Towards Flexible Wireless Charging for Medical Implants Using Distributed Antenna System

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[×] Alibaba Group

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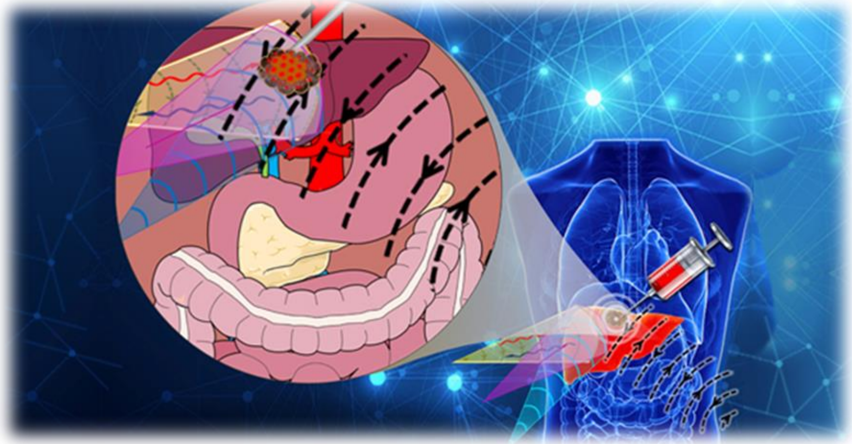
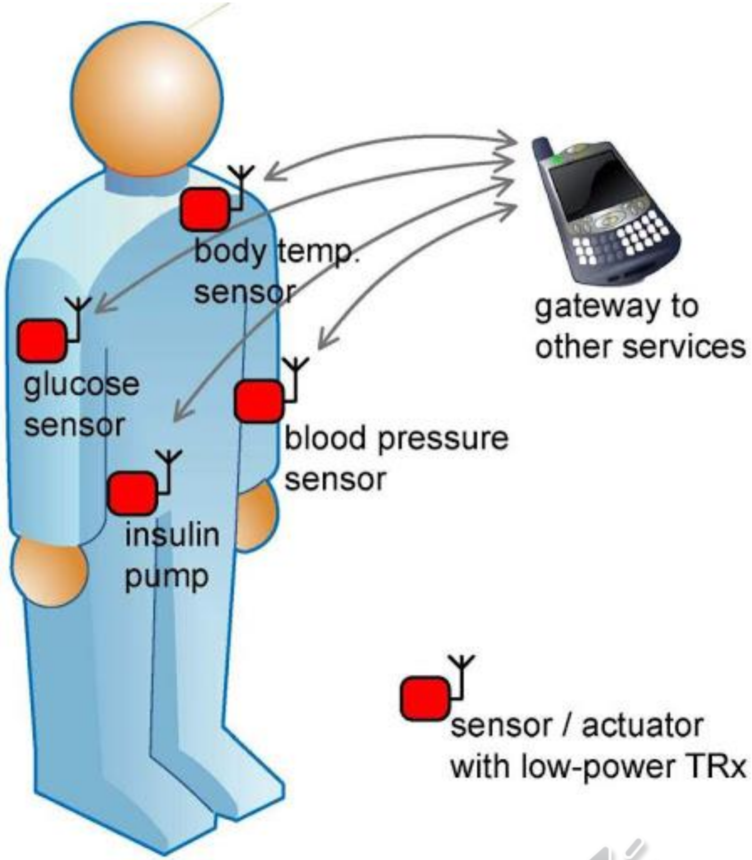
Deep Tissue Wireless Power is Badly Needed

Replacing battery for implants



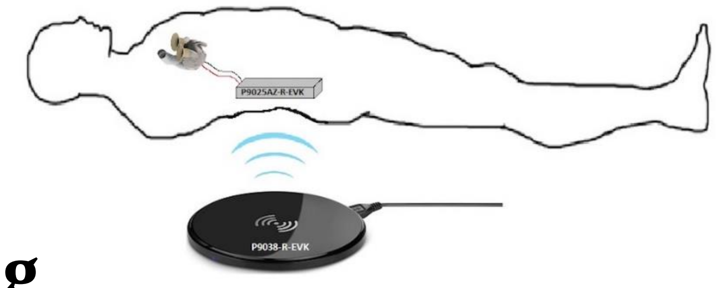
Controlled drug release



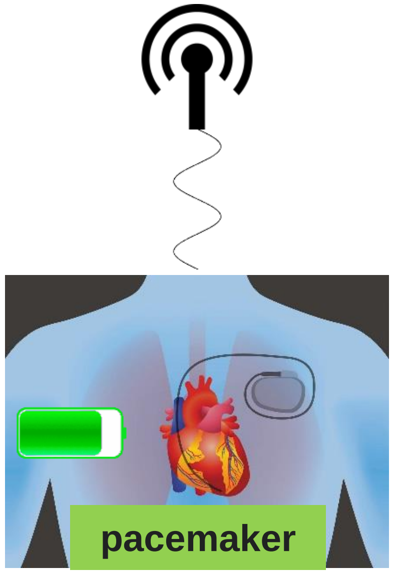
In-body and body-area communication

Existing Approaches

- ❑ **Near-field inductive coupling**
  - ❑ **Coil size – relatively large form factor**
  - ❑ **Coil misalignment – unreliable (blood flow)**
  - ❑ **Bulky – inconvenient**
- ❑ **Mid-far-field wireless charging**
  - ❑ **In tissue attenuation – low power**
  - ❑ **Low efficiency**
  - ❑ **Overheating**



