2.4 GHz ISM band
- Software Defined Radio (SDR) used for transmitter and channel estimator. NI FlexRIO (PXI-7966R) and transceiver module (NI 5791R)
- Channel estimation and waveform design implemented in LabVIEW

Actual Prototype Architecture

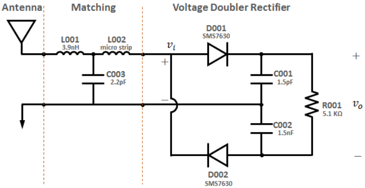
Equipment and peripherals

External Power Amp
Power Supply for external amp
RF Power Meter
Multimeter
PXI equipment
Rx Antenna and Power splitter
Rectenna (Receiver Part. B)

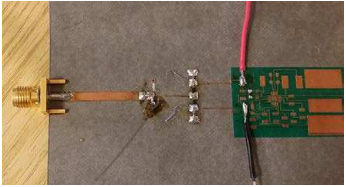


Rectenna Design

Schematic



Fabricated Rectenna Board



Actual Prototype Architecture

Channel estimation: pilot based channel estimation technique

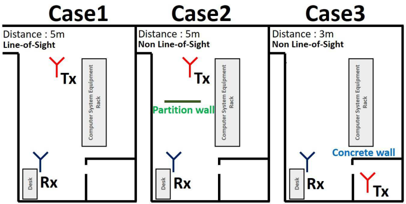
Parameter	Value
Bandwidth	20 MHz
Number of Subcarriers	256
Frequency Spacing	78.125 KHz
Pilot type	Block type pilot
Number of symbols for channel estimation	20 symbols (320 μs)
Method of Channel Estimation	Least-square

Waveform design: Scaled Matched Filter (SMF) because of low complexity and processing time

- $N = 8$ uniformly spaced sinewaves in 10MHz bandwidth, Tx Power of 35dBm

Measurement Results

Measurement setup



Measurement results (N: Non-adaptive waveform, A: Adaptive Waveform)

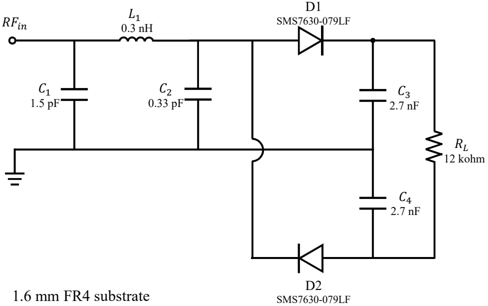
	Case 1		Case 2		Case 3	
	N	A	N	A	N	A
Harvested Power (μW)	1.233	1.354	0.566	0.713	1.032	1.412
Performance gain	9.8%		25.9%		36.8%	

Observation

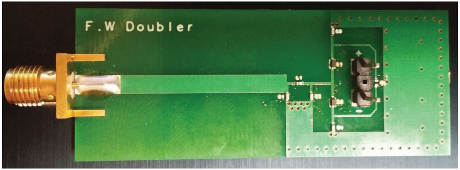
1. ***Measurements confirm theory***: *performance gain (adaptive vs non-adaptive) larger in FS channels than in FF channels*

Actual Prototype Architecture

Latest Rectenna Design

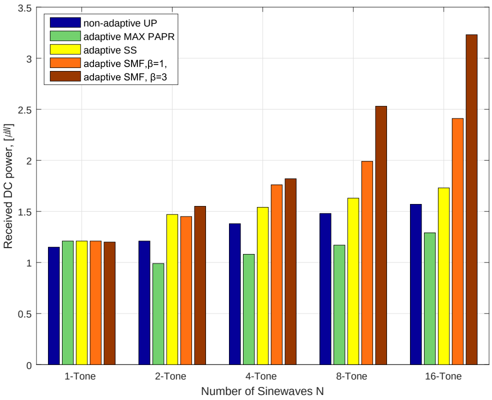


1.6 mm FR4 substrate



Latest Measurement Results

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



Observation

1. ***Measurements confirm theory***: *gains very promising*

Extensions and Future Work

Energy Harvester Modeling and impact on signal design: Non-linearity of rectifier (diode), Non-linearity due to impedance mismatch, Non-linearity due to saturation (use curve fitting based on measured data), Harmonics

