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)

Backscatter-based passive RFID

Energy signal

RFID Reader

Backscatter modulated information signal

Receive energy

RFID Tag

WPT-enabled active RFID

Energy signal

RFID Reader

Energy harvesting circuit

Rechargeable battery

Information bits

Information transmitting circuit
Wireless Powered Communication Applications (3)
Wireless Powered Communication Applications (4)

Hybrid Information and Energy Access Point

EH Receivers (more power, e.g., -30dBm)

ID Receivers (less power, e.g., -100dBm)

Energy transfer

Information transfer
A Generic Model

- Information flow
- Energy flow

Downlink (DL)

Hybrid Access point

Uplink (UL)

Energy and/or Information Receiver

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
- 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

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

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
Overall power transfer efficiency: 
\[ e = \frac{Q}{P_t} = \frac{P_r}{\alpha} \frac{Q}{\xi} \]

- Improve RF-to-RF efficiency \( \alpha \) (decays quickly with distance) by
  - Using high-gain directional antennas: parabolic, horn antennas
  - **Energy beamforming**: adaptive beam control

- Improve RF-to-DC conversion efficiency \( \xi \) (typically 30%-70%) by
  - Rectifier design
  - Waveform optimization
The receiver uses rectifier to convert RF signal into DC signal.

Assuming linear energy harvesting model, the harvested power is

$$Q = E[i_{DC}(t)] \approx \xi E[\| y(t) \|^2] = \xi hP$$
Modulated vs. Unmodulated Energy Signal

Use pseudo-random modulated energy signal to avoid the “spike” in the power spectral density (PSD) with constant unmodulated energy signal.
The harvested energy is $\zeta \|y\|^2 = \zeta \|Hs\|^2 = \zeta \text{tr} (GS)$

Q: What’s the optimal transmit strategy given a limited Tx power budget?

A: Energy beamforming

The optimal EB is the principal eigenvector beamforming

$S^* = P \nu_E \nu_E^H$ \hspace{1cm} $\nu_E$ is the principal eigenvector of $G$

Energy conversion efficiency: 30% - 70%

$Pr = Pt \times G_a \times D^{-\alpha} \times \zeta$

- Antenna gain
- Path loss

$\zeta$
- **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)**
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)

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

- **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.
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

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

(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
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

- 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

Harvest-then-transmit protocol

- DL energy transfer: $\tau T$
- UL information transfer: $(1-\tau)T$
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 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
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Simultaneous Wireless Information and Power Transfer

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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

Maximize energy transfer

Maximize data rate
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

- **SWIPT with Separate EH/ID Receivers**
- **SWIPT with Co-located EH/ID Receivers**

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

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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

\[ x = v_0 s_0 + \sum_{i=1}^{d} w_i s_i \]

- energy signal
- artificial noise

information signal
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 $2 \times 2$ 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)**

- Energy

**Wireless powered communication network (WPCN)**

- Energy
- Information

**Simultaneous wireless information and power transfer (SWIPT)**

- Energy
- Information

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

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

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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