Near-field

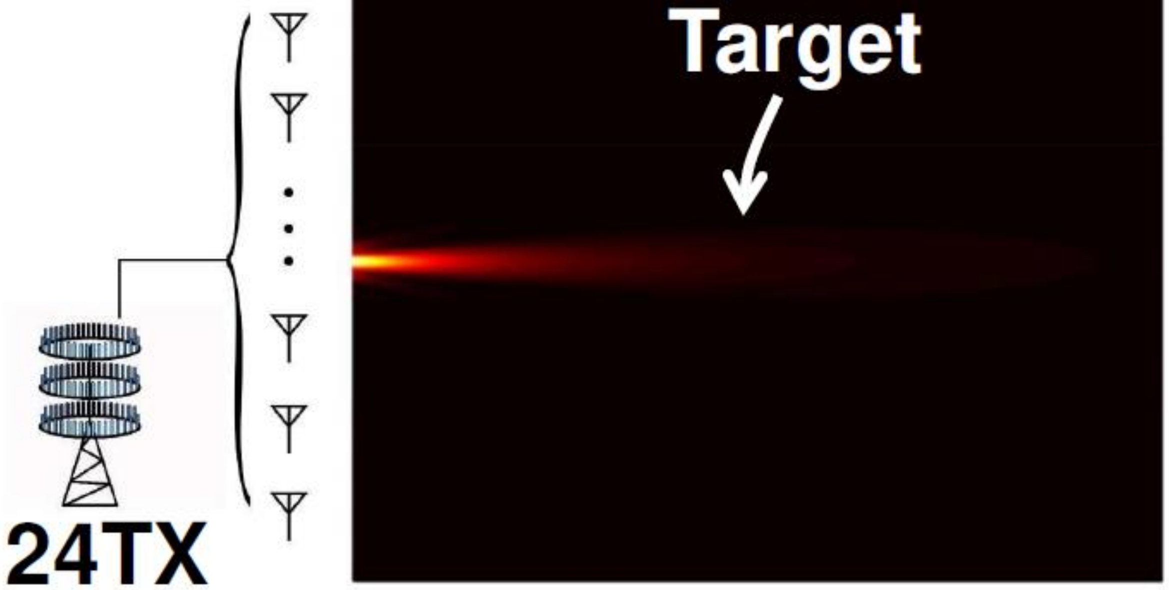


Far-field

[1] Mehdi, Kiani, et al. 2011. Design and optimization of a 3-coil inductive link for efficient wireless power transmission. IEEE transactions on biomedical circuits and systems
[2] Yunfei Ma, et al. 2018. Enabling Deep-Tissue Networking for Miniature Medical Devices. In In ACM SIGCOMM.
[3] Raffaele Guida, et al. 2019. U-Verse: a miniaturized platform for end-to-end closed-loop implantable internet of medical things systems. In In ACM SenSys.

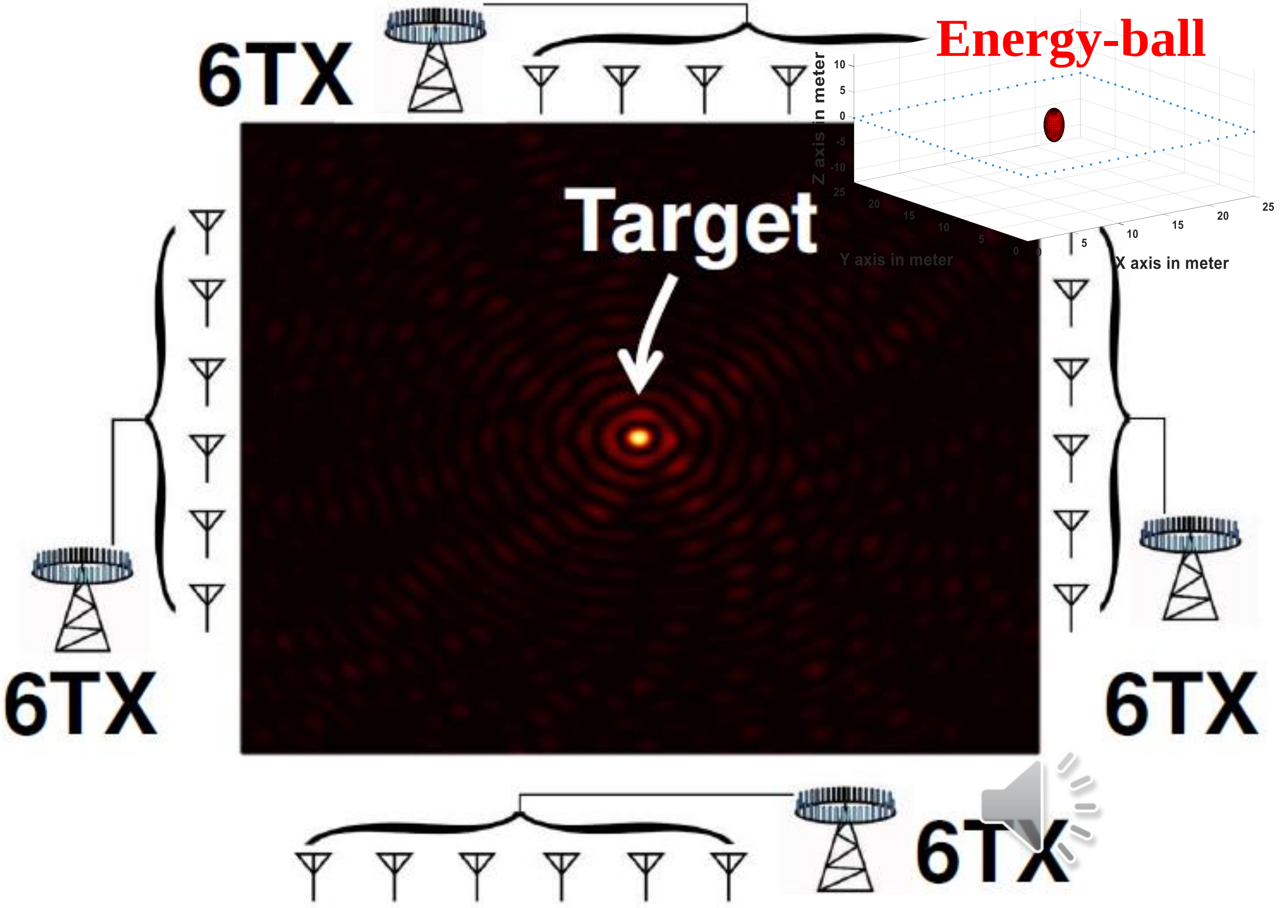
Distributed Beamforming for Deep Tissue Power

