Distributed Beamforming for Safer Wireless Power Transferring

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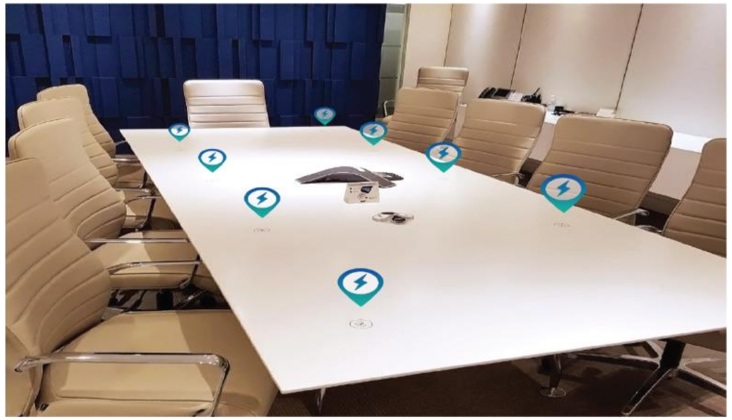
Ubiquitous Wireless Charging

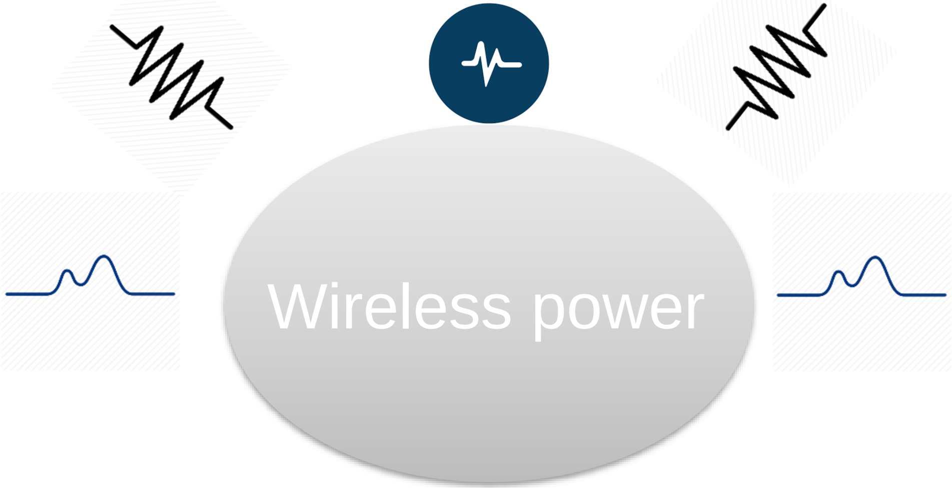
Home

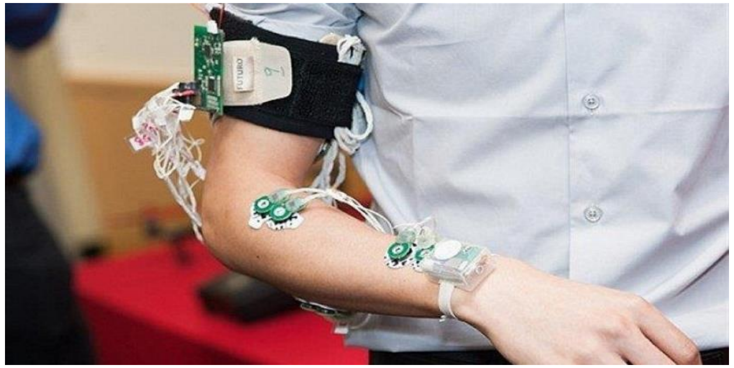
Industrial



Office

Automotive



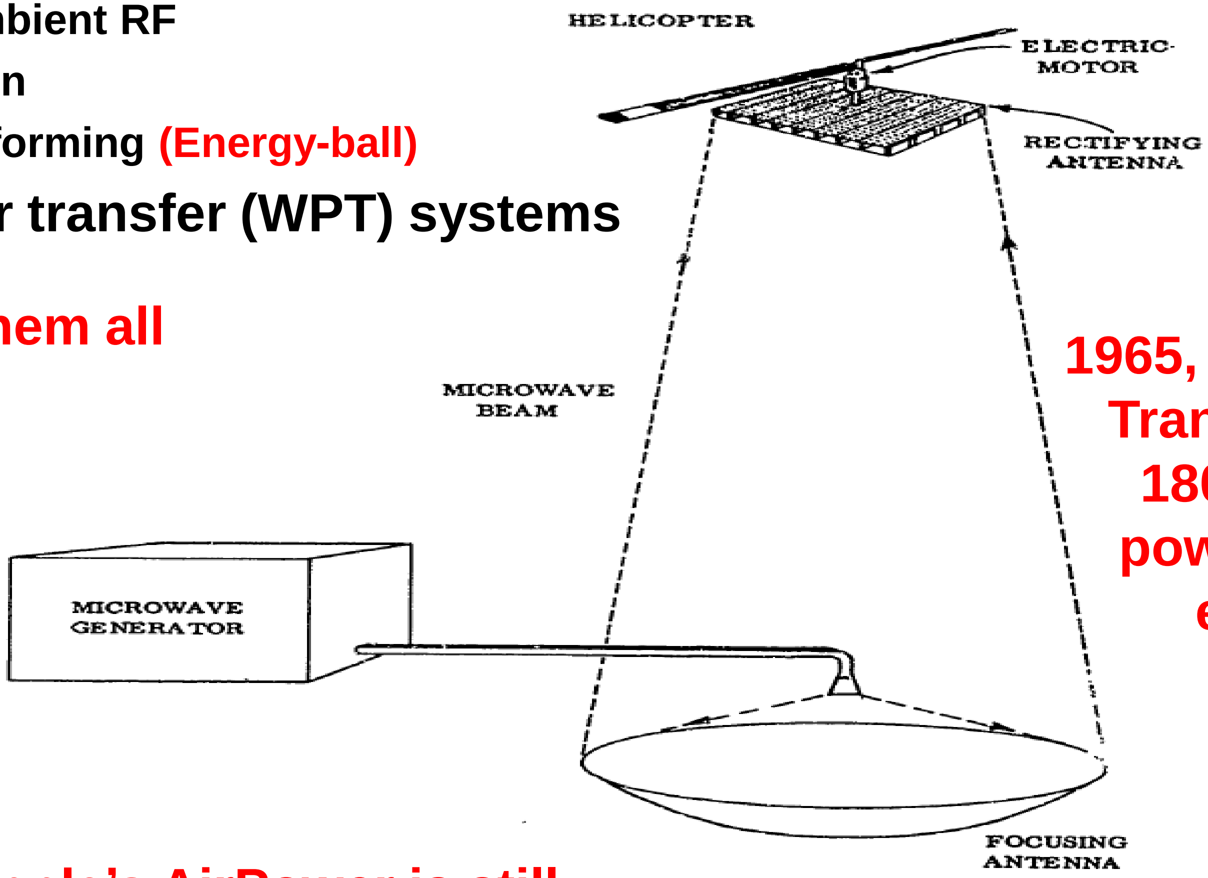


Medical

Underlying Trade-offs in WPT Systems

- Existing Wireless Energy Systems
  - Ambient harvesting: solar, wind, ambient RF
  - Near-field: electromagnetic induction
  - Far-field: directional charger, beamforming (Energy-ball)
- Design goals in wireless power transfer (WPT) systems
  - Distance
  - Safety
  - Delivered power levels

Difficult to have them all



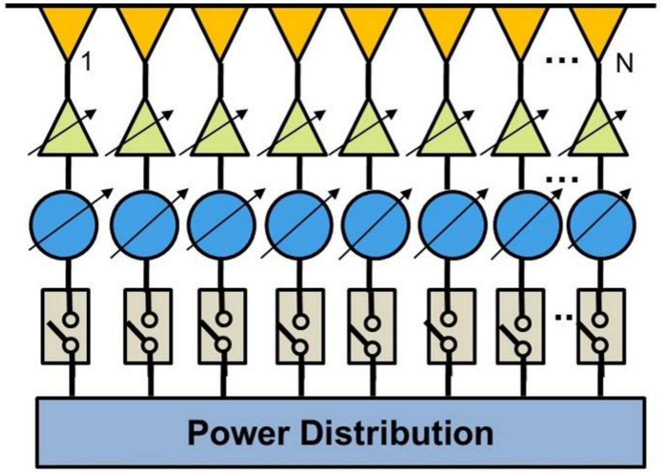
1965, U.S. Air Force. Transferred over 180w wireless power with 65% efficiency

Apple's AirPower is still MIA (missing in action)

