Wireless Powered Communication Networks: An Overview

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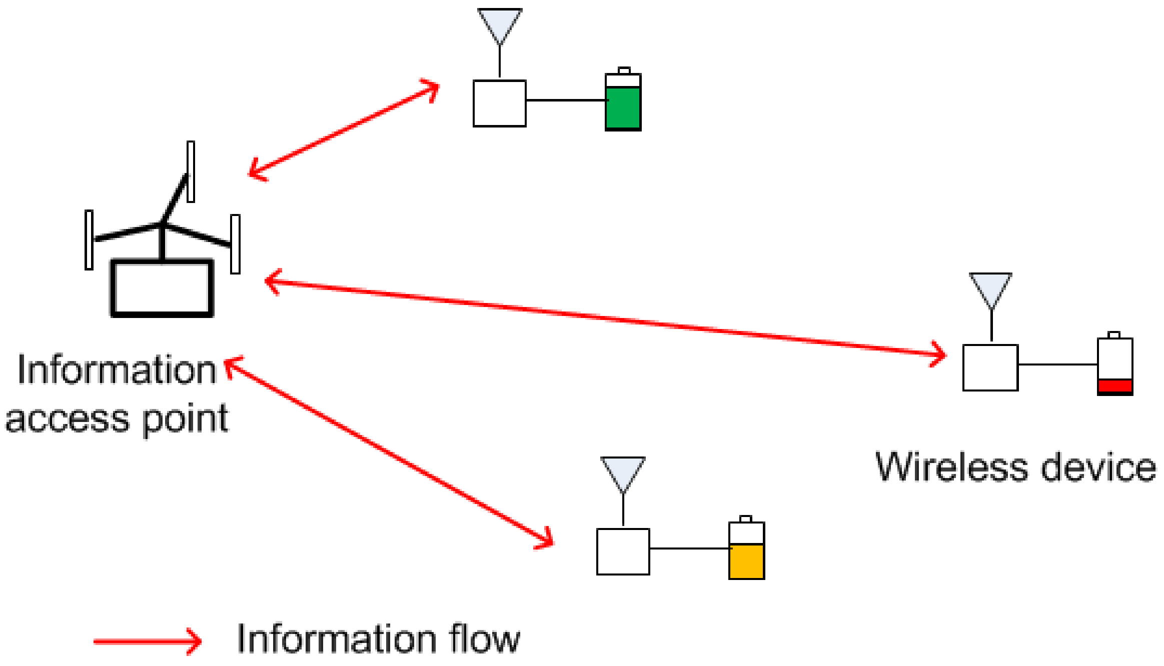
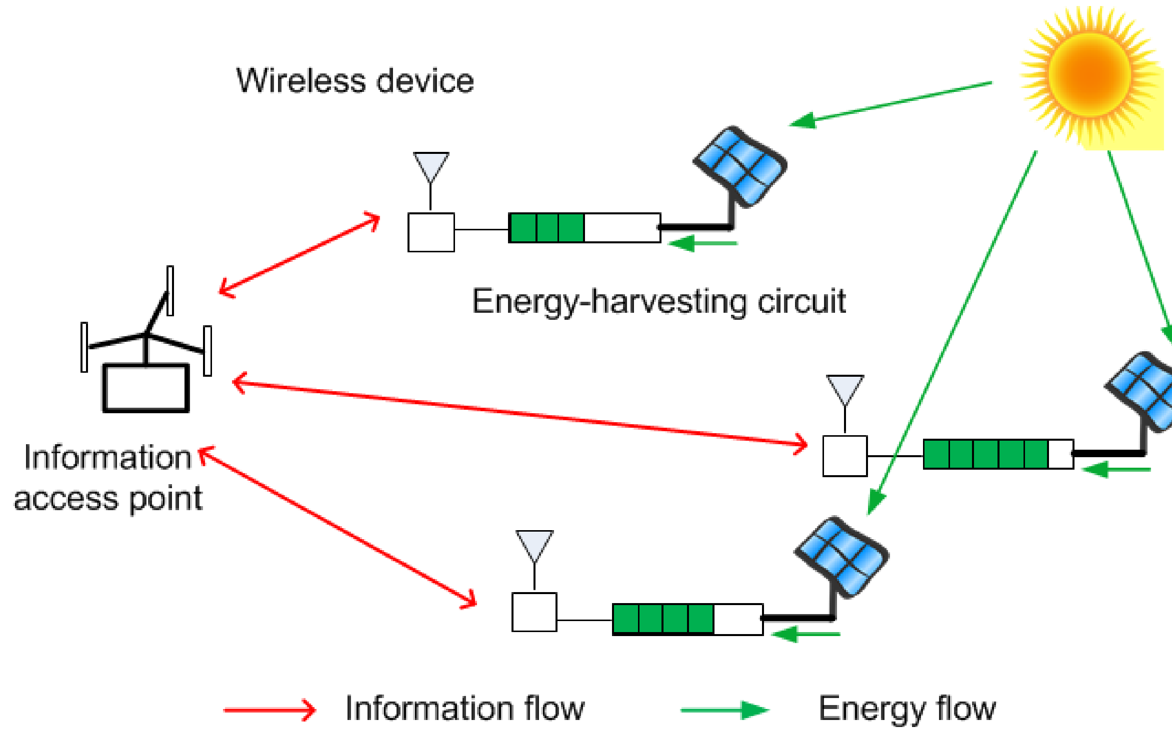
Wireless Communication Powered by Batteries (Conventional)



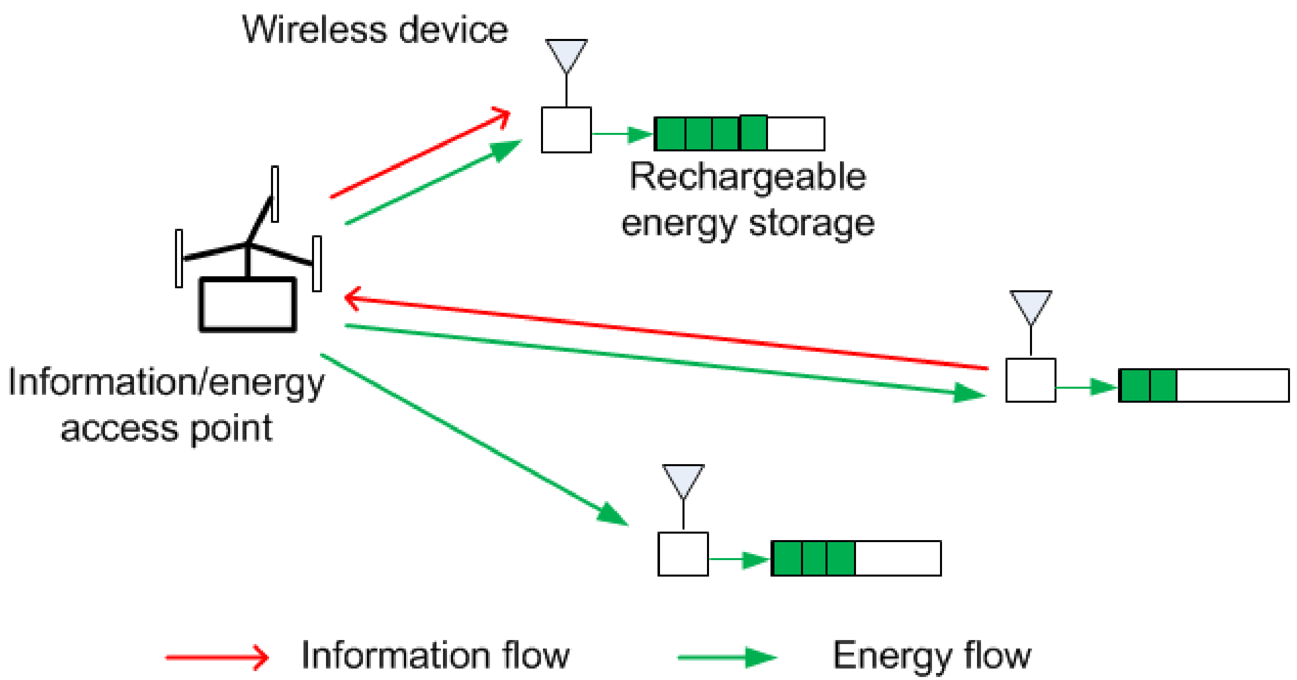
- ❑ Need manual battery recharging/replacement
- ❑ Costly, inconvenient, abruption to use
- ❑ Inapplicable in some scenarios, e.g., implanted medical devices, sensors built in cement structures

Wireless Communication Powered by Energy Harvesting (More Recent)



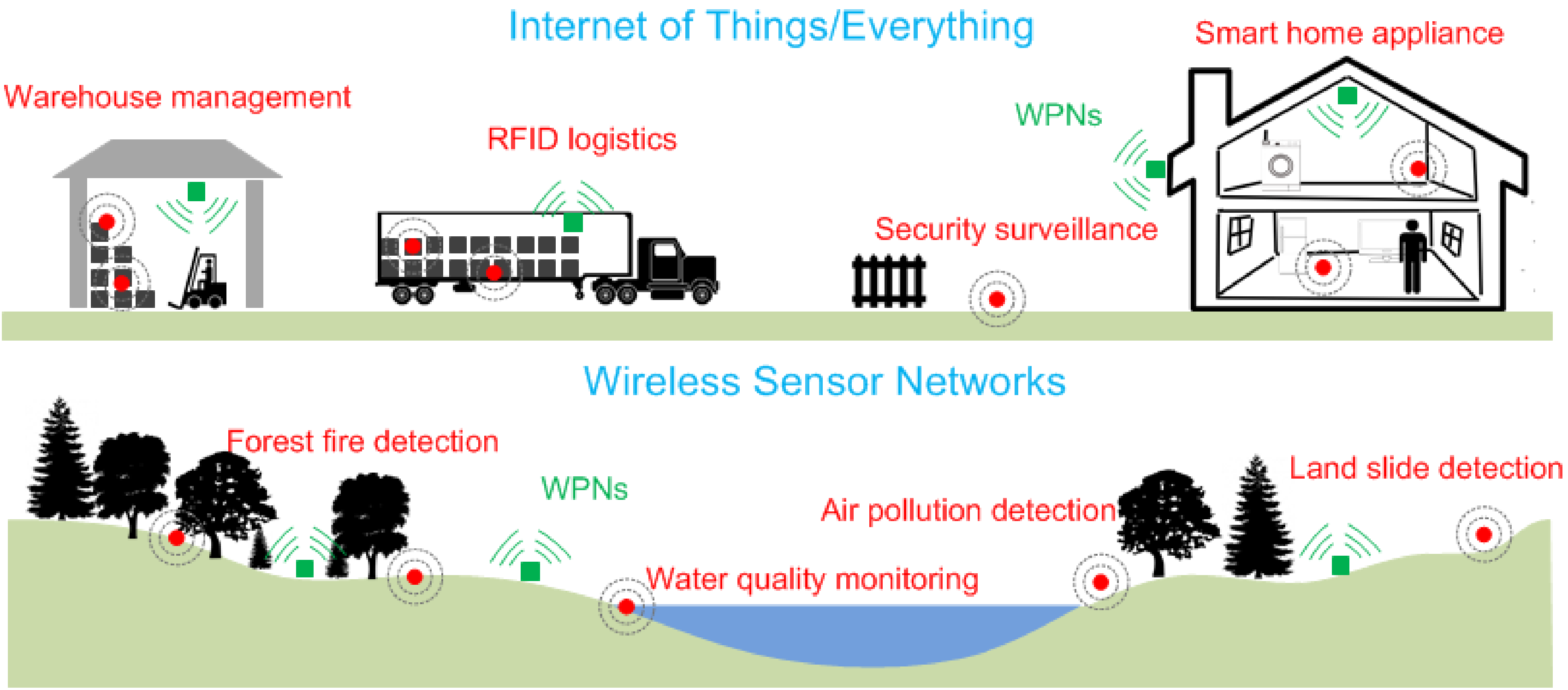
- External energy source: solar, wind, vibration, ambient radio power, etc.
- Inexpensive, green, renewable
- Intermittent and uncontrollable, costly/bulky harvesting and storage devices

Wireless Communication Powered by Wireless Power Transfer (Emerging)