Energy distribution: traditional beamforming



Issues: overheating and blocking

(Proposed)Energy distribution: distributed beamforming



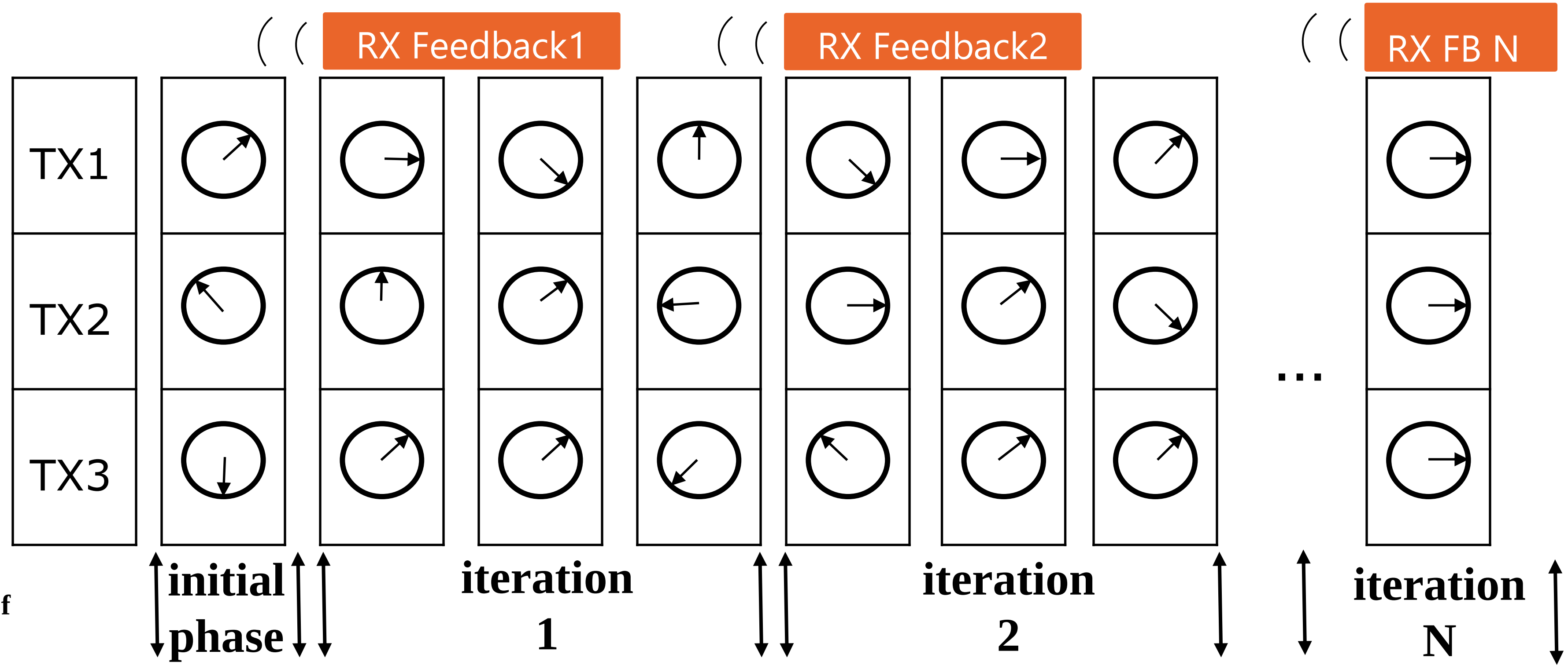
Implication: safer

[1] Xiaoran, Fan, et al. 2018. Energy-ball: Wireless power transfer for batteryless internet of things through distributed beamforming. Proceedings of the ACM UbiComp.

Distributed Beamforming Implementation

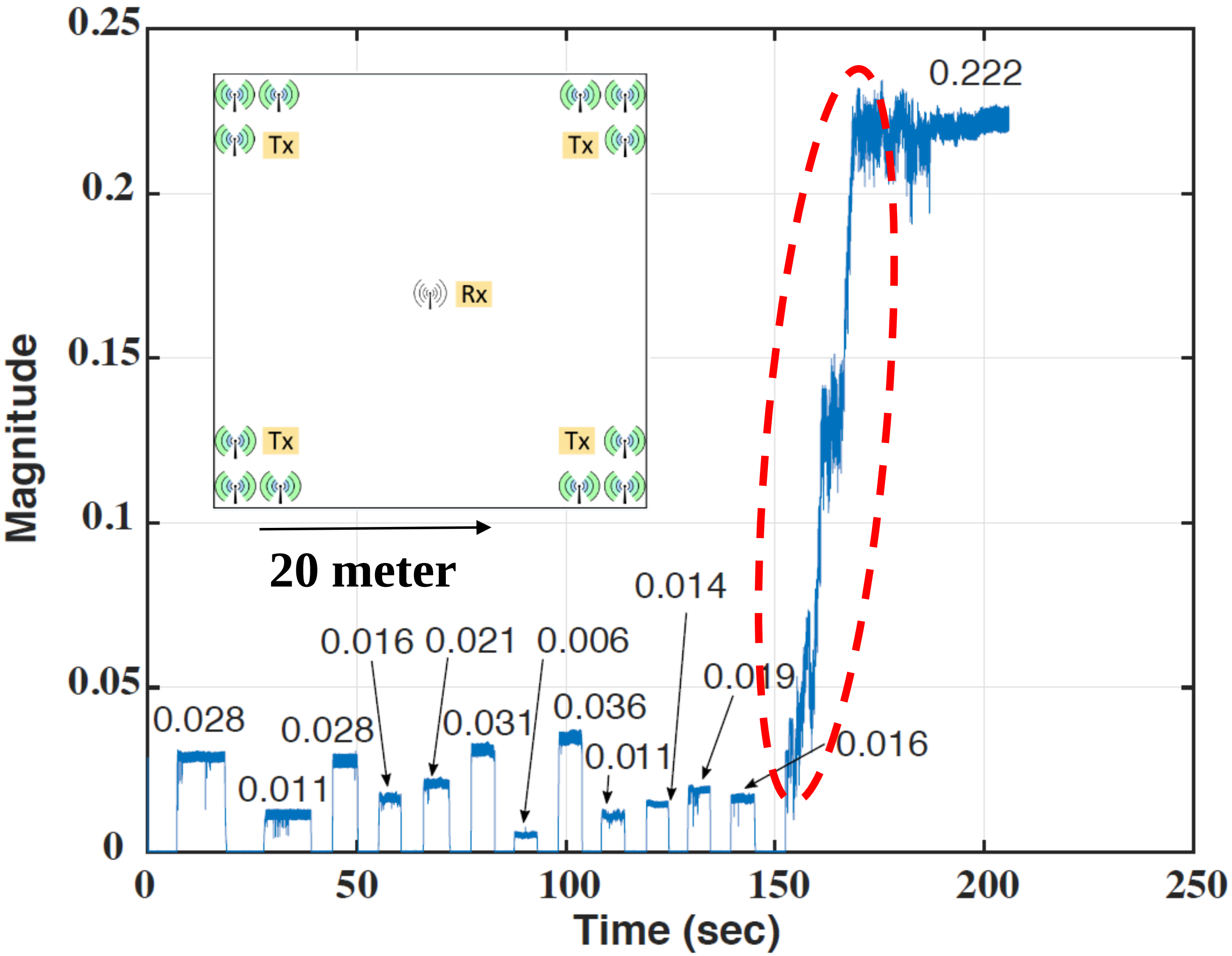
- ❑ **We choose a closed-loop implicit phase alignment method**
  - ❑ **Requires only 1-bit feedback. No CSI feedback needed**
  - ❑ **Transmitters work fully independent. No need a centralized control for the distributed phase array**

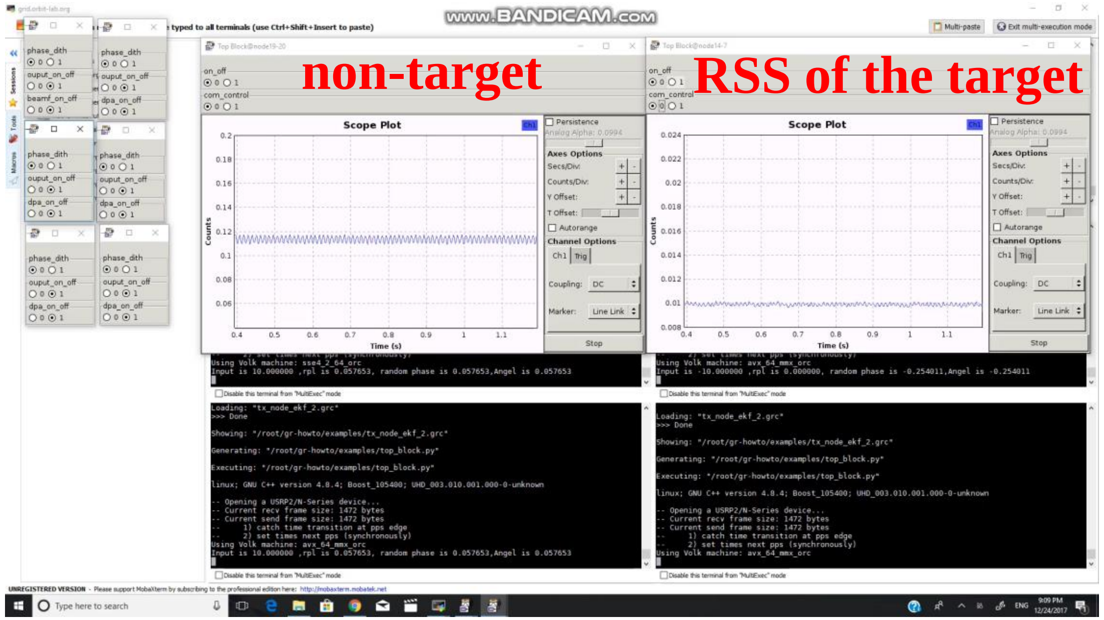
Phases in the unit circle



[1] R. Mudumbai et al. 2005. Scalable feedback control for distributed beamforming in sensor networks. In Proceedings of IEEE ISIT