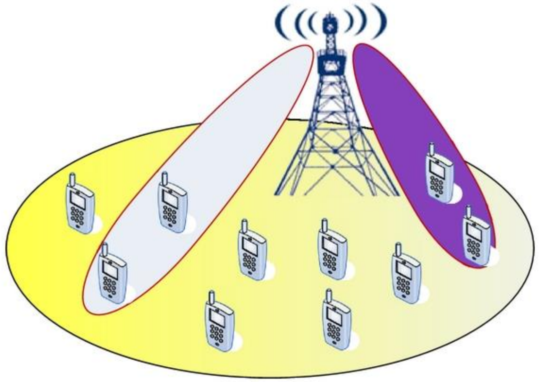
Traditional Beamforming

Feedback

Plane wave: Same injection angle θ for each TXs

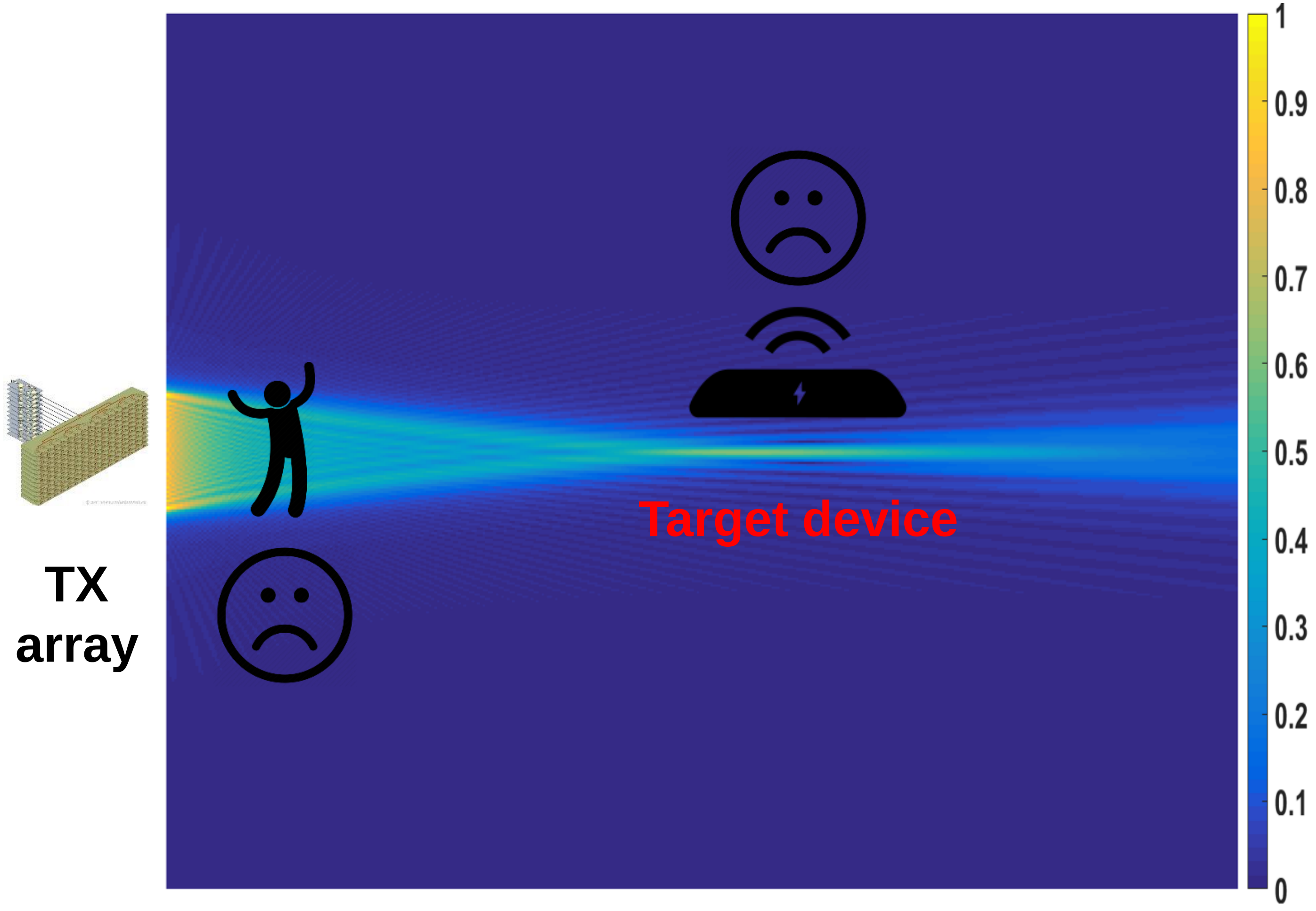


- A popular solution for WPT
- Clustered transmitters, faraway receiver
- Math assumption: Plane incoming wave
- Optimization based beamformer: MRC, ZF



Creating energy beams towards targets, and increasing energy gain

Traditional Beamforming for WPT



Energy distribution in a typical traditional beamforming WPT system

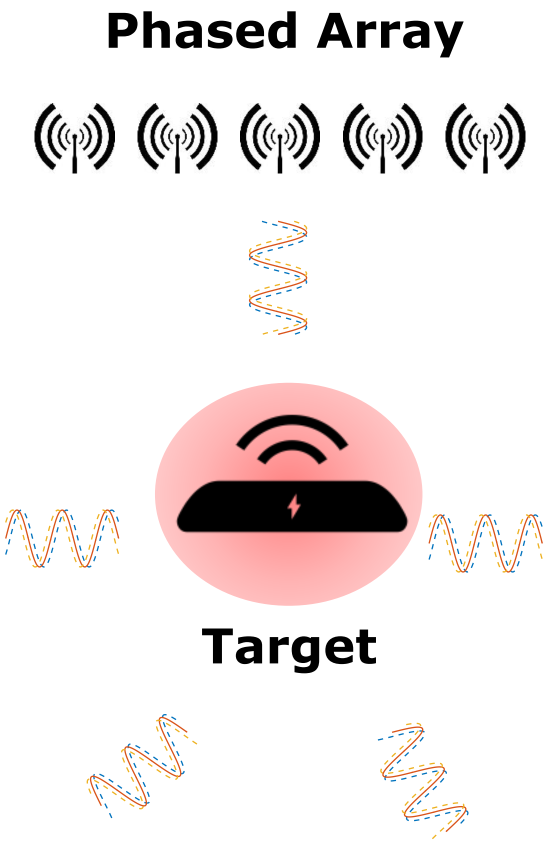
- ❑ **Generating a high energy beam towards target devices**
  - ❑ **Directionality, increase efficiency**
- ❑ **Minimizing energy in non-target directions**

Concerns:

- ❑ **High energy along the energy beam path**
  - ❑ **Overheating along the beam**
- ❑ **Blocking**
  - ❑ **Largely decrease the charging efficiency**

Overview of Energy-Ball

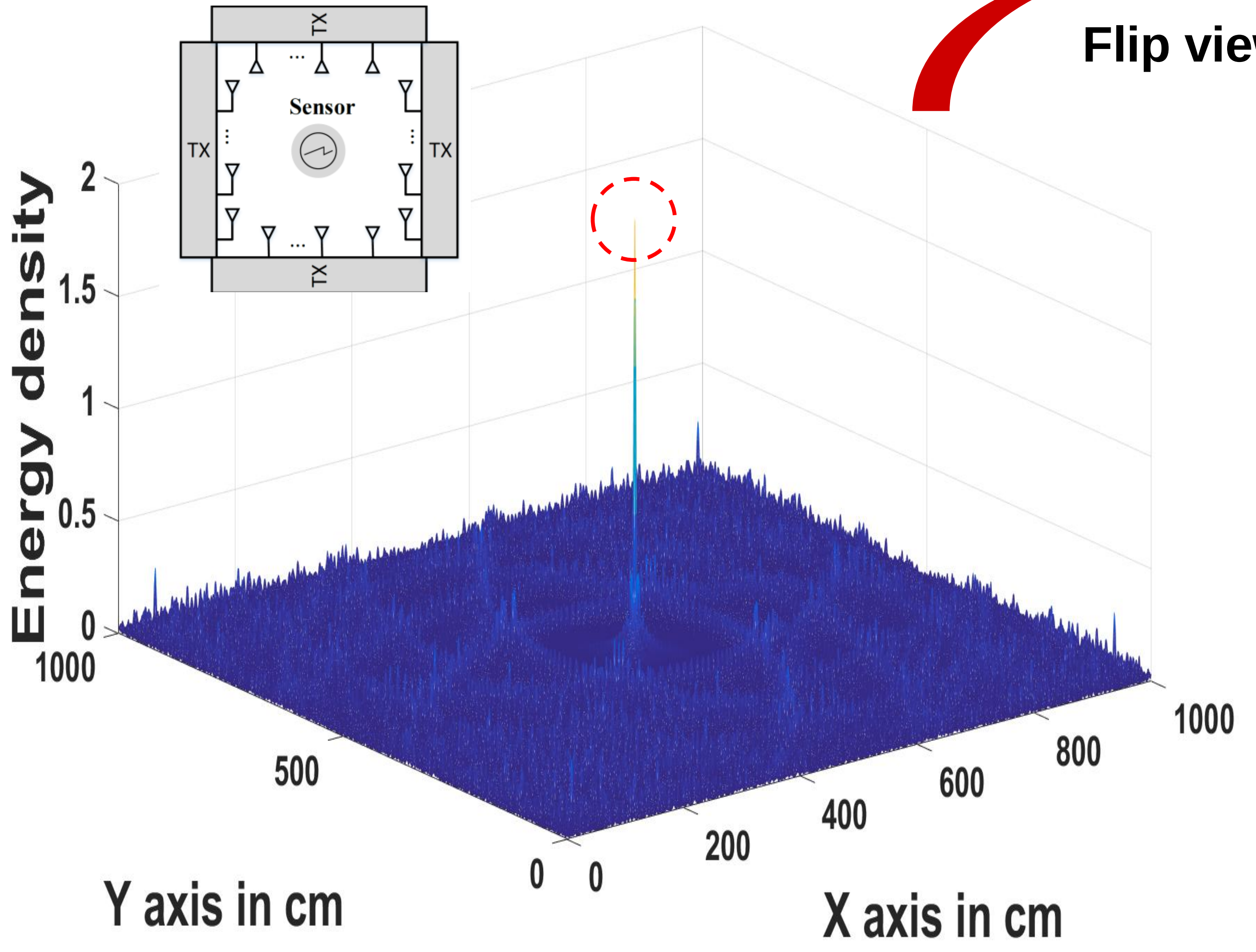
- Distributed Transmitters
  - No communication among transmitters
  - Distributed synchronization
  - Transmitters are not clustered, but distributed around the receiver



