Distributed Beamforming for Safer Wireless Power Transferring

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Ubiquitous Wireless Charging

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Wireless power
Underlying Trade-offs in WPT Systems

- Design goals in wireless power transfer (WPT) systems
  - Distance
  - Safety
  - Delivered power levels

- Existing WPT Systems
  - Ambient harvesting: solar, wind, ambient RF
  - Near-field: electromagnetic induction
  - Far-field: directional charger, beamforming (Energy-ball)

  Difficult to have them all

Apple’s WPT is still MIA (missing in action)

1965, US Air Force. Transferred over 180w wireless power with 65% efficiency
Traditional Beamforming

- A popular solution for WPT
- Clustered transmitters, faraway receiver
- Math assumption: Plane incoming wave
- Optimization based beamformer: MRC, ZF

Creating energy beams towards targets, and increasing energy gain
Traditional Beamforming for WPT

- Generating a high energy beam towards target devices
  - Directionality, increase efficiency
- Minimizing energy in non-target directions

Concerns:
- High energy along the energy beam path
  - Overheating along the beam
- Blocking
  - Largely decrease the charging efficiency
Overview of Energy-Ball

- **Distributed Transmitters**
  - No communication among transmitters
  - Distributed synchronization
  - Geometric: transmitters are not clustered, but distributed around the receiver
  - Injection angle for each transmitter is different

- **Distributed Phase Alignment at the receiver**
  - Distributed Beamforming
  - Received signals are constructively added up at the target receiver
  - Intuition: zone plates focusing the light

![Phased Array Diagram]

High energy at the focus point
Energy-ball: Closer Look at the Energy Distribution

Flip view

Spatial view of the ‘energy-ball’
A Unique Energy Peak (Hot Spot)

Only one hot spot exists!

RSS as a function of distance:

$$Y(d) = \left| \lim_{N \to \infty} \frac{R}{N} \sum_{i=1}^{N} \frac{1}{d} e^{i2\pi \frac{\sqrt{R^2 + d^2 - 2Rd \cos \varphi} - R}{\lambda}} \right| = \frac{R}{2\pi} \left| \int_{0}^{2\pi} \frac{e^{i2\pi \frac{\sqrt{R^2 + d^2 - 2Rd \cos \varphi} - R}{\lambda}}}{\sqrt{R^2 + d^2 - 2Rd \cos \varphi}} d\varphi \right|.$$
Energy-Ball Design Goals

- Align phases among distributed transmitters
- Adapt phases for mobile receivers
We choose a closed-loop feedback controlled phase alignment method

- Random phase searching at the TX end
- Feedback from the RX end

Phases in the unit circle:

<table>
<thead>
<tr>
<th>TX1</th>
<th>Feedback1</th>
<th>Feedback2</th>
<th>Aligned</th>
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<tbody>
<tr>
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<td>TX2</td>
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<tr>
<td>TX3</td>
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</tbody>
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Initial: iteration 1

Feedback1: iteration 2

Feedback2: iteration N
Align Phases through Feedback Control Loop

- We choose a closed-loop feedback controlled phase alignment method
  - Random phase searching at the TX end
  - Feedback from the RX end

![Graph showing RSS over time with an initial state at the beginning]
Align Phases through Feedback Control Loop

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![Diagram showing RSS and phase adjustments](image-url)
Align Phases through Feedback Control Loop

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![Graph showing RSS over iterations](image)
Align Phases through Feedback Control Loop

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![Graph showing RSS vs iterations with convergence point marked]
Orbit Testbed

Orbit: a general purpose testbed
http://www.orbit-lab.org/
An Example Distributed Beamforming Realization

- Theoretical RSS optimum:
  \[ \sum_{k=1}^{12} RSS_{\{k\}} = 0.237 \]

- Actual received RSS after feedback controlled phase alignment method: 0.222

- We reached 94% theoretic optimum
Energy Distribution Measurements

Alfred scans Chilitags

Energy-ball also works when RX is not placed at center

Received power distribution in BF

Received power distribution in Energy-ball
While Receivers are Mobile

Why: 10-15 sec alignment process

Idea: infer BF channel CSI from the feedback channel

Observed partial channel reciprocity: strong correlation in CSI
Phase Prediction and Beamforming Performance

PDD estimation using Kalman filter

Actual BF performance for mobile receiver

- Energy-ball w. Kalman filter
- Energy-ball wo. Kalman filter

80% opt. vs. 15% opt.
Precise Energy Delivery at PIPs Sensors

- PIPs collects moist./temp. data
- PIPs reports data
- Distributed BF location: Red
- Target location
- Other tested locations: Blue
- Others: not working A,B,C and D: not working properly

Energy harvester

PIPs sensor
Energy-Ball Summary

- Energy-ball focuses energy on the receiver while having low energy density at other areas – safer

- Open access distributed beamforming system

- Fast phase adjustment algorithm – mobile receiver

Thank you!