Far-Field Wireless Power Transmission: RF, Signal and System Designs

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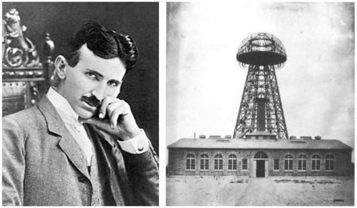
WPT and WIPT: Introduction and Applications

Wireless is More than just Communications

Radio waves carry both energy and information

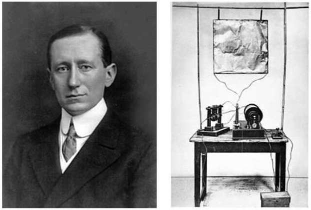
Wireless Power Transmission
(WPT)



Tesla 1901

0G

Wireless Information Transmission
(WIT)

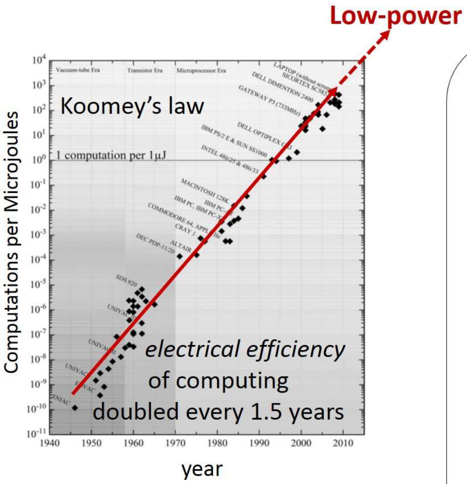


Marconi 1896

5G

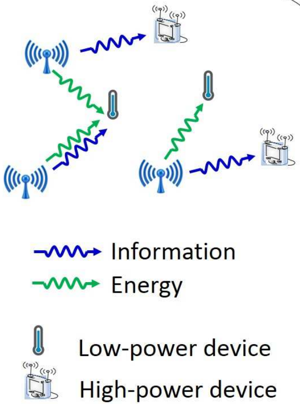
Unified Wireless Information and Power Transmission
(WIPT)

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



2017: 5 Billions phones

2035: **Trillions** IoT devices



Future of Wireless:

Communicate and Energize

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

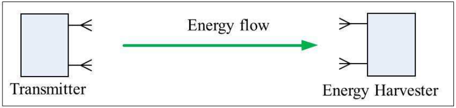
Comparison of the main technologies for WPT

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 Power via RF

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



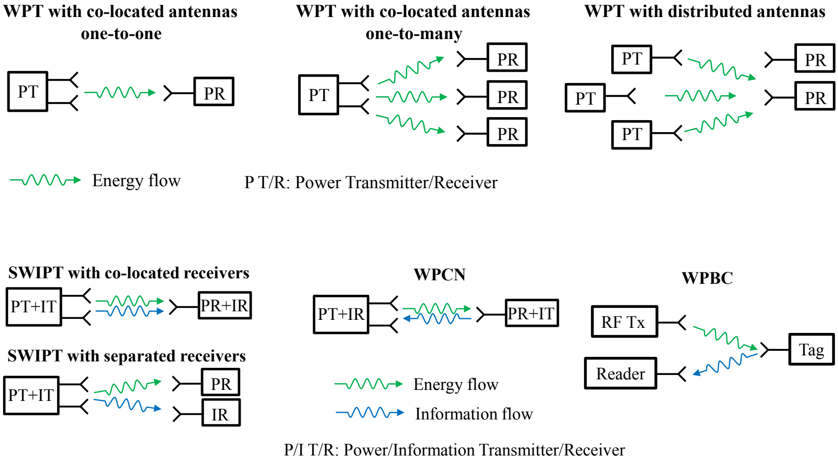
Two **far-field** techniques: **Wireless Power Transfer** (WPT) and **Wireless Energy Harvesting** (WEH)

- 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 ($10\mu W$)

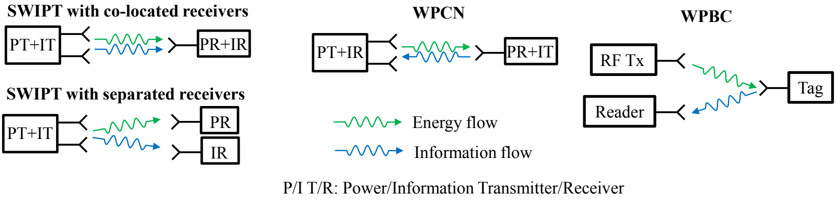
Applications: Wireless charging for

- 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 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

Wireless Information and Power Transfer

... applications in all usual communication channels

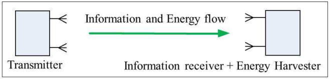


Figure: Point-to-point

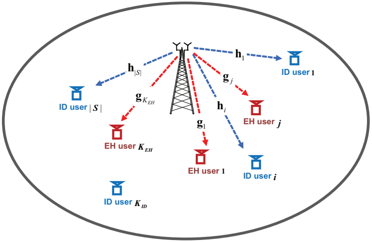


Figure: Broadcast Channel

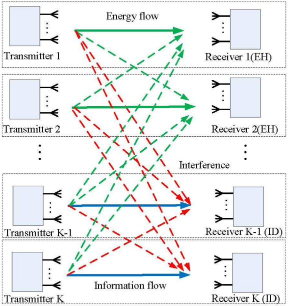


Figure: Interference Channel

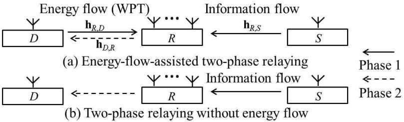


Figure: Relay Channel

RF, Signal and System Design for WPT

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:

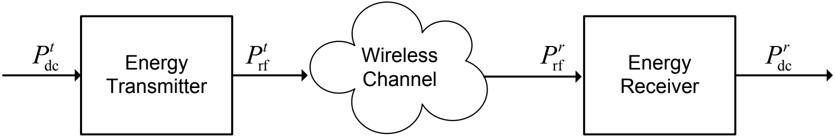
- Low-power (e.g., from μW to a few W) delivery over moderate distances (e.g., from a few m to possibly hundreds of m)
- Need to build reliable and convenient WPT systems for remotely charging various low- to medium-power devices (RFID tags, wireless sensors, smart phones, ...)

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



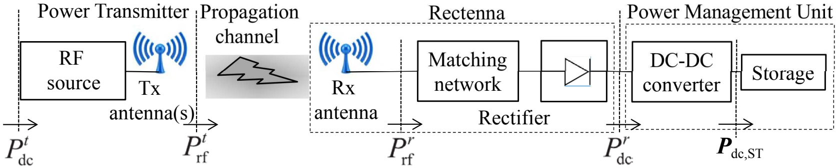
End-to-End Power Transfer Efficiency

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

- 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

WPT Architecture

... slightly more detailed



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

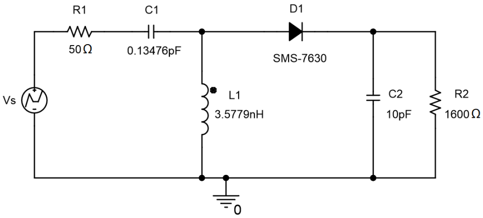
DC-to-RF conversion efficiency e_1: efficient power amplifier (PA) design and transmit signals with constrained PAPR

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 beamforming and accurate channel knowledge at Tx

WPT Architecture

RF-to-DC conversion efficiency e_3: rectenna design

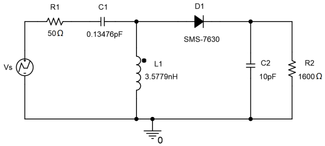


- **Antenna + Rectifier** (a non-linear device + a low-pass filter and load)
- Assuming $P_{\rm rf}^{t} = 1W$, 5-dBi Tx/Rx antenna gain, a continuous wave (CW) at 915MHz, $e_3 \approx 50\%$ (1m), 25% (10m), 5% (30m)
- With CW, $e_3 \approx 80\%$ (10mW), 40% (100μW), 20% (10μW), 2% (1μW)
- For input power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

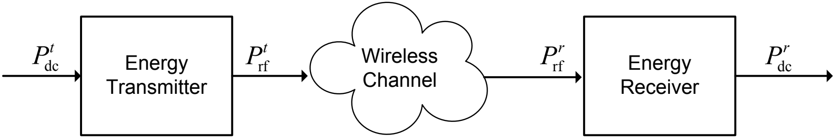
- Due to rectifier nonlinearity, e_3 *influenced by input waveform power and shape* in the low input power regime ($1\mu W$-$1mW$)!



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

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

Rectenna Design

Rectenna Functions

London Underground **RF Spectral Survey** – Harvesting/Transfer

Wireless Power **Receiver Design**

What is the **Design Strategy** ?

Rectifier Topologies

Multi-Tone Wireless Power Receiver

Wireless Power Receiver (WPRx) Rectenna Design

Mahmoud Ouda, Paul D. Mitcheson, Bruno Clerckx

Outline

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- Rectenna Functions
- London Underground RF Spectral Survey –Harvesting/Transfer
- Wireless Power Receiver Design
  - Challenges
  - Blocks
- What is the Design Strategy ?
- Rectifier Topologies
- Multi-Tone Wireless Power Receiver

Rectenna Functions

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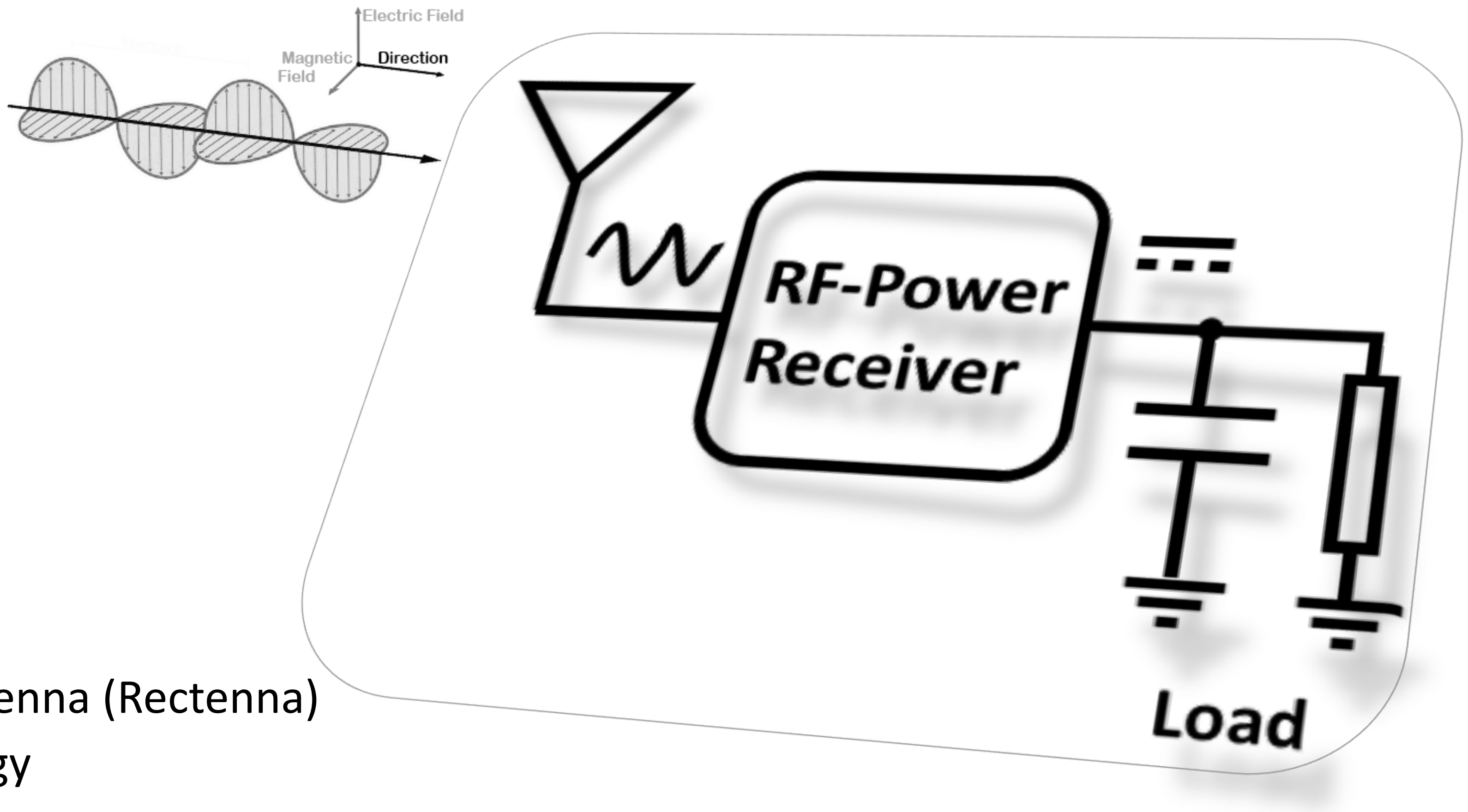


- Antenna + rectifier = Rectifying antenna (Rectenna)
  - Picks up electromagnetic energy
  - Converts it into dc power
  - Stores it as an electrical energy
  - Supplies dc voltage (power) to an electrical load.

How Good is Ambient RF?

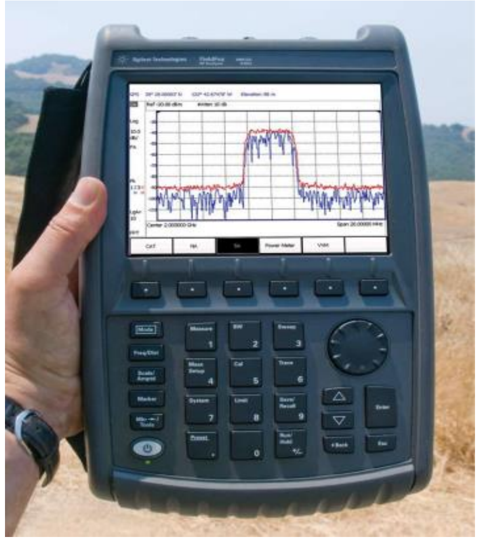
London Underground RF Spectral Survey

270 Tube stations
Hours: 10:00 – 14:00

- Measurement concentration on dense areas
- Urban to “Semi-Urban” environment
- Different scenarios

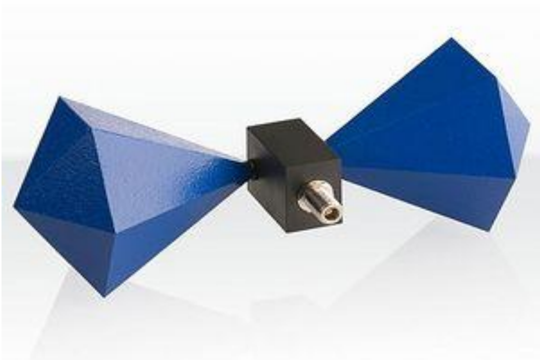
http://www.tfl.gov.uk

Spectral Survey Equipment



Agilent Fieldfox 0.03 - 6 GHz

Spectrum analyzer
Network analyzer
Cable and antenna analyzer



Aaronia Bicolog 20300

0.3-3 GHz calibrated omnidirectional antenna.
296 calibration points, 10 MHz steps

Survey Procedure
Based on FCC, ECC and ICNIRP standards

Max Hold
5 dB attenuation when possible
20 dBµV/m reference level

“Panning approach”
Several sweeps in three axis

http://www.cept.org/ecc

London Underground RF Spectral Survey

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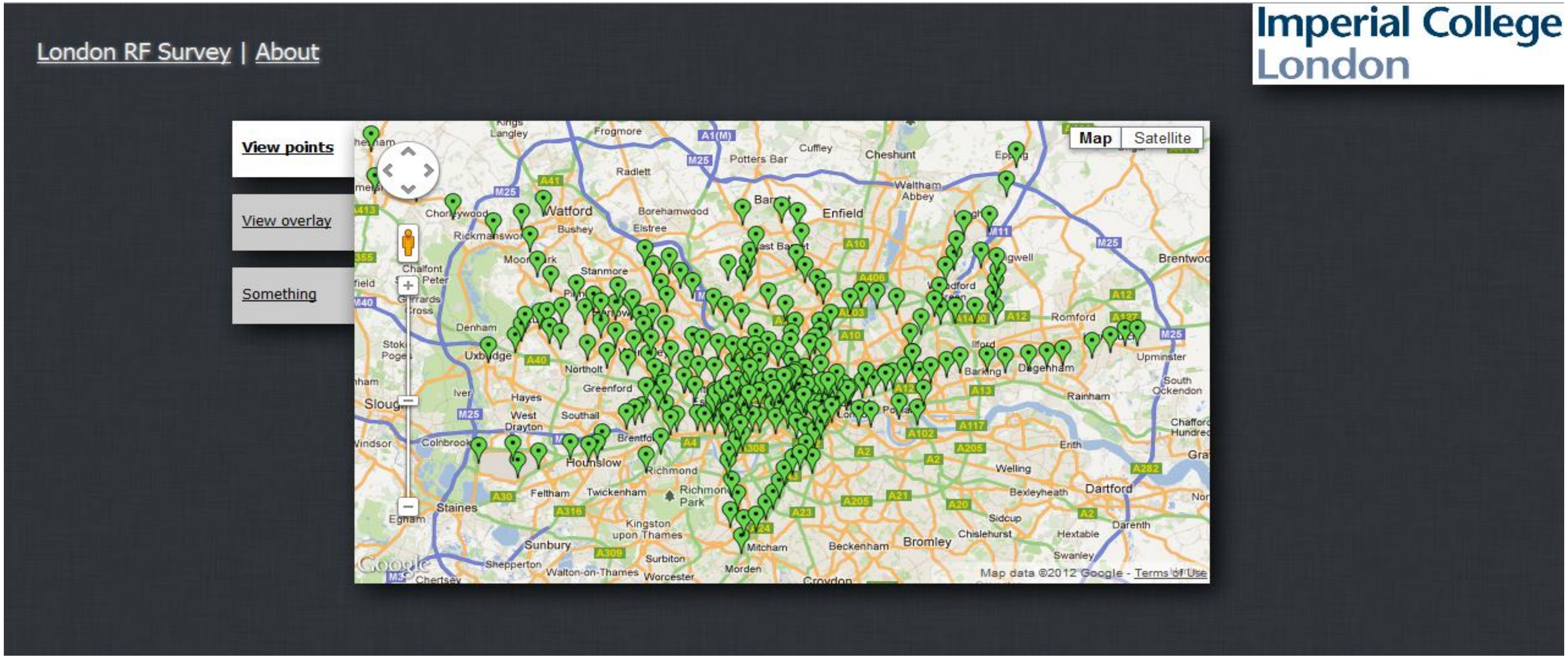