Example Realizations





```
Using Volk machine: sse4_2_64_orc
Input is 10.000000 ,rpl is 0.057653, random phase is 0.057653,Angel is 0.057653
```

☐ Disable this terminal from "MultiExec" mode

```
Using Volk machine: avx_64_mmx_orc
Input is -10.000000 ,rpl is 0.000000, random phase is -0.254011,Angel is -0.254011
```

☐ Disable this terminal from "MultiExec" mode

```
Loading: "tx_node_ekf_2.grc"
>>> Done

Showing: "/root/gr-howto/examples/tx_node_ekf_2.grc"

Generating: "/root/gr-howto/examples/top_block.py"

Executing: "/root/gr-howto/examples/top_block.py"

linux; GNU C++ version 4.8.4; Boost_105400; UHD_003.010.001.000-0-unknown

-- Opening a USRP2/N-Series device...
-- Current recv frame size: 1472 bytes
-- Current send frame size: 1472 bytes
--     1) catch time transition at pps edge
--     2) set times next pps (synchronously)
Using Volk machine: avx_64_mmx_orc
Input is 10.000000 ,rpl is 0.057653, random phase is 0.057653,Angel is 0.057653
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☐ Disable this terminal from "MultiExec" mode

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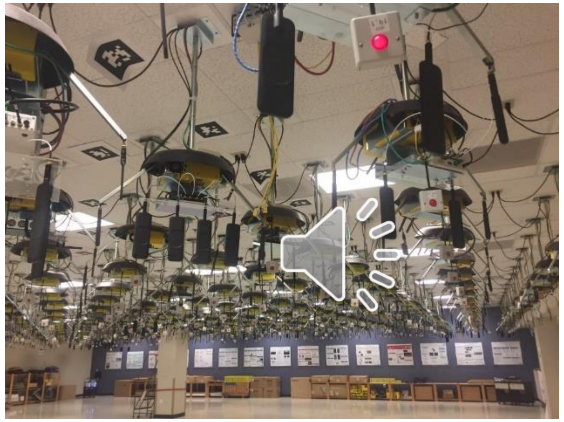
$$\sum_{k=1}^{12} RSS_{\{k\}} = 0.237$$

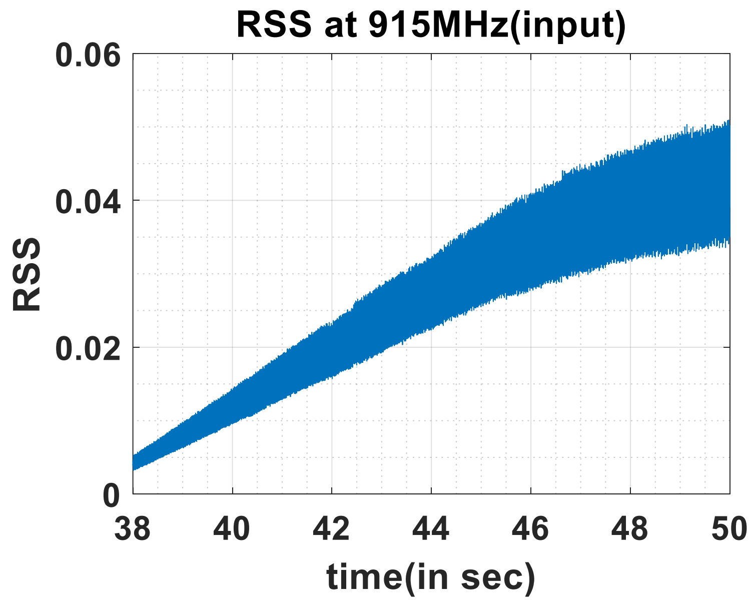
Actual received: 0.222
(94% optimal)



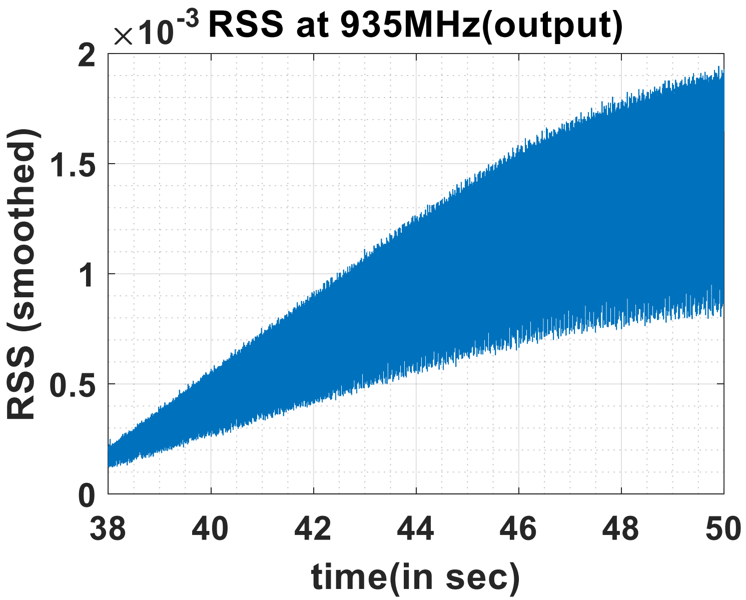
High Level Challenges 1

- **Implanted devices are power limited**

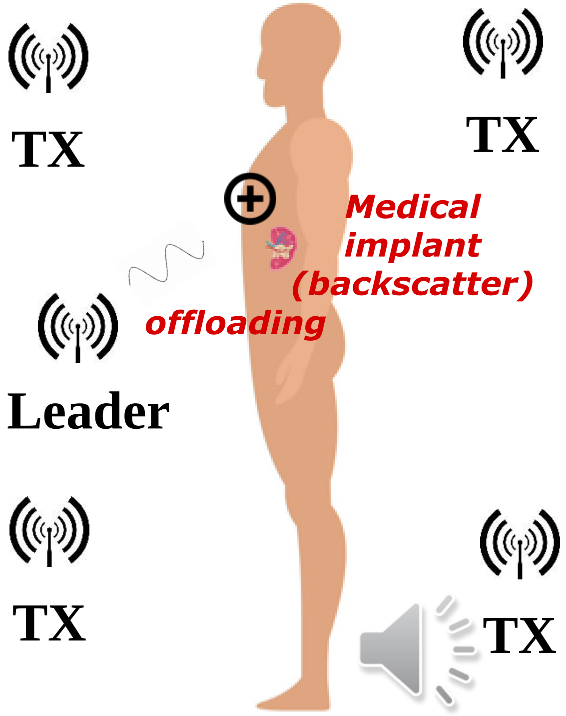
  Solutions: offloading computations to an out-of-body leader node using backscatter



Input signal at the backscatter (915 MHz)

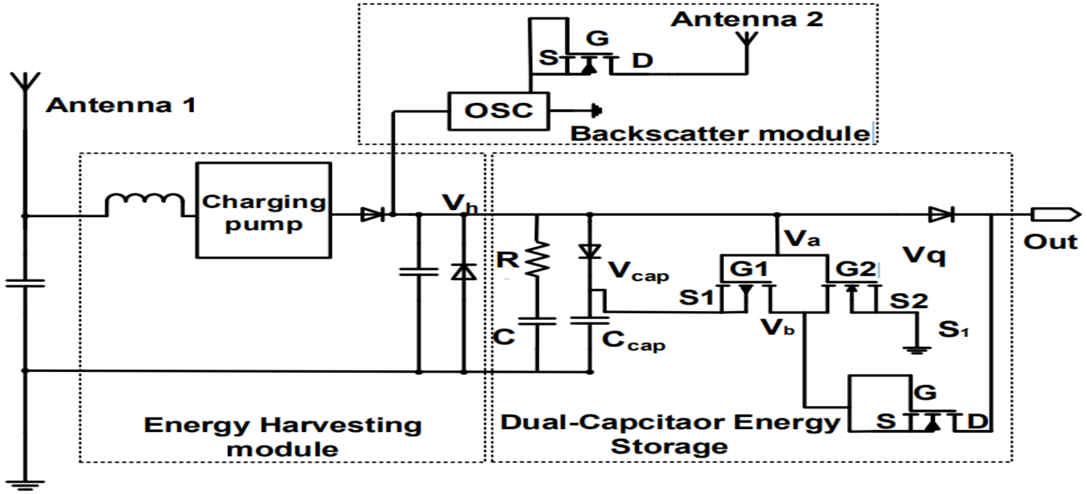


Reflected signal from the backscatter (935 MHz)