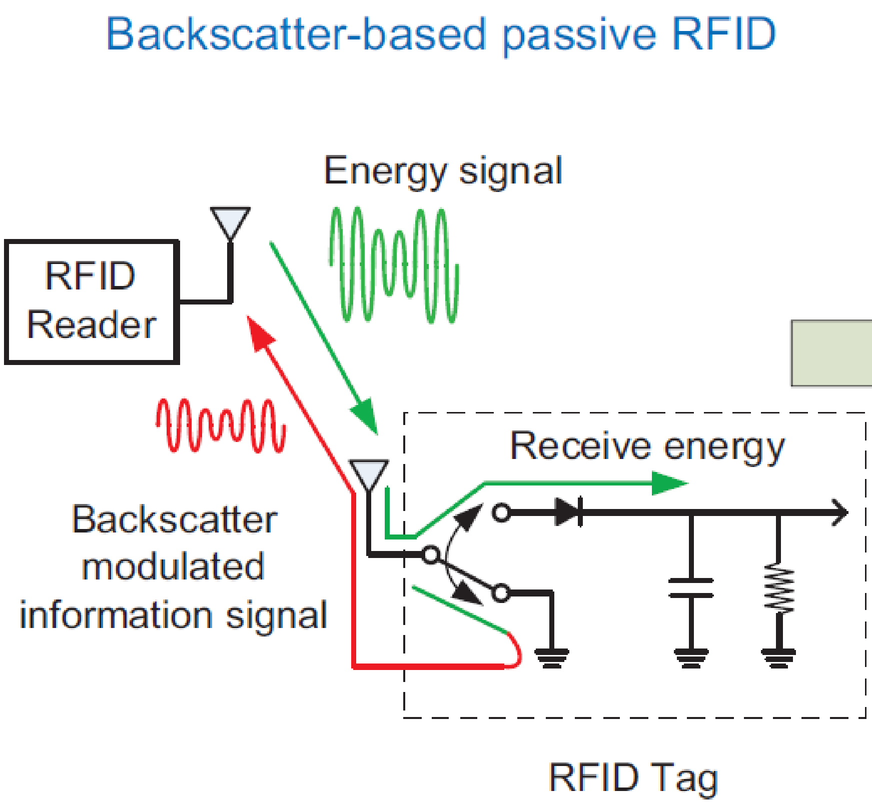


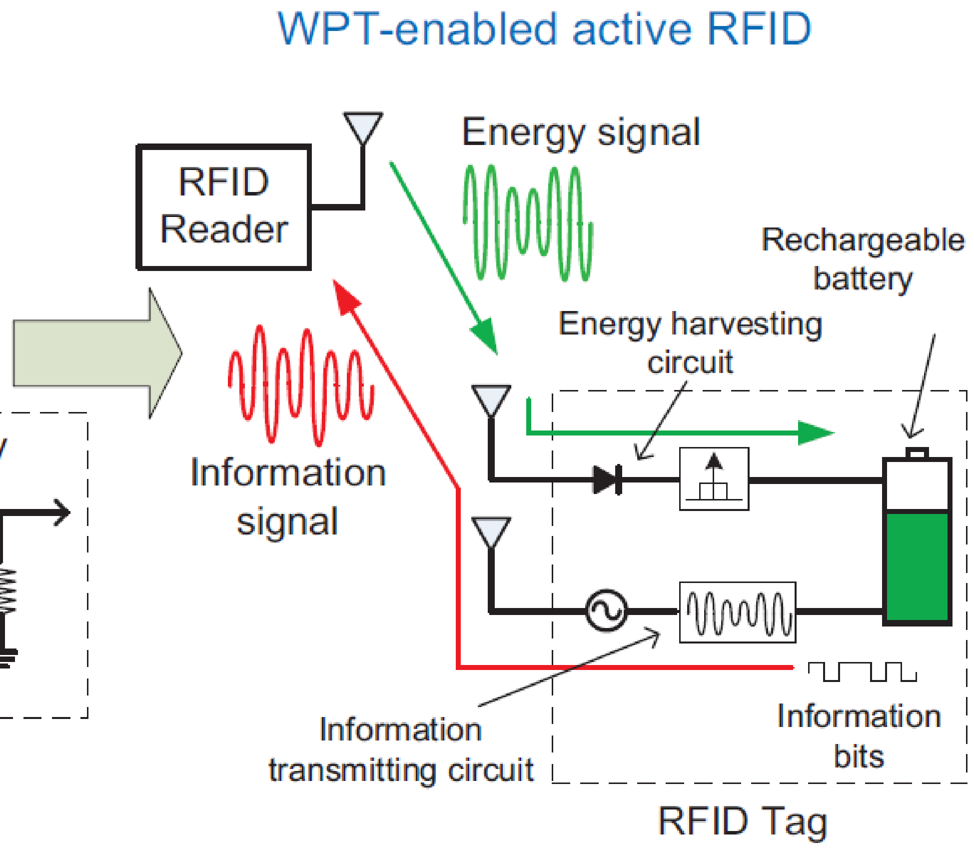
- ❑ Wireless charging fully controllable
- ❑ Wide coverage, low production cost, and small receiver
- ❑ Main challenges: low efficiency of wireless power transfer, wireless information and power transfer joint design

Wireless Powered Communication Applications (1)

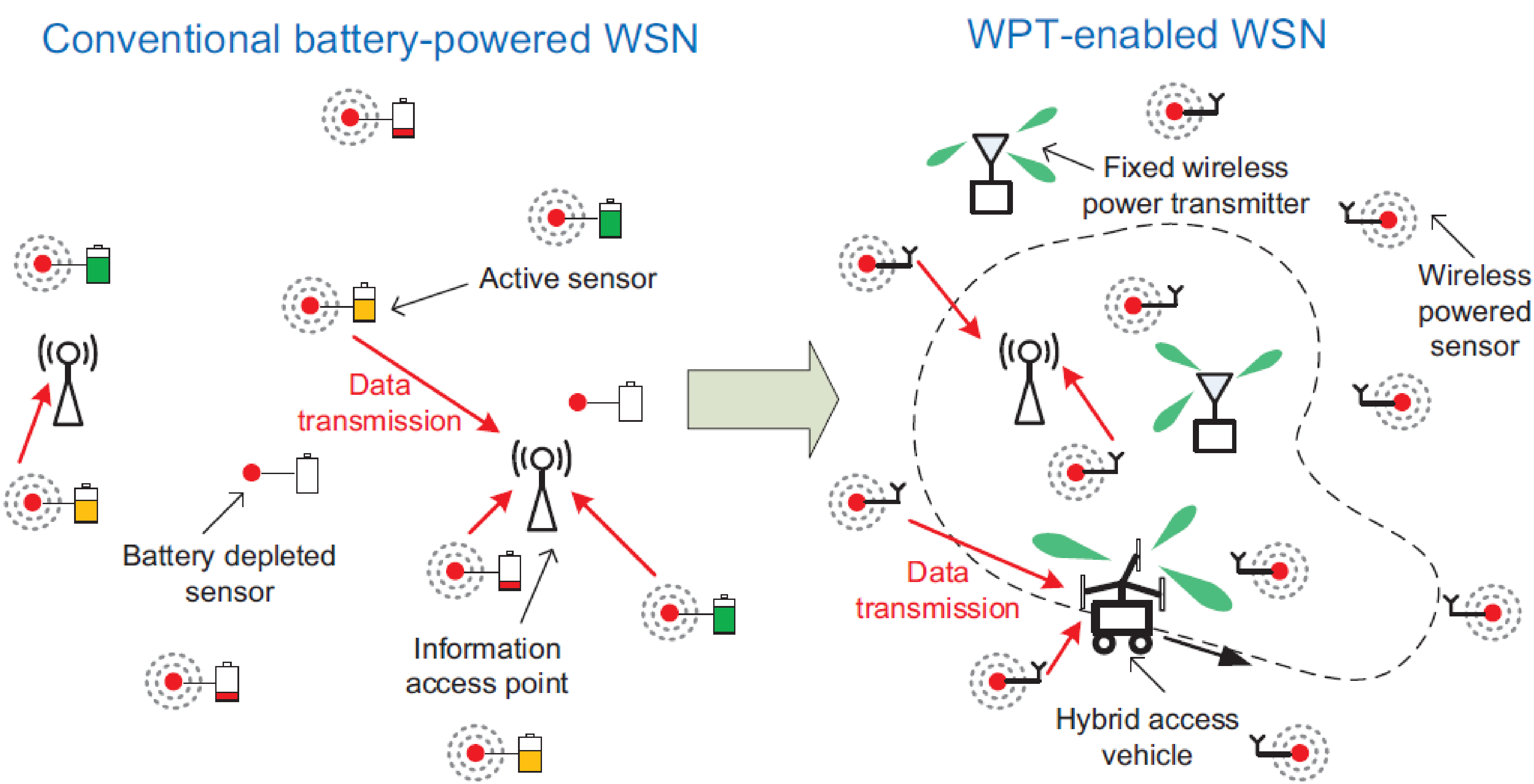


Wireless Powered Communication Applications (2)





Wireless Powered Communication Applications (3)



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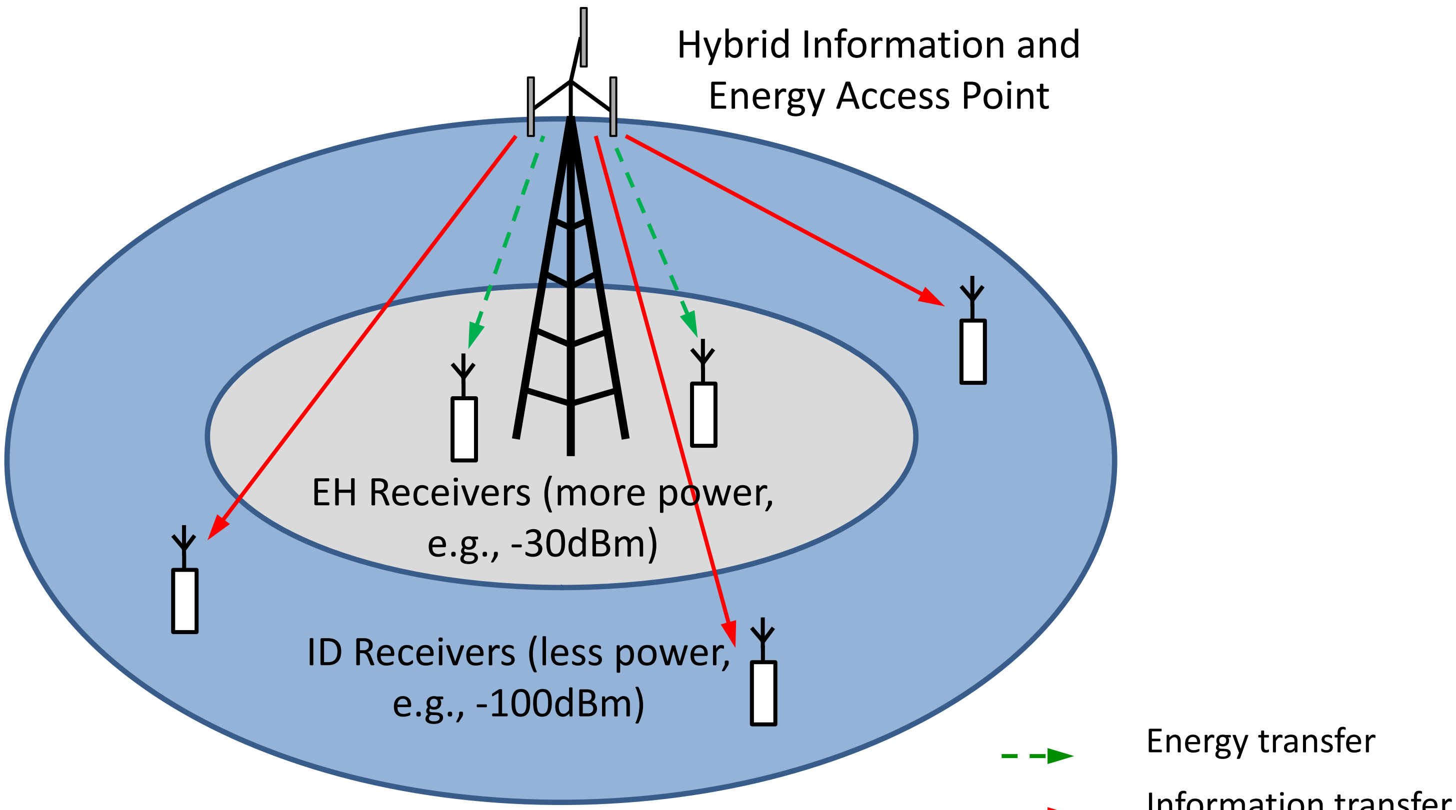
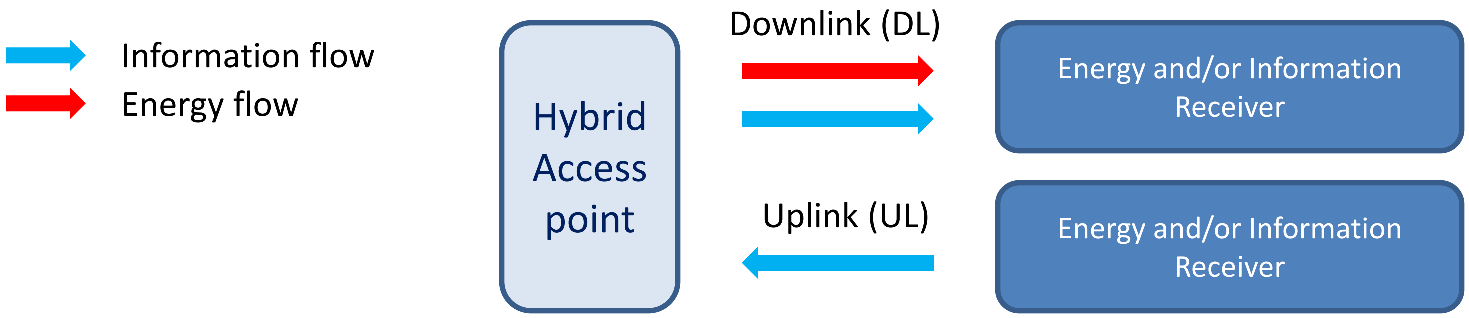
Wireless Powered Communication Applications (4)



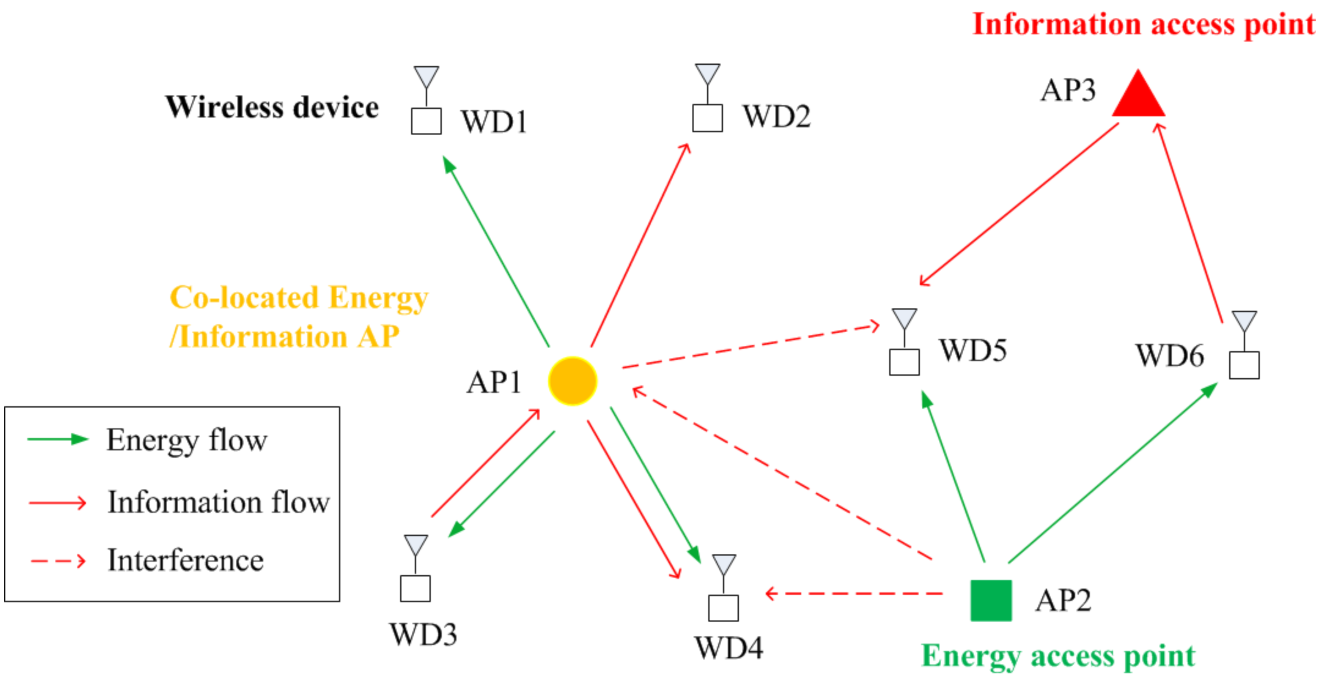
A Generic Model



❑ Three "Canonical" Models/Modes

- Wireless Power Transfer (WPT) in DL
- Wireless Powered Communication Network (WPCN): DL WPT and UL wireless information transmission (WIT)
- Simultaneous wireless information and power transfer (SWIPT): DL WPT and WIT at the same time