(Interactive website: www.londonrfsurvey.org/)

London Underground RF Spectral Survey

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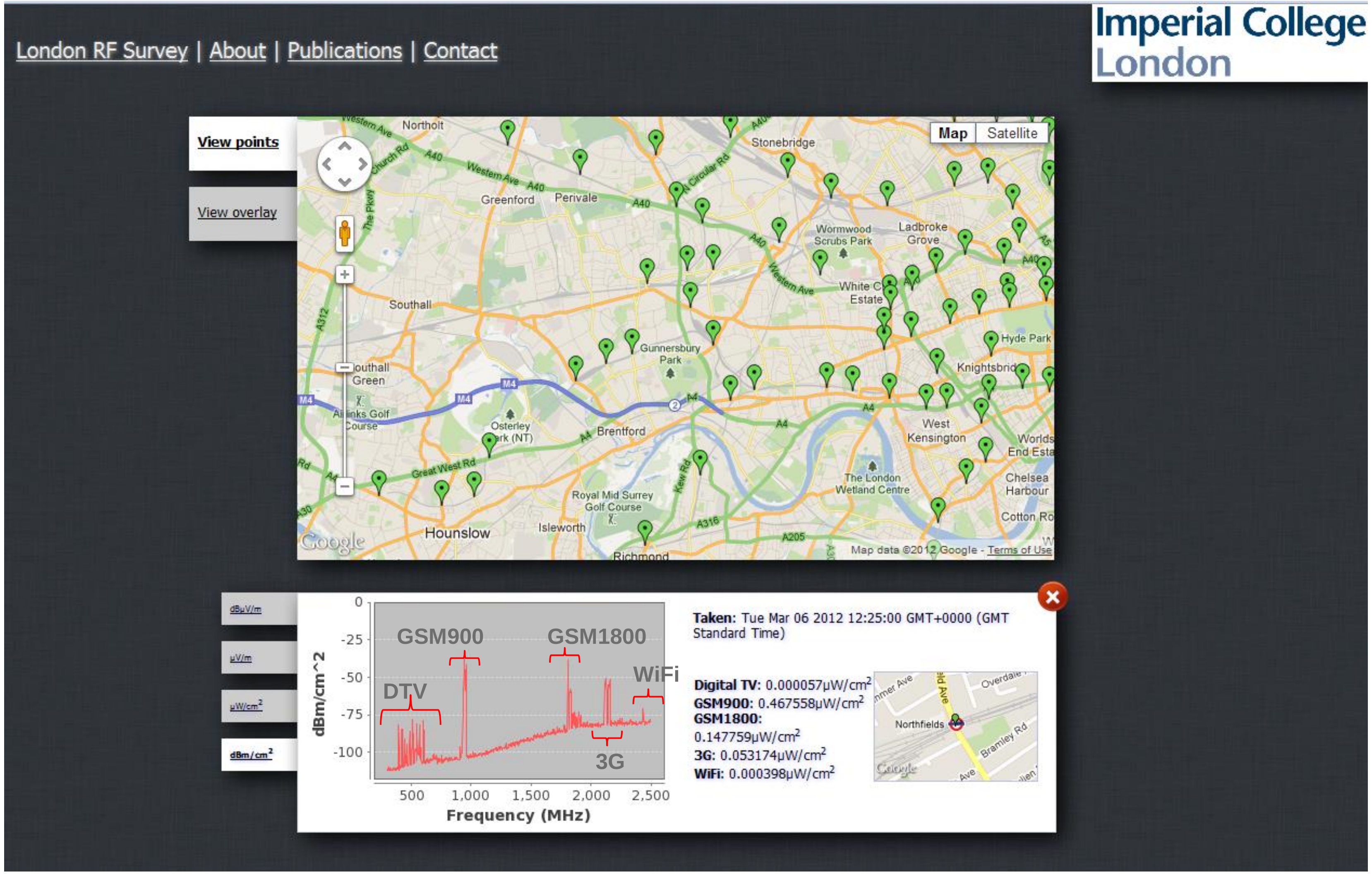

London Underground RF Spectral Survey Summary

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Band name	Frequency (MHz)	BW (MHz)	Average P (μW/cm^2)	Maximum P (μW/cm^2)
DTV	470 - 610	140	0.89x10-3	0.046
GSM 900	921 - 960	39	0.036	1.93
GSM 1800	1805 - 1876	71	0.084	6.39
WiFi	2400 - 2473	73	0.18x10-3	6.47x10-3
3G	2110 - 2170	60	0.012	0.24

London Underground RF Spectral Survey

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(Interactive website : www.londonrfsurvey.org)

London Underground RF Spectral Survey

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Band	S_{BA} Threshold [nW/cm^2]	Number of Stations Urban	Number of Stations Semi-urban
DTV*	40	10	0
GSM900	230	8	2
GSM1800	450	7	3
3G	62	6	4

**During switch over*

(Interactive website : www.londonrfsurvey.org/)

WPT – Design Considerations

WPT Challenges

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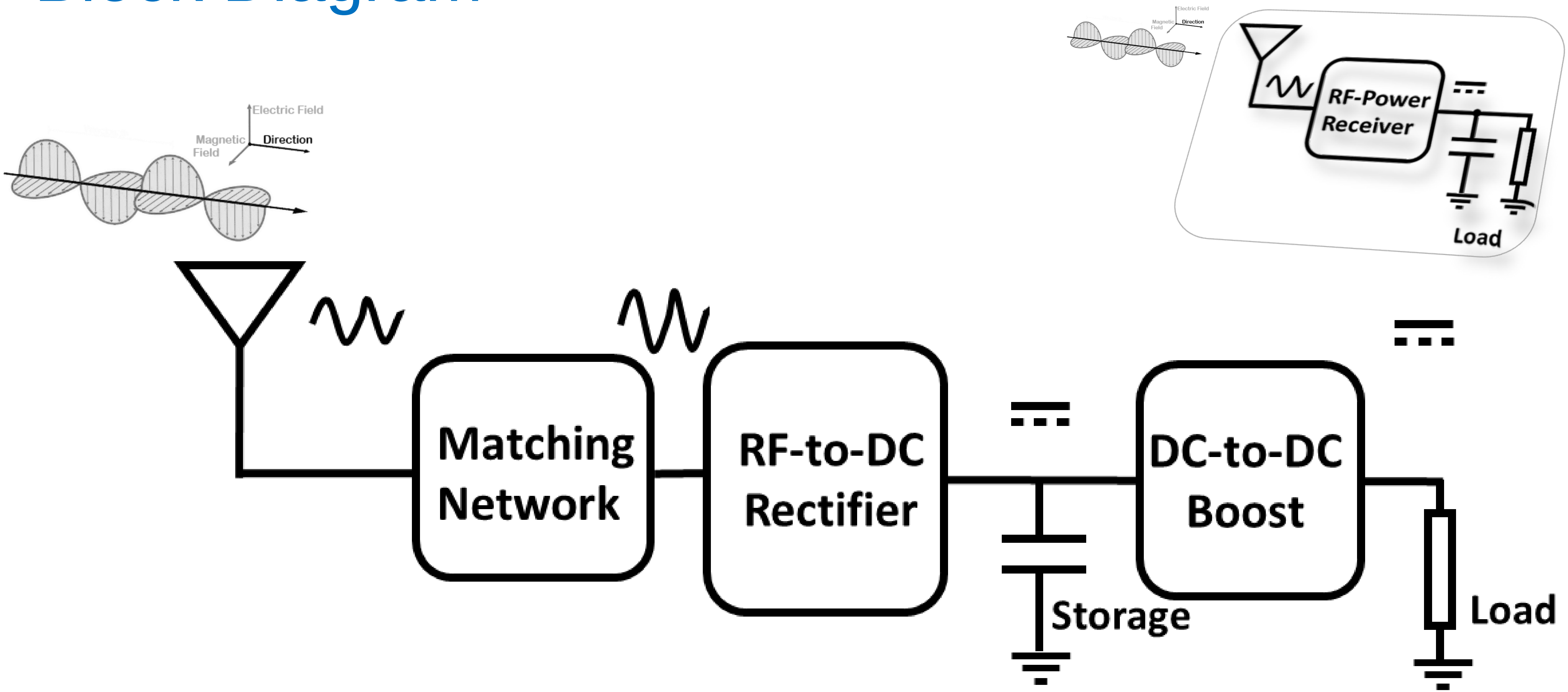
- Very low power levels on antenna
  - Implies low voltage swing on diode
  - Difficulty in rectification
  - Thus a low efficiency
- Circuit is inherently non linear
  - Function of power level
  - Makes impedance match difficult
  - Analysis is tricky
- High frequency
  - Limits choice of diodes

Block Diagram



Block Diagram(1)

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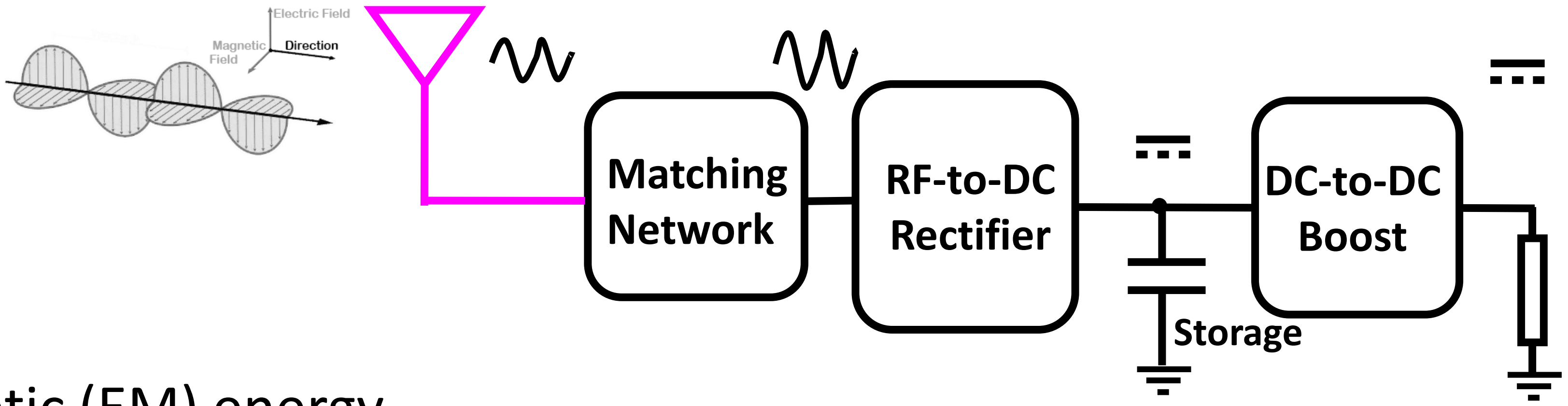


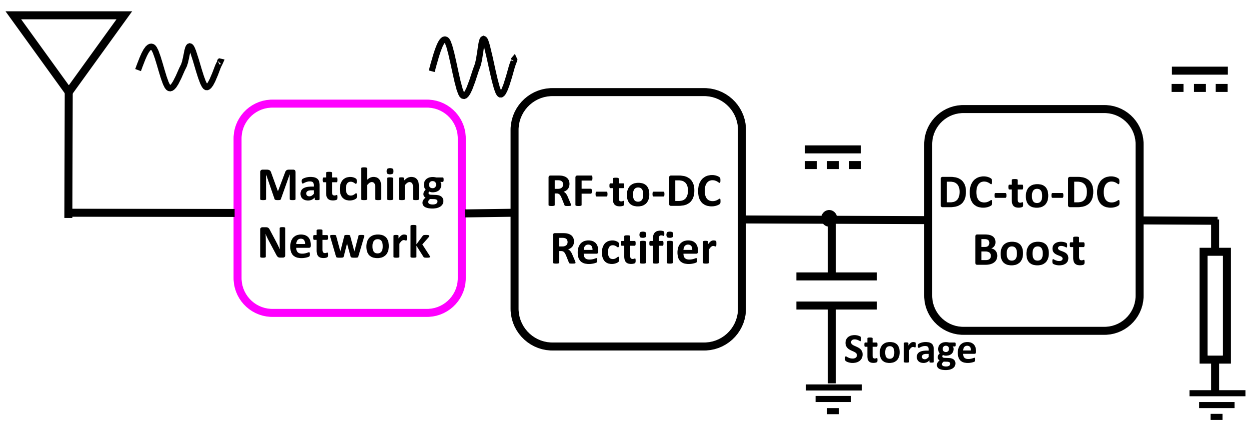
1. Antenna (Gr)

- Picks up electromagnetic (EM) energy
- Generates RF voltage (V_{RF})

Specifications:

- Antenna gain (Gr) dBi (high could be good for WPT, but bad for harvesting)
- Impedance (Za) (not necessarily 50 Ω...)
- Geometry (defines the system size)

Block Diagram(2)



1. Antenna (Gr)
2. RF matching network
   - Maximizes RF-power transfer to the converter
   - Conjugately matches the antenna/converter impedances
   - Boosts the RF voltage (V_{RF}) to turn on the next rectifying diode.
   - Needs to be low loss

Specifications:

- Matching efficiency=$(1-|\Gamma|^2)$; $|\Gamma|$ Reflection $= |\frac{Z_{in}-Z_a^*}{Z_{in}+Z_a}|$

Block Diagram(3)

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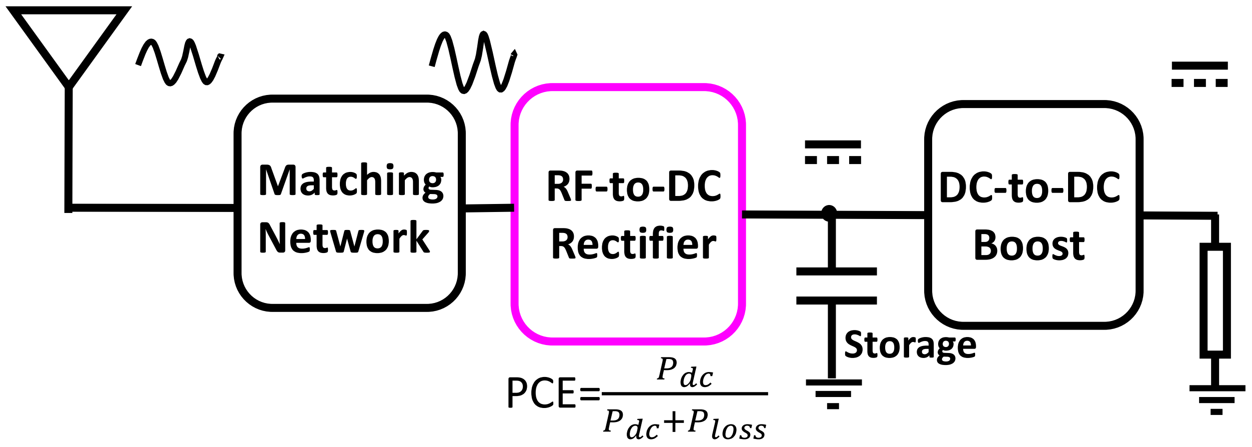

1. Antenna (Gr)
2. RF matching network
3. RF-to-dc power converter (Rectifier)
   - Converts RF power into dc power
   - Nonlinear diode impedance with diode operating point (V_{diode}, I_{diode})
   - Function of input power P_{RF} & loading condition RL(Vo)

Specifications:

- RF-to-dc efficiency $= \frac{P_{dc}}{P_{RF}} = \frac{P_{dc}}{P_{dc}+P_{loss}}$; P_{loss} = conduction and reverse leakage losses

Block Diagram(4)

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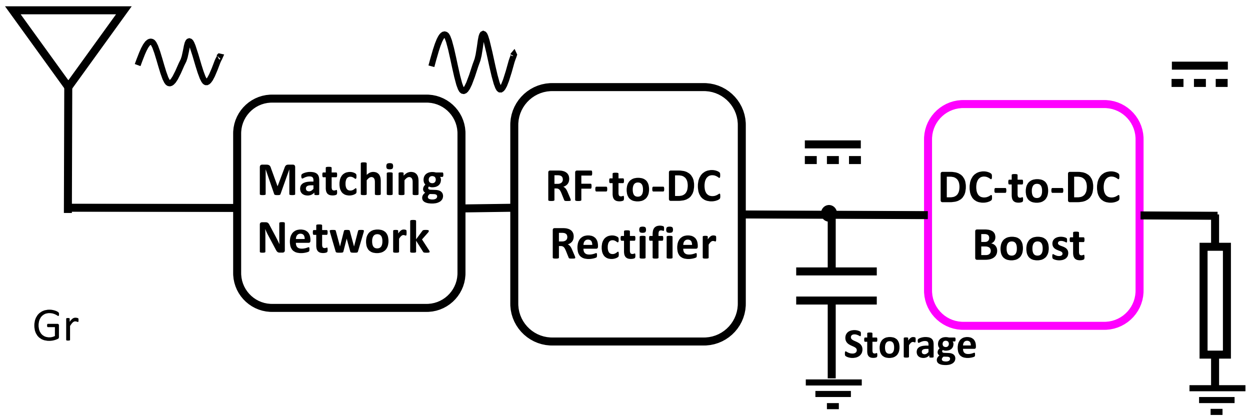


