Waveform and Passive Beamforming Design for Intelligent Reflecting Surface-Aided Wireless Information and Power Transfer

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Early Stage Assessment, July 2, 2020

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What is WPT?

Wireless Power Transfer (WPT) varies electromagnetic fields to deliver power.

Table: WPT Technologies

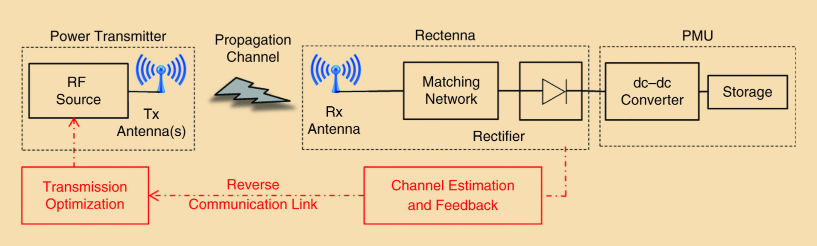
Categories	Technology	Devices	Power	Frequency	Range
Near-field	Magnetic resonant coupling	Resonators	Up to 10 W	kHz – MHz	m
	Inductive coupling	Wire coils	Up to 10 W	Hz – MHz	mm – cm
	Capacitive coupling	Metal plates	Up to 1 W	kHz – MHz	mm
Far-field	RF waves	Rectennas	μW – mW	MHz – GHz	m – km
	Light waves	Lasers	μW – mW	THz	km

Characteristics:

- no wires and batteries
- everlasting, controllable, reliable, sustainable

WPT by RF waves

Energy flow: DC $\rightarrow$ RF $\rightarrow$ RF $\rightarrow$ DC



Pros:

- long range (up to hundreds of m) with NLoS support
- compact receiver (few cm), easy integration
- suitable for mobile devices

Cons:

- low power level (μW – mW)
- low energy harvesting efficiency (40% at 100 μW, 20% at 10 μW)

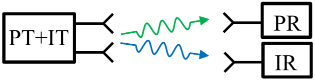
Figure from [1]

Why RF waves?

RF waves enables:

- Wireless communication (WIT)
- WPT

Simultaneous Wireless Information and Power Transfer (SWIPT): downlink WIT and WPT at the same time. Receivers can be either separated or co-located.



(a) Separated

(b) Co-located

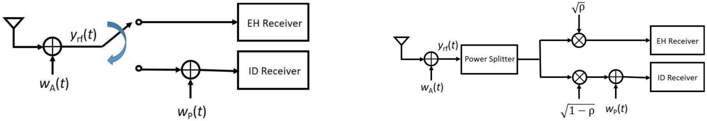
Figure: SWIPT receivers

Figure from [2]

Co-located receiver architecture

Two practical receiver architecture:

- **Time-Switching** (TS) switches between Information Decoding (ID) and Energy Harvesting (EH) modes on time basis.
- **Power-Splitting** (PS) splits the received signal into individual components for ID and EH.



(a) TS (b) PS

Figure: Co-located receiver architecture

Design issue

- TS can be achieved by a time sharing between WIT and WPT. Waveform is optimized individually for both cases.
- In PS, the splitting ratio ρ is coupled with the waveform design.

Figure from [2]

Harvester model

RF-to-DC conversion requires **rectenna** (receive antenna + rectifier), whose behavior is dominated by diode I-V characteristics.

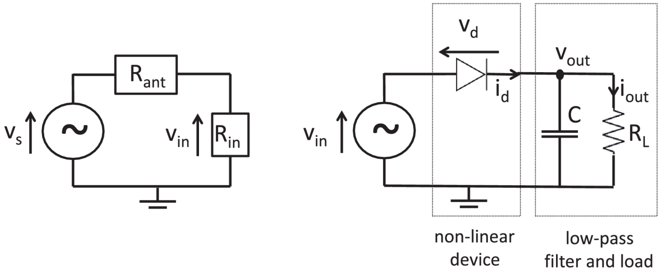


Figure: Rectenna equivalent circuit and a single diode rectifier [1]

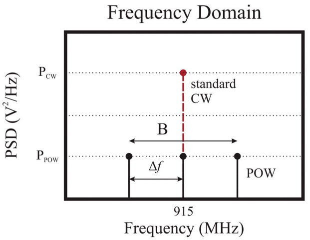
Consider small-signal model and truncate its Taylor expansion to the n_0-th order:

- diode linear model ($n_o = 2$): output power is proportional to input power
- diode nonlinear model ($n_o > 2$): significant contribution from high-order terms

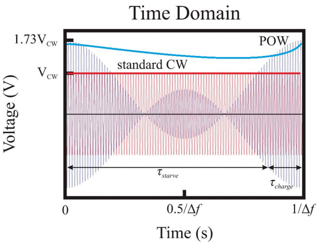
Waveform design

A superposed signal containing modulated information waveform and multisine power waveform is demonstrated to bring a two-fold benefit:

- **rate**: multisine is deterministic with no interference on information waveform (by waveform cancellation or translated codebook)
- **energy**: multisine brings high PAPR and triggers the diode nonlinear model more often (reduce threshold from -20 dBm to -30 dBm)



(a) Frequency domain



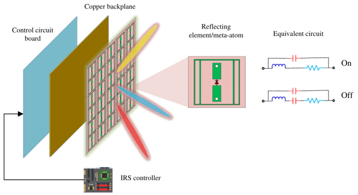
(b) Time domain

Figure: Multisine waveform

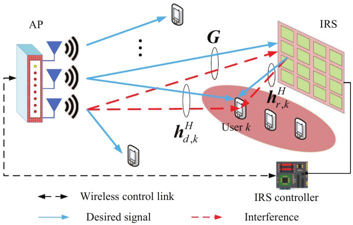
Figure from [3]

What is IRS?

Intelligent Reflecting Surface (IRS) consists of multiple individual passive reflecting elements that adjust the amplitude and phase of the incident signal.



(a) IRS architecture



(b) Application scenario

- outer layer: redistribute incident signals
- middle layer: avoid signal energy leakage
- inner layer: adjust reflection amplitude and phase shift

- enhance primary transmission by constructive reflection
- null interference by destructive reflection

Figure from [4, 5]

Why IRS?

Characteristics:

- passive (different from AF relay)
  - no RF chains
  - low power consumption
  - no additional thermal noise
  - squared gain: received power scales quadratically with the number of reflectors (boost receive power and array gain in equal gain transmission)
- full-duplex
- assistant (different from backscatter node)
- adjustable in real-time

Challenges:

- channel estimation
  - cannot separate incident and reflective channels
  - large number of extra channels
- practical restriction
  - discrete phase shifts
  - phase shift are coupled with reflection amplitude (by impedance equation)

Why IRS-aided SWIPT?

- both aim at improving spectral/energy efficiency
- enhanced channel boosts received power to benefit from harvester nonlinearity
- extra links increase system diversity and stability, which is essential for SWIPT
- SWIPT can potentially support low-power IRS

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