General Network Model

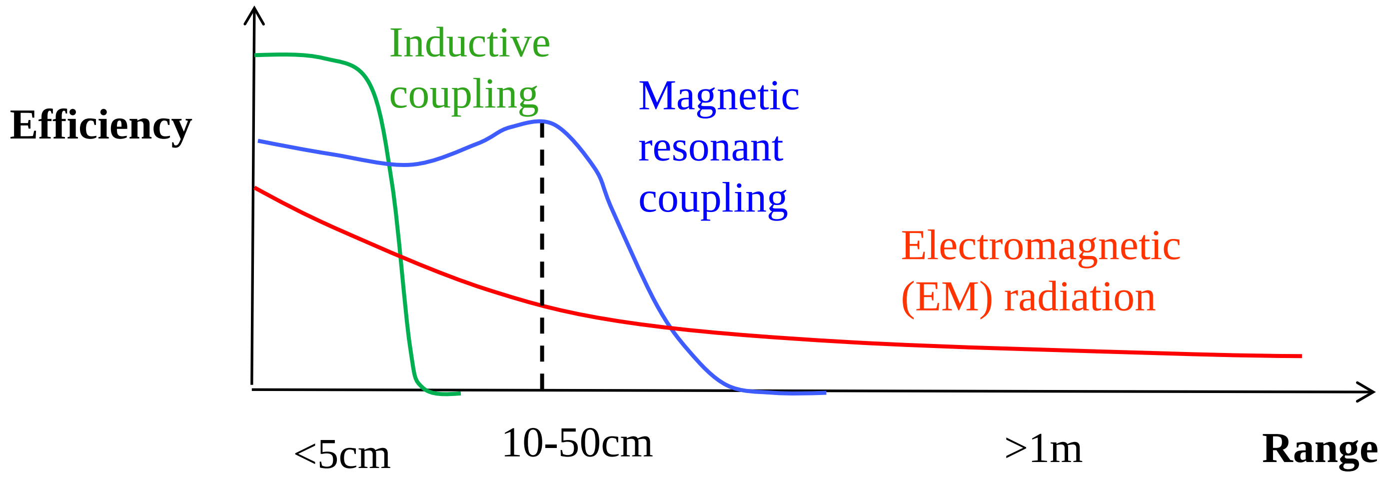


- Three canonical operating modes
  - Wireless power transfer: AP2 -> WD5;
  - Wireless powered communication: AP1 <-> WD3, AP2->WD6->AP3;
  - Simultaneous wireless information and power transfer: AP1->WD4, AP1->WD1,WD2

Outline

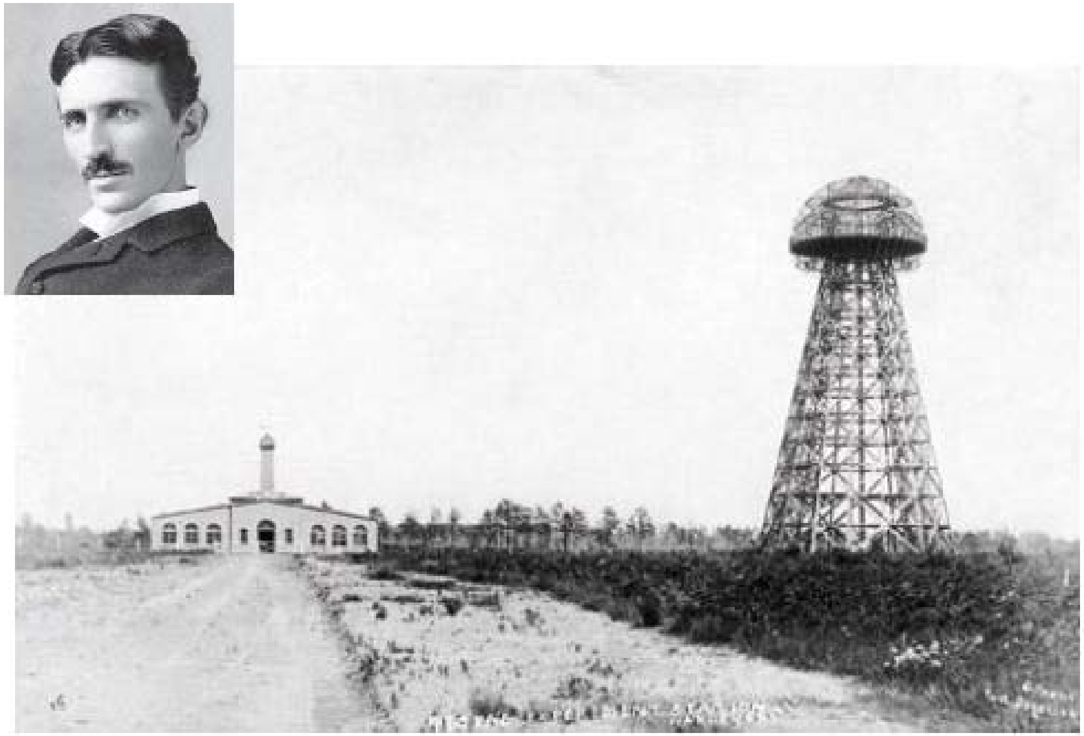
- Wireless Power Transfer
- Wireless Powered Communications
- Simultaneous Wireless Information and Power Transfer

Wireless Power Transfer: Main Technologies



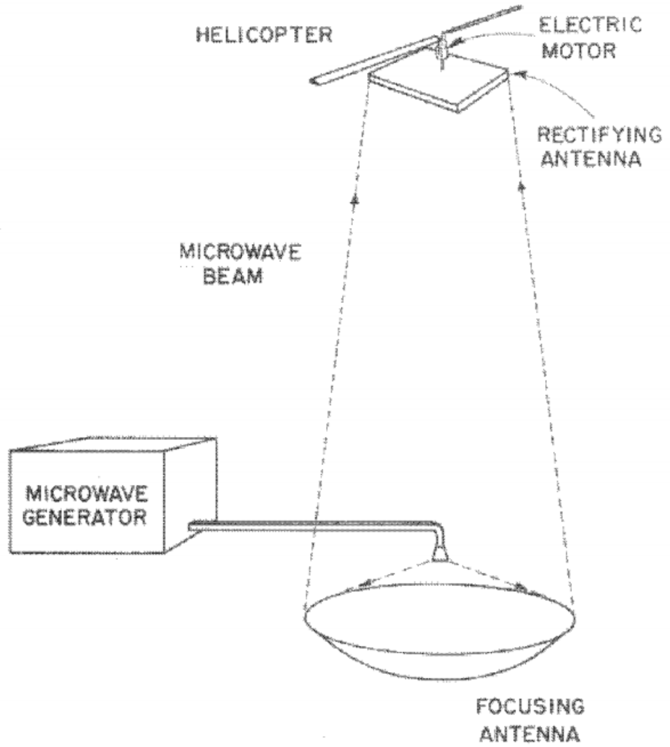
	Field	Advantages	Disadvantages
Inductive Coupling	Near field	Very high efficiency	Very short distance Require stringent TX-RX alignment
Magnetic Resonant Coupling	Near/Mid field	High efficiency	Short distance Unsuitable to charge moving devices Bulky energy RX
EM/Microwave Radiation (focus of this talk)	Far field	Long distance Energy multicasting Small RX form factor Mobility support	Low efficiency Safety issue with high power

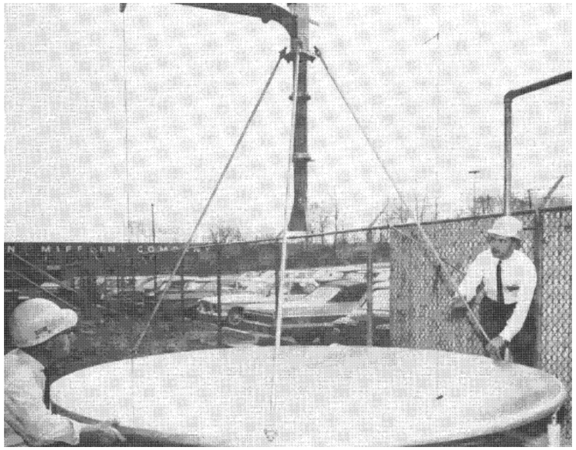
Microwave Enabled Wireless Power Transfer: Nikola Tesla and his Wardenclyffe Project in early 1900

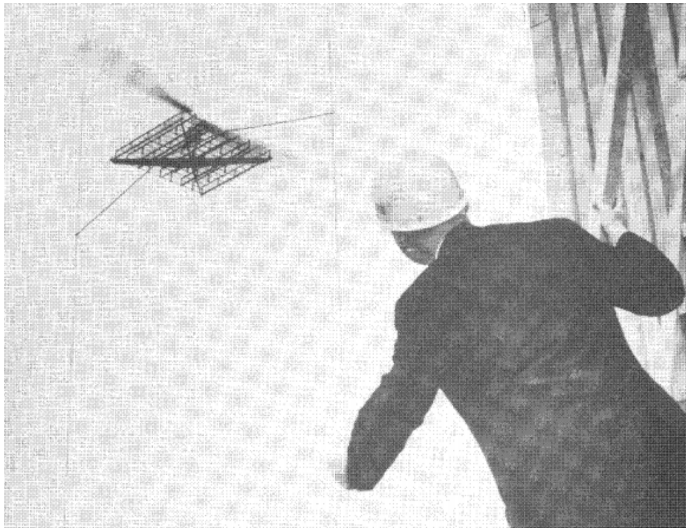


150 KHz and 300 kW. Unsuccessful and never put into practical use.

The Invention of ``Rectenna" for Microwave Power Transmission: the Microwave Powered Helicopter by William C. Brown in 1960s

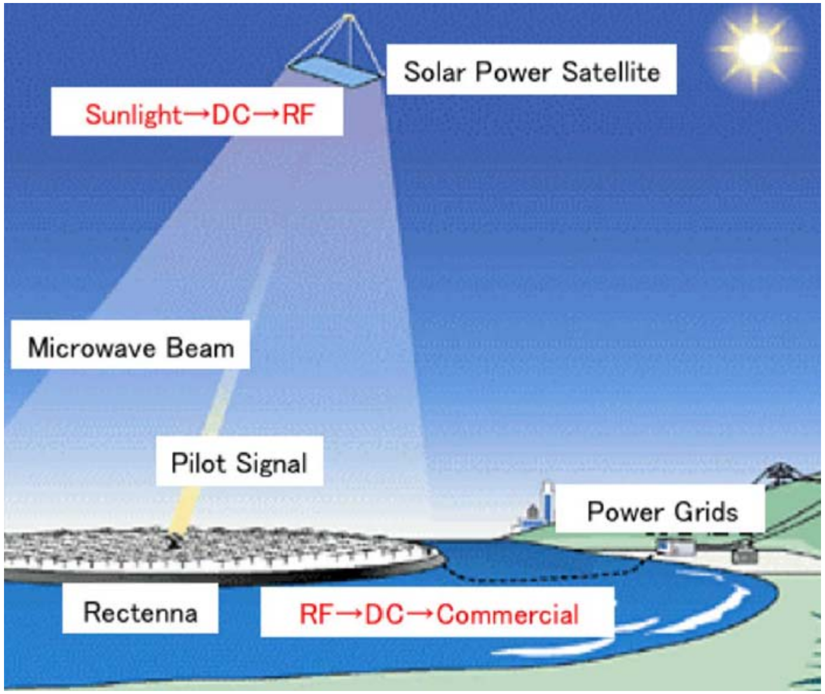


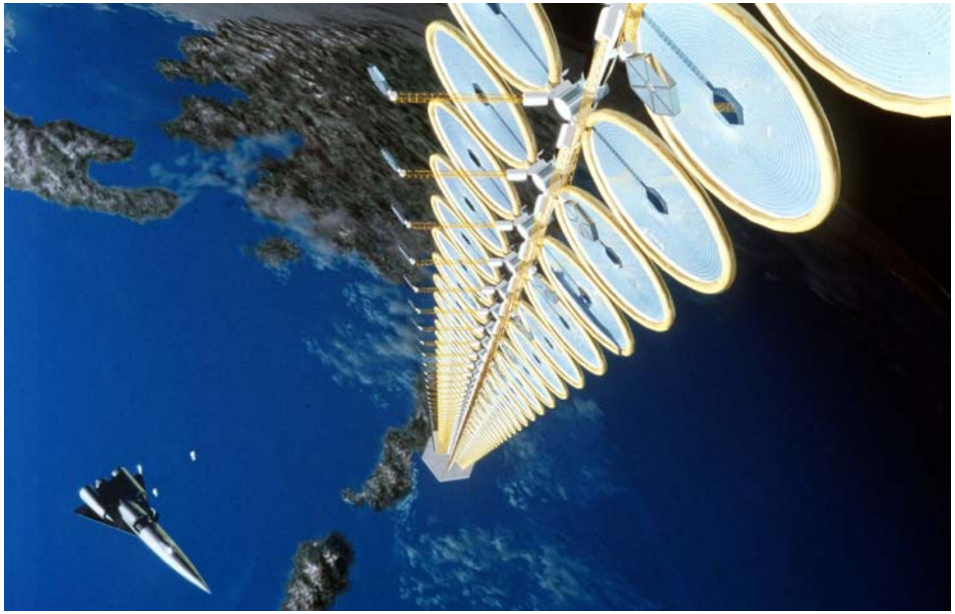




2.45 GHz and less than 1kW. Overall 26% transfer efficiency at 7.6 meters high.

Solar Satellite with Microwave Power Transmission (1970s-current)