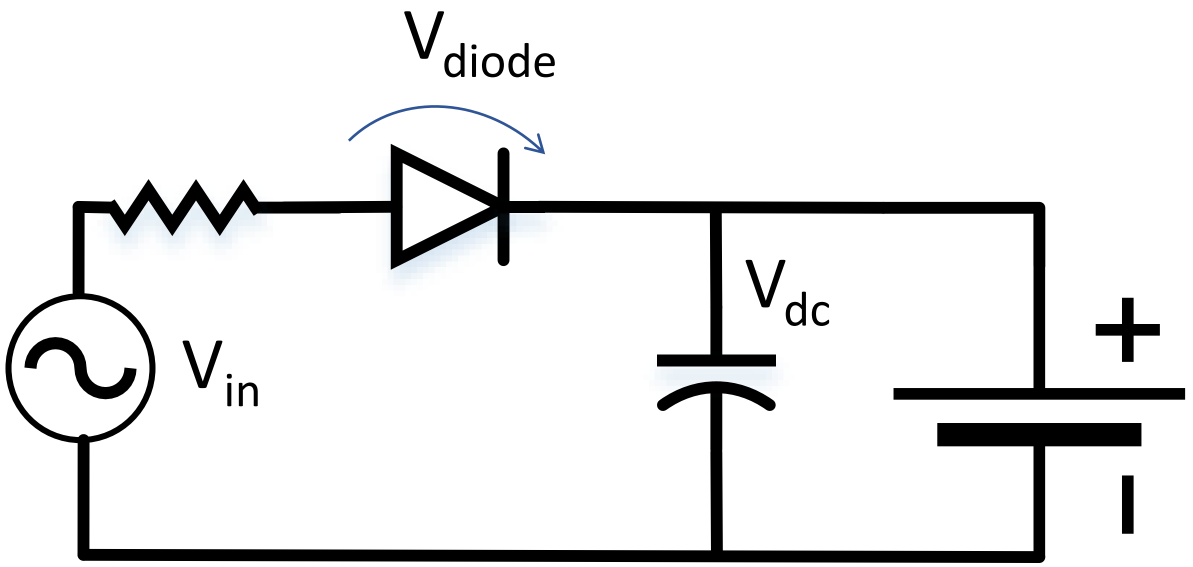
1. Antenna (Gr)
2. RF matching network
3. RF-to-dc power converter (Rectifier)
4. DC-to-dc voltage boost converter
   - Supplies a usable dc voltage level from low voltage RF-DC stage
   - Decouples the system load dynamics
   - Could apply MPPT

Specifications:

- DC-to-dc efficiency $= f(Vin = Vdc)$

What is the Design Strategy (1)?

$$\text{Efficiency} = \frac{P_{dc}}{P_{in}} = \frac{P_{dc}}{P_{dc}+P_{loss}}$$



- *Considering diode conduction loss:*

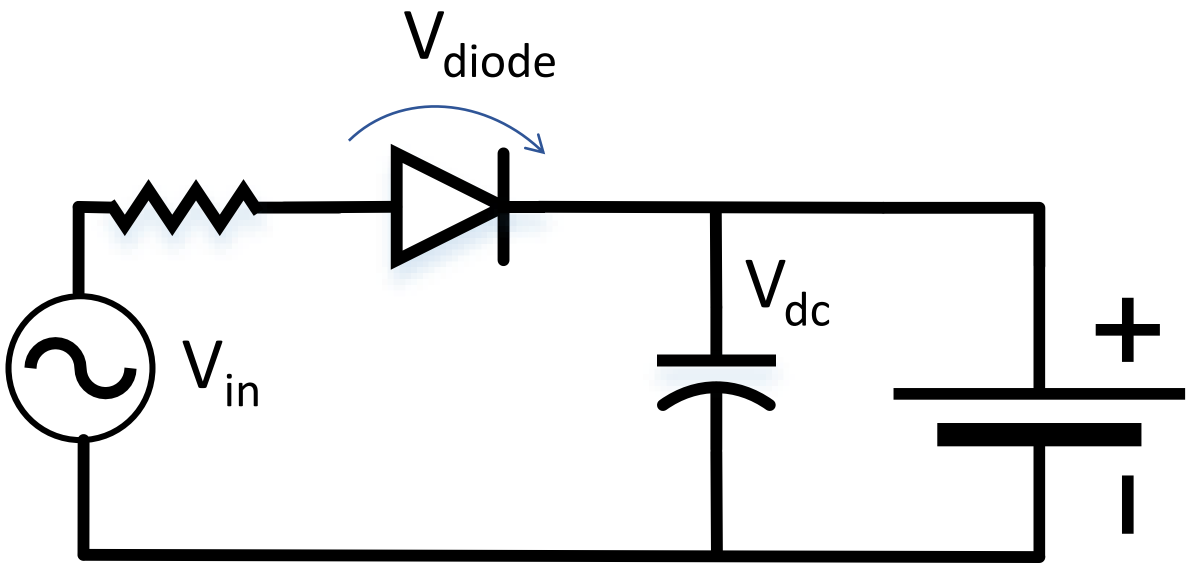
→ $\text{Efficiency} \approx \frac{V_{dc}}{V_{dc}+V_{diode}}$

where $V_{diode} \approx 0.3 : 0.5$ V

✓Target #1 : the highest possible V_{dc} out of the available input power, P_{in}

What is the Design Strategy (2)?

$$\text{Efficiency} = \frac{P_{dc}}{P_{in}} = \frac{P_{dc}}{P_{dc}+P_{loss}}$$



- *Considering diode reverse loss:*

  $V_{diode\ rvs}$ $(= V_{dc}-V_{in}) < V_{BD}$ (for peak rectifier)

→ $V_{in\ peak}$ should be < VBD/2

where $V_{BD} \approx 2V$ (SMS7630)

- To maintain the peak efficiency,

✓Target #1 : the highest possible V_{dc} out of the available input power, P_{in}

✓Target #2: V_{dc} should not breakdown the diode

Optimal RF-to-dc efficiency

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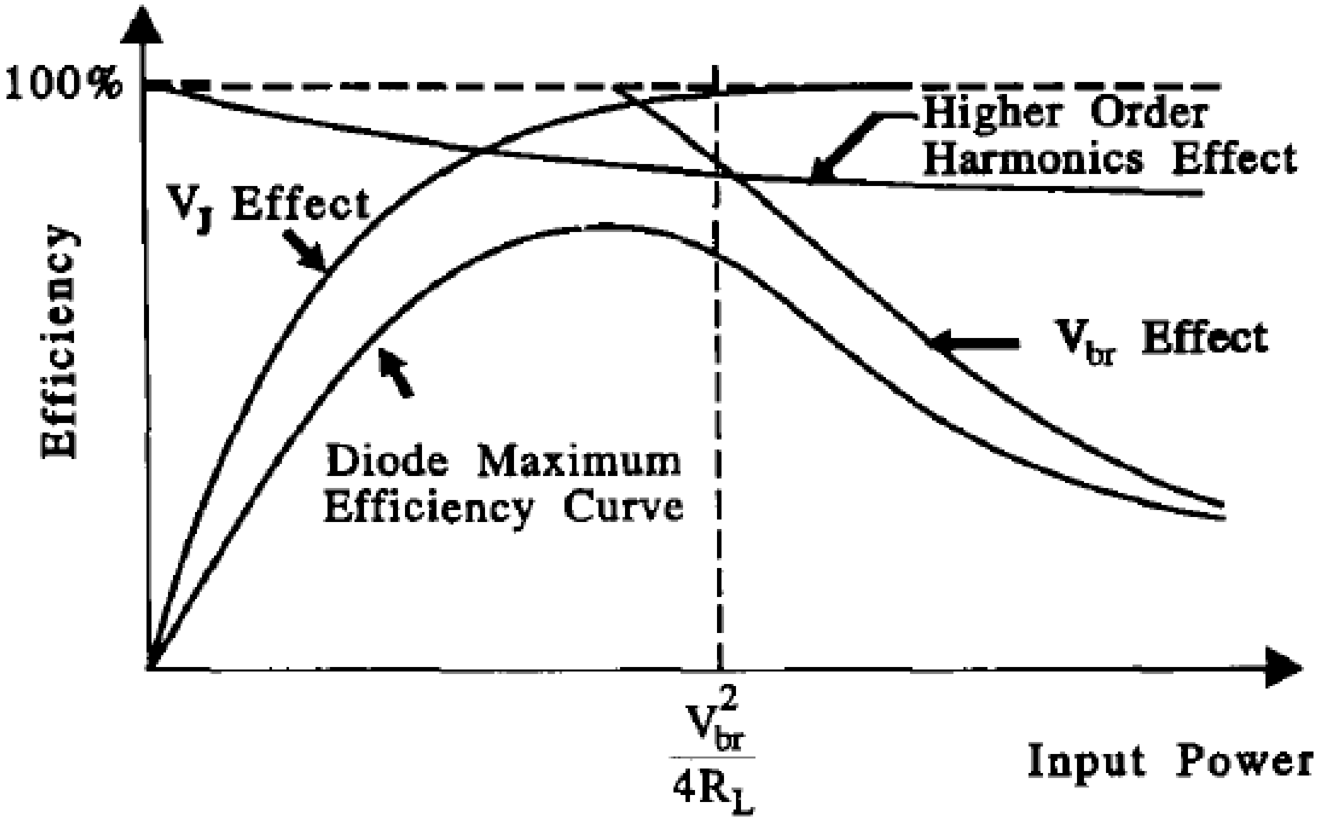
$$\text{RF-to-dc efficiency} = \frac{P_{dc}}{P_{RF}} = \frac{P_{dc}}{P_{dc}+P_{loss}};$$

$$P_{loss} = P_{fwd} + P_{rvs};$$

- The peak efficiency is an optimum between:
  - The forward (junction) loss
  - The reverse (breakdown) leakage loss.



T. W. Yoo and K. Chang, "Theoretical and experimental development of 10 and 35 GHz rectennas," in IEEE Transactions on Microwave Theory and Techniques, vol. 40, no. 6, pp. 1259-1266, Jun 1992.

Optimal operating point for diode rectifiers

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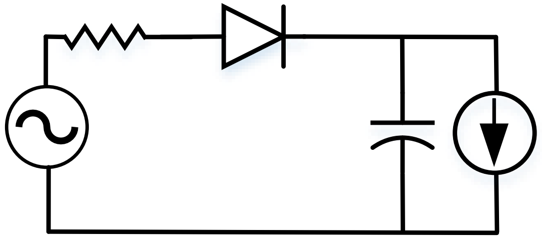
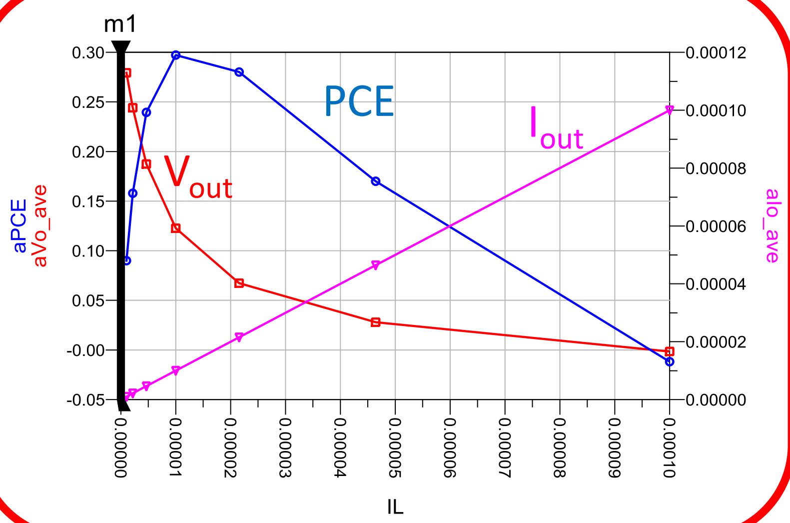
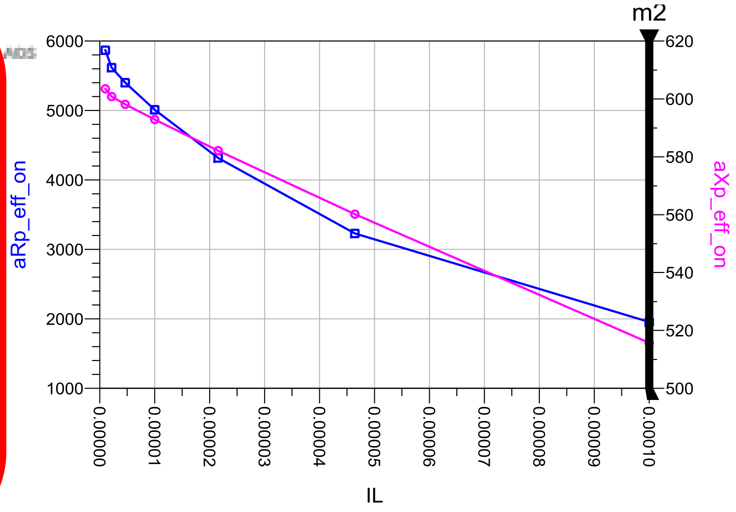
Vin=8 tones* 0.07V
CL=10pF,   f=2.4GHz

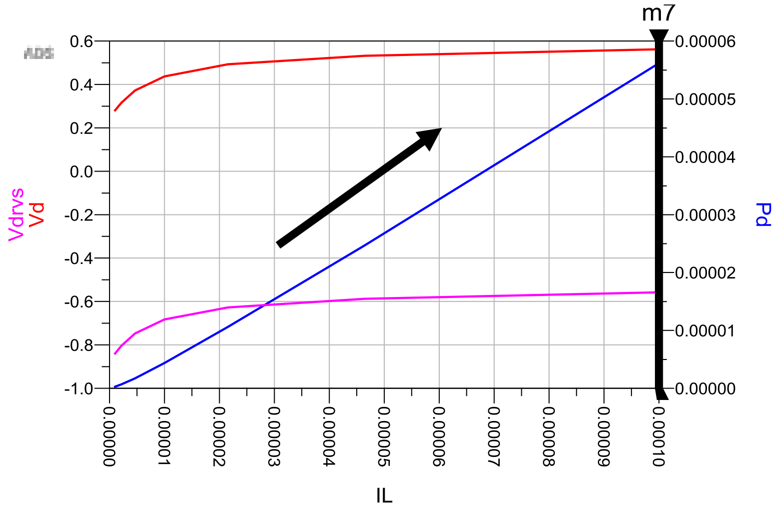


- Constant input voltage excitation with 8 tones
- As output current increases (R_L decreases) we see the expected peak in efficiency
- Diode impedance changes with operating point
- No matching (but PCE doesn't include matching)

The optimal operation at the minimum I_d before the $V_{breakdown}$







What is the Design Strategy (3)?

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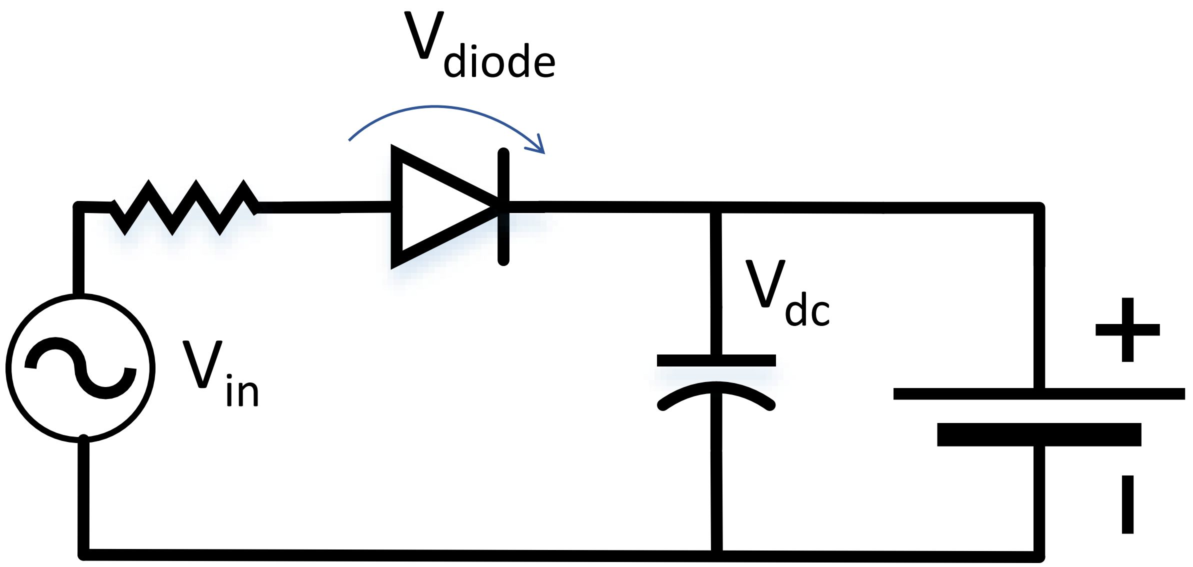
$$\text{Efficiency} = \frac{P_{dc}}{P_{in}} = \frac{P_{dc}}{P_{dc}+P_{loss}}$$



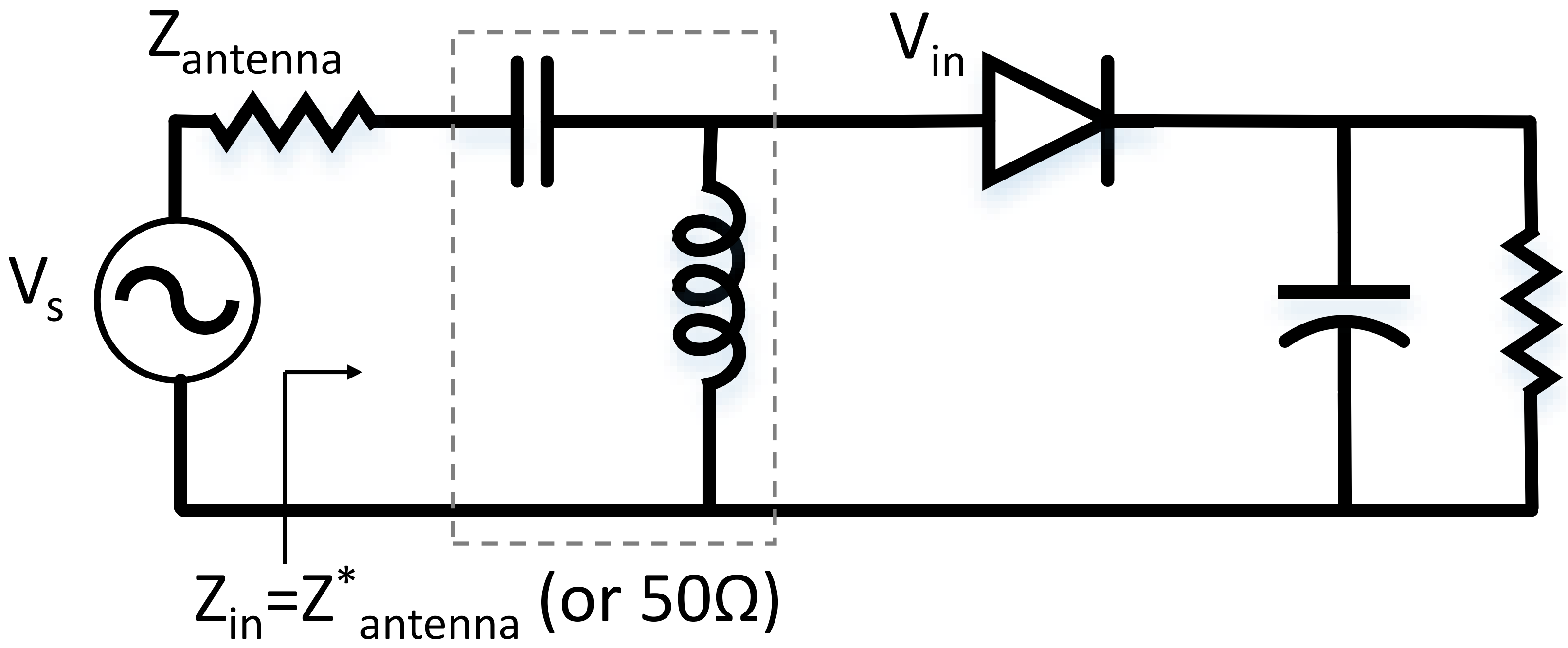
- To maintain the peak efficiency,

✓Make V_{dc} as large as possible before breakdown

→Increasing V_{dc} will increase input impedance (Z_{in})

→Need to match Z_{in} (>>50 Ω) to the antenna

What is the Design Strategy (4)?