Optimal transmit signal for WPT unknown: optimal input distribution, deterministic or modulated waveforms, role of modulation, energy outage minimization

Role played by CSI in WPT remains largely unknown: channel acquisition in frequency-selective and/or multi-user channels, impact of CSIT on signal design, distributed channel training and waveform

Low-complexity algorithm

Massive MIMO and **mmWave** WPT

safety and health: importance of CSI acquisition, distributed antenna system and signal design

Coexisting with wireless communication and interference management

Higher layer (MAC, Network, etc.) design issues in WPT

Hardware development and applications

Simultaneous Wireless Information and Power Transfer

Early works on SWIPT motivated by inductive coupling

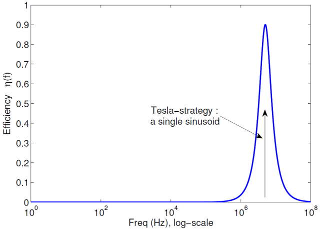
Assumptions

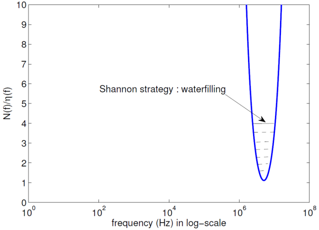
- Receiver harvests energy and decode information from the same signal
- Linear model: $E \leq P_{\mathrm{rf}}^{r}$, $P_{\mathrm{rf}}^{r} = |h|^2 P_{\mathrm{rf}}^{t}$

From Grover and Sahai 2010 "...the problem of simultaneous information and power transmission was first considered by Varshney, where using a general "capacity-energy function," tradeoffs between capacity and power delivered were characterized for some discrete channels, and an AWGN channel with an amplitude constraint on the input. Without fading in the average power-constrained AWGN case, the two goals of maximum rate and maximum efficiency of power transfer are aligned, and there is no non-trivial tradeoff. The coupled-inductor circuit problem posed here is a special case of an AWGN channel with frequency-selective fading. In that respect, the contribution of this paper is to show that an AWGN channel with frequency-selective fading has nontrivial tradeoffs between the information and power transfer."

Rate-Energy Tradeoff in Frequency-Selective AWGN Channel

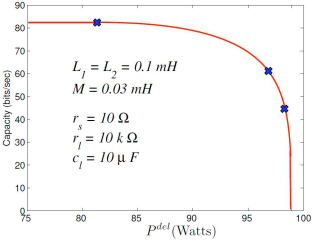
Maximize energy transfer vs **Maximize data rate**





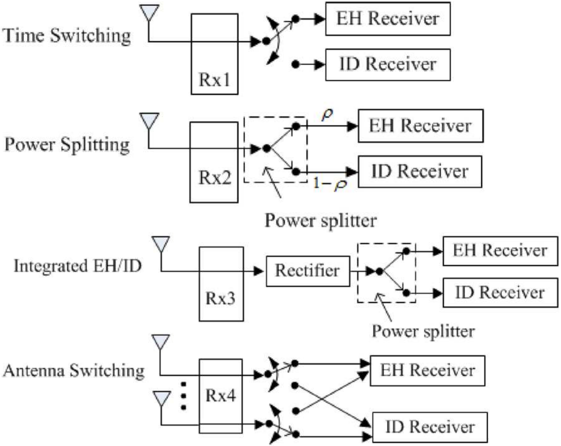
Tradeoff between capacity and power in frequency-selective AWGN channel

- Maximum received power (corresponding to Pdel = 98.9 W) obtained at zero-capacity, i.e. a sinusoid of fixed frequency has zero-bandwidth
- Maximum rate obtained by waterfilling