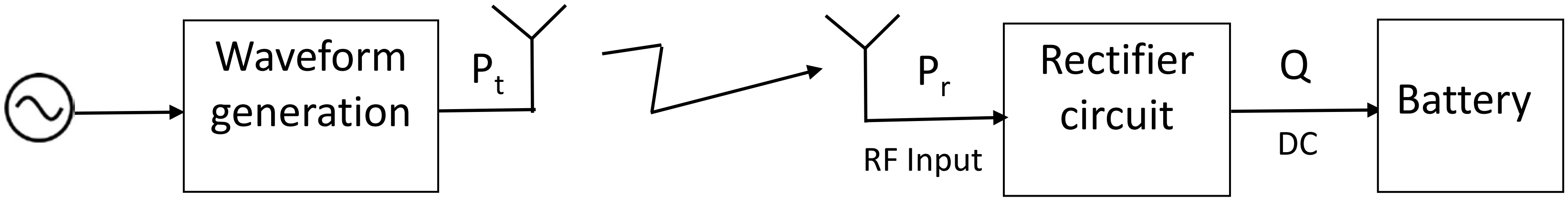
NASA Sun Tower

Target at GW-level power transfer with more than 50% efficiency

Microwave Power Transfer Field Experiment with Phased Array (1992)

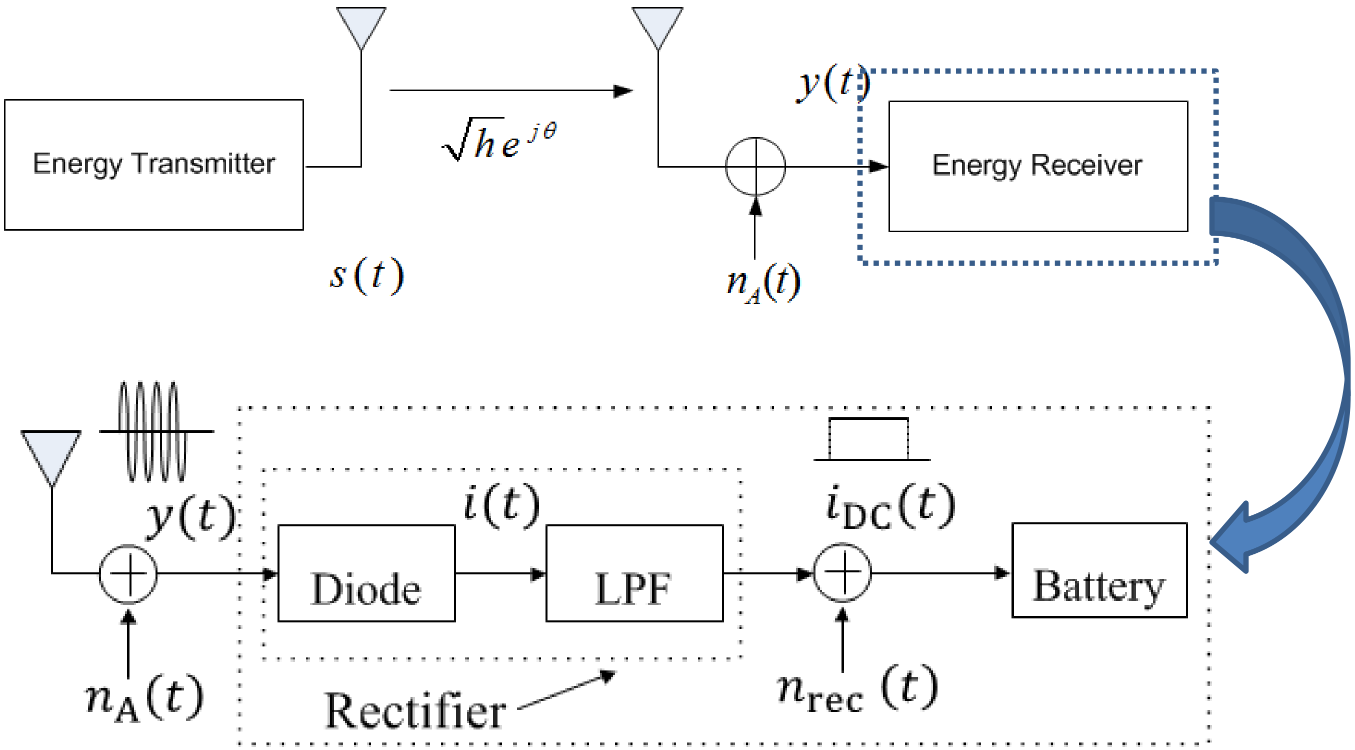
- 2.411 GHz
- 288 elements phased array on the roof of the car
- 120 rectennas on the fuel-free airplane
- DC output power ~88W

WPT: End-to-End Efficiency



- Overall power transfer efficiency: $e = \frac{Q}{P_t} = \underbrace{\frac{P_r}{P_t}}_{\alpha} \underbrace{\frac{Q}{P_r}}_{\xi}$
- Improve RF-to-RF efficiency α (decays quickly with distance) by
  - Using high-gain directional antennas: parabolic, horn antennas
  - **Energy beamforming**: adaptive beam control
- Improve RF-to-DC conversion efficiency ξ (typically 30%-70%) by
  - Rectifier design
  - Waveform optimization

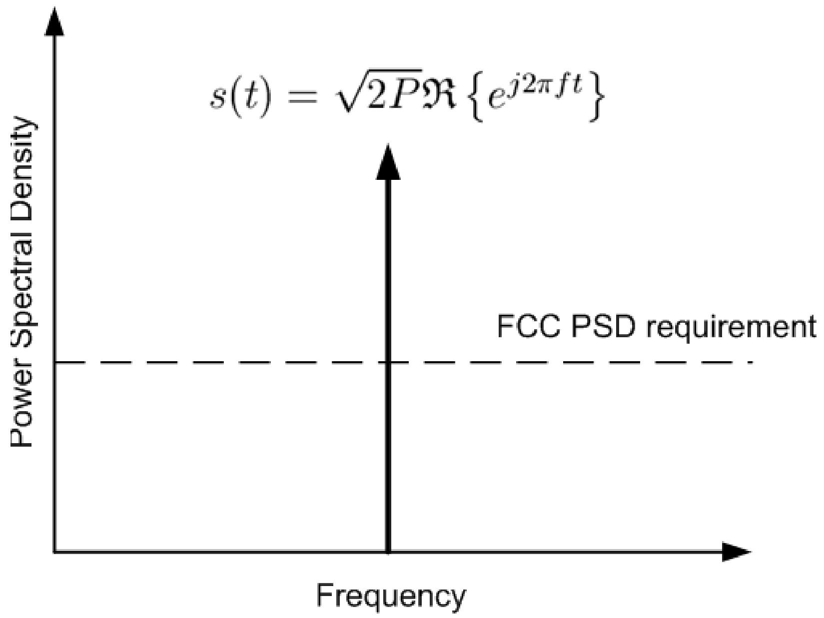
Energy Receiver Architecture



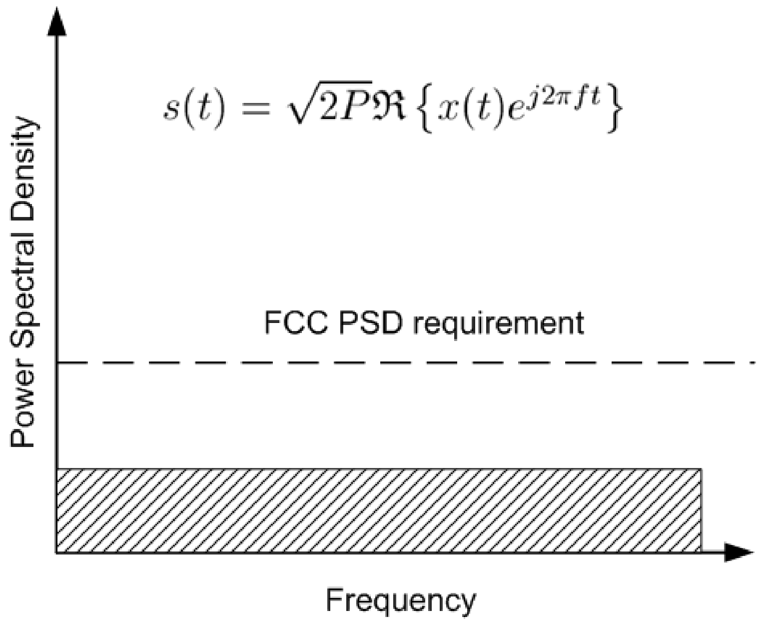
- The receiver uses rectifier to convert RF signal into DC signal
- Assuming linear energy harvesting model, the harvested power is

$$Q = E\left[i_{DC}(t)\right] \approx \xi E\left[\| y(t) \|^2\right] = \xi h P$$

Modulated vs. Unmodulated Energy Signal



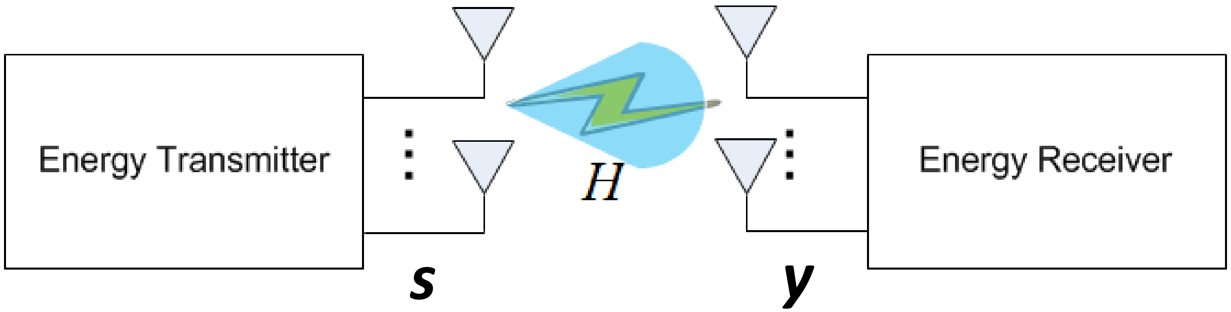
PSD of unmodulated energy signal



PSD of modulated energy signal

Use pseudo-random modulated energy signal to avoid the "spike" in the power spectral density (PSD) with constant unmodulated energy signal

Scaling Up WPT: Energy Beamforming in MIMO Channel



$$P_r = P_t \times G_a \times D^{-\alpha} \times \zeta$$

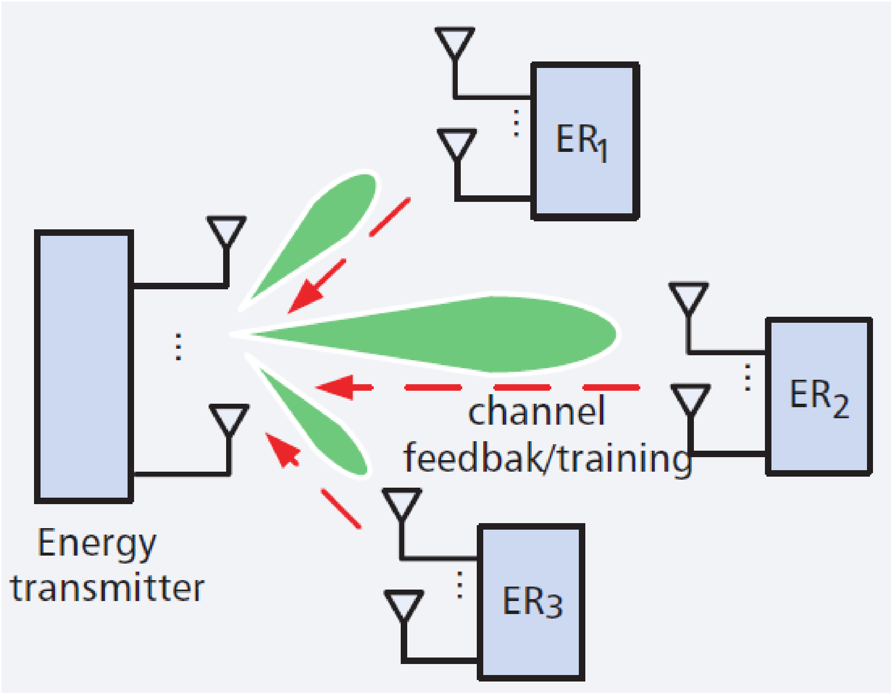
Antenna gain (G_a) · Path loss ($D^{-\alpha}$) · Energy conversion efficiency (ζ): 30% - 70%

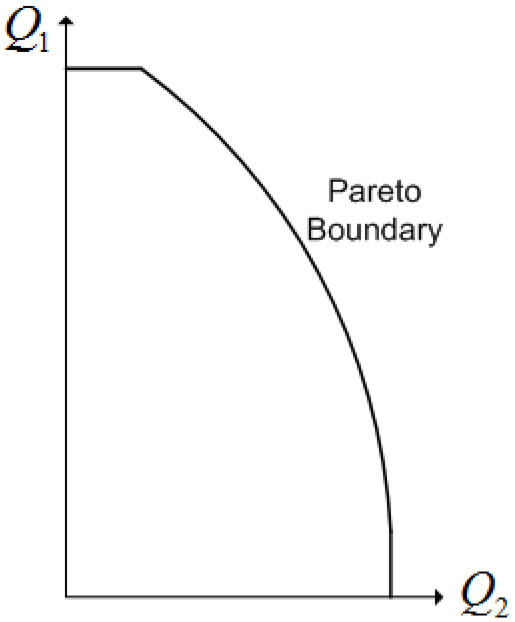
- The harvested energy is $\zeta ||\mathbf{y}||^2 = \zeta ||\mathbf{H}\mathbf{s}||^2 = \zeta \text{tr}(\mathbf{G}\mathbf{S})$
- Q:What's the optimal transmit strategy given a limited Tx power budget?
- A: Energy beamforming
- The optimal EB is the principal eigenvector beamforming

$$\begin{aligned} &\underset{\mathbf{S}}{\text{maximize}} \quad \text{tr}(\mathbf{G}\mathbf{S}) \\ &\text{subject to} \quad \text{tr}(\mathbf{S}) \leq P, \quad \mathbf{S} \succeq \mathbf{0} \\ &\text{where } \mathbf{G} = \mathbf{H}^H\mathbf{H} \end{aligned}$$

$$\mathbf{S}^* = P\mathbf{v}_E\mathbf{v}_E^H \quad \mathbf{v}_E \text{ is the principal eigenvector of } \mathbf{G}$$