Matching network

- Conjugately matching $Z_{in}=Z^*_{antenna}$
- Consequently boosts the input voltage to the diode

Typical Diode Parameters

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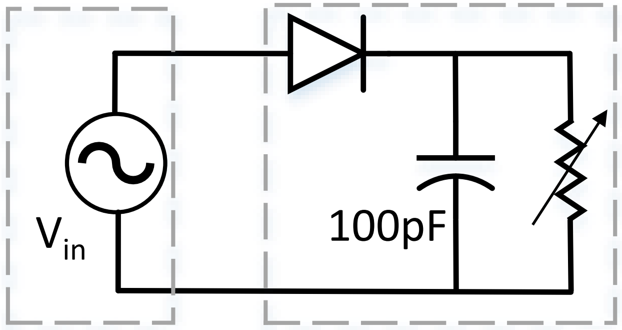
Parameter	Units	SMS7621 Series	SMS7630 Series
I_S	A	4E-8	5E-6
R_S	Ω	12	20
N	–	1.05	1.05
TT	sec	1E-11	1E-11
C_{JO}	pF	0.1	0.14
M	–	0.35	0.40
E_G	eV	0.69	0.69
XTI	–	2	2
F_C	–	0.5	0.5
B_V	V	3	2
I_{BV}	A	1E-5	1E-4
V_J	V	0.51	0.34

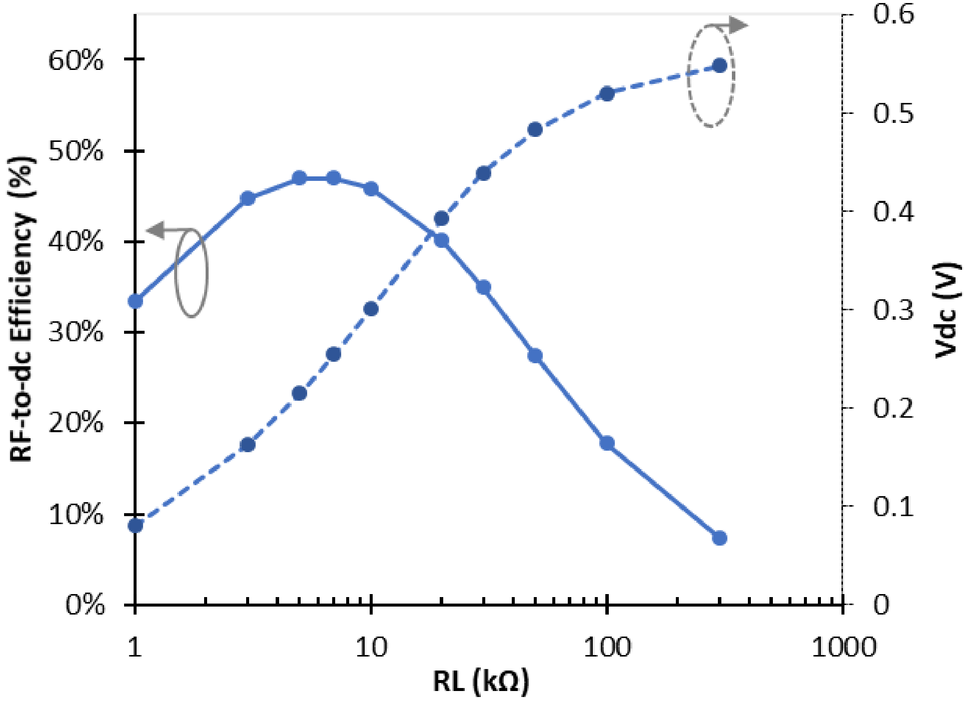
Far-Field Wireless Power Transmission: RF, Signal and System Designs, 2018 Mahmoud Ouda, Paul D. Mitcheson, B, Clerckx

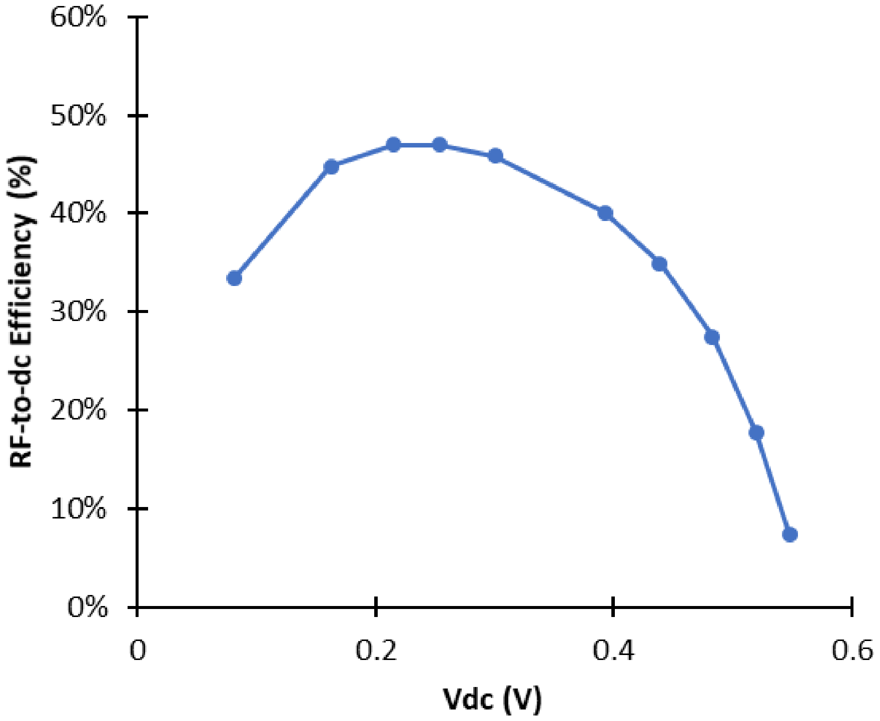
How to Implement the Optimal Voltage (1)?



peak detector

- Are we controlling the output voltage, current or load resistance?





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How to Implement the Optimal voltage (2)?

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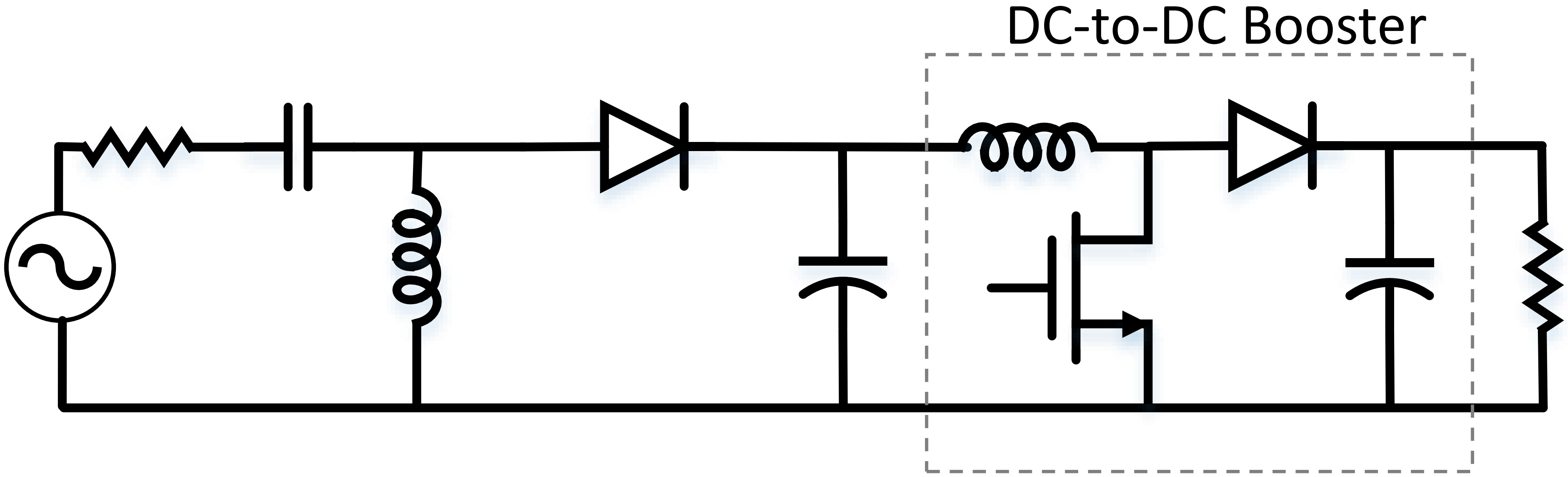

DC-to-dc boost voltage converter controls its input impedance (i.e: rectifier load R_L) to set V_{dc} at the optimal value

What Other Options Do We Have?

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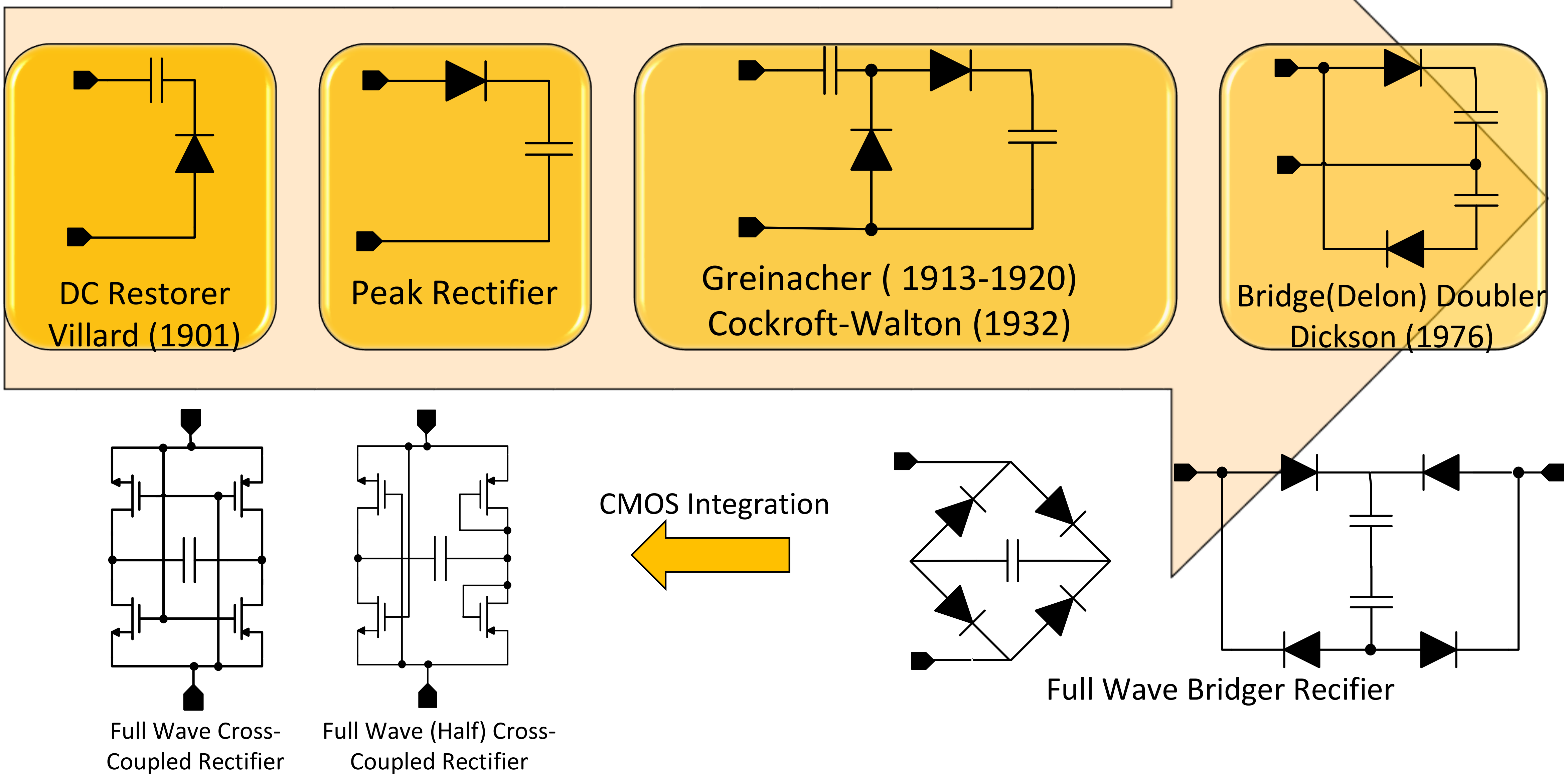
- Choice of diode
- Rectifier topology
- Matching network topology
- DC-DC converter implementation
- Antenna impedance

Rectifier Topologies (1)



Rectifier Topologies (2)

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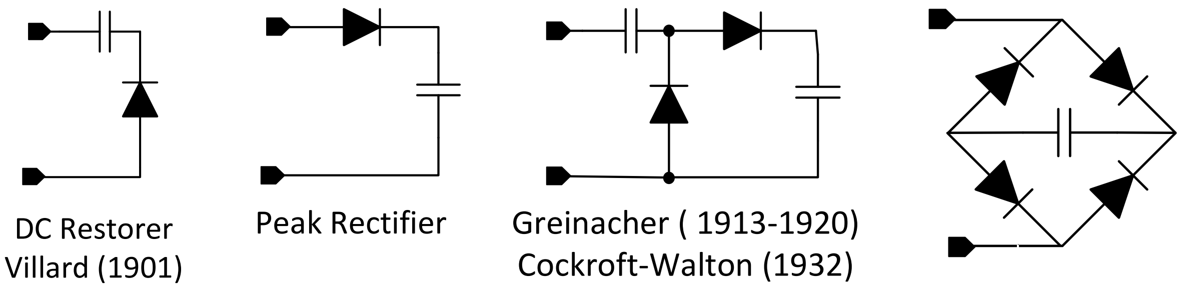
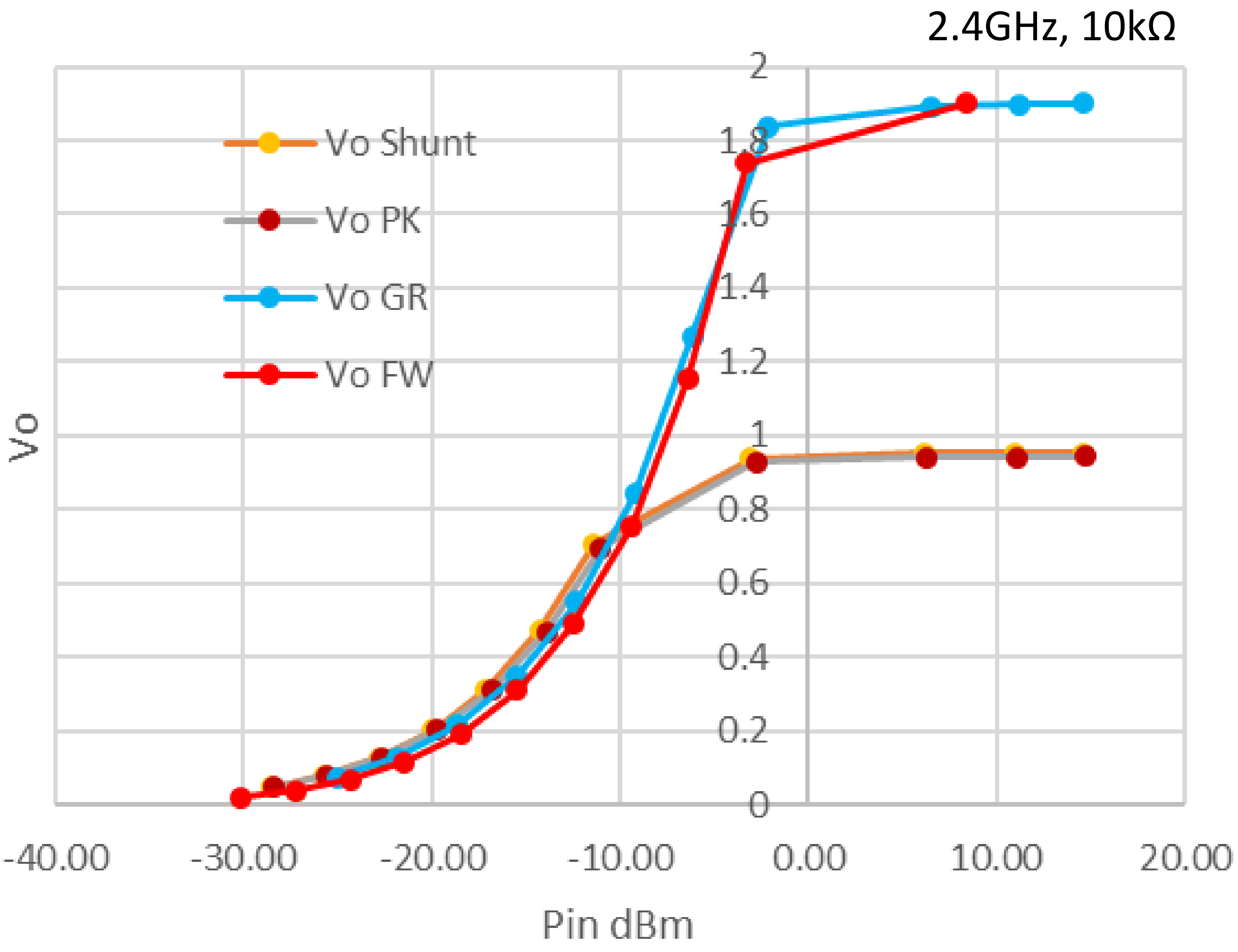
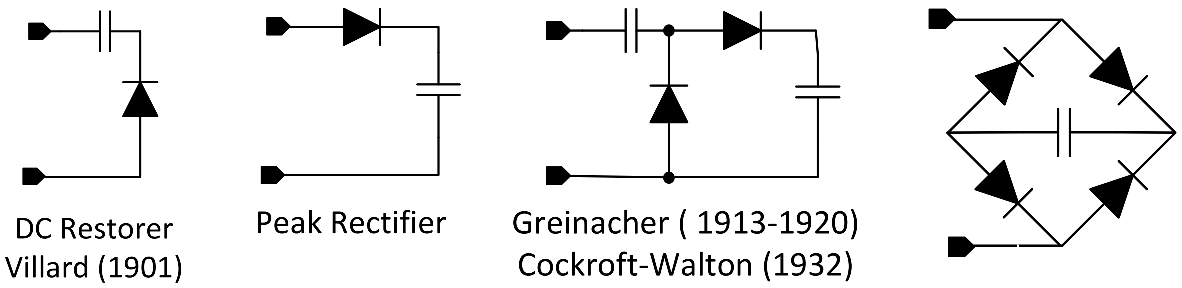