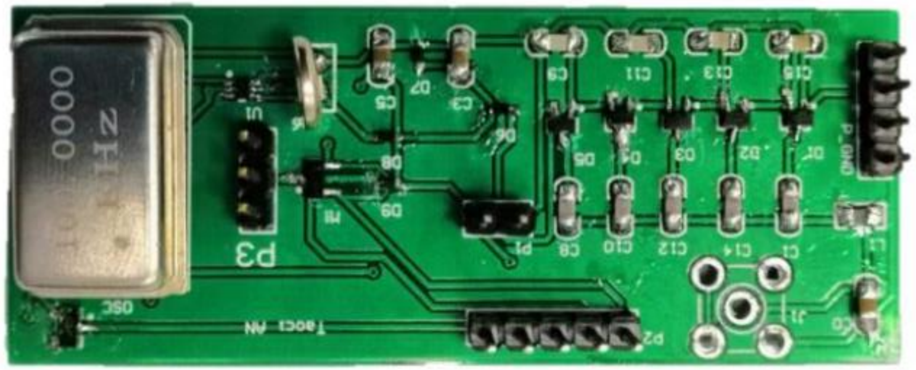


Key: the backscatter works like a mirror (with a frequency shifted reflect signal)

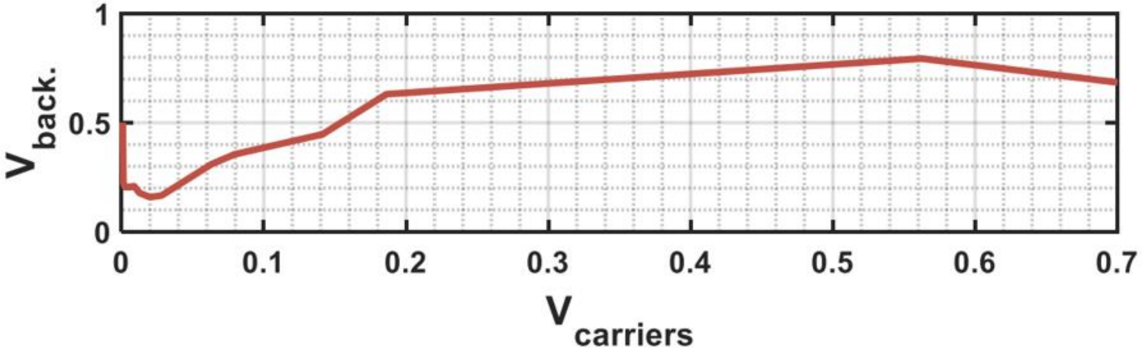
Sub-challenge 1: Monotonic Backscatter Design

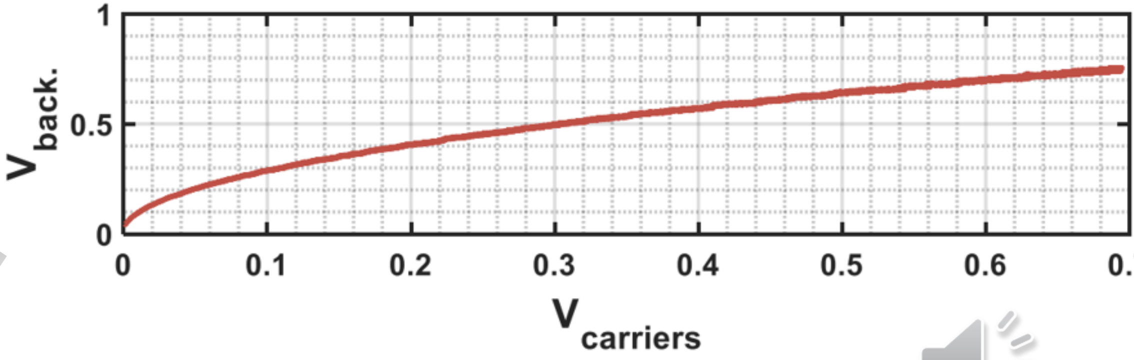


Dual antenna monotonic backscatter design – isolate input and reflecting radio chain



A typical passive backscatter – implicit BF algorithm will fail

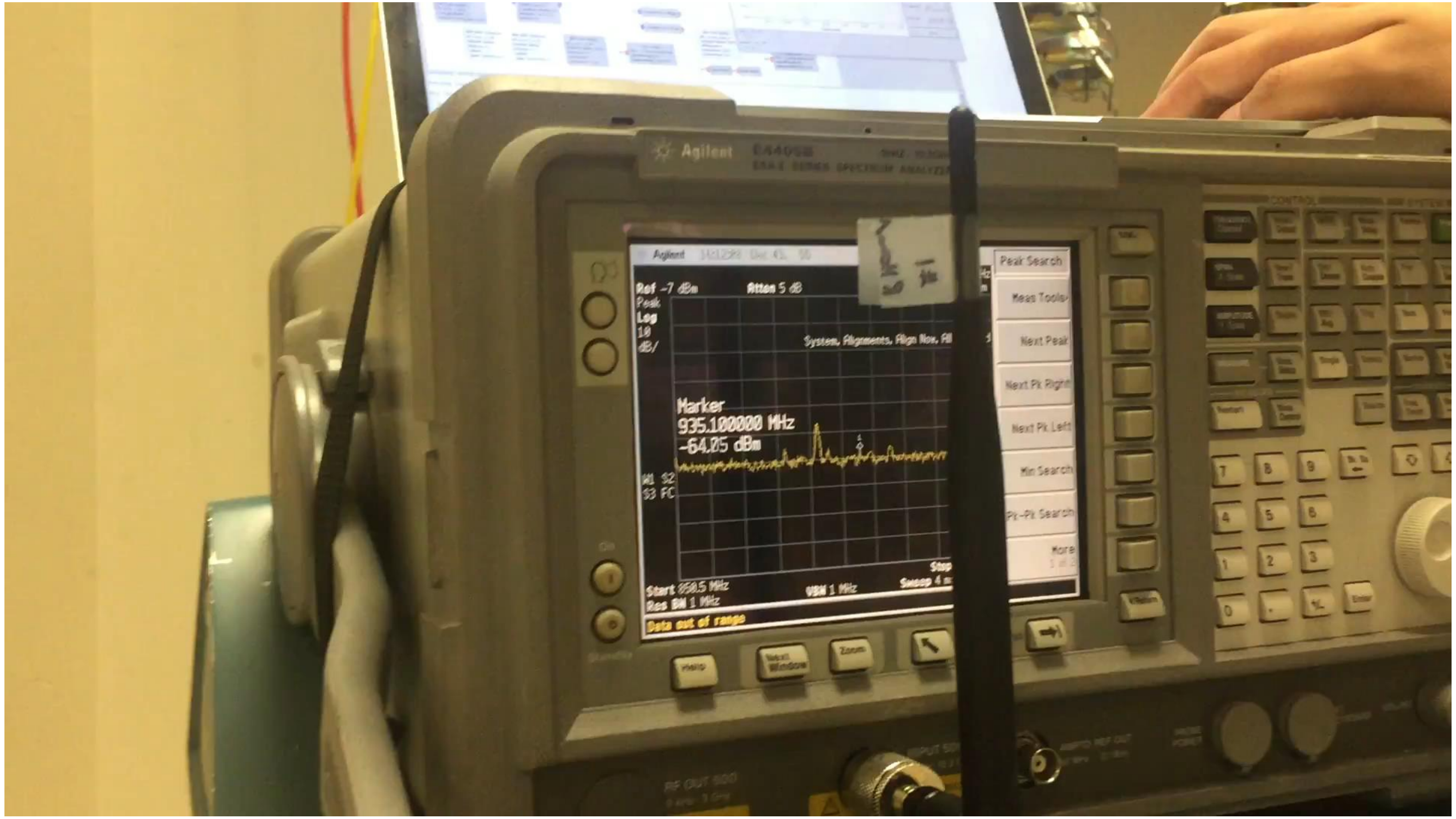




Our designed backscatter

Demo video next slide

Monotonic Backscatter Demo



TX (915MHz)

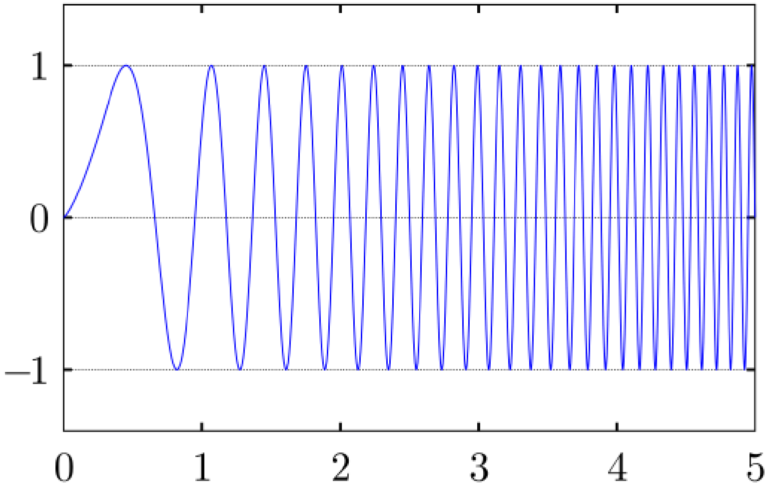
Backscatter (20MHz shift)

Spectrum analyzer (915+935MHz)

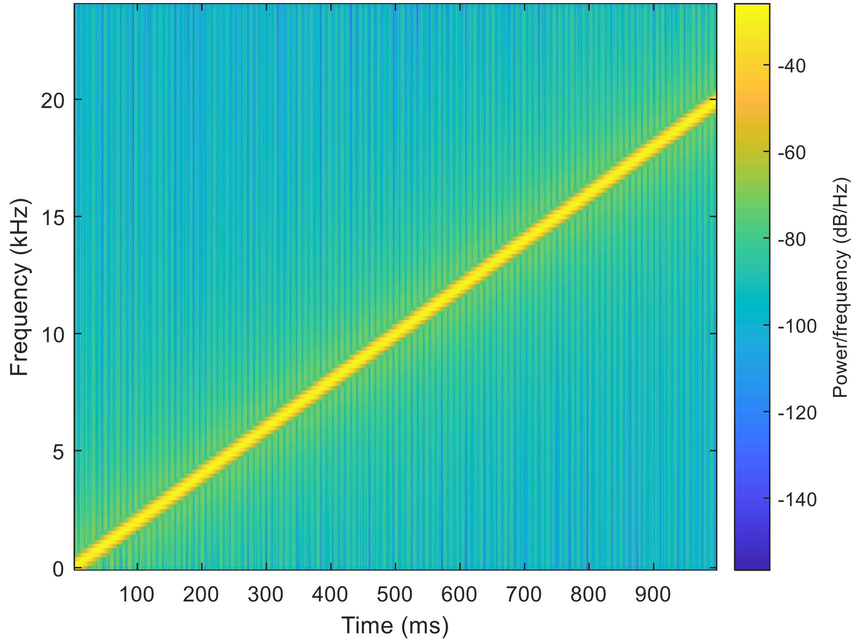
High Level Challenges 2

- ❑ **Severe path loss in animal tissues – no CSI or even RSS available**