MIMO Energy Multicasting

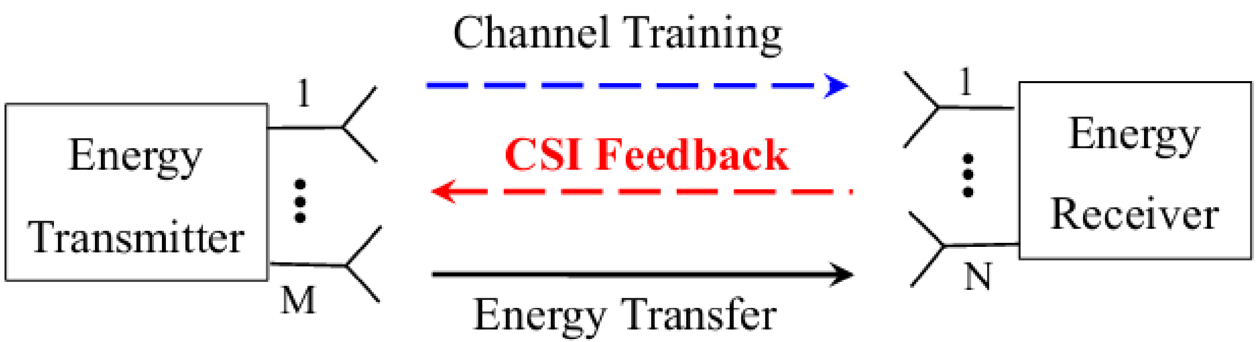




Power region of energy multicasting

- Energy near-far problem: fairness is a key issue in the multi-user EB design
- Challenge: EB requires accurate channel state information at the transmitter (CSIT)

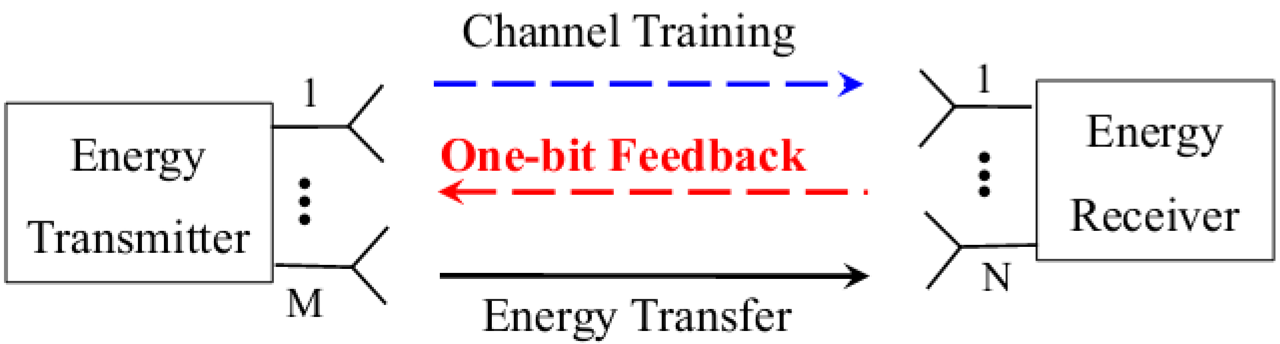
Channel Estimation for Energy Beamforming (1)



(a) **Forward-link** training with **CSI** feedback

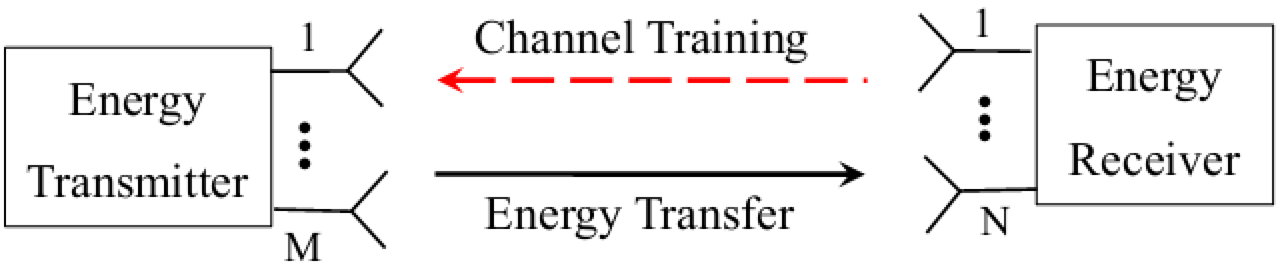
- Conventional training in Wireless Communication:
  - Forward link training with CSI feedback
  - Objective: Efficient pilot design to minimize spectral efficiency loss
- New considerations for WPT:
  - Energy receiver (ER) has limited energy and processing capability
  - ER does not need CSI for energy harvesting (vs. information receiver)
- Potential solutions:
  - Energy feedback
  - Reverse-link training

Channel Estimation for Energy Beamforming (2)



(b) **Forward-link** training with **one-bit** feedback

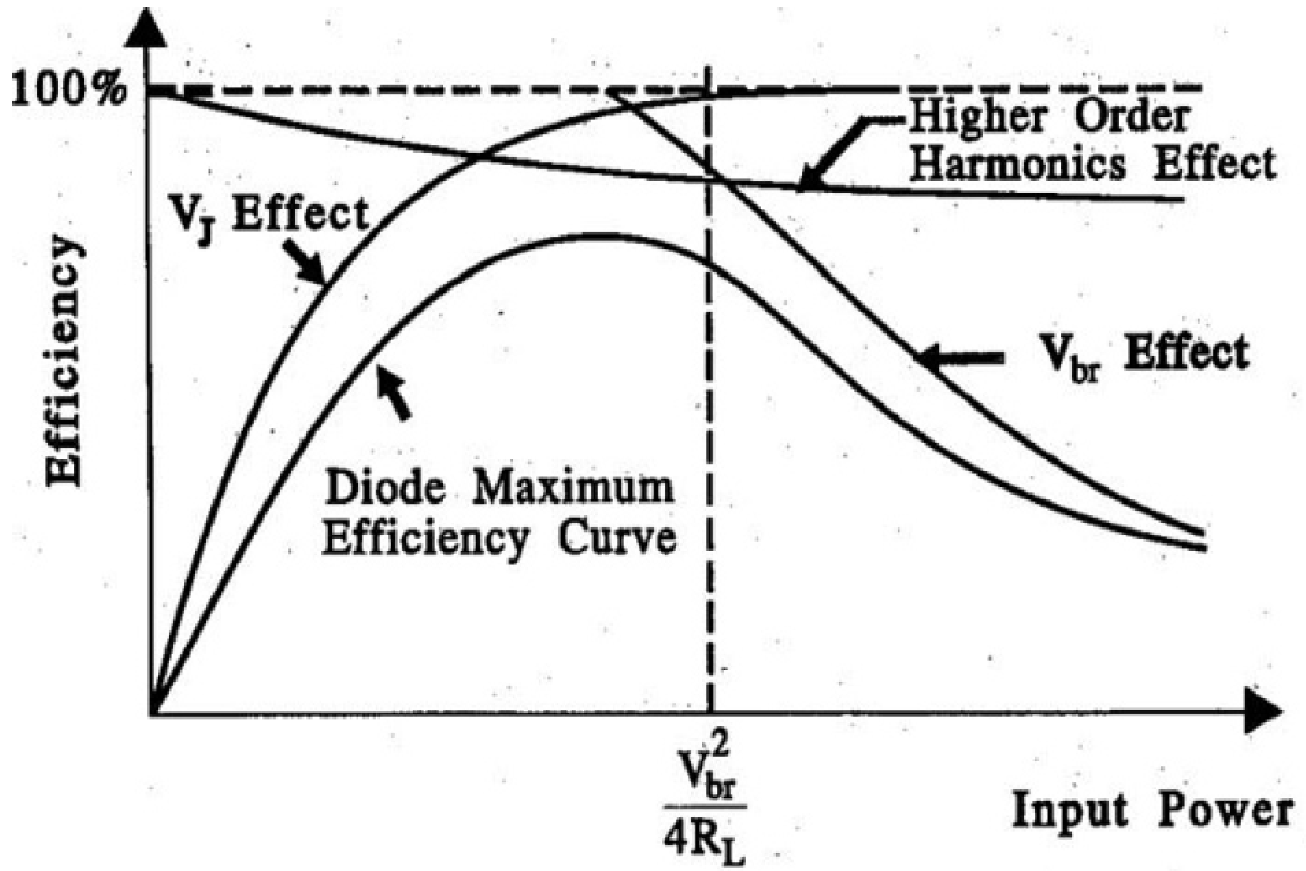
- One-bit energy feedback based on the change of received power level



(c) Reverse-link training w/o feedback

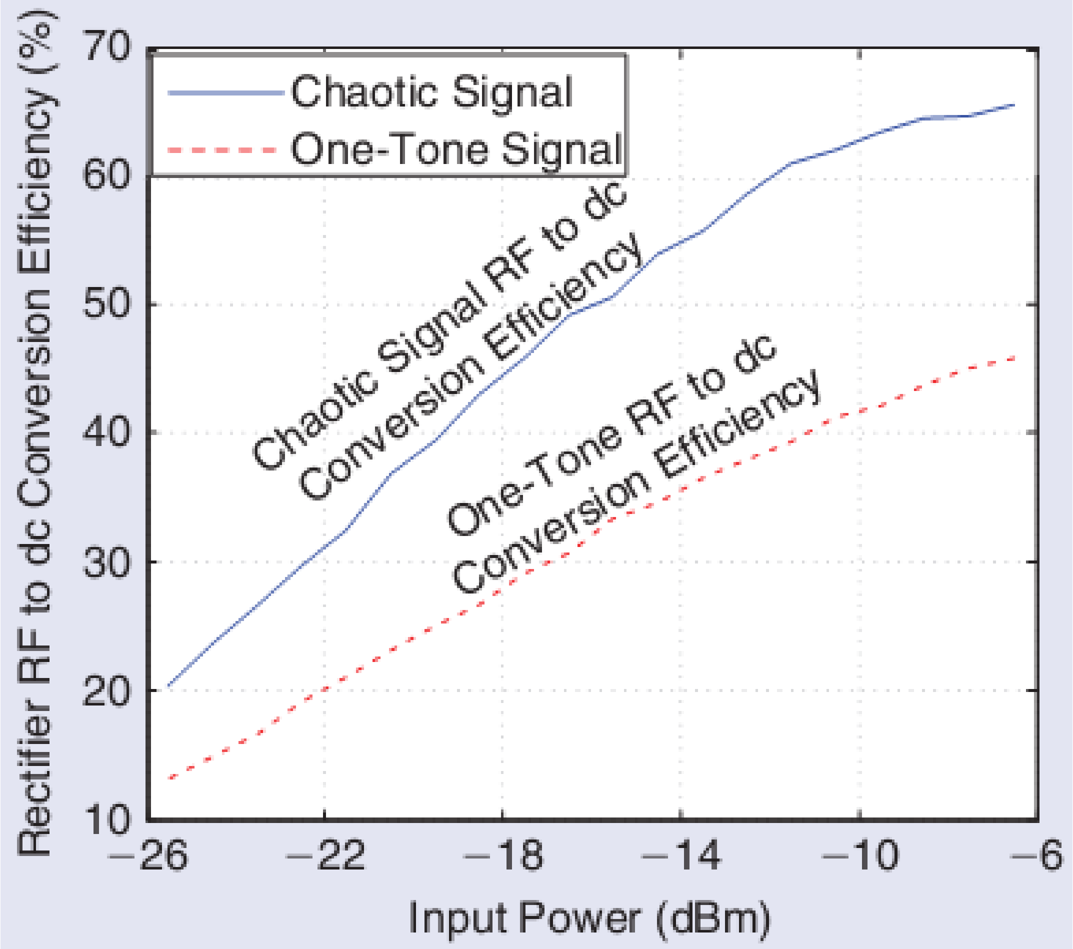
- Reverse link training: exploit channel reciprocity, no feedback required
- Maximize Rx's NET energy:=harvested energy – energy consumed for training

Nonlinear Energy Harvesting Model (1): Efficiency vs. Input Power



- ❑ In practice, the RF-DC conversion efficiency varies with input power
- ❑ Energy beamforming needs to take into account this non-linear model