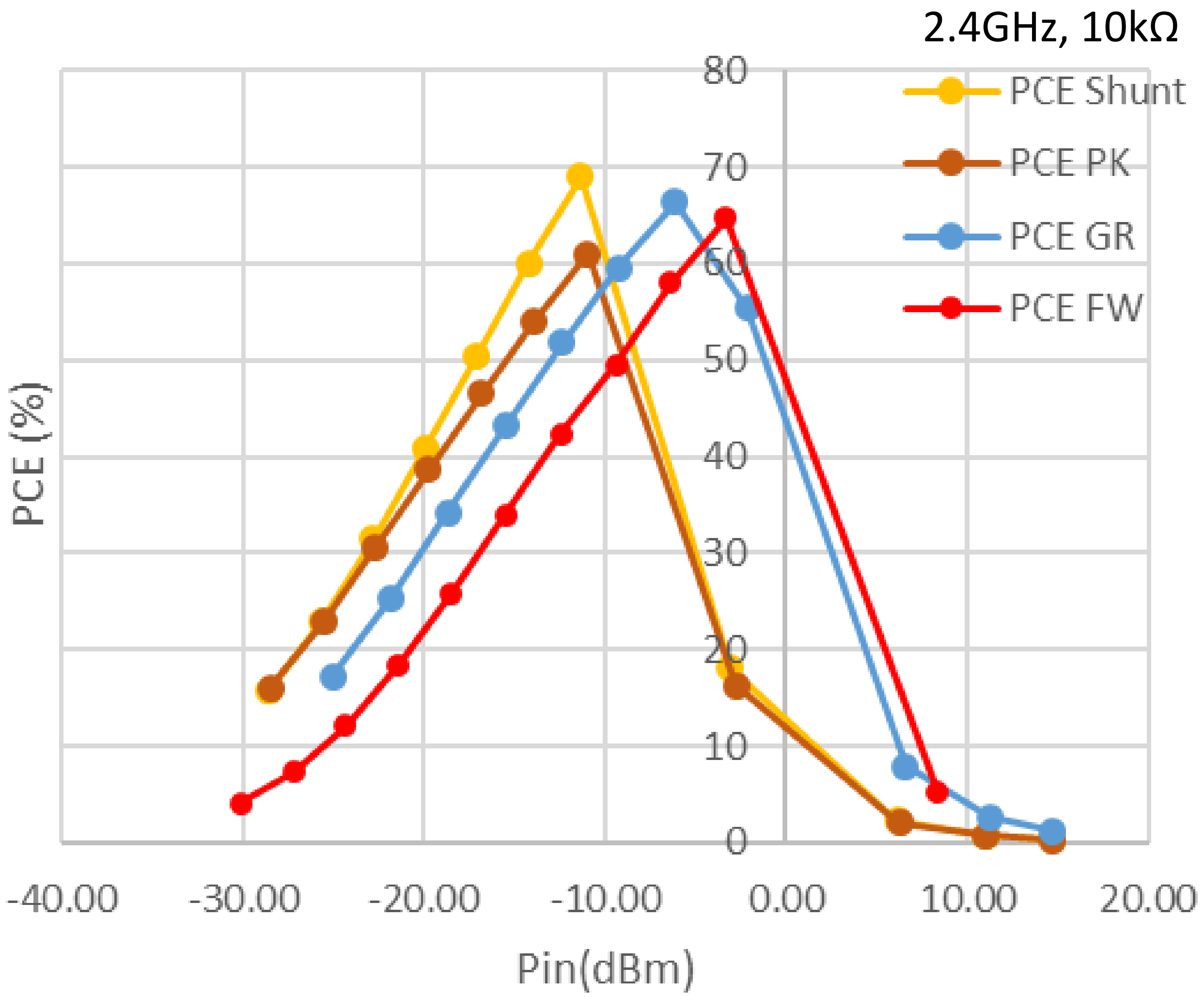


- Cockroft-Walton and full-wave rectifier “double” voltage in different ways
- Voltage doubler & full-wave bridge have higher output voltage (due to higher effective breakdown)

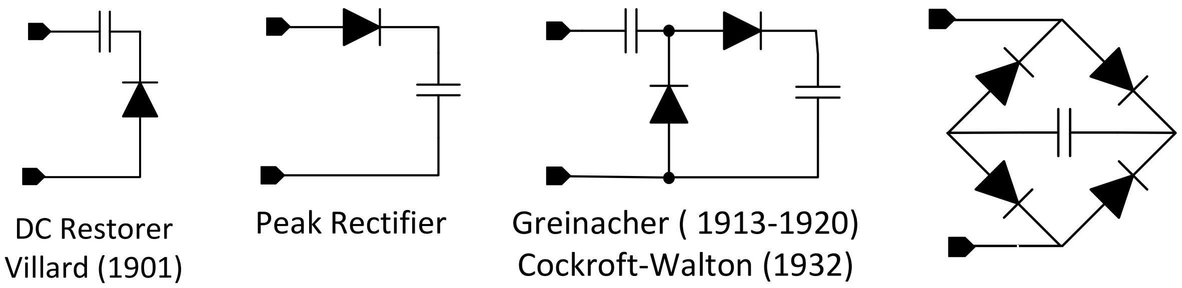
Rectifier Topologies (3)

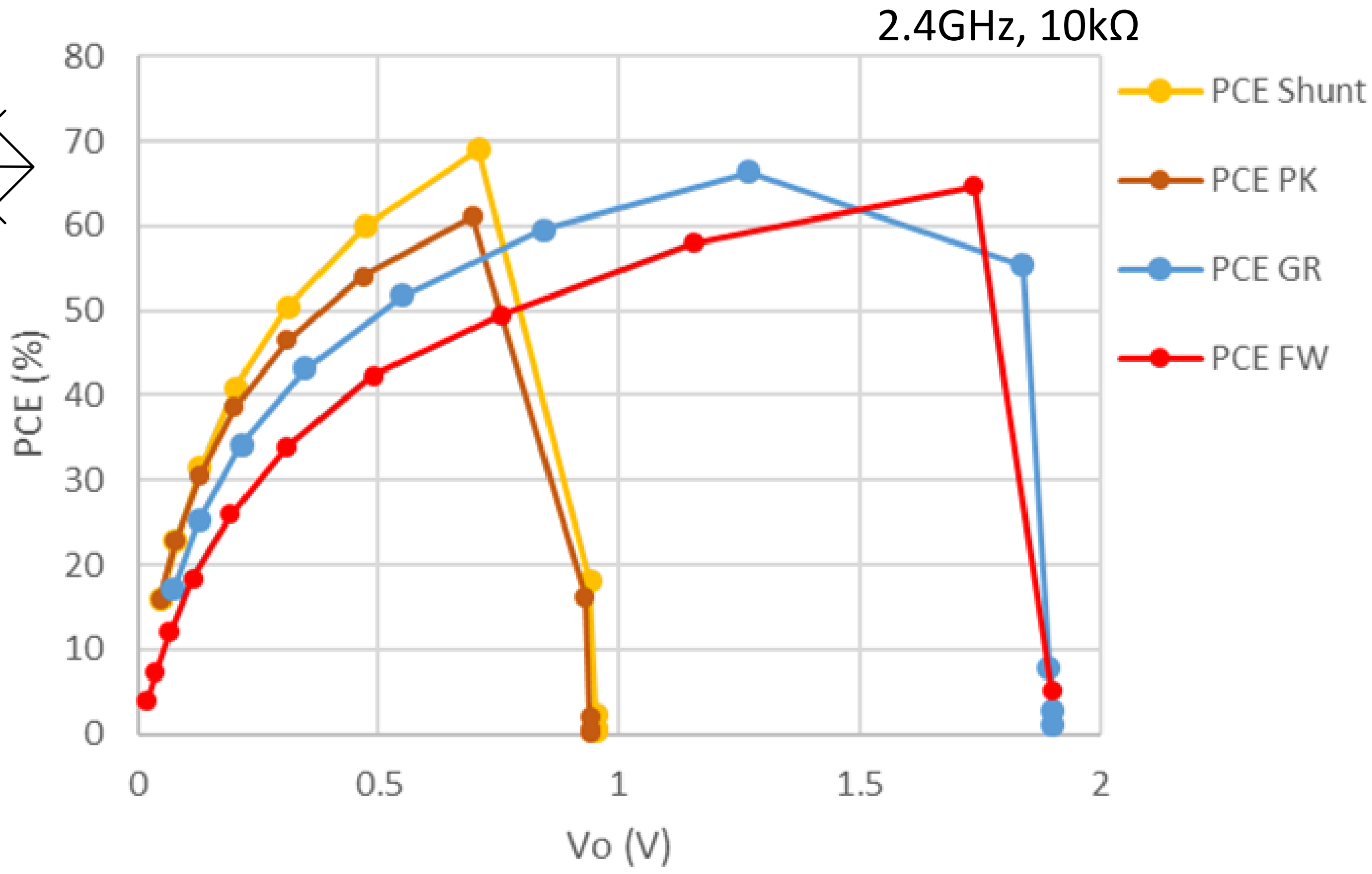


- Voltage doubler & full-wave bridge have higher breakdown voltage
- The FW has greater conduction loss and hence requires greater input power
- At expense of sensitivity at low Prf



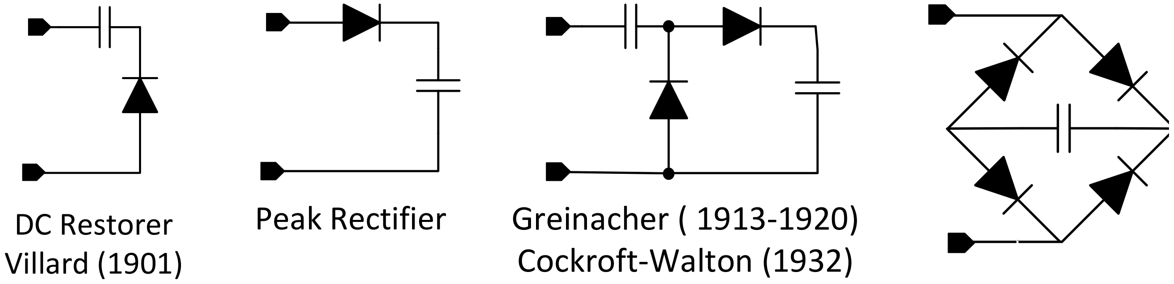
Rectifier Topologies (4)

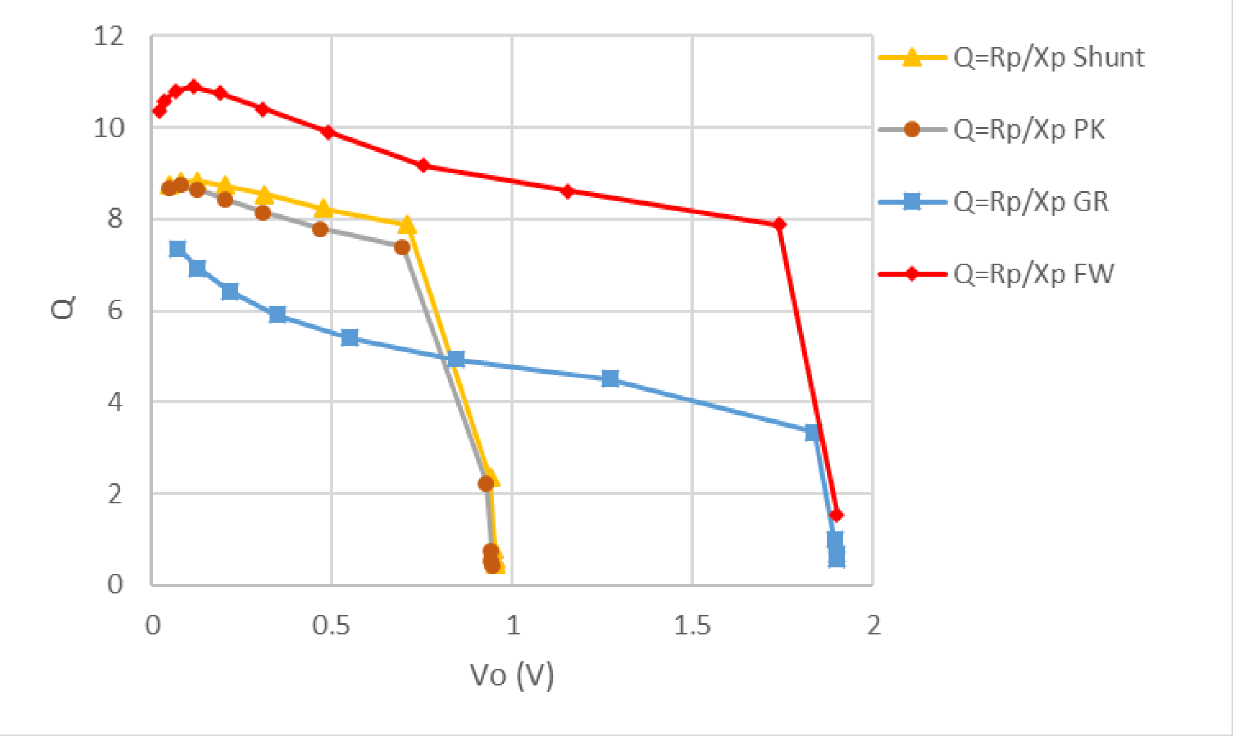




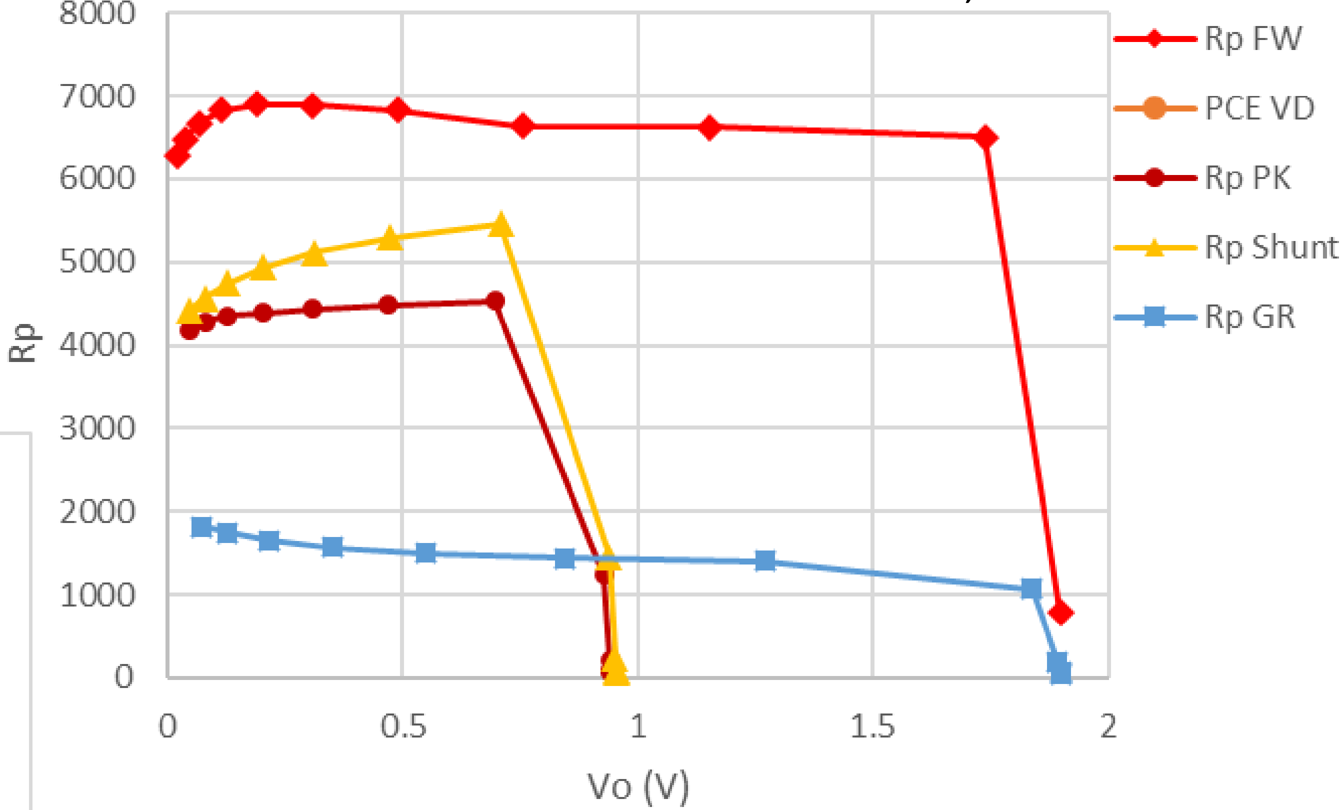
- Voltage doubler & full-wave bridge have higher breakdown voltage
  - FW has two series diodes
  - Doubler has one diode plus the capacitor doing the blocking
- On expense of sensitivity at low Prf