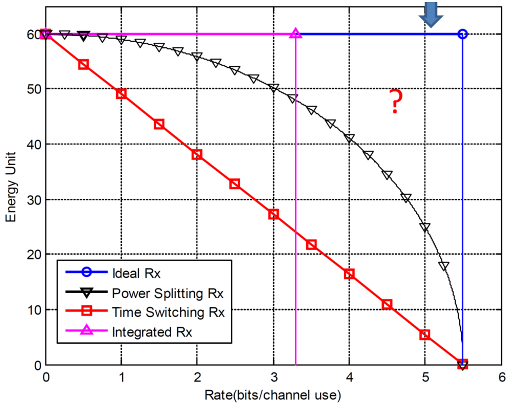


Receiver Architecture

Practical receivers **cannot** harvest energy and decode information from the same signal



Rate-Energy Region in Frequency-Flat AWGN Channel



Observation

1. *No tradeoff for ideal Rx:* $R \leq \log_2(1 + P_{\rm rf}^r/\sigma_n^2)$, $E \leq P_{\rm rf}^r$, $P_{\rm rf}^r = |h|^2\, P_{\rm rf}^t$
2. *Tradeoff induced by the receiver architecture*
3. *Power splitting outperforms time switching*

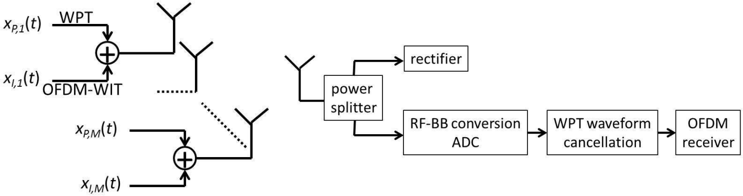
Rectifier Non-Linearity

...**but** based on the (oversimplified and inaccurate) **linear model**

- From linear model: modulated and unmodulated WFs are equally suitable
- From nonlinear model: $N = 1$: modulated>unmodulated, $N >> 1$: unmodulated>modulated

Rectifier nonlinearity changes the design of SWIPT

- Consider a multicarrier system over frequency-selective channel
- **Key idea**: superimposed deterministic and modulated waveforms



- Energy is harvested from the information and the power waveform
- How to design SWIPT signals?
- Account for non-linearity and leverage our previous WPT waveform design

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

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

$\rightarrow$ 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 $\bar{R}$)

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

Rate-Energy Region and Waveform Design

Energy: Maximizing i_{out} is equivalent to maximizing z_{DC}

$$
\begin{aligned}
z_{DC}(\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P, \mathbf{\Phi}_I, \rho) = k_2 \rho R_{ant} \mathcal{A}\left\{y_P(t)^2\right\} + k_2 \rho R_{ant} \mathcal{E}\left\{\mathcal{A}\left\{y_I(t)^2\right\}\right\} \\
+ k_4 \rho^2 R_{ant}^2 \mathcal{A}\left\{y_P(t)^4\right\} + k_4 \rho^2 R_{ant}^2 \mathcal{E}\left\{\mathcal{A}\left\{y_I(t)^4\right\}\right\} \\
+ 6 k_4 \rho^2 R_{ant}^2 \mathcal{A}\left\{y_P(t)^2\right\} \mathcal{E}\left\{\mathcal{A}\left\{y_I(t)^2\right\}\right\}
\end{aligned}
$$

Note the contribution from the information and the power waveforms weighted by the power splitting ratio ρ

Rate: deterministic waveform does not incur any rate loss

$$
I(\mathbf{S}_I, \mathbf{\Phi}_I, \rho) = \sum_{n=0}^{N-1} \log_2 \left(1 + \frac{(1-\rho)\left|\mathbf{h}_n \mathbf{w}_{I,n}\right|^2}{\sigma_n^2}\right)
$$

Rate-Energy Region and Waveform Design

Globally optimal phases in closed-form: same as WPT

Locally optimal amplitudes (convergence to a KKT point guaranteed): non-convex posynomial maximization problem formulated as a **Reversed Geometric Program**