Nonlinear Energy Harvesting Model (2): Efficiency vs. Waveform

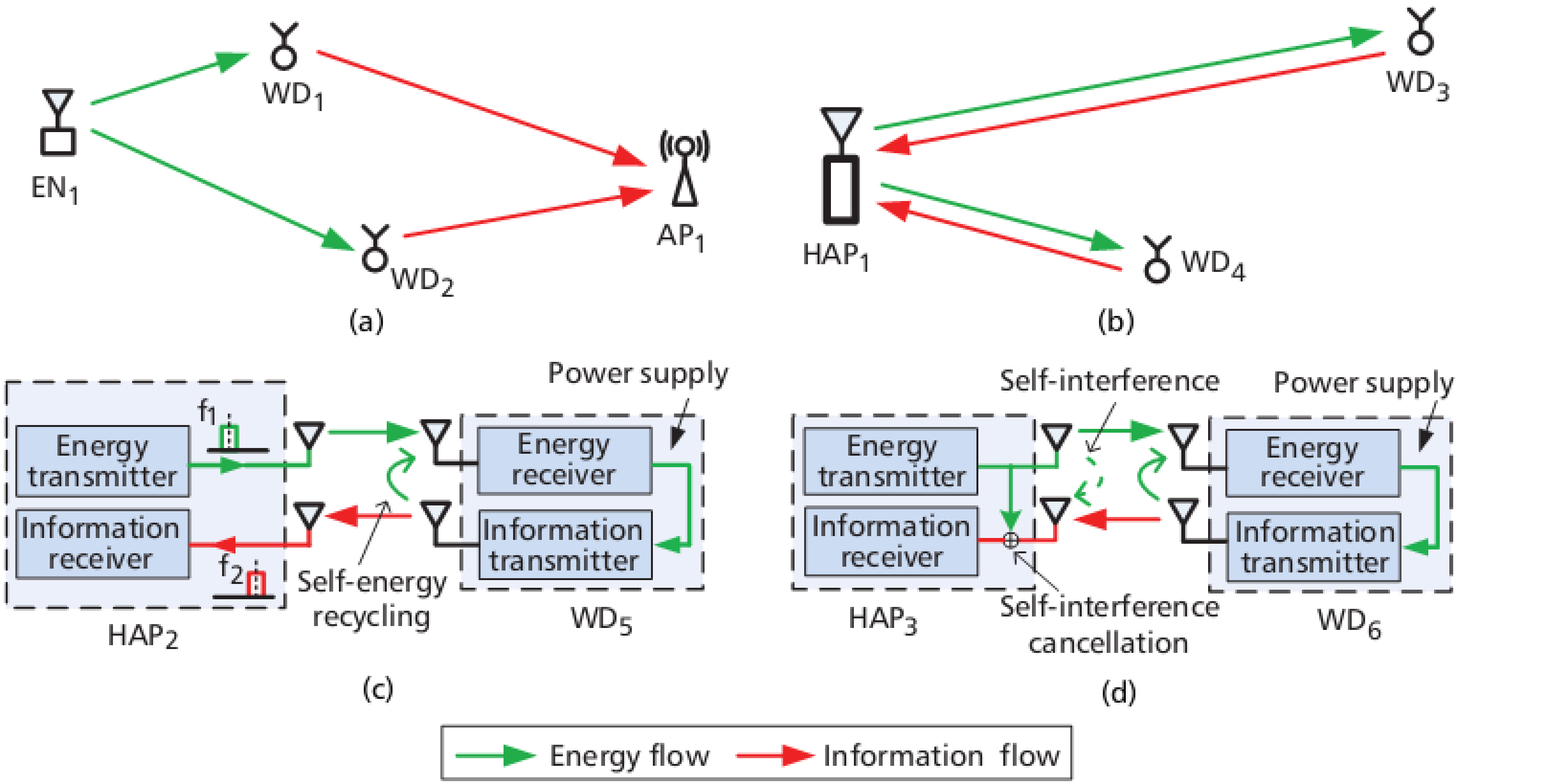


- Waveform with high peak-to-average power ratio (PAPR) tends to give better energy conversion efficiency, thus new waveform design is needed for WPT

Outlines

- ❑ Wireless Power Transfer
- ❑ Wireless Powered Communications
- ❑ Simultaneous Wireless Information and Power Transfer

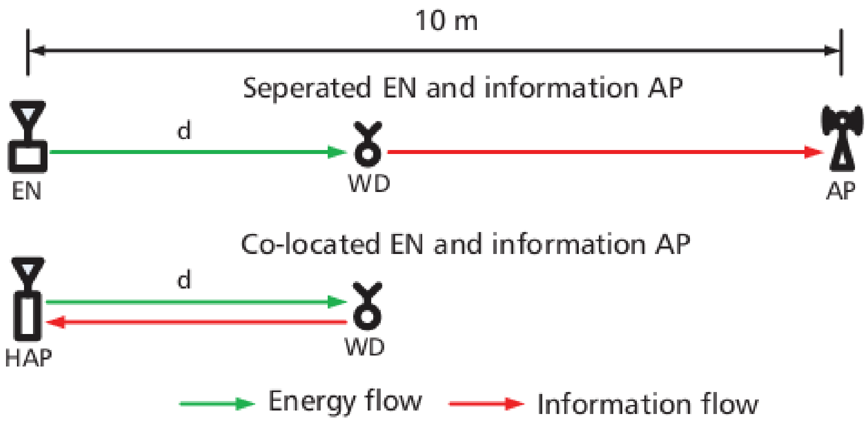
Wireless Powered Communication: Basic Models



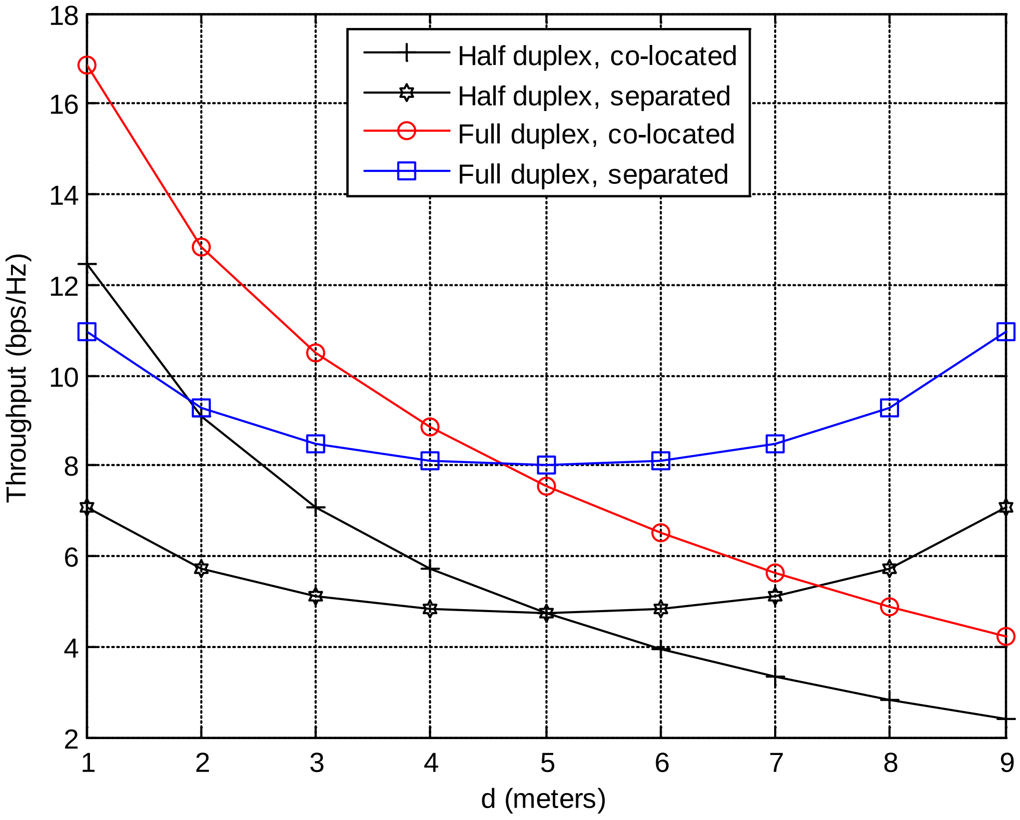
(a): Separate energy/information APs; (b): co-located energy/information AP
(c): Out-band half-duplex energy/information; (d): In-band full-duplex energy/information

- Coupled DL (energy) and UL (information) transmissions
- Need joint energy and communication scheduling and resource allocation

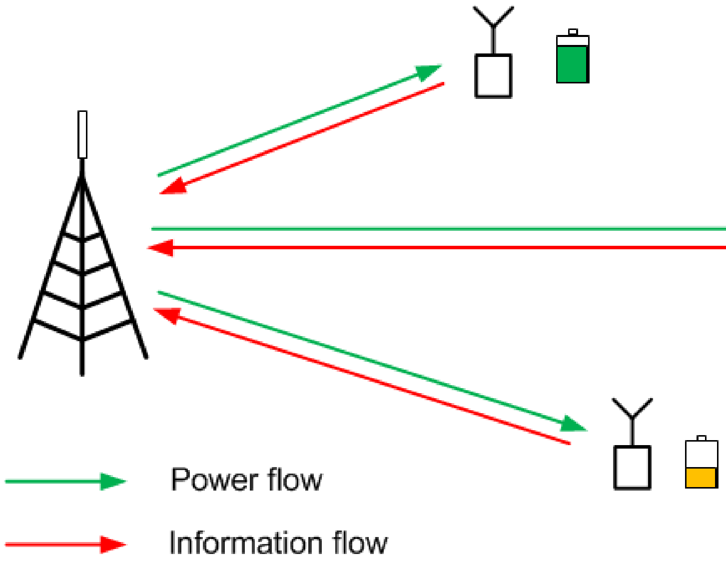
Throughput Comparison of Different Setups



- For full-duplex:
  - 80 dB self-interference cancellation at AP
  - 10% self-energy recycling at wireless device (WD)



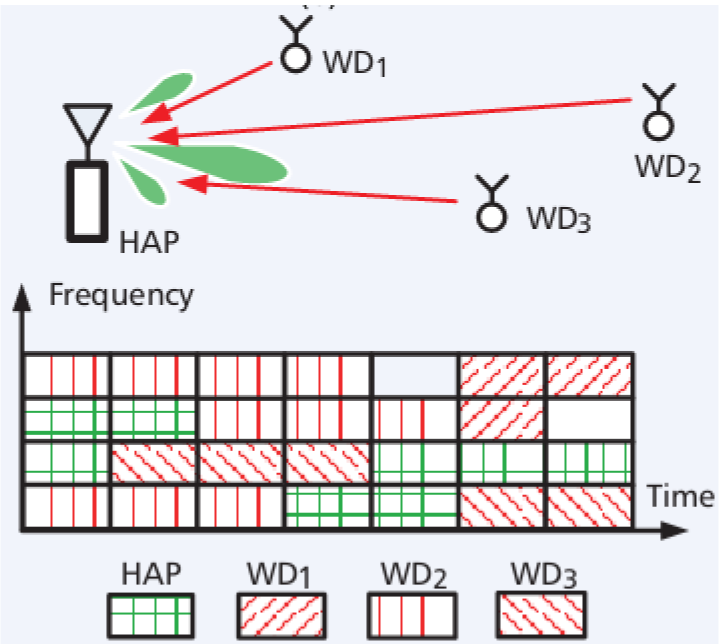
"Doubly" Near-far Problem



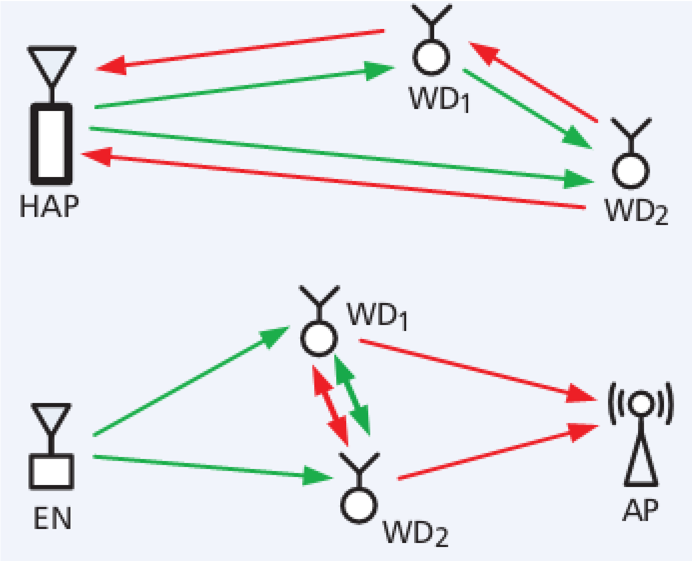
Harvest-then-transmit protocol

- Doubly Near-Far Problem
  - Near user harvests more energy in DL but requires less power in UL communication
  - Far user harvests less energy in DL but requires more power in UL communication

Solutions to Doubly Near-far Problem

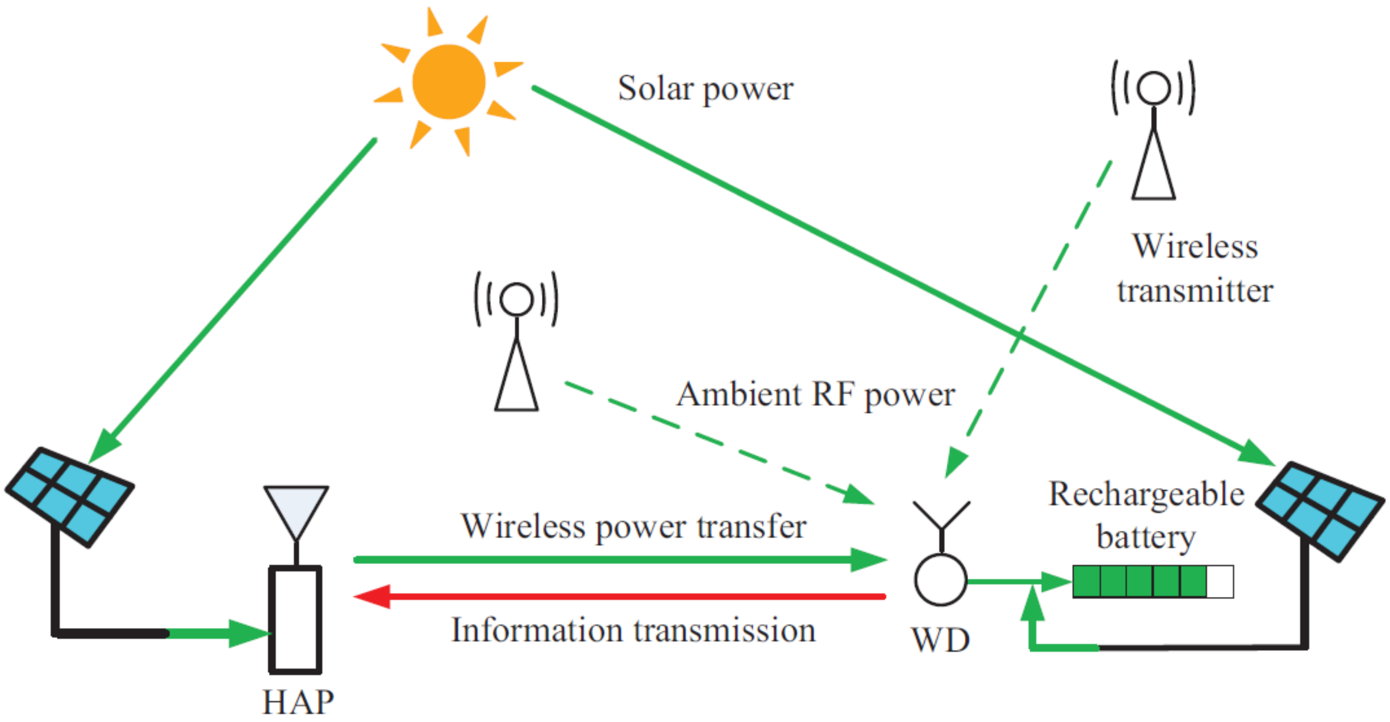


(a): Joint communication and energy scheduling, transmit (energy)/receive (information) beamforming