Rectifier Topologies (5)



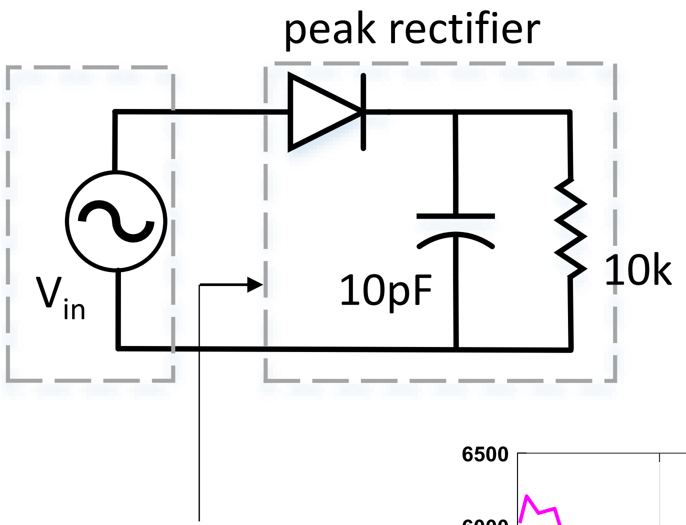


2.4GHz, 10kΩ



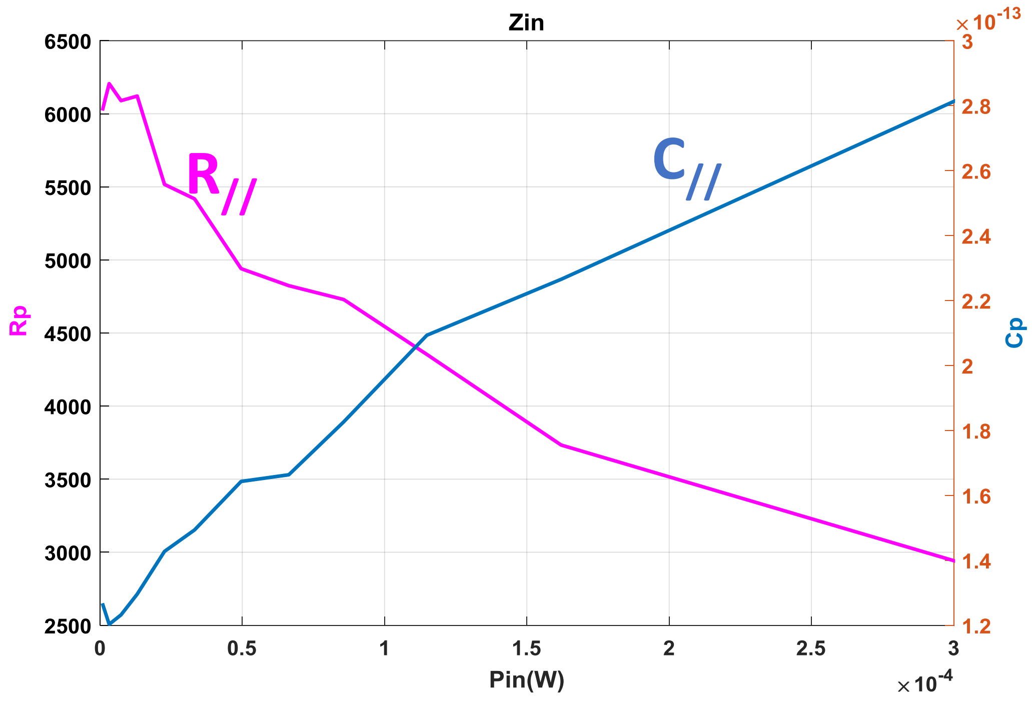
- FW rectifier has the highest Q (lowest series input resistance) due to differential drive input.

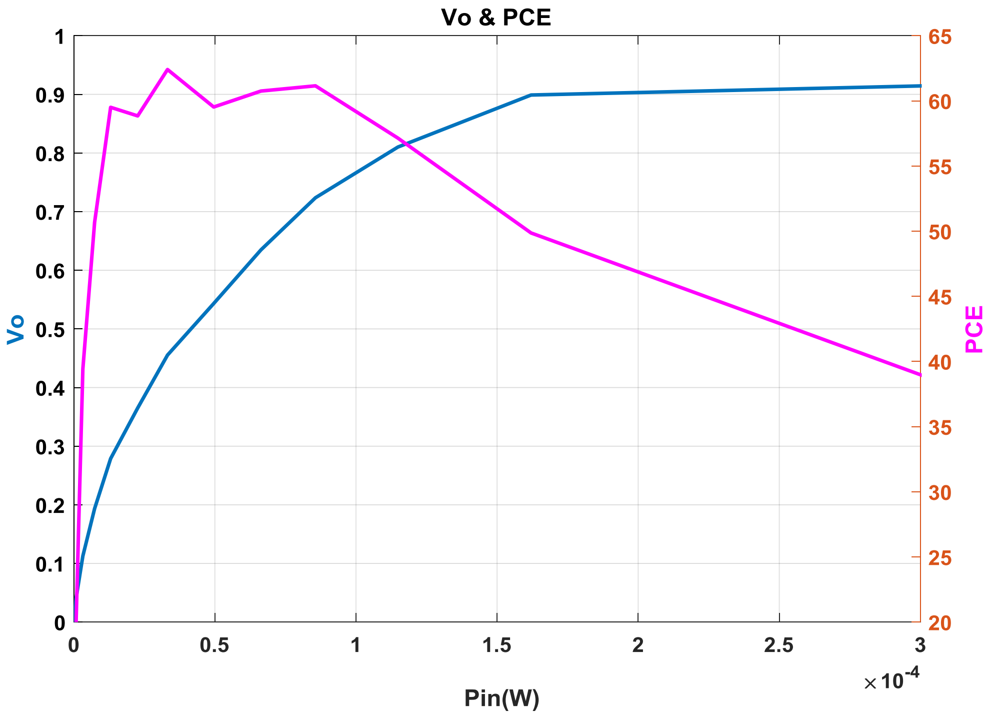
Impedance Matching Challenges



$Z_{in}=R_p \,//\, C_p$
$= \boldsymbol{f}\,(P_{in})$

- Impedance match needs to change depending on input power and output voltage.





Multi Tone Receivers

Why multitone?

- More representative of real, modulated, communication signals
- Gives high peak to average ratio – perhaps good for loweing the conduction loss of the diode and boosting output voltage

Is this really the case?

Multi-Tone Wireless Power Receiver

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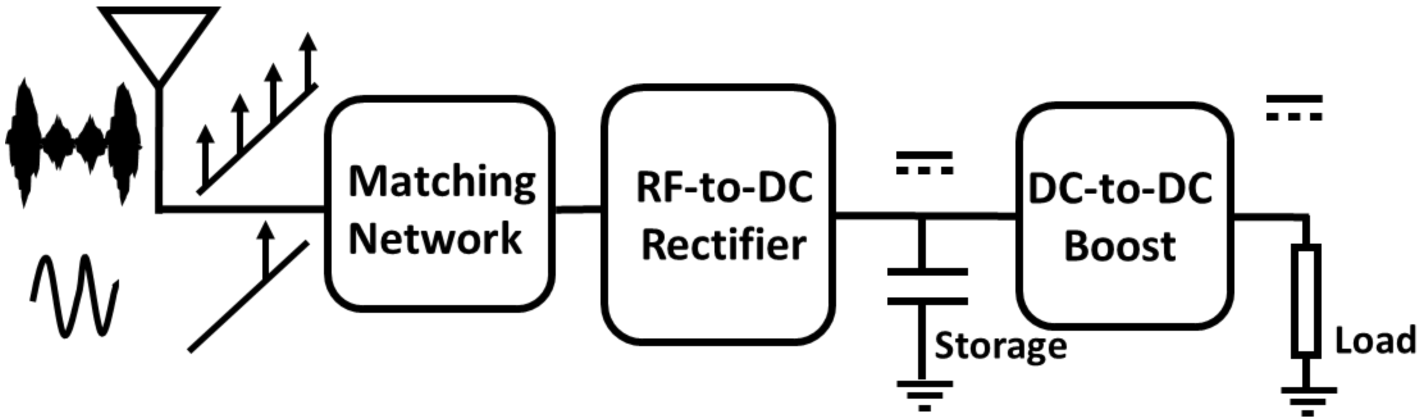

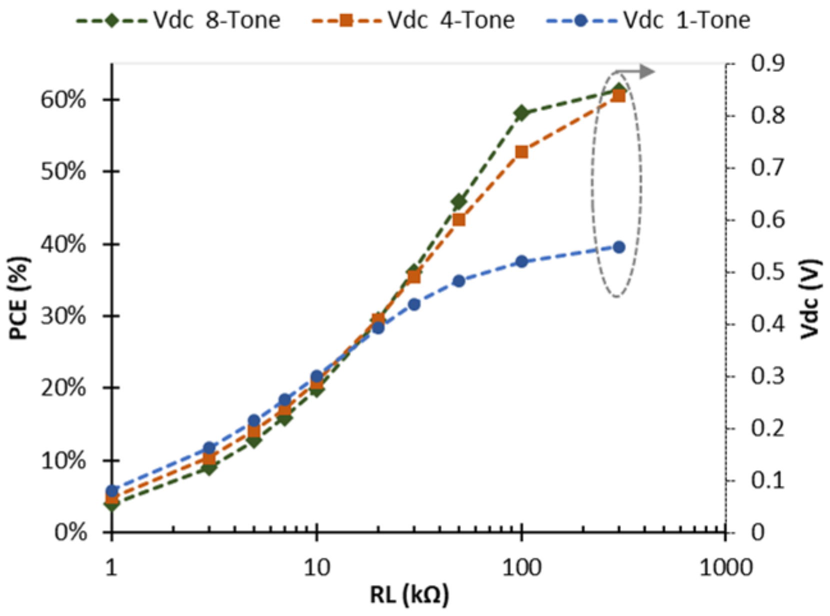

- Multi-tone signals have high peak-to-average power ratio (PAPR)
- Enable the rectifier to produce higher Vdc for the same input power (-17dBm)

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Multi-Tone Wireless Power Receiver

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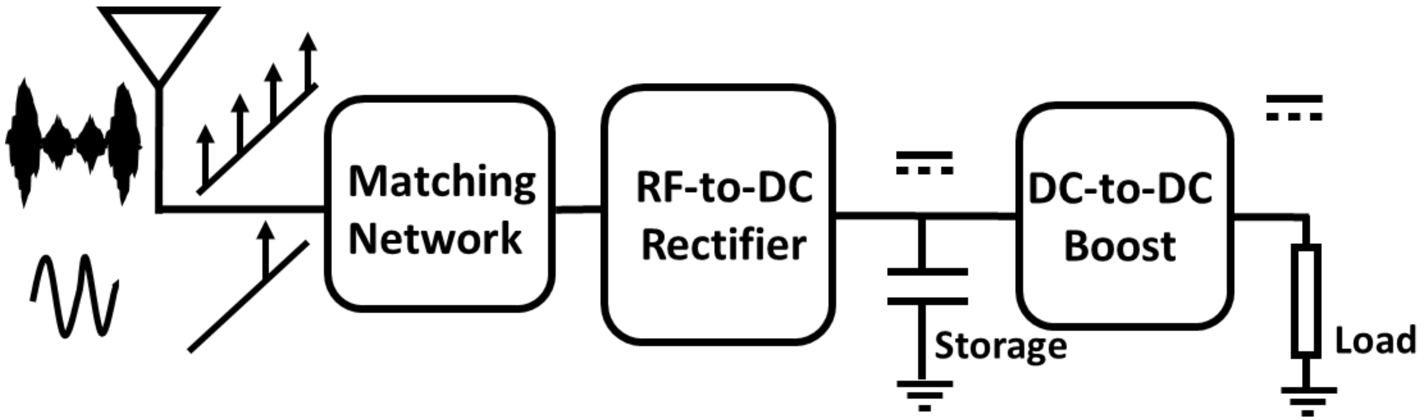

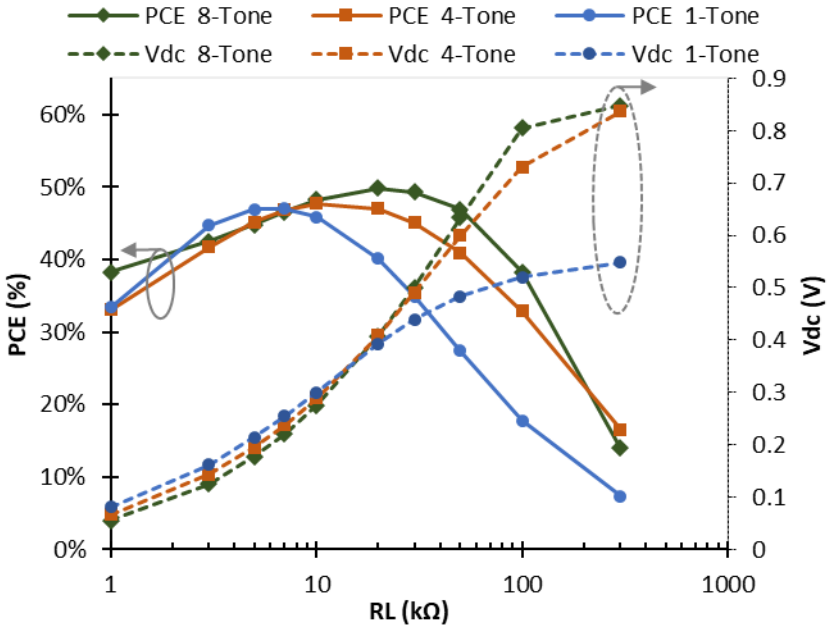

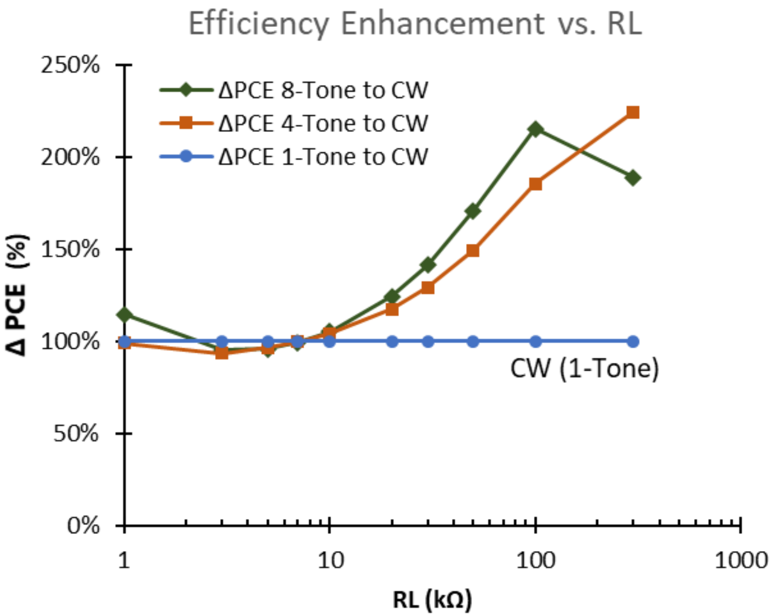

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Multi-Tone Wireless Power Receiver

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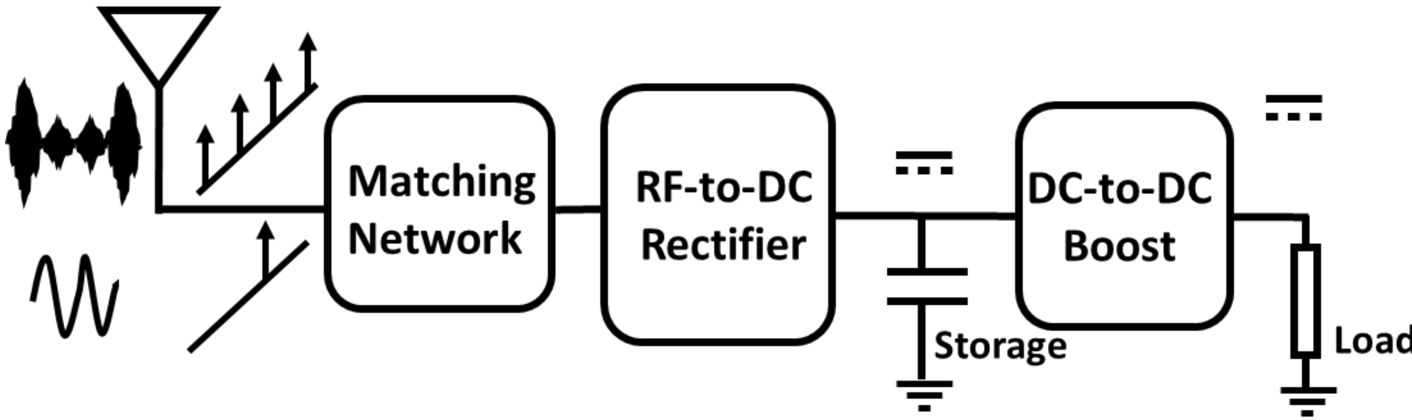