Solutions: chirp spreading (spectrum spreading) with implicit BF algorithms

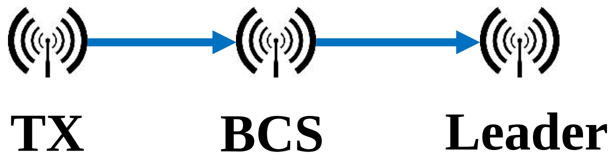


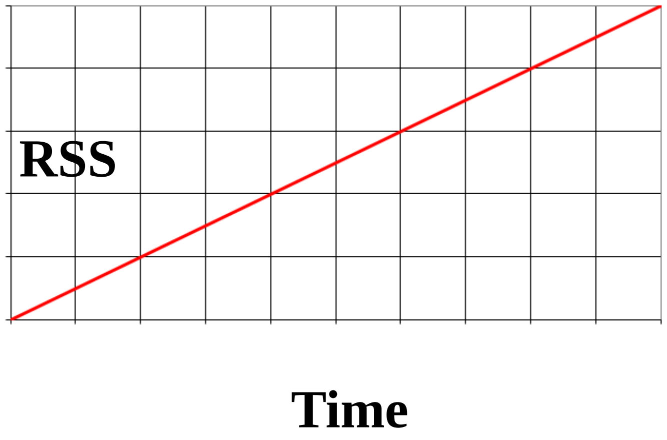
Chirp in time domain

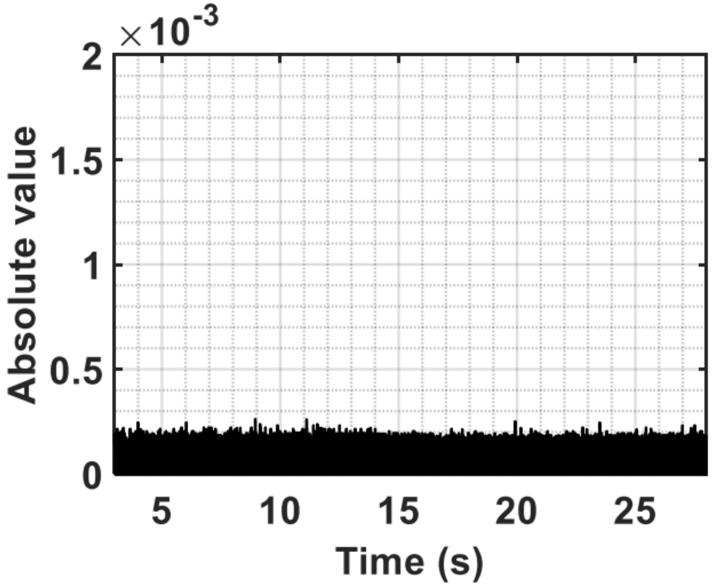


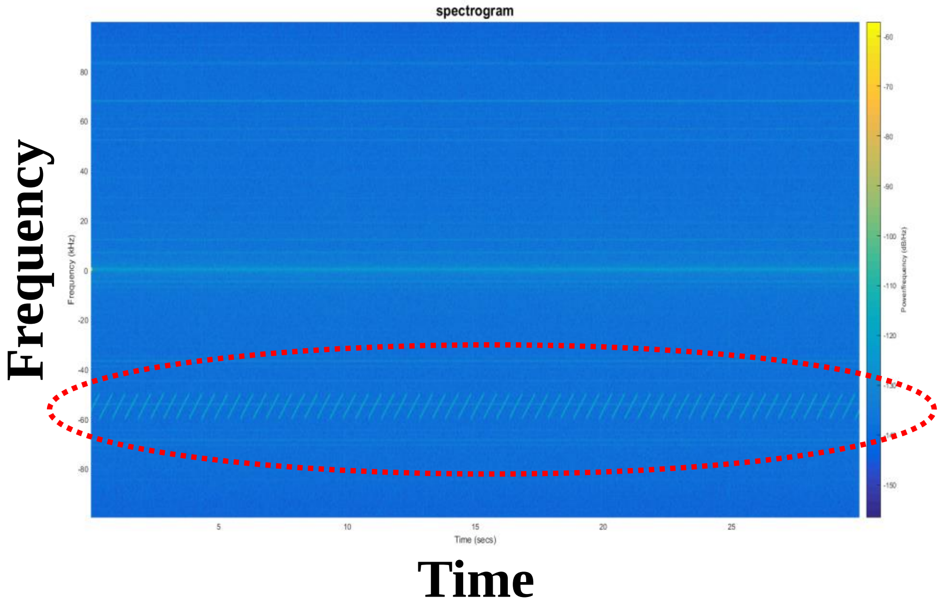
Spectrum of chirp

Why Chirp Spreading – an Experiment









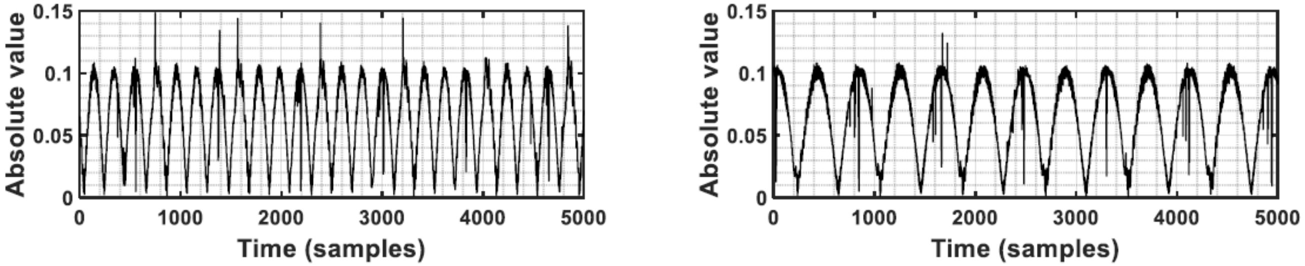
Transmission power increases at TX side

Leader's RSS (reflected from the backscatter) is under the noise floor

Chirps are visible in the spectrum domain

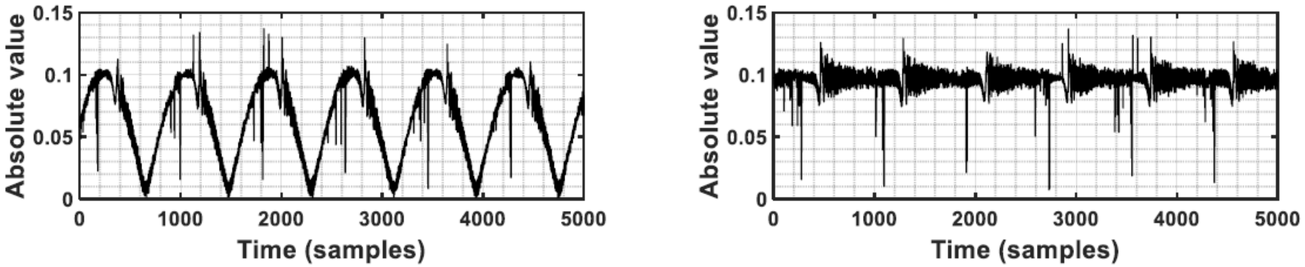
Sub-challenge 2: Tight Chirp Synchronization is Needed

RSS needs to be stable in beamforming. Large time offset among carrier chirps leads to RSS fluctuation



(a) 50 μs time offset

(b) 25 μs time offset

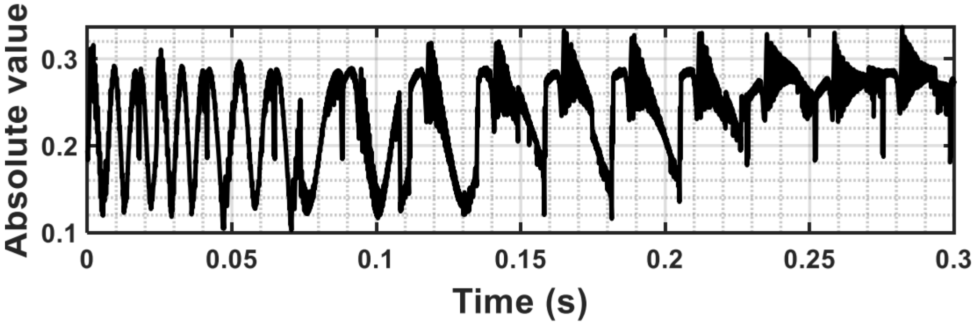