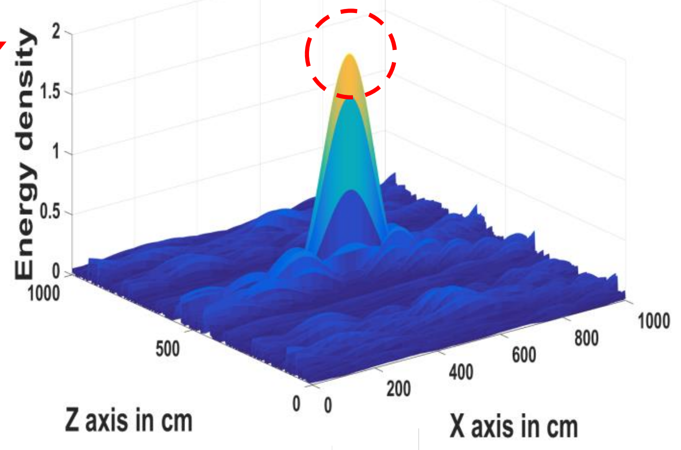
High energy at the focus point

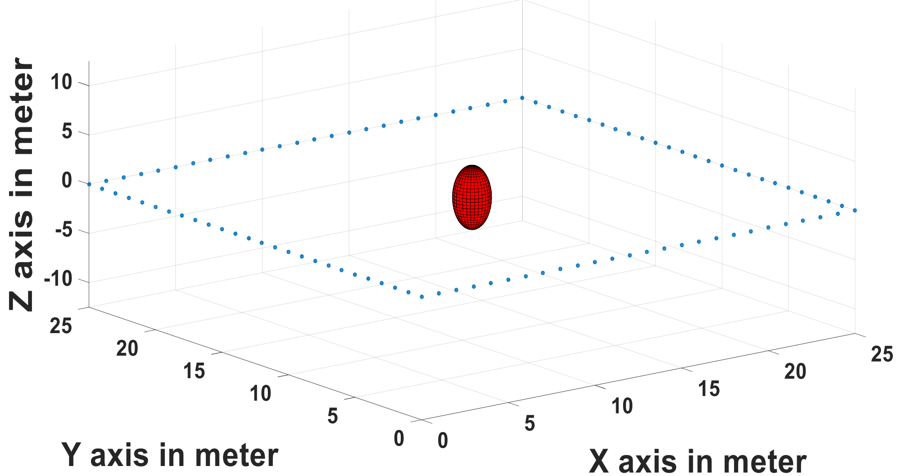
- Distributed Phase Alignment at the receiver
  - Distributed Beamforming
  - Received signals are constructively added up at the target receiver
  - Intuition: zone plates focusing the light

Energy-ball: Closer Look at the Energy Distribution



Flip view

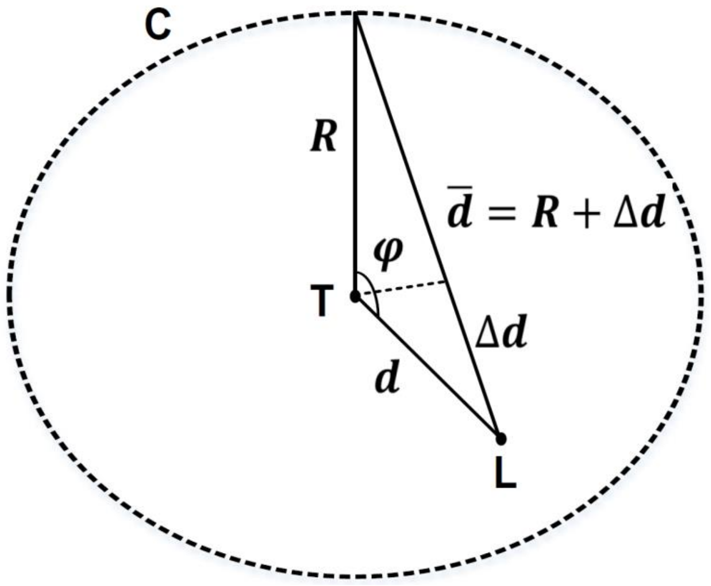




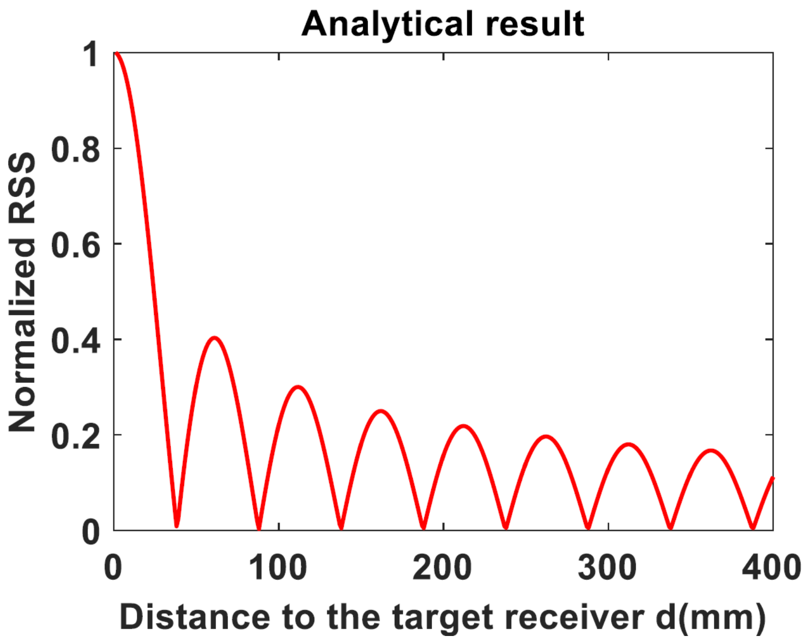
Spatial view of the 'energy-ball'

A Unique Energy Peak (Hot Spot)

Only one hot spot exists!



3dB energy-ball width: $d_{3db} \approx 0.22\lambda$

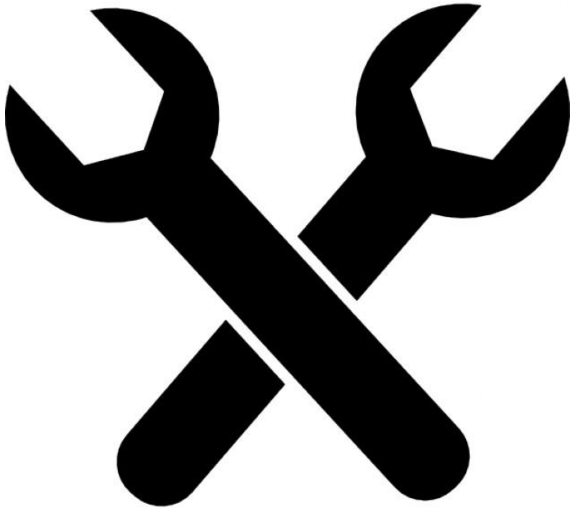


Key reason for safety:
only the target device has focused energy

RSS as a function of distance: $$Y(d) = \left| \lim_{N\to\infty} \frac{R}{N} \sum_{i=1}^{N} \frac{1}{\bar{d}} e^{j2\pi \frac{\sqrt{R^2+d^2-2Rd\cos\varphi_i}-R}{\lambda}} \right| = \frac{R}{2\pi} \left| \int_0^{2\pi} \frac{e^{j2\pi \frac{\sqrt{R^2+d^2-2Rd\cos\varphi}-R}{\lambda}}}{\sqrt{R^2+d^2-2Rd\cos\varphi}} d\varphi \right|.$$