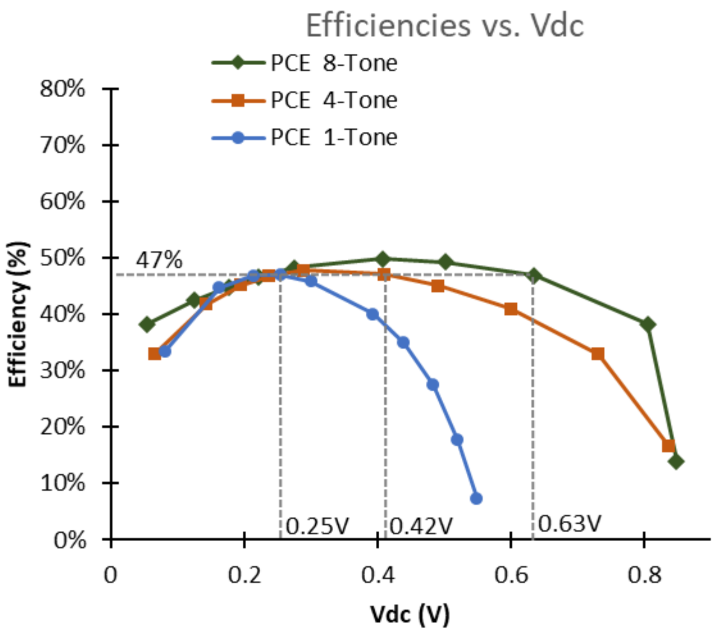

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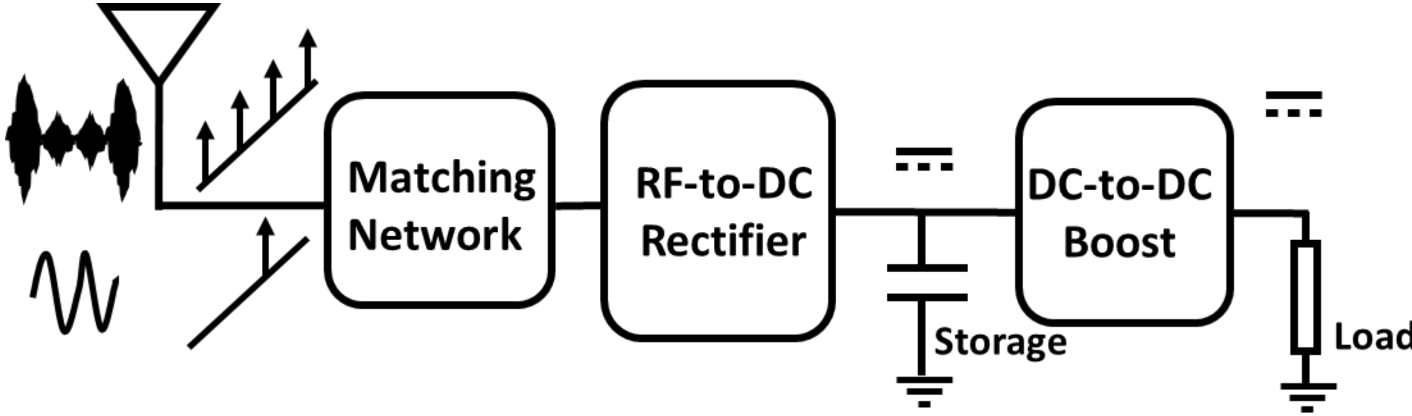
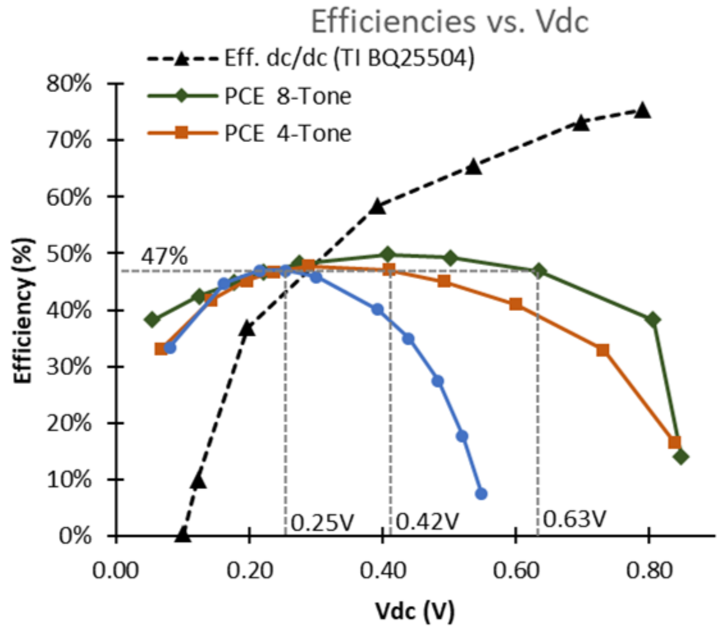
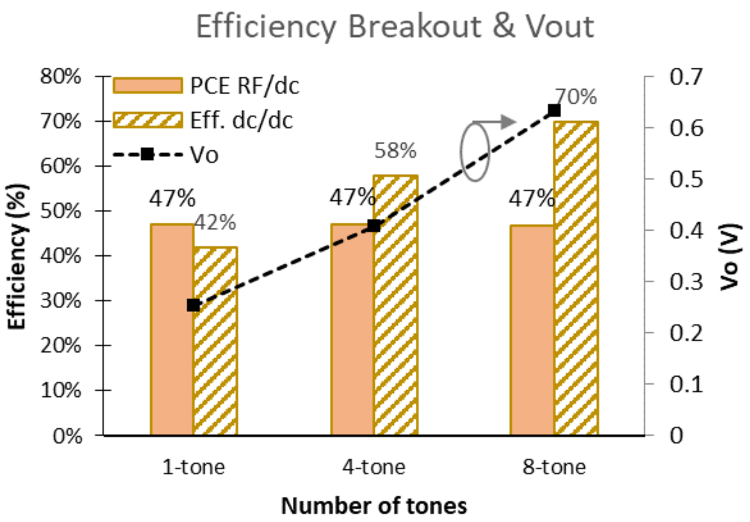
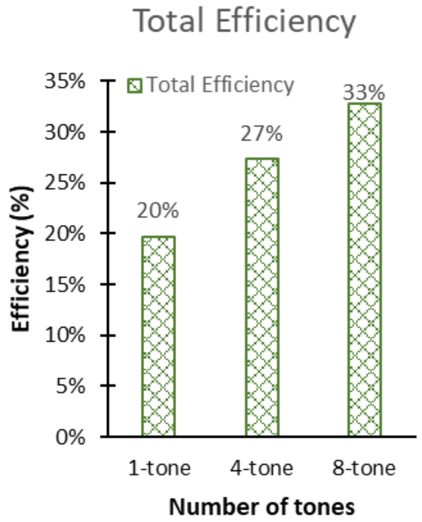
Multi-Tone Wireless Power Receiver



All at -17 dBm







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Conclusions

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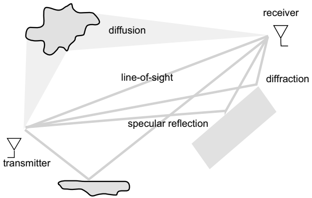
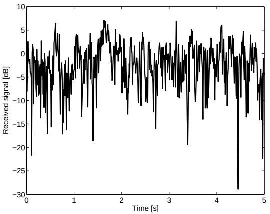
- RF harvesting is very low power, and not practical. A dedicated source is required
- The basic design philosophy of the system is simple: operate close to the maximum diode breakdown voltage
- Then design the rest of the system to allow this:
  - DC-DC Converter
  - Matching network
- Multi-tone signals have an optimal load at higher DC voltage and hence can increase overall system efficiency

Towards WPT Signal Design

Observations from RF literature

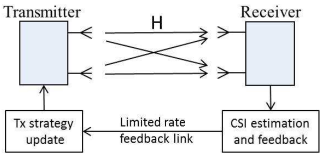
1. Most efforts devoted to rectenna design but less on signals design
2. Emphasis much remained on point-to-point (single user) transmission
3. Rectenna non-linearity known (in RF literature) but design focused on decoupling and optimizing Tx and Rx independently from each other
4. Focus on open-loop 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

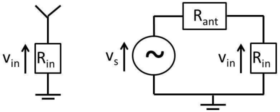
$$y(t) = \sum_{m=1}^{M} \sum_{n=0}^{N-1} s_{n,m} A_{n,m} \cos(2\pi f_n t + \underbrace{\phi_{n,m} + \bar{\psi}_{n,m}}_{\psi_{n,m}}) = \Re\left\{ \sum_{n=0}^{N-1} \mathbf{h}_n \mathbf{w}_n e^{j2\pi f_n t} \right\}$$

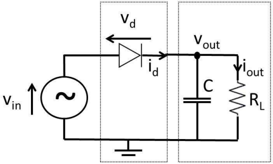
Frequency response of the channel of antenna m at w_n

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

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): $i_d(t) = i_s\left(e^{\frac{v_d(t)}{nv_t}} - 1\right)$
- 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 $k_0' = i_s\left(e^{\frac{a}{nv_t}} - 1\right)$ and $k_i' = i_s \frac{e^{\frac{a}{nv_t}}}{i!(nv_t)^i}$, $i = 1, \ldots, \infty$.

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

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

- Make the dependence explicit

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

- 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

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

- $\max z_{DC} = \max \mathcal{E}\left\{y(t)^2\right\} = \max P_{\mathrm{rf}}^r$
- Tx strategy that maximizes P_{rf}^r is the same strategy that maximizes P_{dc}^r
- 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
- Assume sufficiently low input RF power such that the higher-order terms would not contribute to z_{DC}

Nonlinear Model

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

$$z_{DC} = \underbrace{k_2 R_{ant} \mathcal{E}\left\{y(t)^2\right\}}_{\text{Linear term}} + \underbrace{k_4 R_{ant}^2 \mathcal{E}\left\{y(t)^4\right\}}_{\text{Nonlinear term}}$$

- 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** (frequency response $h_{n,m}$) **known to the Tx** (CSIT)

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}

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

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

Design based on Linear Model

Problem

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

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

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

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**

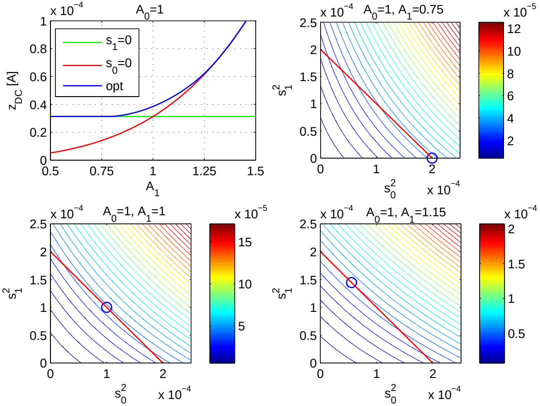
Design based on Nonlinear Model: A Toy Example

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

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

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

Lagrangian optimization: 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, N, M?

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

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

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

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**

$$\min_{\mathbf{S}, t_0} \quad 1/t_0$$

$$\text{s.t.} \quad \frac{1}{2}\|\mathbf{S}\|_F^2 \leq P,$$

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

Algorithm

1: **Initialize**: $i \leftarrow 0$, $\mathbf{\Phi}^\star$, $\mathbf{S}$, $z_{DC}^{(0)} = 0$

2: **repeat**

3: $\quad i \leftarrow i + 1$, $\ddot{\mathbf{S}} \leftarrow \mathbf{S}$

4: $\quad \gamma_k \leftarrow g_k(\ddot{\mathbf{S}}, \mathbf{\Phi}^\star)/z_{DC}(\ddot{\mathbf{S}}, \mathbf{\Phi}^\star)$, $\forall k$

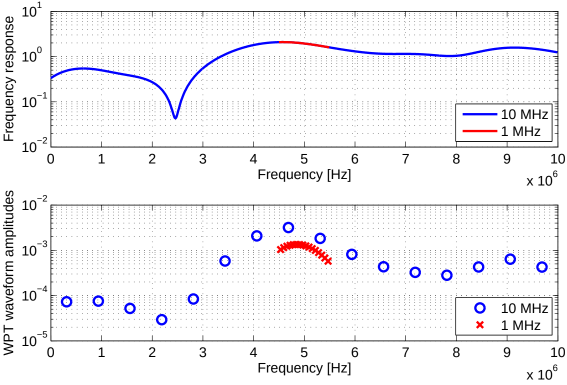
5: $\quad \mathbf{S} \leftarrow \arg\min$ Problem 1

6: $\quad z_{DC}^{(i)} \leftarrow z_{DC}(\mathbf{S}, \mathbf{\Phi}^\star)$

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**

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

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

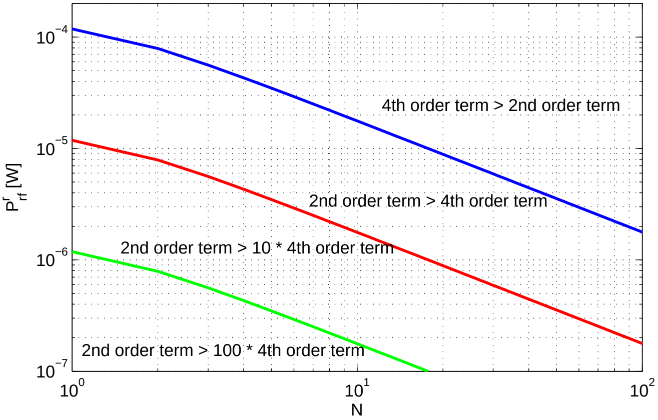
The **large dimension** enables to significantly **simplify the waveform design**

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

$$P_{\text{rf}}^{r} \leq \frac{k_2}{k_4} \frac{1}{R_{ant}} \frac{1}{N} \frac{1}{G}$$



Performance Evaluations

WiFi-like environment

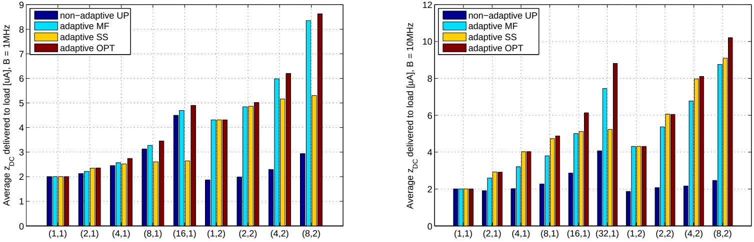
- 5.18GHz, 36dBm Tx power, 2dBi Rx antenna gain, 58dB path loss, office.
- Average received power of about -20dBm.
- Frequency gap fixed as $\Delta_w = 2\pi\Delta_f$ with $\Delta_f = B/N$.

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)

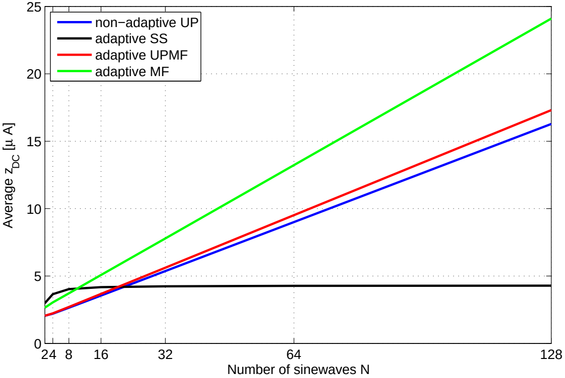


Observation

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 - $M = 1$

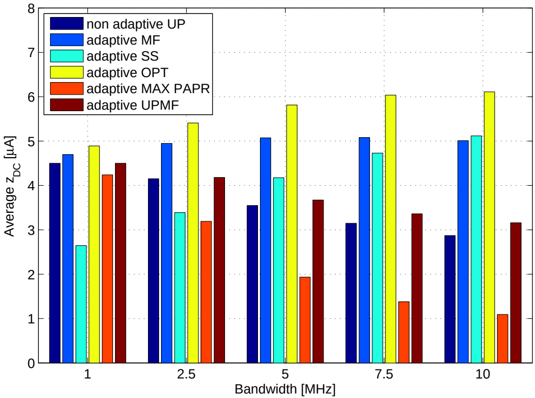


Observation

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 $M = 1$.

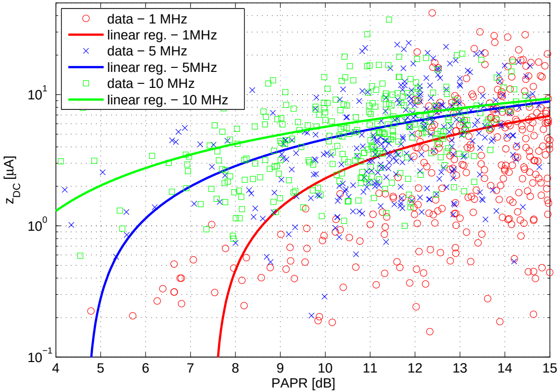


Observation

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 $M = 1$.

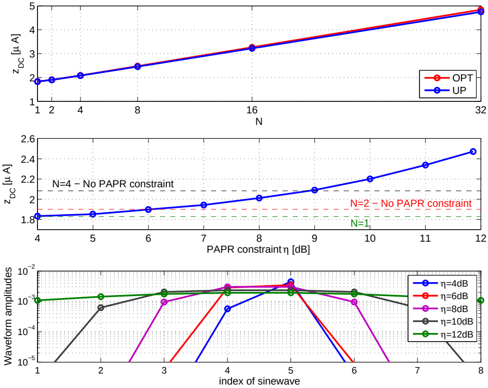


Observation

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 $M = 1$.