Problem 2: **Standard GP**

$$\min_{\mathbf{S}_P,\mathbf{S}_I,\rho,\bar{\rho},t_0} \quad 1/t_0$$

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

$$t_0 \prod_{k=1}^{K} \left(\frac{g_k}{\gamma_k}\right)^{-\gamma_k} \leq 1,$$

$$2^{\bar{R}} \prod_{n=0}^{N-1} \prod_{k=1}^{K_n} \left(\frac{g_{nk}}{\gamma_{nk}}\right)^{-\gamma_{nk}} \leq 1,$$

$$\rho + \bar{\rho} \leq 1.$$

Algorithm

1: **Initialize**: $i \leftarrow 0$, $\bar{R}$, $\mathbf{\Phi}_P^\star$ and $\mathbf{\Phi}_I^\star$, $\mathbf{S}_P$, $\mathbf{S}_I$, ρ, $\bar{\rho} = 1 - \rho$, $z_{DC}^{(0)} = 0$

2: **repeat**

3: $i \leftarrow i + 1$, $\ddot{\mathbf{S}}_P \leftarrow \mathbf{S}_P$, $\ddot{\mathbf{S}}_I \leftarrow \mathbf{S}_I$, $\ddot{\rho} \leftarrow \rho$, $\ddot{\bar{\rho}} \leftarrow \bar{\rho}$

4: $\gamma_k \leftarrow g_k / z_{DC}$, $\forall k$

5: $\gamma_{nk} \leftarrow g_{nk} / \left(1 + \frac{\ddot{\bar{\rho}}}{\sigma_n^2} C_n(\ddot{\mathbf{S}}_I)\right)$, $\forall n, k$

6: $\mathbf{S}_P, \mathbf{S}_I, \rho, \bar{\rho} \leftarrow \arg\min$ Problem 2

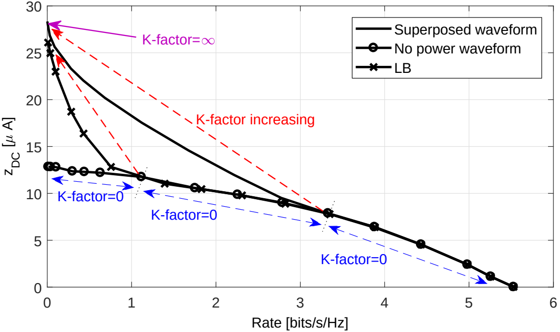
7: $z_{DC}^{(i)} \leftarrow z_{DC}(\mathbf{S}_P, \mathbf{S}_I, \mathbf{\Phi}_P^\star, \mathbf{\Phi}_I^\star, \rho)$

8: **until** $\left| z_{DC}^{(i)} - z_{DC}^{(i-1)} \right| < \epsilon$ or $i = i_{\max}$

Decoupling space and frequency domains also possible

Nonlinearity Changes The Whole Signal Design

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

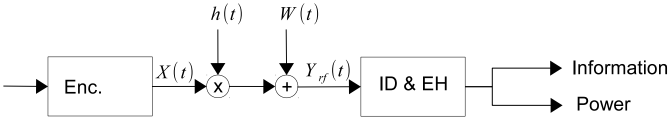


Observation

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!*

Characterizing Fundamental Limits of SWIPT

... in frequency-flat AWGN channel with Nonlinear Energy Harvester



- $W(t)$ additive white Gaussian process
- $h(t) = h$ constant known channel gain
- X_{rf} RF input, Y_{rf} RF output processes
- Joint Information Decoding (ID) and Energy Harvesting (EH)

Rate-Energy Region: Maximize information rate and delivered power

- Information rate (R): (Mutual information)

$$R = \mathcal{A}\left[I\left(X_{\text{rf}}(t); Y_{\text{rf}}(t)\right)\right]$$

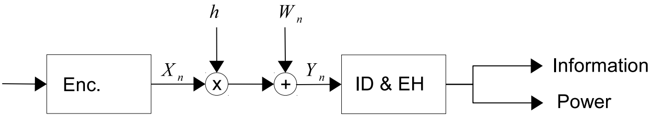
- Delivered power (P_{del}): (Nonlinear approximation)