Energy-Ball Design Goals

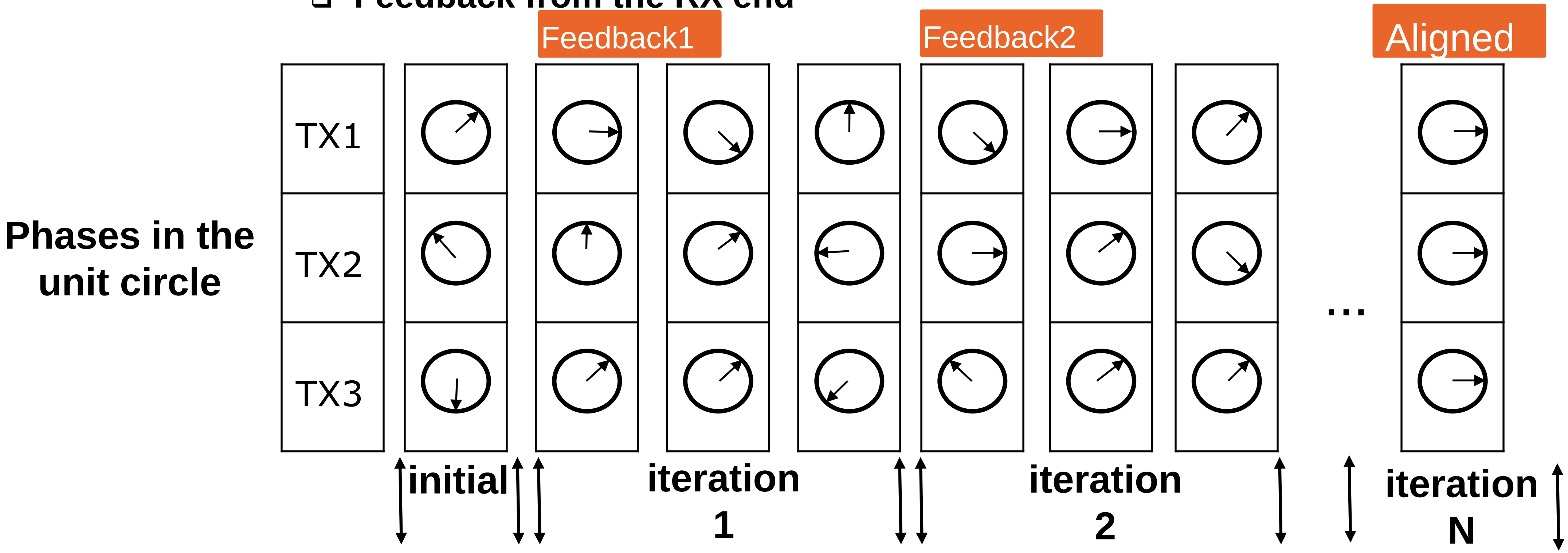
- Align phases among distributed transmitters



- Adapt phases for mobile receivers

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



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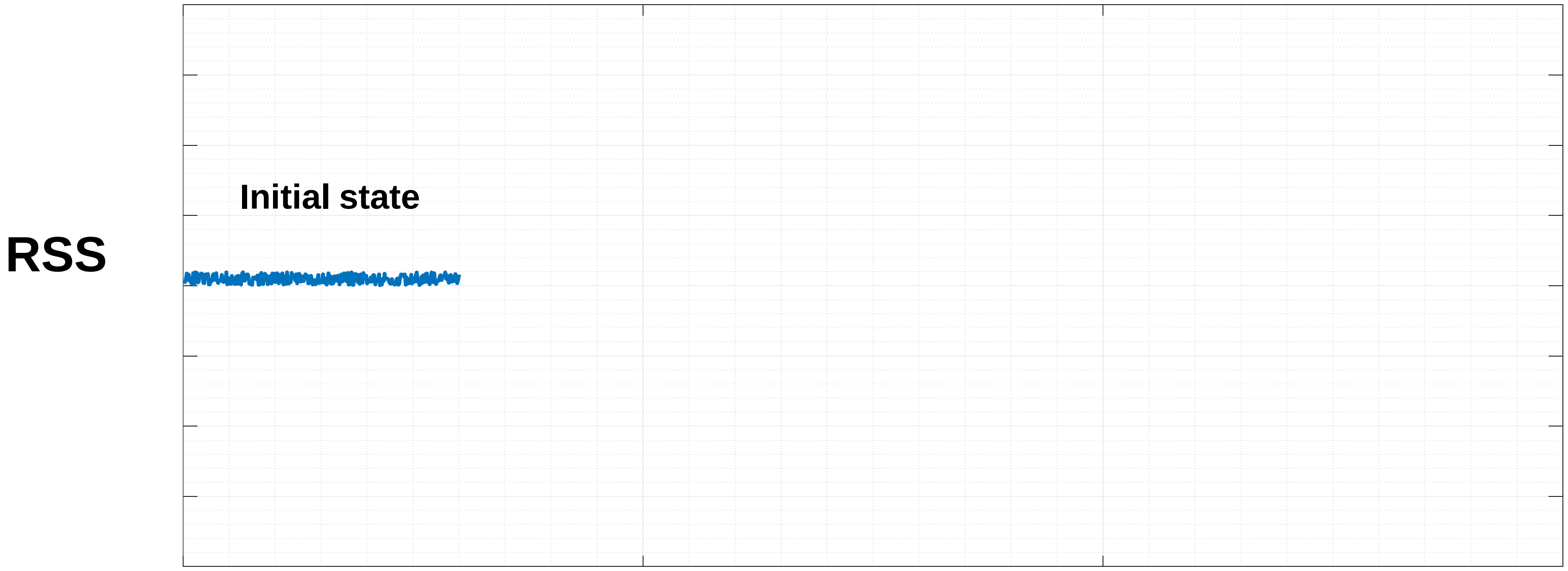

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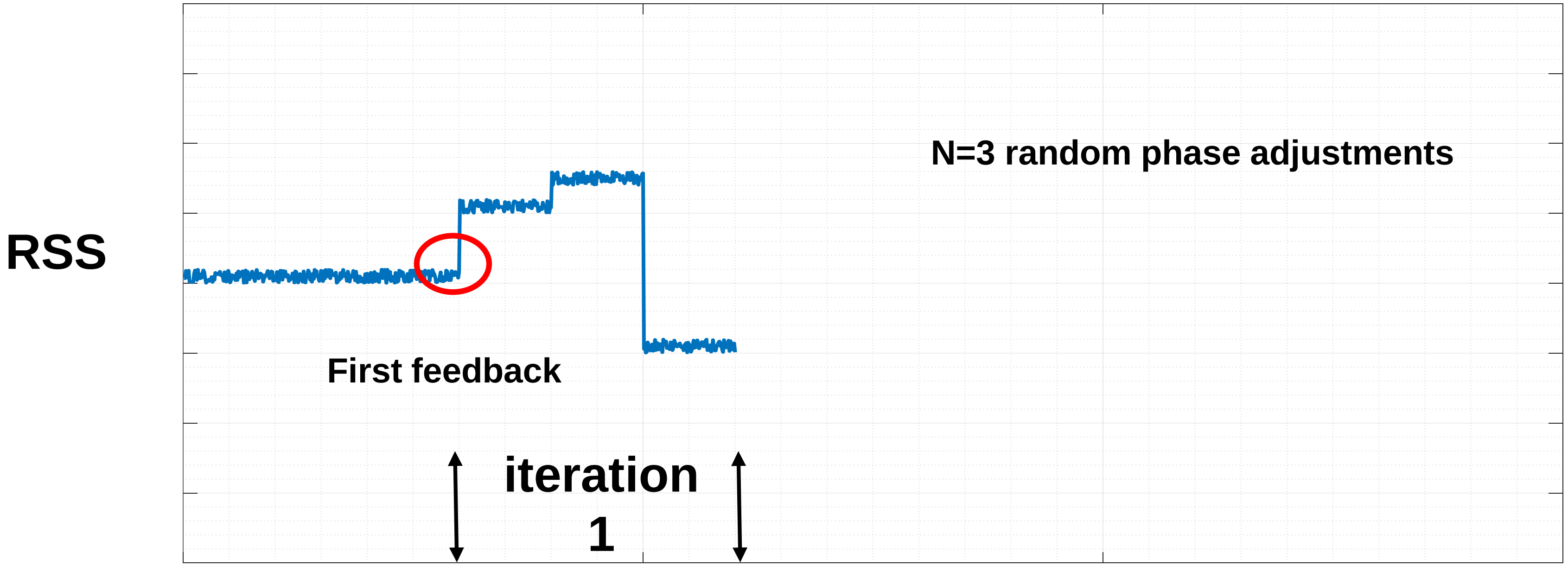