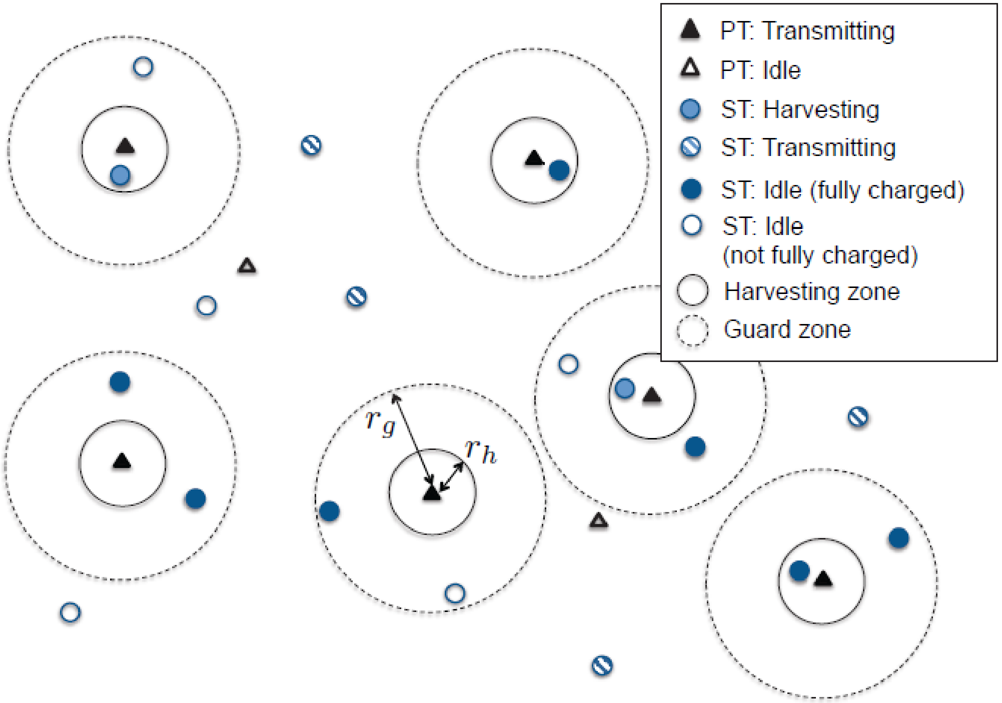
(b): Wireless powered cooperative communication

Wireless Power Meets Energy Harvesting



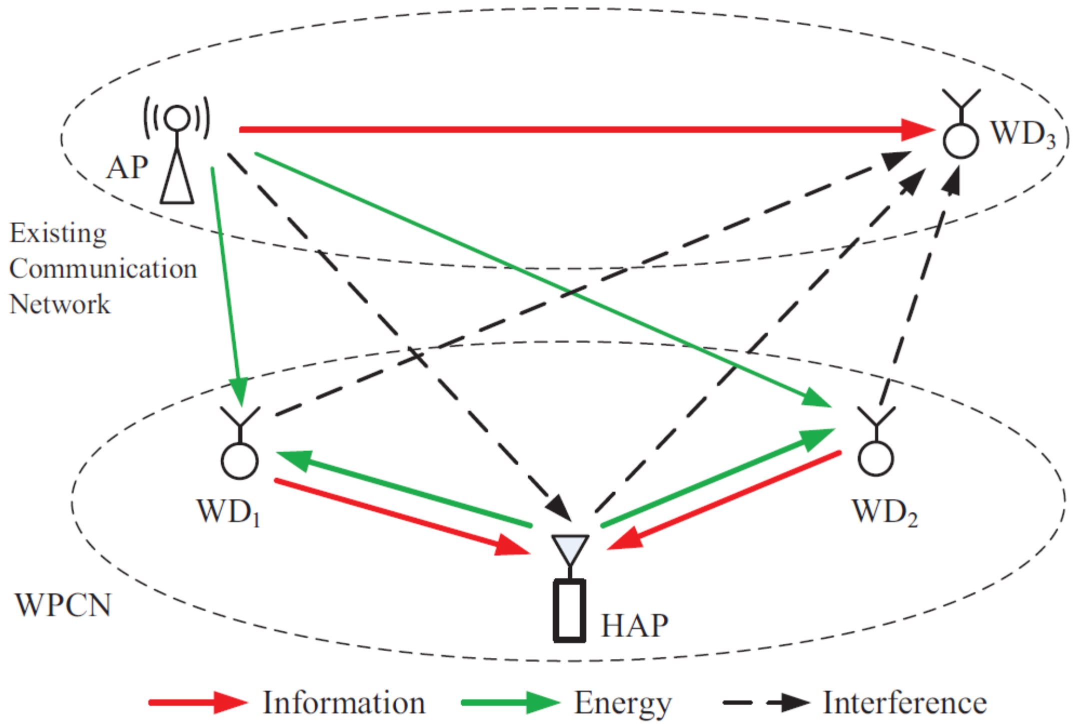
- ❑ Hybrid energy supplies via both environmental energy harvesting and dedicated wireless power transfer
- ❑ Wireless powered communication needs to be jointly designed with energy harvesting communication

Wireless Powered Cognitive Radio Network



- Conventional cognitive radio (CR): secondary user is idle when nearby primary user is transmitting
- Wireless powered CR: secondary user harvests energy from nearby active primary transmitters

Wireless Information and Power Transfer Coexisting

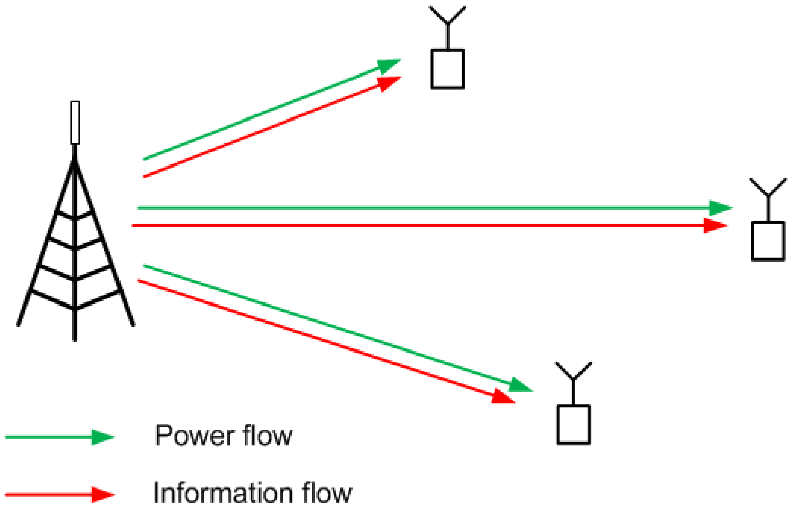


- Wireless power transfer/wireless powered communication coexists with existing communication systems
- New spectrum sharing models and techniques needed to maximize spectrum/energy efficiency

Outlines

- ❑ Wireless Power Transfer
- ❑ Wireless Powered Communications
- ❑ Simultaneous Wireless Information and Power Transfer

SWIPT: Rate-Energy Tradeoff at Transmitter Side

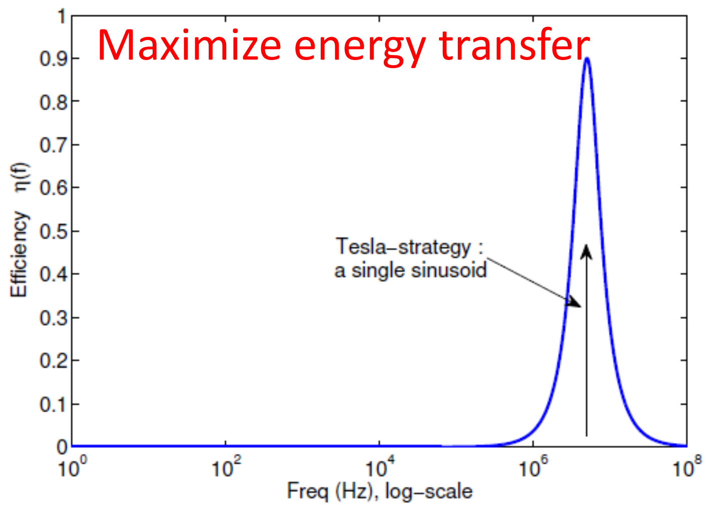


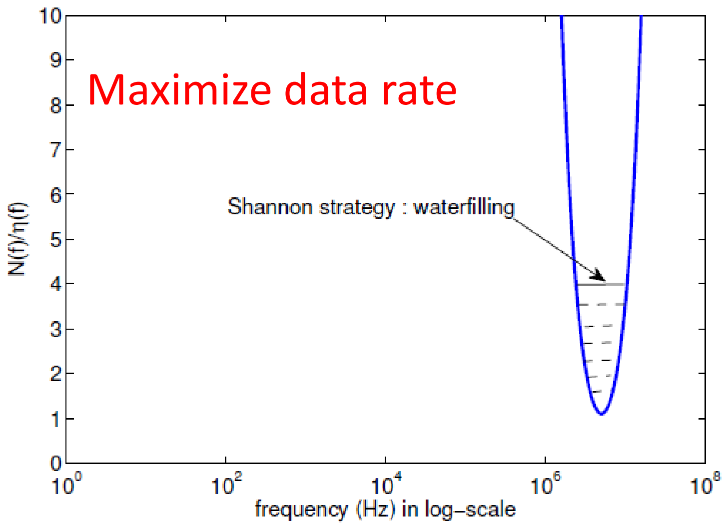
- Wireless Power Transfer vs. Wireless Information Transfer
  - Power Transfer :

$$Q \propto \zeta hPT$$

  - Information Transfer :

$$R \propto T \log_2 (1 + hP)$$

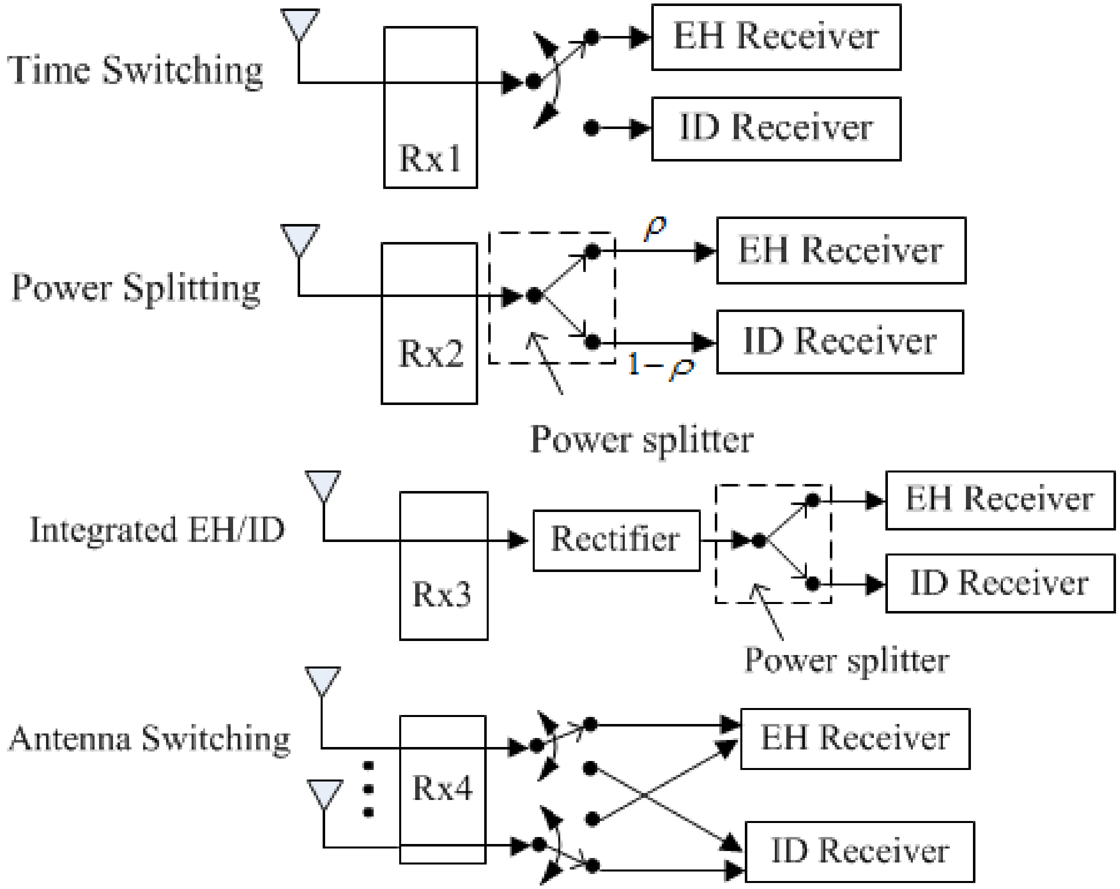




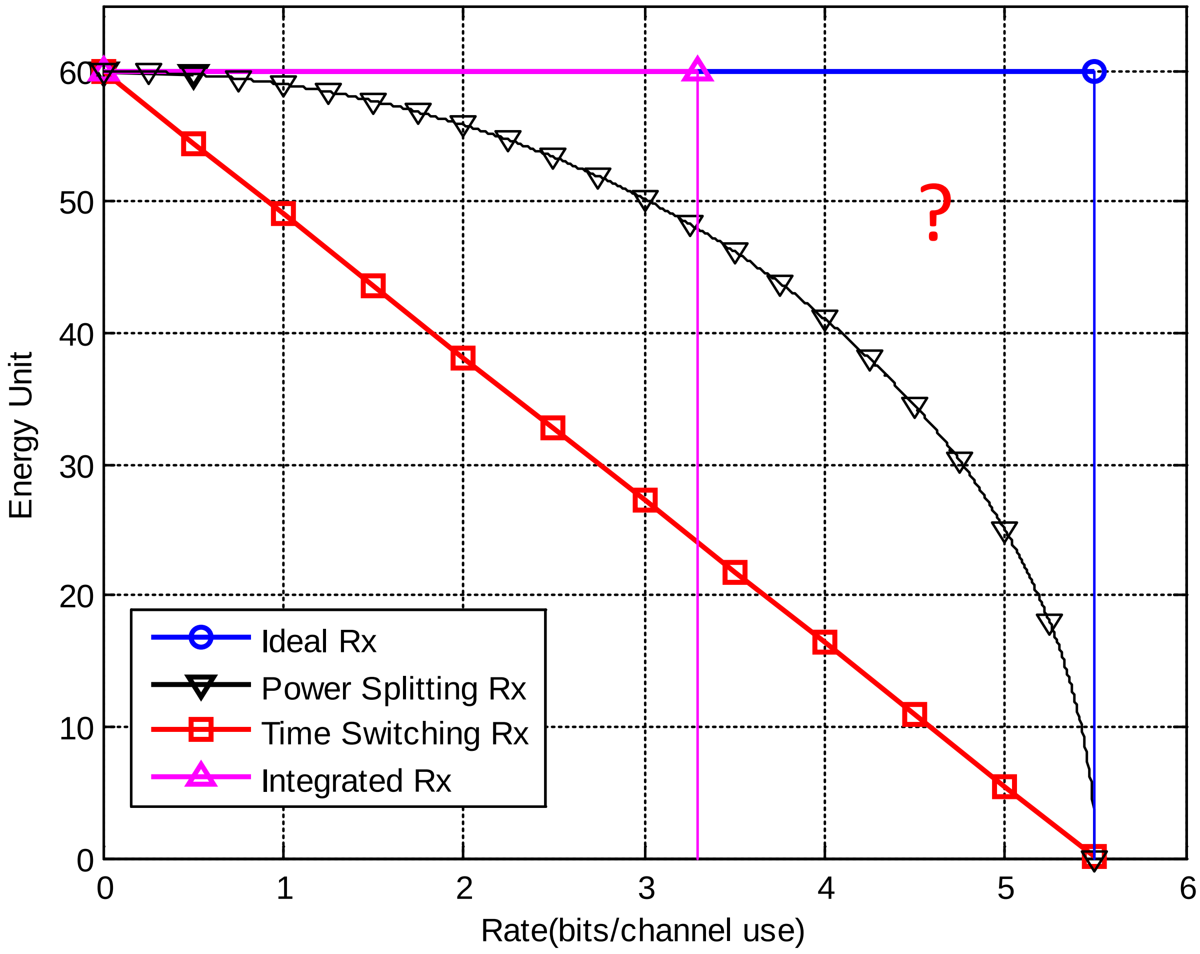
Optimal transmit power allocation in frequency-selective channel