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

subject to average power constraint at TX: $\mathcal{E}\mathcal{A}[X_{\text{rf}}(t)^2] \leq P_{\text{rf}}^t$

Characterizing Fundamental Limits of SWIPT

Baseband representation



- Y_n, X_n: samples at time n/f_w of downconverted $Y_{\text{rf}}(t)$, $X_{\text{rf}}(t)$
- W_n: sample at time n/f_w of downconverted $W(t)$
- Assume a memoryless channel (Y_n only depends on X_n and W_n) and iid channel inputs (neglect n)
- Delivered DC power P_{del} dependent on higher order statistics of the channel input distribution

Tradeoff between rate and energy

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

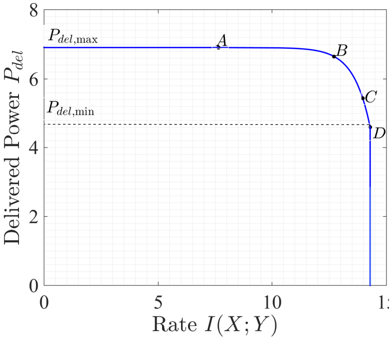
$$\text{s.t.} \quad \begin{cases} P \leq P_{\text{rf}}^t \\ P_{\text{del}} \geq P_d \end{cases}$$

Characterizing Fundamental Limits of SWIPT

Assumption: channel inputs determined by 1^{st} and 2^{nd} moment statistics

Supremum achievable by Gaussian inputs: $\Re\{X\} \sim \mathcal{N}(0, P_r)$, $\Im\{X\} \sim \mathcal{N}(0, P_i)$ such that $P = P_r + P_i = P_{\text{rf}}^t$.

Points A, B, C, D correspond to $(P_r, P_i) = (0,1)$, $= (0.03, 0.97)$, $= (0.2, 0.8)$, $= (0.5, 0.5)$ with $P_{\text{rf}}^t = 1$

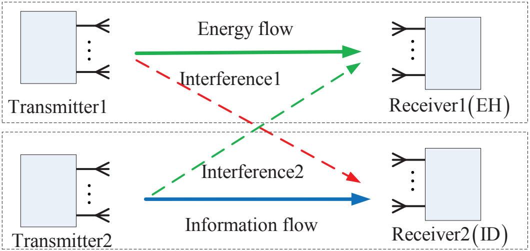


Observation

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***

SWIPT - Multiuser and Interference

Energy flow and Information flow in SWIPT network



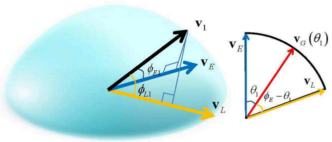
Mitigate or Exploit interference? Interfere or not interfere?

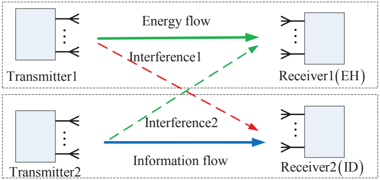
- Interference harmful to information receiver but useful to energy harvesting
- Opportunistic mode switching (EH and ID) in fading channel
- Receivers use time switching (TS) or power splitting (PS)
- Transmitters cooperate in joint information and energy transmission
- Interference channel rate-energy tradeoff
- New paradigm for interference management

Optimality of Energy Beamforming

Theorem

For two-user MIMO IC (one energy transceiver and one information transceiver), the optimal energy beamforming vector that yields the optimal boundary of the achievable two-user rate-energy region lies in the Geodesic curve between $[\mathbf{V}_{11}]_1 (\triangleq \mathbf{v}_E)$ *and* $[\mathbf{V}_{21}]_M (\triangleq \mathbf{v}_L)$.