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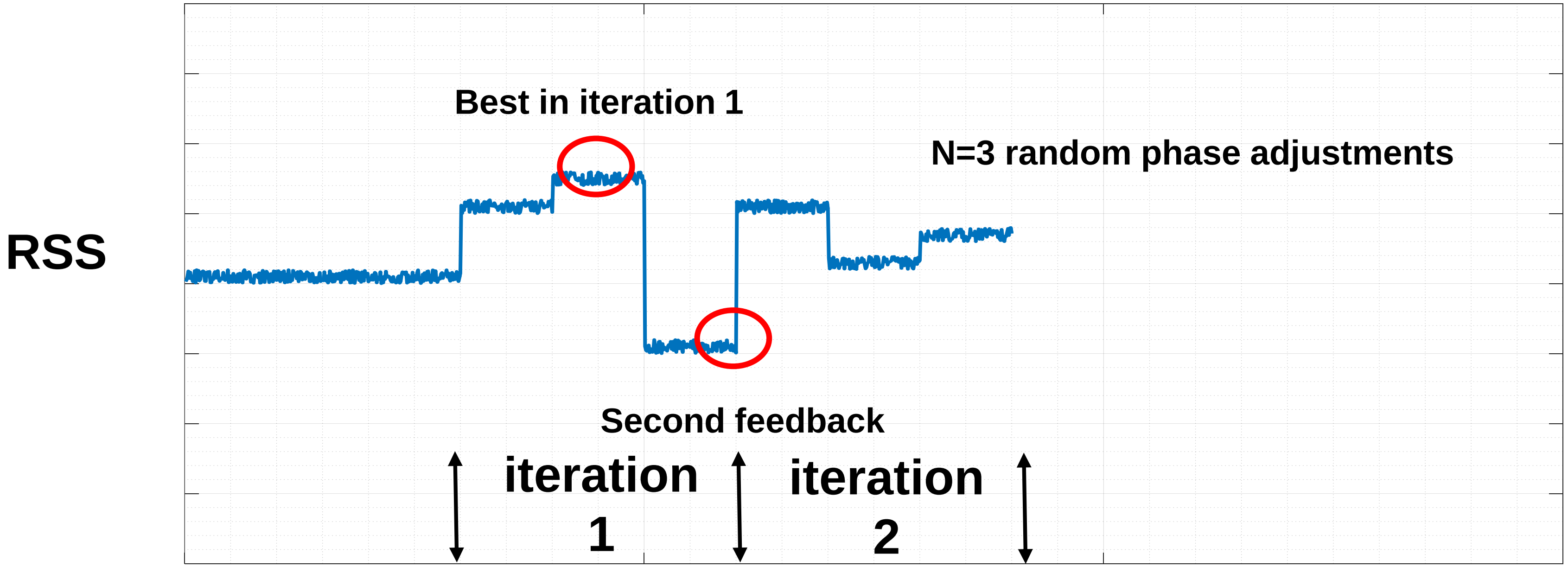

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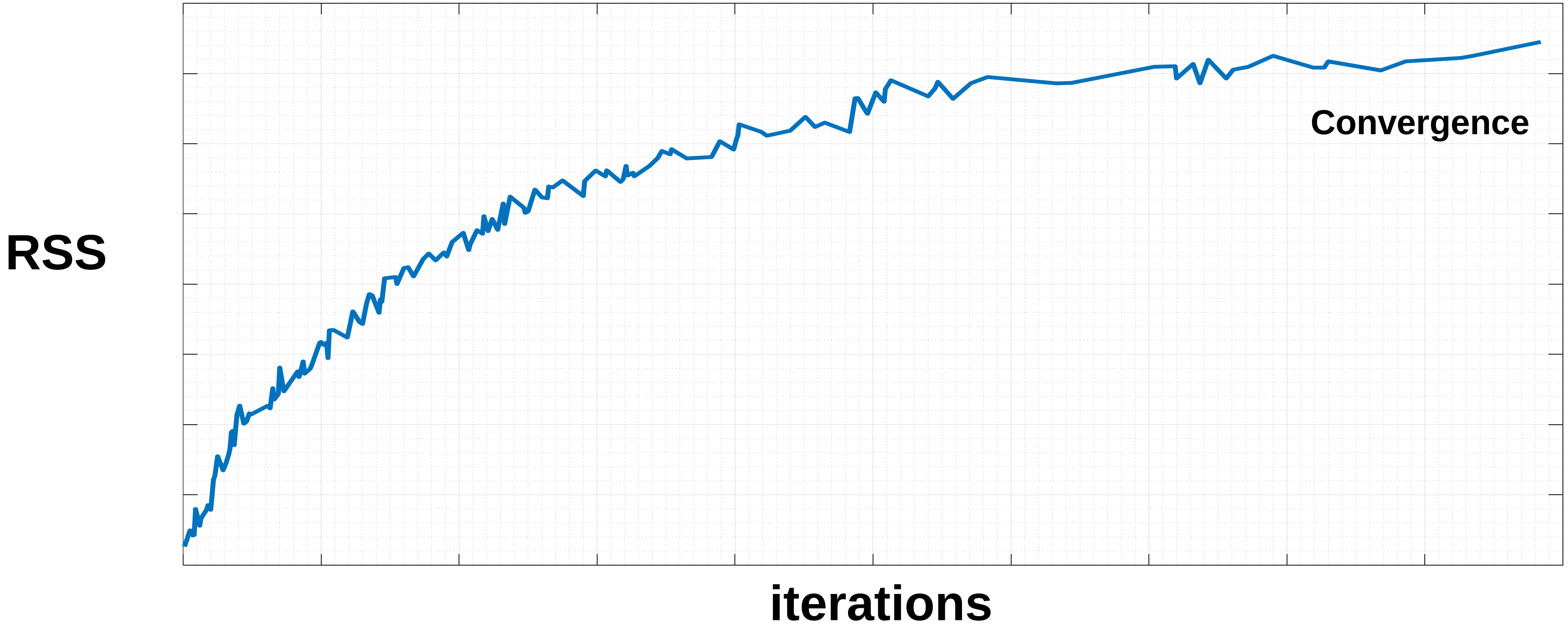
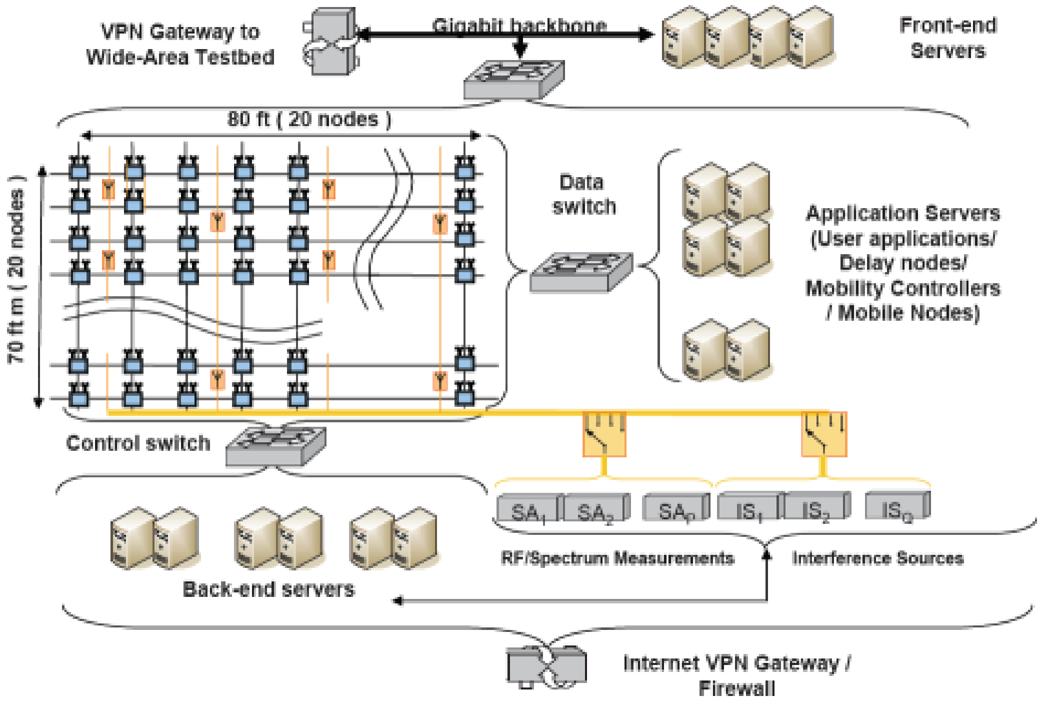
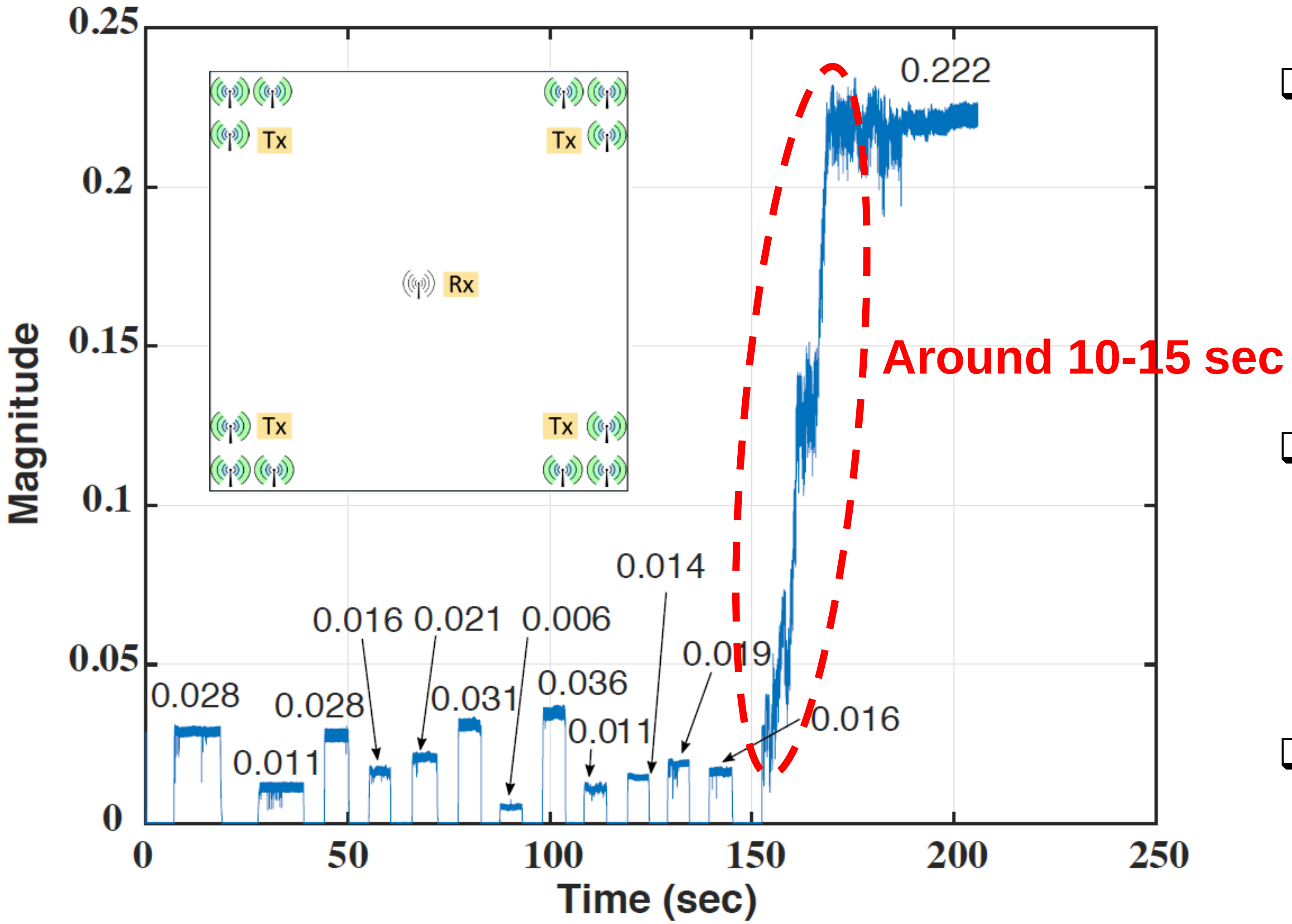