SWIPT: Rate-Energy Tradeoff at Receiver Side

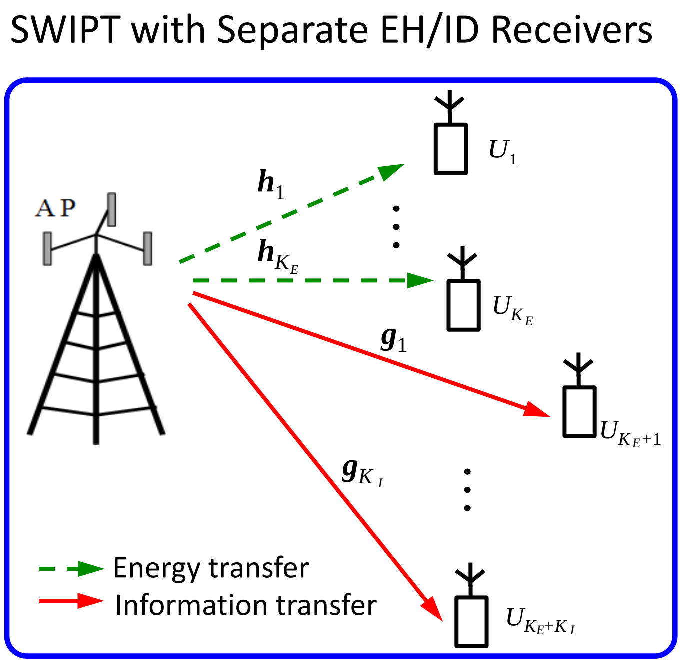
- Practical receiver cannot harvest energy and decode information from the same signal
  - Time switching receiver
  - Power splitting receiver
  - Integrated EH/ID receiver
  - Antenna switching receiver

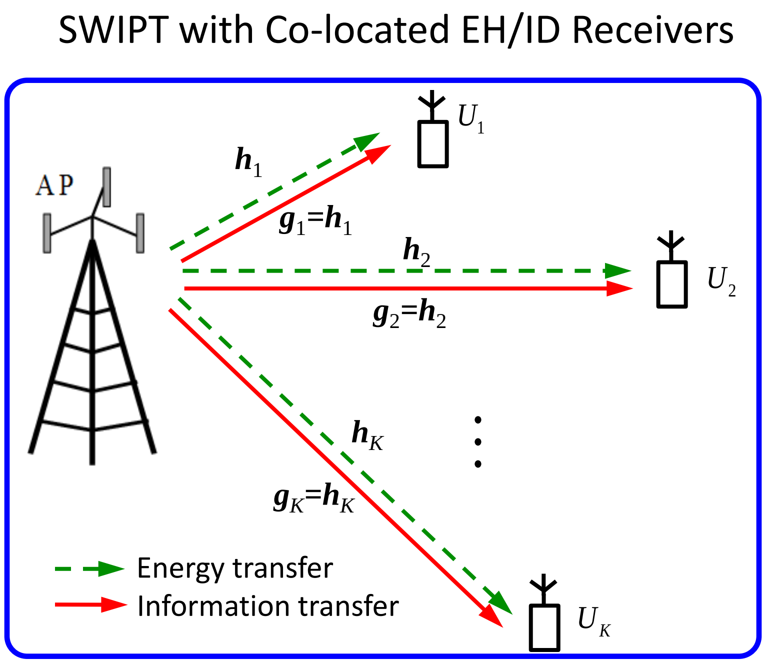


Rate-Energy Region of SWIPT in Point-to-Point AWGN



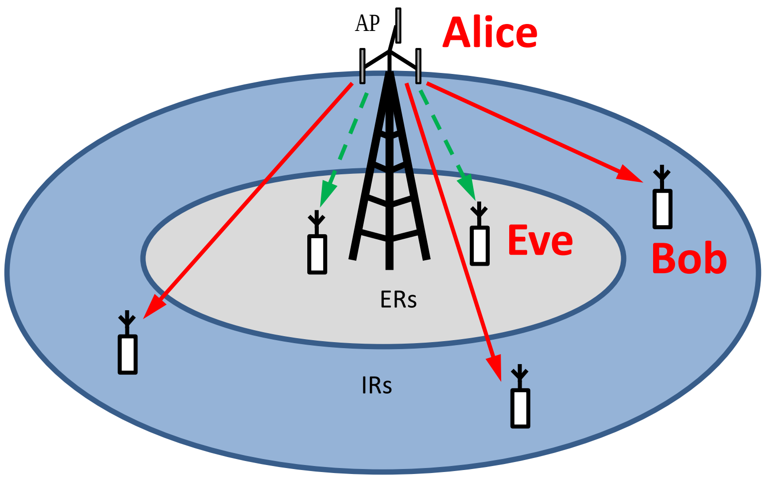
Joint Information and Energy Beamforming for SWIPT





- Joint transmit beamforming and receiver design optimization to maximize transferred energy and information under heterogeneous power/rate requirements of the users

Secure Communication in SWIPT



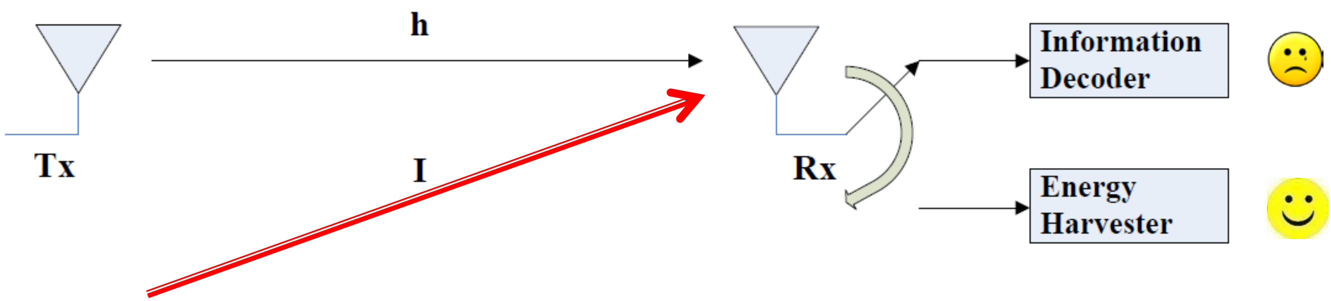
- ❑ Security issue in SWIPT
  - ➢ ER can easily eavesdrop IR's information
- ❑ Two conflicting goals:
  - ➢ Energy transfer: received power at each ER should be large
  - ➢ Secure information transfer: received power at each ER should be small
- ❑ How to resolve this conflict? Exploiting artificial noise

$$\boldsymbol{x} = \boldsymbol{v}_0 s_0 + \sum_{i=1}^{d} \boldsymbol{w}_i s_i$$

$\boldsymbol{v}_0 s_0$ → information signal

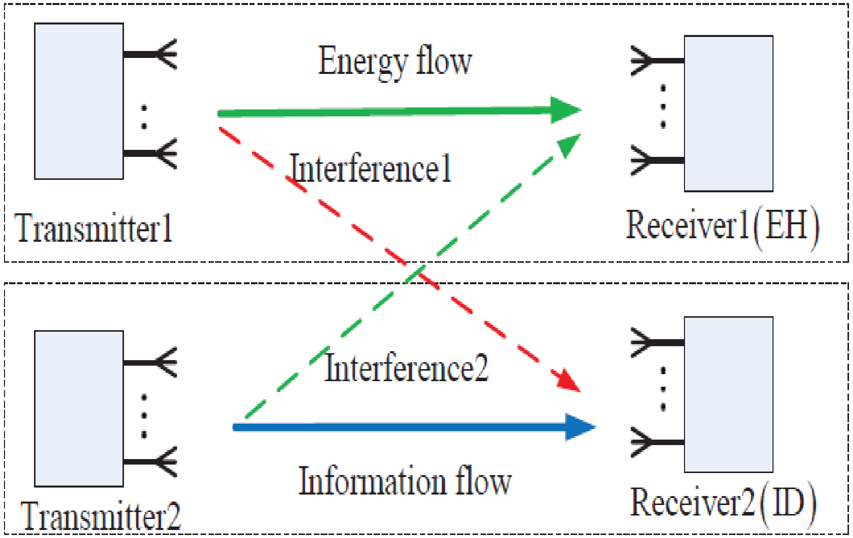
$\sum_{i=1}^{d} \boldsymbol{w}_i s_i$ → ❑ energy signal ❑ artificial noise

Dual Role of Interference in SWIPT



- ❑ Interference is harmful to information receiver but useful to energy harvesting
- ❑ Opportunistic EH and ID in fading channel via receiver mode switching
- ❑ In general, this opens a new paradigm for interference management

Multi-Transmitter Collaborative SWIPT



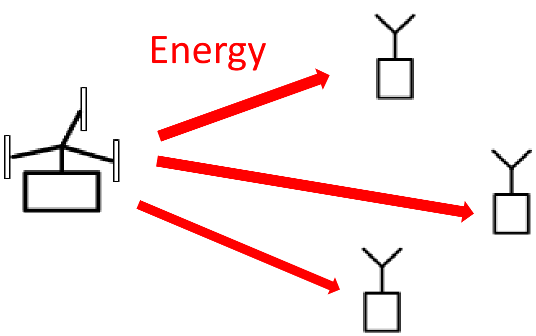
An 2×2 interference channel for SWIPT with TS receivers

- ❑ Receivers use time switching (TS) or power splitting (PS)
- ❑ Transmitters cooperate in joint information and energy transmission
- ❑ Interference channel rate-energy tradeoff

Conclusions

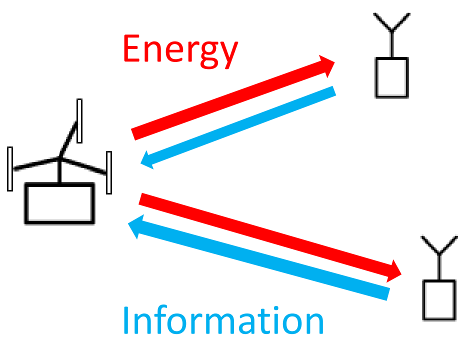
- Energy beamforming
- Energy feedback
- Energy multicasting
- Multiuser power region
- Nonlinear energy receiver model
- Waveform optimization

Wireless power transfer (WPT)



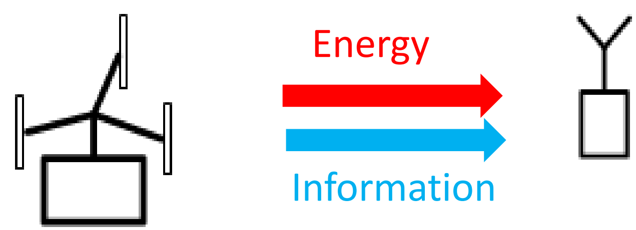
- Joint energy and communication scheduling
- Doubly near-far problem
- Energy/Communication full-duplex
- Self-energy recycling
- Wireless information and power transfer coexisting

Wireless powered communication network (WPCN)



- Rate-energy tradeoff
- Separated vs. Integrated receivers
- Joint information and energy beamforming
- Secrecy SWIPT
- Harmful vs. useful interference

Simultaneous wireless information and power transfer (SWIPT)



Future Work Directions

- Nonlinear energy harvesting model, waveform design for WPT
- Near-field WPT/WPCN/SWIPT: energy beamforming, etc.
- Information-theoretic limits and coding for WPCN/SWIPT
- Massive MIMO/Millimeter wave based WPT/WPCN/SWIPT
- Small-cell, C-RAN, and distributed antennas for WPT/WPCN/SWIPT
- Imperfect CSIT and practical feedback in WPT/WPCN/SWIPT
- Full-duplex WPCN/SWIPT
- Coexistence of wireless communication and power transfer
- Higher layer (MAC, Network, etc.) design issues in WPT/WPCN/SWIPT
- Safety/security/economic issues in WPT/WPCN/SWIPT
- Hardware development, applications, ……

References

- For more details, please refer to
  - S. Bi, C. K. Ho, and **R. Zhang**, "Wireless powered communication: opportunities and challenges," *IEEE Communications Magazine,* vol. 53, no. 4, pp.117-125, April, 2015.
  - S. Bi, Y. Zeng, and **R. Zhang,** "Wireless powered communication networks: an overview," *IEEE Wireless Communications, to appear.* (available on-line at arXiv:1508.06366)