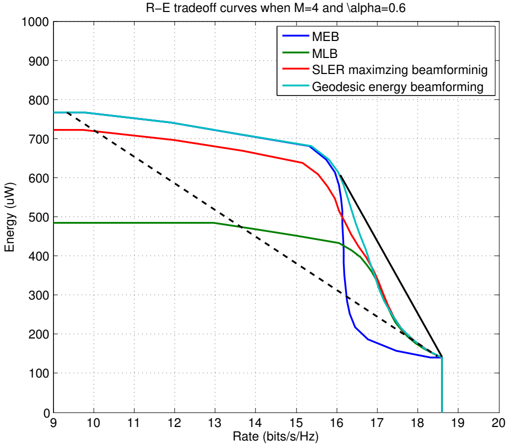




Analogy with conventional IC - Competition vs. Cooperation:

- The optimal geodesic energy beamforming vector is a linear combination of MEB (signal maximization) and MLB (interference minimization) vectors
- Analogous to the optimal beamforming in conventional IC: linear combination of a matched filter beamformer (signal maximization) and a zero-forcing beamformer (interference minimization)

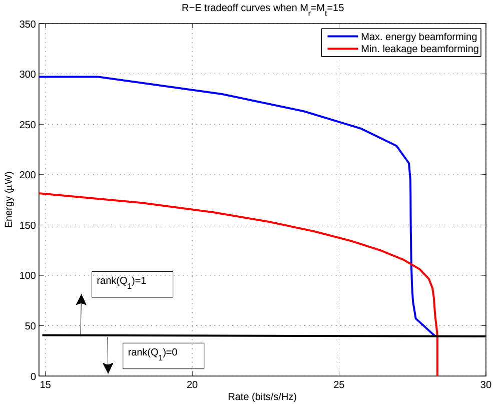
R-E region



Observation

1. *R-E region of the Geodesic beamforming covers those of all other beamforming schemes*

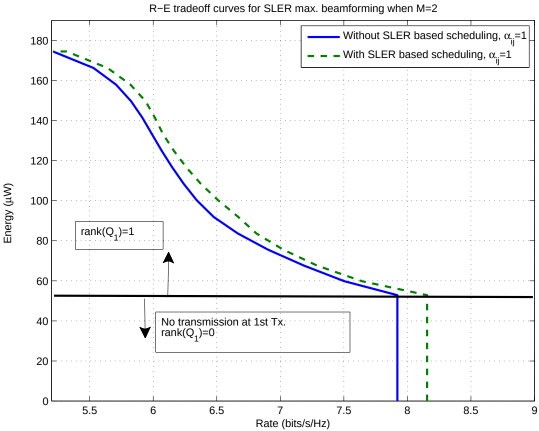
As MIMO gets massive



Observation

1. *Gap between the achievable rates of MEB and MLB is less apparent*
2. *MEB exhibits a wider R-E region than MLB*
3. *SWIPT design split into disjoint WIT and WPT in two non-interfering links*

Opportunistic Scheduling



Observation

1. *Dynamic switching between modes* (EH_1, ID_2) *and* (ID_1, EH_2) *extends the achievable R-E region*

SWIPT in many other channels

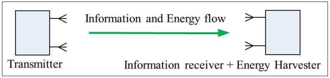


Figure: Point-to-point

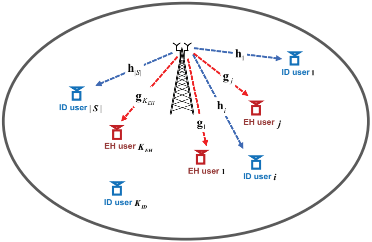


Figure: Broadcast Channel

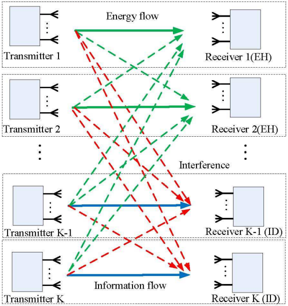


Figure: Interference Channel

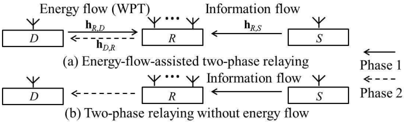
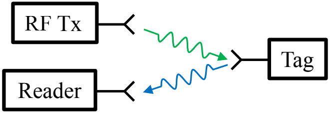