Orbit Testbed



Orbit: a general purpose testbed
http://www.orbit-lab.org/

An Example Distributed Beamforming Realization



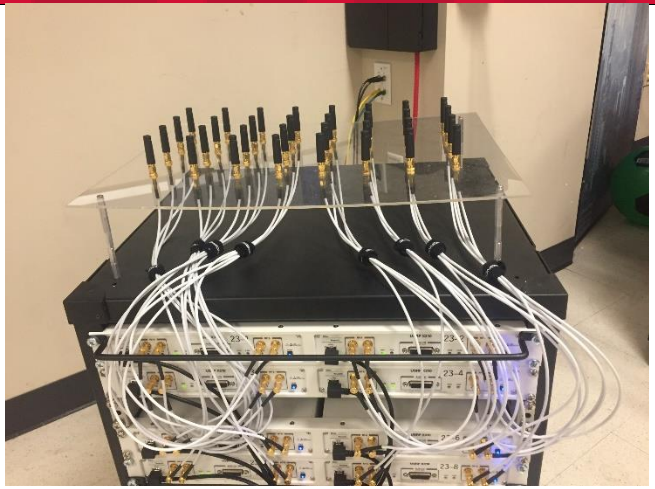
- Theoretical RSS optimum:

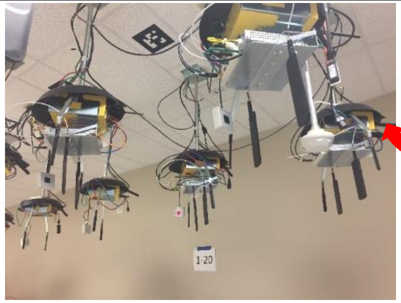
$$\sum_{k=1}^{12} RSS_{\{k\}} = 0.237$$

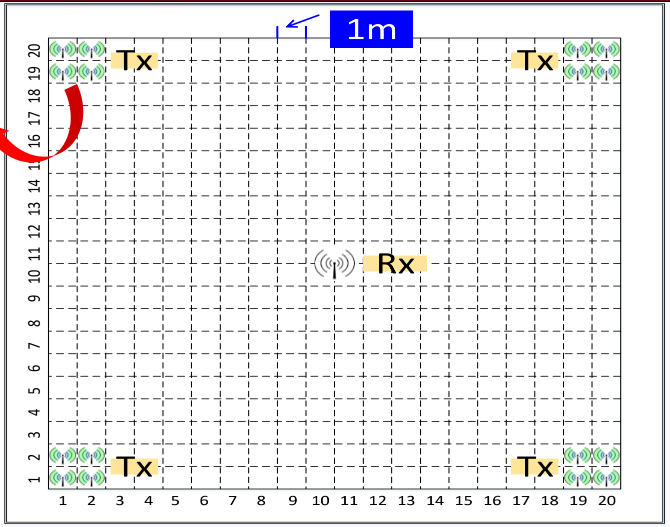
- Actual received RSS after feedback controlled phase alignment method: 0.222