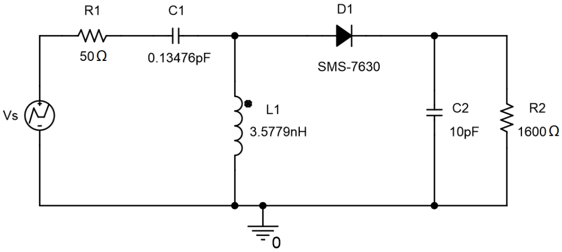
Observation

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 $B = 10\text{MHz}$.

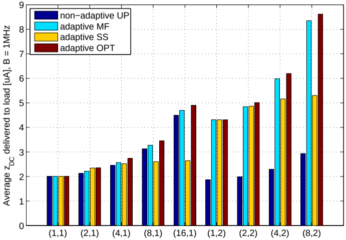
- Designed for an input power of -20 dBm
- Good matching between the rectifier and the antenna and minimize impedance mismatch due to variations in frequency and input power level
- C1 and L1 optimized to match the antenna impedance to the average input impedance of the rectifier resulting from an input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

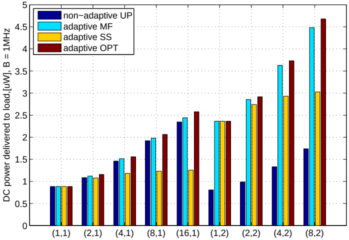


The output capacitor chosen as C2 $= C_{out} = 100\text{pF}$ for $B = 1\text{MHz}$

Circuit Evaluations

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



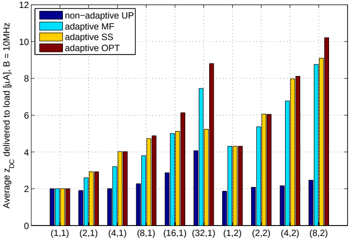


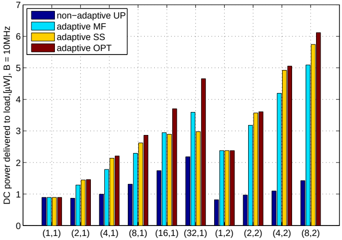
Observation

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.*
4. *Nonlinearity beneficial and exploitable in the low-power regime!*

Circuit Evaluations

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





Observation

1. *CSIT needed in frequency-selective channels.*
2. *Careful with PAPR metric!*
3. *OPT exploits BF gain + channel FS + rectifier nonlinearity.*

Circuit Evaluations

Observation

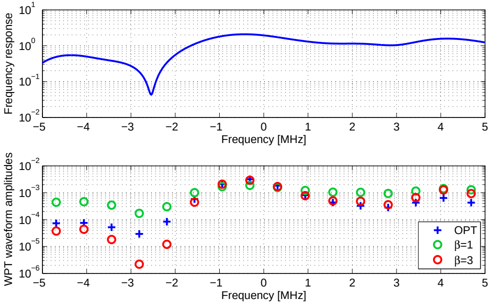
1. *Promising architecture: large-scale multisine multiantenna waveforms.*
2. *Sensors need 10 μW DC (see e.g. PsiKick's Fully Integrated Wireless SoC sensors)*
3. *Think big: up to 2048 subcarriers in LTE! 100s antennas/Tx in 5G (Massive MIMO)!*

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

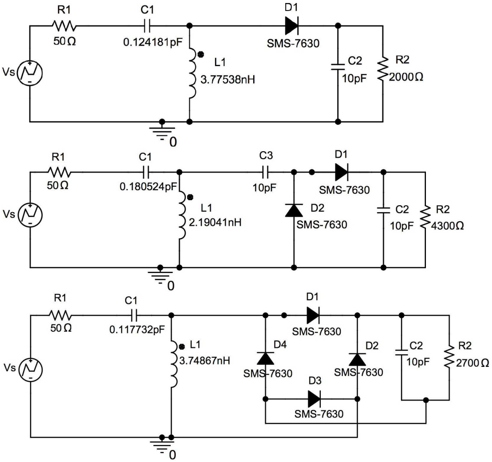
Low-Complexity Adaptive Multisine Waveform

- 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
- A_n^{β}: amplify strong frequency components and attenuate weak ones

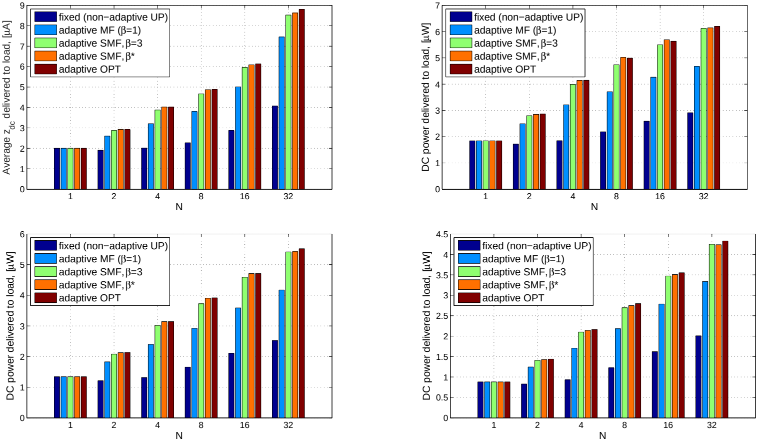


Circuit Evaluations

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

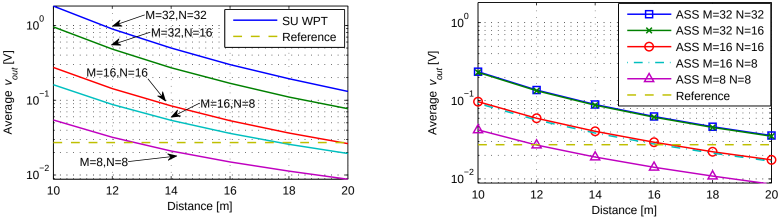
Algorithms	Average v_{out} [V]	Average elapsed time [s]	Average convergence time
SU WPT	9.532×10^{-2}	1.752×10^{-3}	4.18 iterations
Reversed GP	8.417×10^{-2}	99.04	17.16 iterations

- $M = 1$, $N = 8$, $P = 3.98107\,\text{W}$ 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 (CSCG)	
z_{DC}	$k_2 R_{ant} P + 6k_4 R_{ant}^2 P^2$
Unmodulated (CW)	
z_{DC}	$k_2 R_{ant} P + 3k_4 R_{ant}^2 P^2$

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.*

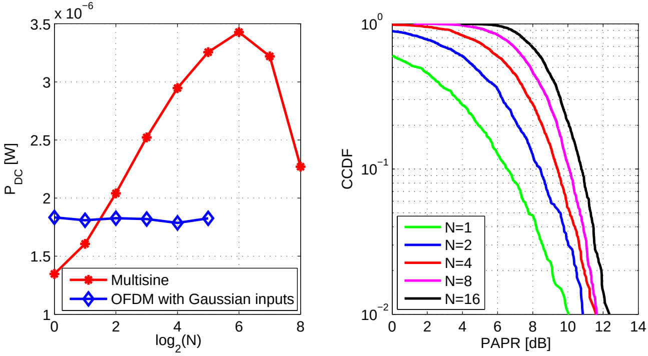
Scaling Laws - Multi-Carrier

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.*

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!*

Modulated Signals

Energy Modulation for WPT? Complex Gaussian, Real Gaussian, something else?

Flash signaling distribution

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

with $l \geq 1$.

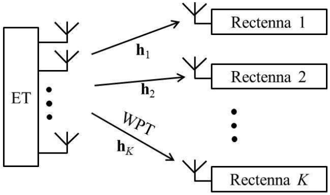
Low probability of high amplitude signal

Boost the **fourth order term** in the Taylor expansion: $\mathbb{E}\left\{r^4\right\} = l^2$

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 $z_{DC,p}$, $p \neq q$

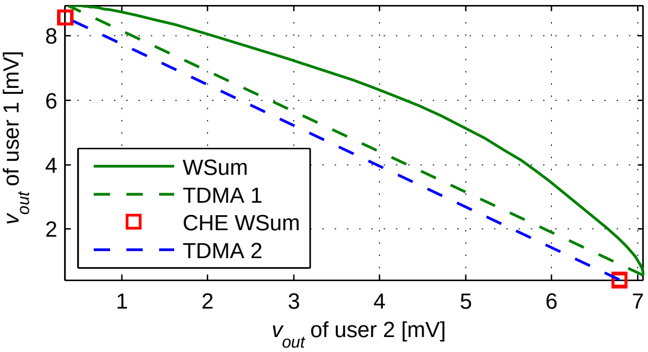
Energy Region $\mathcal{Z}_{DC}$: set of all rectenna harvested energy $(z_{DC,1}, \ldots, z_{DC,K})$ that are simultaneously achievable

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 $N = 10$



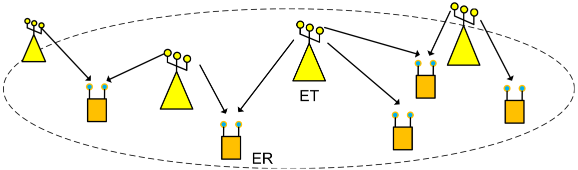
Observation

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

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

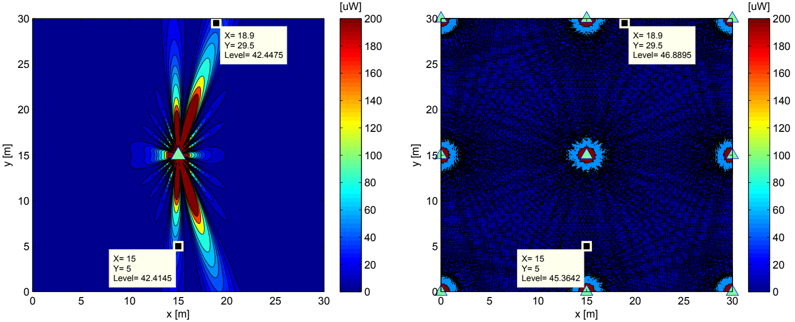
Single-ET WPT: Each ER served by exactly one ET

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

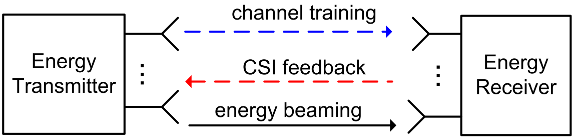
Unique considerations for CSI acquisition in WPT in contrast to conventional wireless communication

- **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

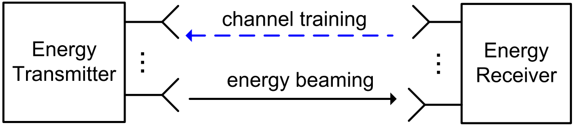
Candidate solutions depending on the **antenna architecture** at Rx

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

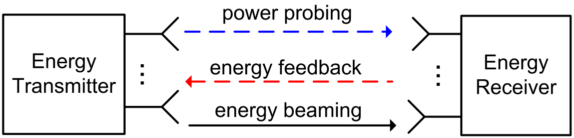
Channel Acquisition Schemes for WPT



(a) Forward-link training with CSI feedback



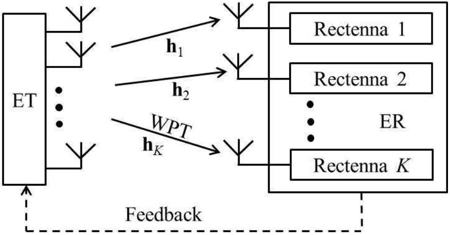
(b) Reverse-link training with channel reciprocity



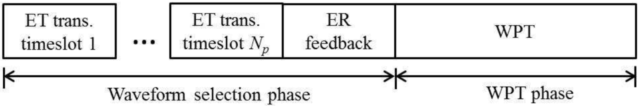
(c) Power probing with energy feedback

Multi-Antenna Multi-Sine WPT with Limited Feedback

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



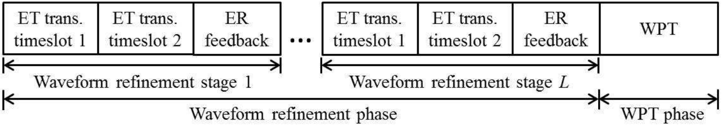
Waveform Selection-based WPT



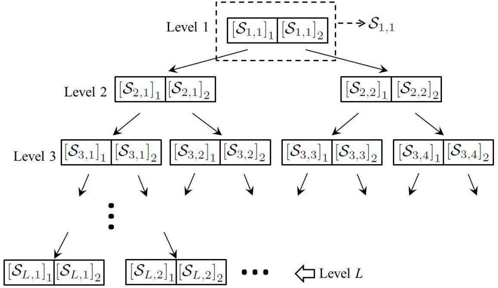
- Waveform precoders: a predesigned N_p-codeword codebook
- ER feedback: $n_p^\star = \arg\max_{n_p \in \{1,\ldots,N_p\}} Z_{DC}([\mathcal{S}]_{n_p})$
- $\log_2 N_p$ feedback bits and N_p energy signals transmitted in the WS phase

Multi-Antenna Multi-Sine WPT with Limited Feedback

Waveform Refinement-based WPT



- Waveform precoders: a predesigned tree-structured codebook

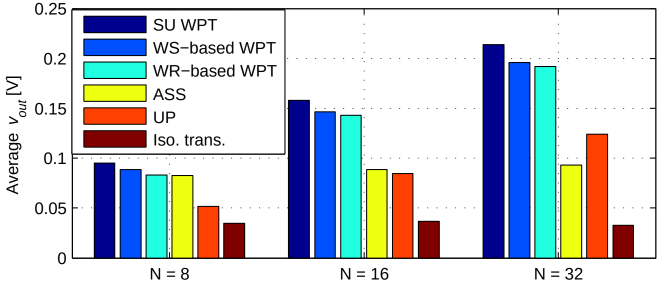


- ER: $f_b = 1$, for $Z_{DC,q}([\mathcal{S}_{l,n_s}]_1) > Z_{DC,q}([\mathcal{S}_{l,n_s}]_2)$; otherwise, $f_b = 0$.
- $\log_2 N_p$ feedback bits and $2\log_2 N_p$ energy signals sent in WR phase

Multi-Antenna Multi-Sine WPT with Limited Feedback

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

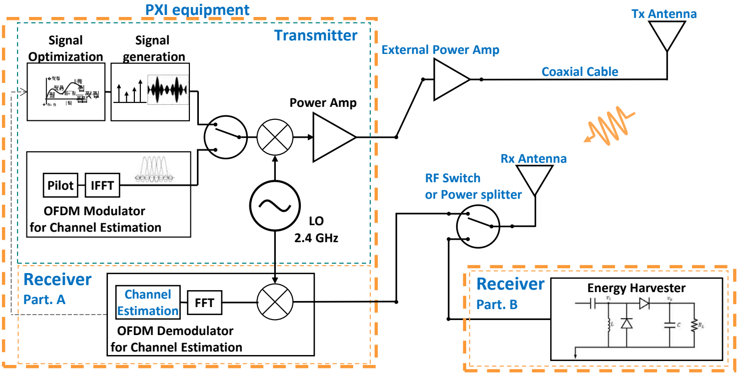
Demonstrate the first prototype of a closed-loop WPT system with adaptive waveform optimization based on CSI acquisition

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

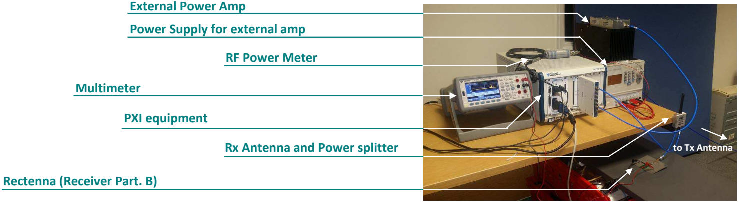
Actual Prototype Architecture



- 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



Actual Prototype Architecture

Channel estimation: pilot based channel estimation technique

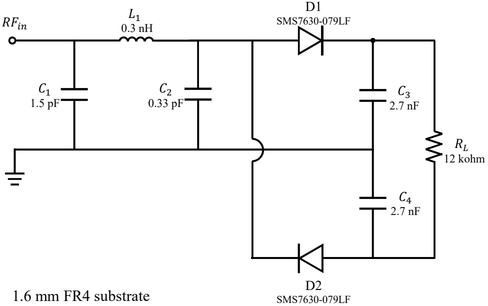
Parameter	Value
Bandwidth	20 MHz
Number of Subcarriers	256
Frequency Spacing	78.125 KHz
Pilot type	Block type pilot
Number of symbols for channel estimation	20 symbols (320 μs)
Method of Channel Estimation	Least-square

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

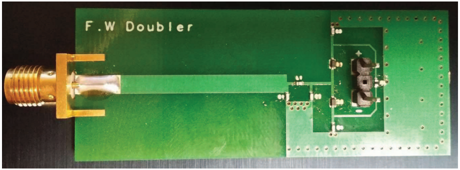
- N uniformly spaced sinewaves in 10MHz bandwidth, Tx Power of 35dBm

Actual Prototype Architecture

Latest Rectenna Design

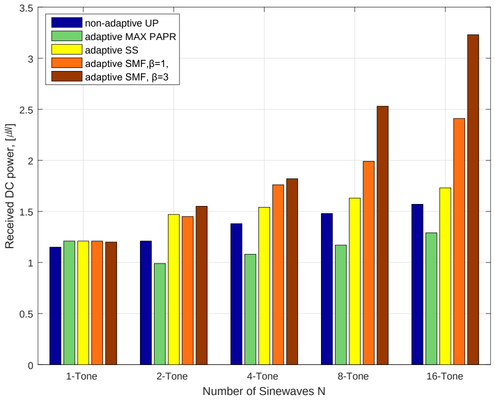


1.6 mm FR4 substrate



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*

Conclusions and Future Challenges

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**

WPT 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, 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

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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