Figure: Relay Channel

Wireless Powered Backscatter Communication

Backscatter Communication



- Tags harvest energy from the transmit RF signal
- Tags reflect and modulate the incoming RF signal
- Low power consumption: no need for oscillators at tags

SNR-Energy Tradeoff and Waveform Design

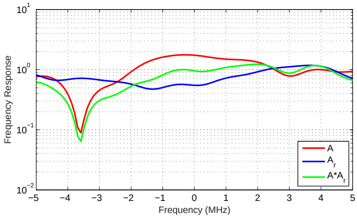
- Energy at tag: nonlinear function of forward channel and Tx signal
- SNR at reader: linear function of backscatter channel and Tx signal
- Waveform design for SNR and energy maximization are different

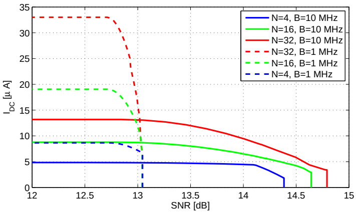
$$C_{SNR-I_{DC}}(P) \triangleq \Big\{(SNR, I_{DC}) : SNR \leq \rho(\mathbf{s}),$$

$$I_{DC} \leq z_{DC}(\mathbf{s}, \mathbf{\Phi}), \frac{1}{2}\|\mathbf{s}\|^2 \leq P\Big\}$$

Wirelessly Powered Backscatter Communication

Channel frequency responses and **SNR-Energy trade-off** with B=1,10MHz





Observation

1. *SNR and energy indeed subject to a fundamental tradeoff*
2. *Increasing N beneficial: exploits rectifier nonlinearity and frequency diversity gain*

Conclusions

Communications and signals for WIPT systems (WPT, SWIPT, WPCN, WPBN)

- Lay the foundations and tackle the challenges of the envisioned network
- Establish a mobile power 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

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 rectenna in any design involving wireless power: WPT, SWIPT, WPCN, WPBN

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

Future Work Directions

- Wireless energy harvesting (WEH) and wireless power transfer (WPT)
- Simultaneous wireless information and power transfer (SWIPT)
- Wirelessly powered communication networks (WPCNs)
- Wirelessly powered backscatter communication (WPBC)
- Analytical models of energy harvesters for signal, system and architecture design
- Fundamental limits of signal design for WPT, SWIPT, WPCN and WPBC
- Communications and signal design for WPT, SWIPT, WPCN and WPBC
- Waveform and beamforming design for WPT, SWIPT, WPCN and WPBC
- Channel estimation, feedback and acquisition for WPT, SWIPT, WPCN and WPBC
- WEH, WPT, SWIPT, WPCN and WPBC in pt-to-pt, BC, IC and relay channels
- Multi-node coordination/cooperation for WPT, SWIPT, WPCN and WPBC
- Network architecture and protocols for WEH, WPT, SWIPT, WPCN and WPBC
- Wireless charging control, energy management, resource allocation and scheduling strategies for WPT, SWIPT, WPCN and WPBC
- Large-scale multi-antenna/massive MIMO in WPT, SWIPT, WPCN and WPBC
- WEH, WPT, SWIPT, WPCN and WPBC at mmWave frequencies
- Safety, security and economic issues in WPT, SWIPT, WPCN and WPBC
- Spectrum sharing an interference management for coexisting WPT and WIT systems
- Prototyping and experimentation of WEH, WPT, SWIPT, WPCN and WPBC
- Applications of WEH, WPT, SWIPT, WPCN and WPBC in wireless sensor networks (WSNs), machine-to-machine (M2M), device-to-device (D2D), Internet-of-Things (IoT), WiFi, cellular networks and 5G

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