- We reached 94% theoretic optimum

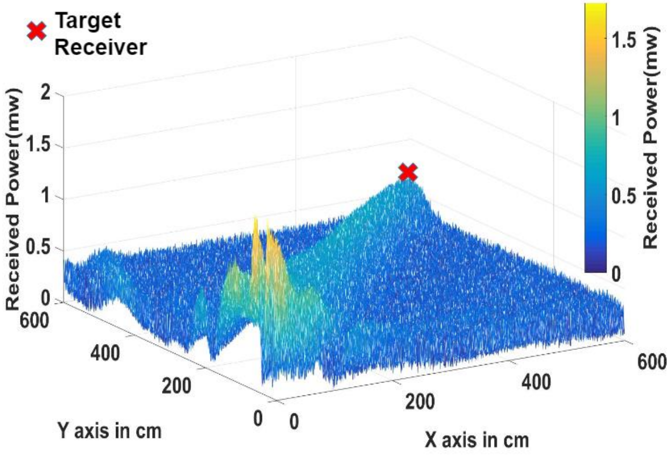
Energy Distribution Measurements



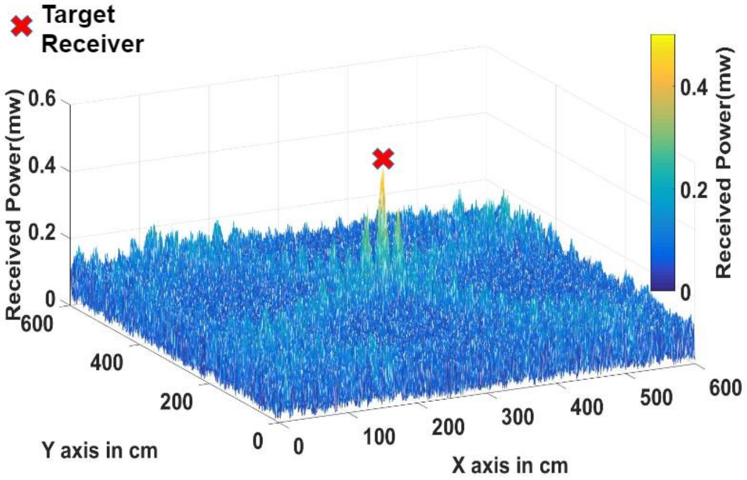




Rooftop GPS → GPS splitter → Octoclock-G → Octoclock → USRPs

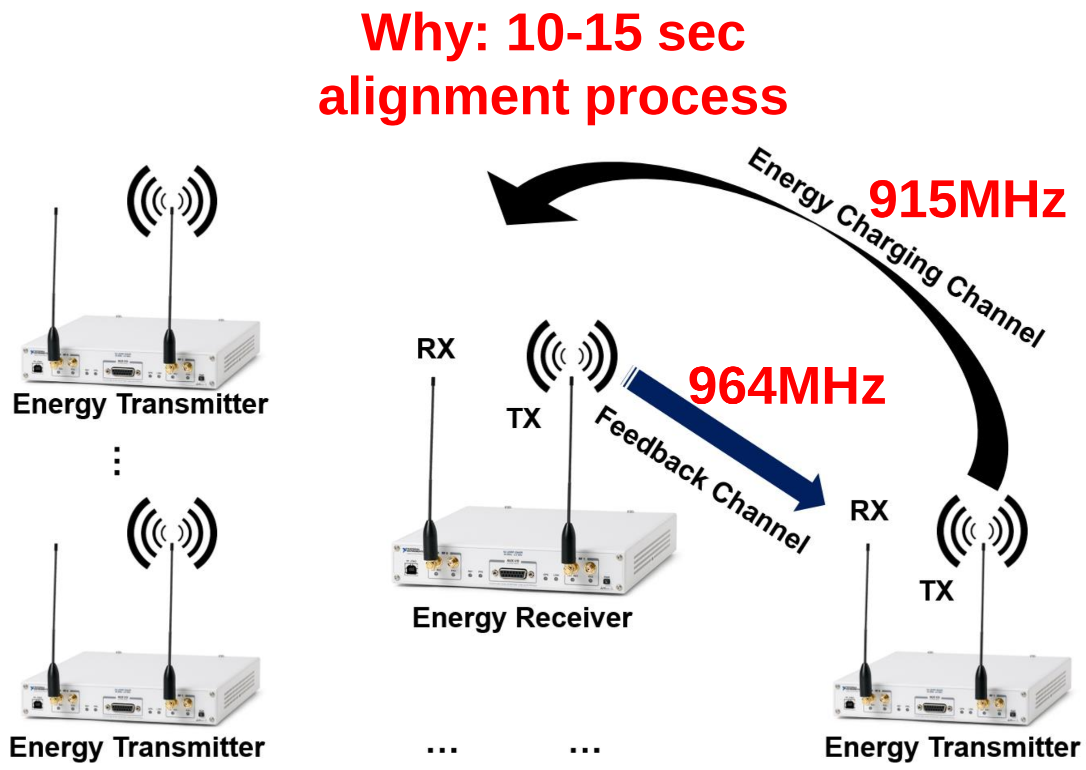


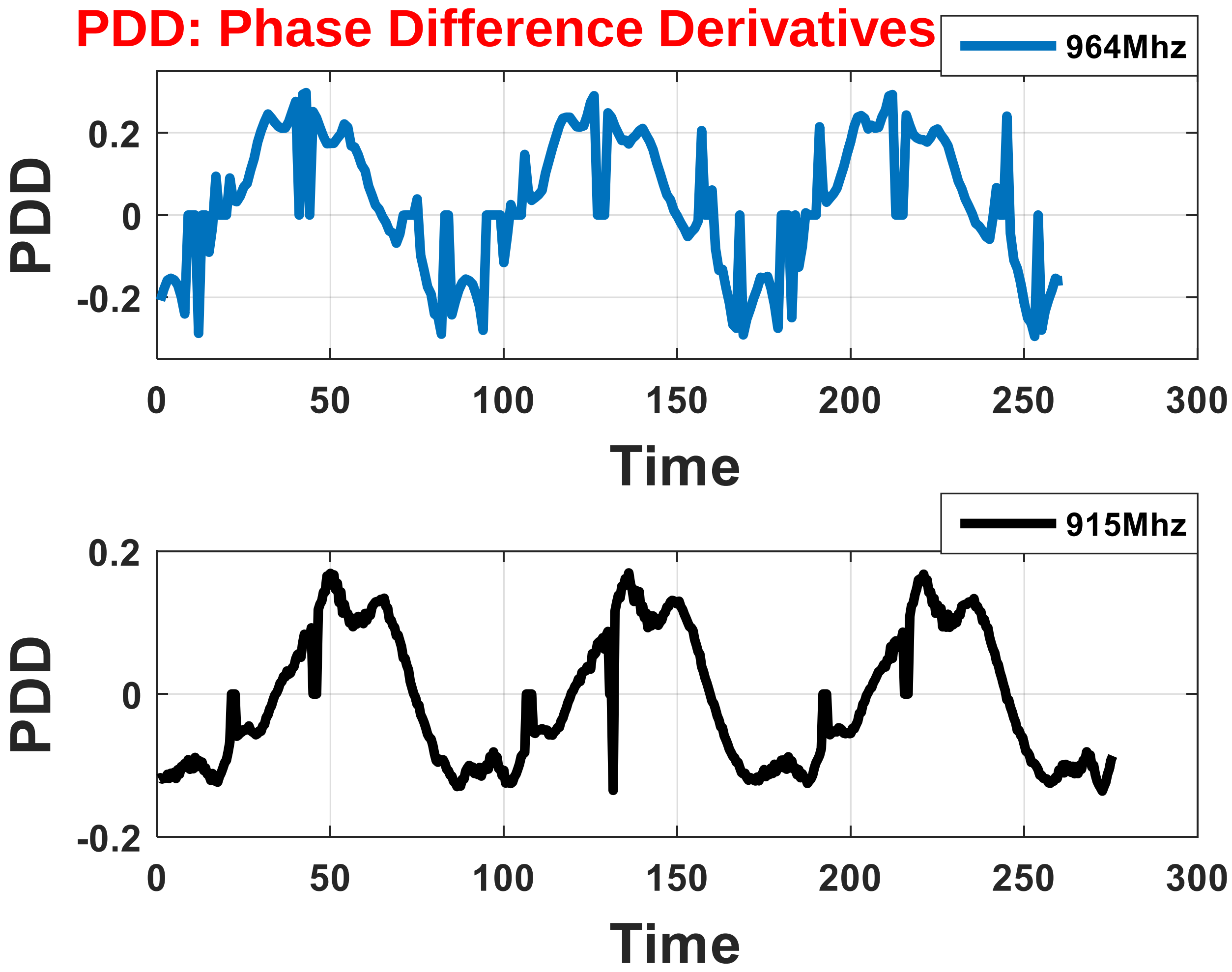
Received power distribution in BF



Received power distribution in Energy-ball

While Receivers are Mobile



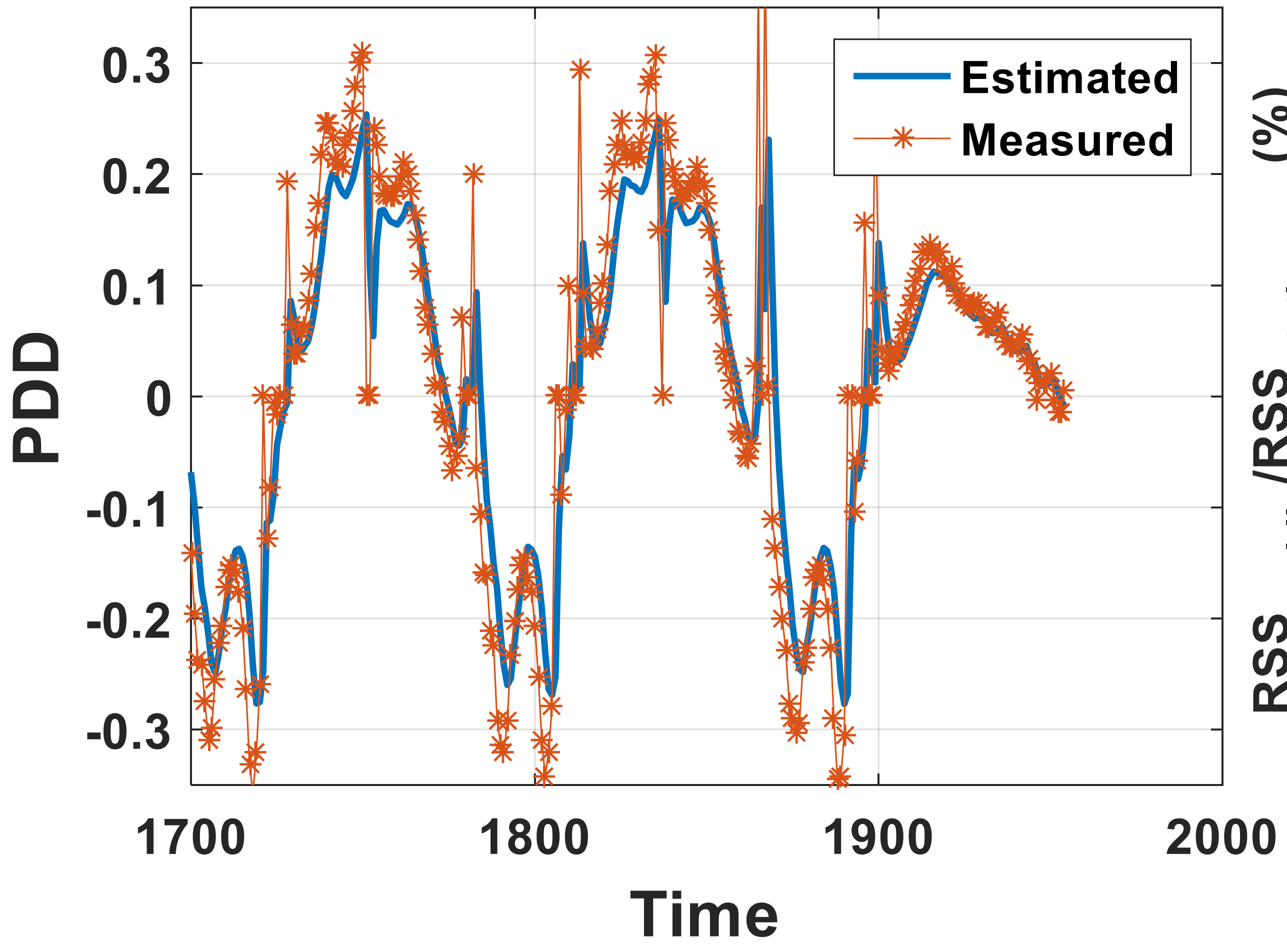


Idea: infer BF channel from the feedback channel

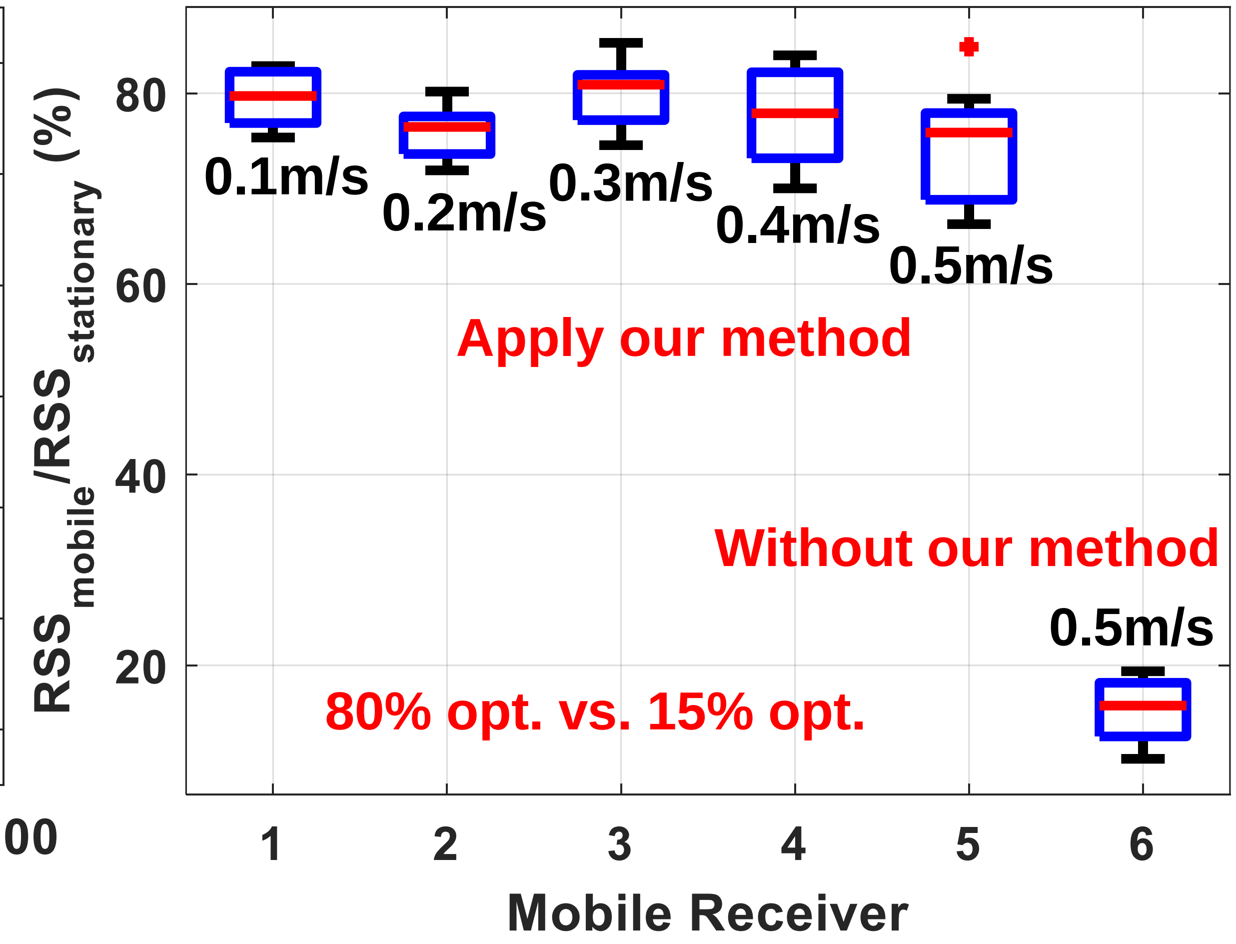
Observed partial channel reciprocity: strong correlation in CSI

Phase Prediction and Beamforming Performance

PDD estimation using Kalman filter

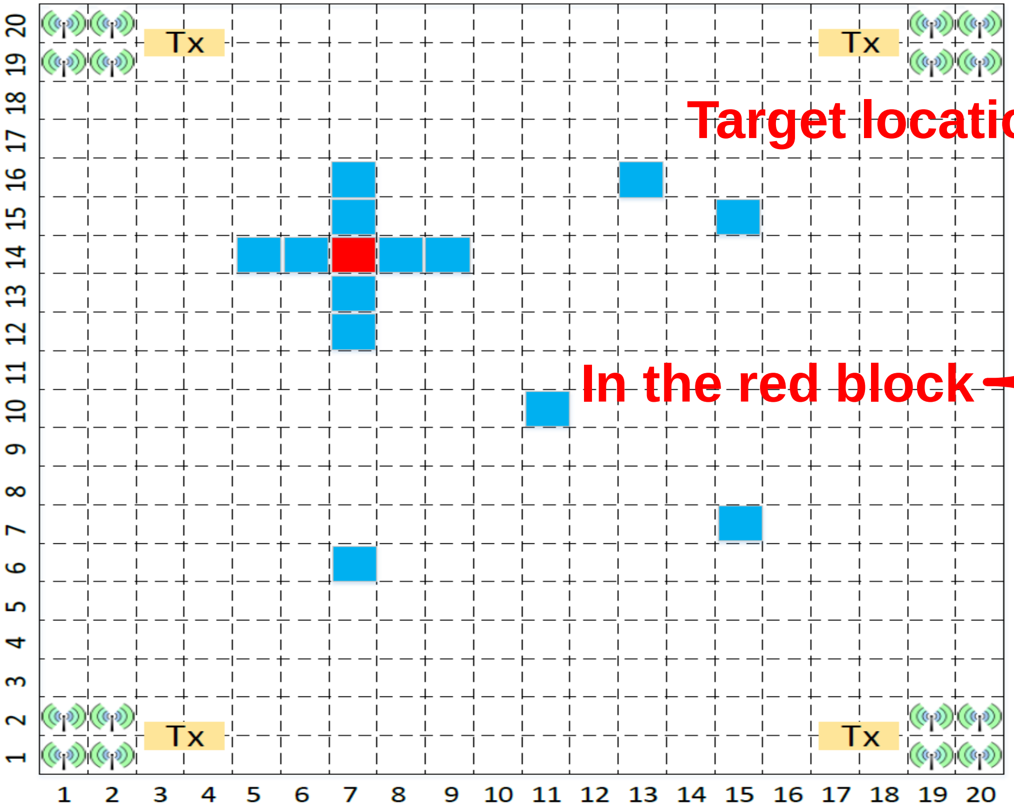


Actual BF performance for mobile receiver

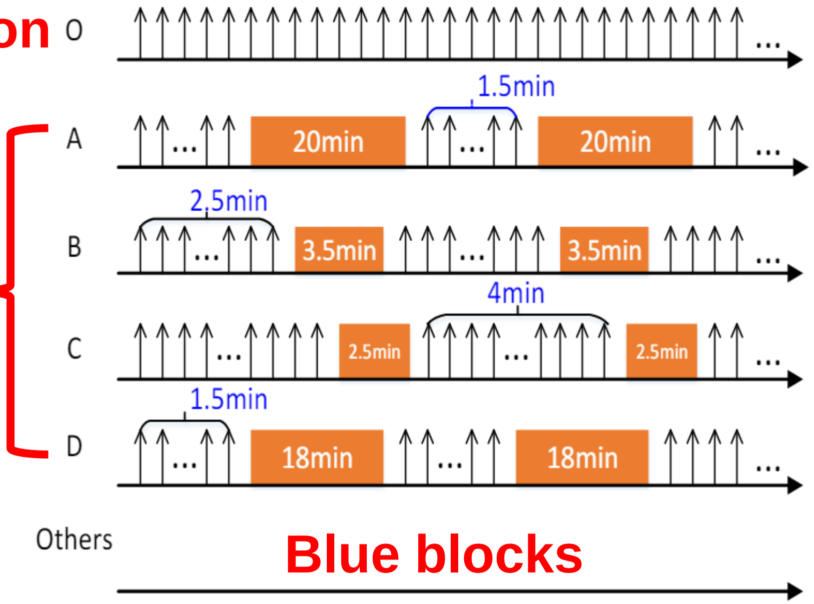


Pinpoint Energy at IoT Sensors

PIPs collects moist./temp. data



Distributed BF location: Red
Other tested locations: Blue
20 distributed TXs



Others: not working
A,B,C and D: not working properly

Energy-Ball Summary

- **Energy-ball focuses energy on the receiver while having low energy density at other later – safer**
- **Open access distributed beamforming system**
- **Fast phase adjustment algorithm – mobile receiver**

Thank you!