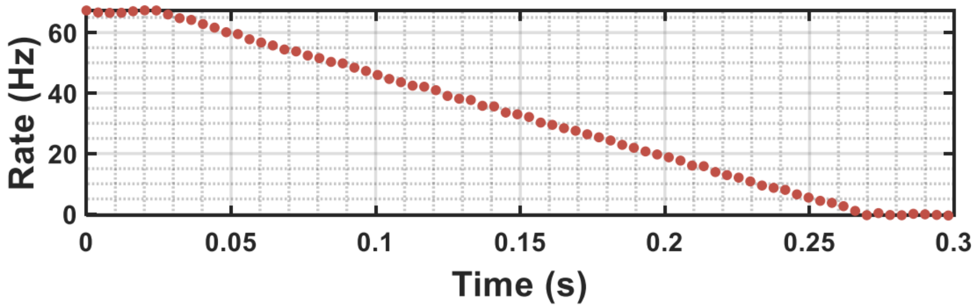
(c) 12.5 μs time offset

(d) 0 μs time offset

Minimizing time offset makes stable RSS

Step 1: compensate the carrier frequency offset (CFO) for macro sync





Step 2: use the fluctuation rate as feedback for micro sync

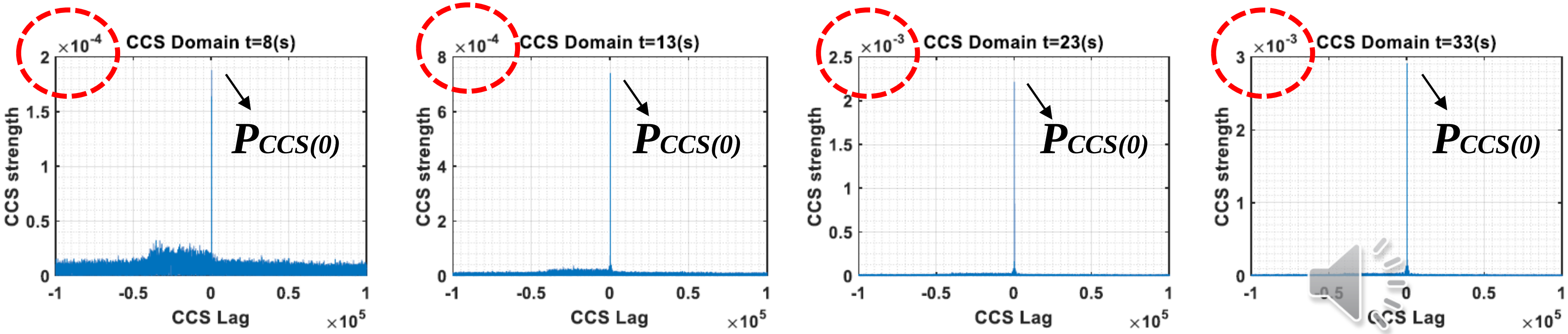
Chirp Decoding after the Synchronization

- ❑ **Decoding method: the peak of frequency domain correlation between the received backscatter signal and the reference chirp**

- ❑ **Denoted as $P_{CCS(0)}$**

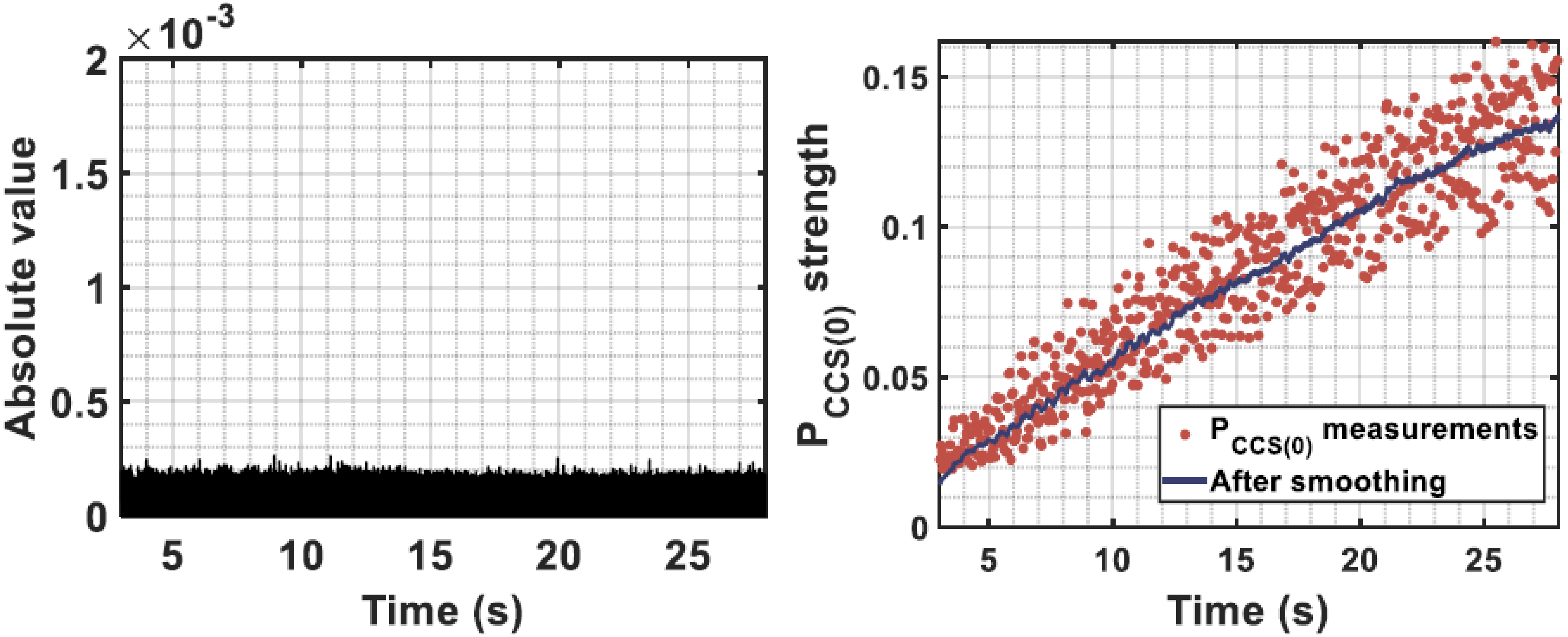
> ***Lemma 1:*** **$P_{CCS(0)}$ is linearly proportional to the power of backscatter reflected signal $p(\cdot)$**

Example of decoded $P_{CCS(w)}$ for increasing input signal



$P_{CCS(0)}$ is clearly increasing

An Example Chirp Decoding Result



a RSS measurements

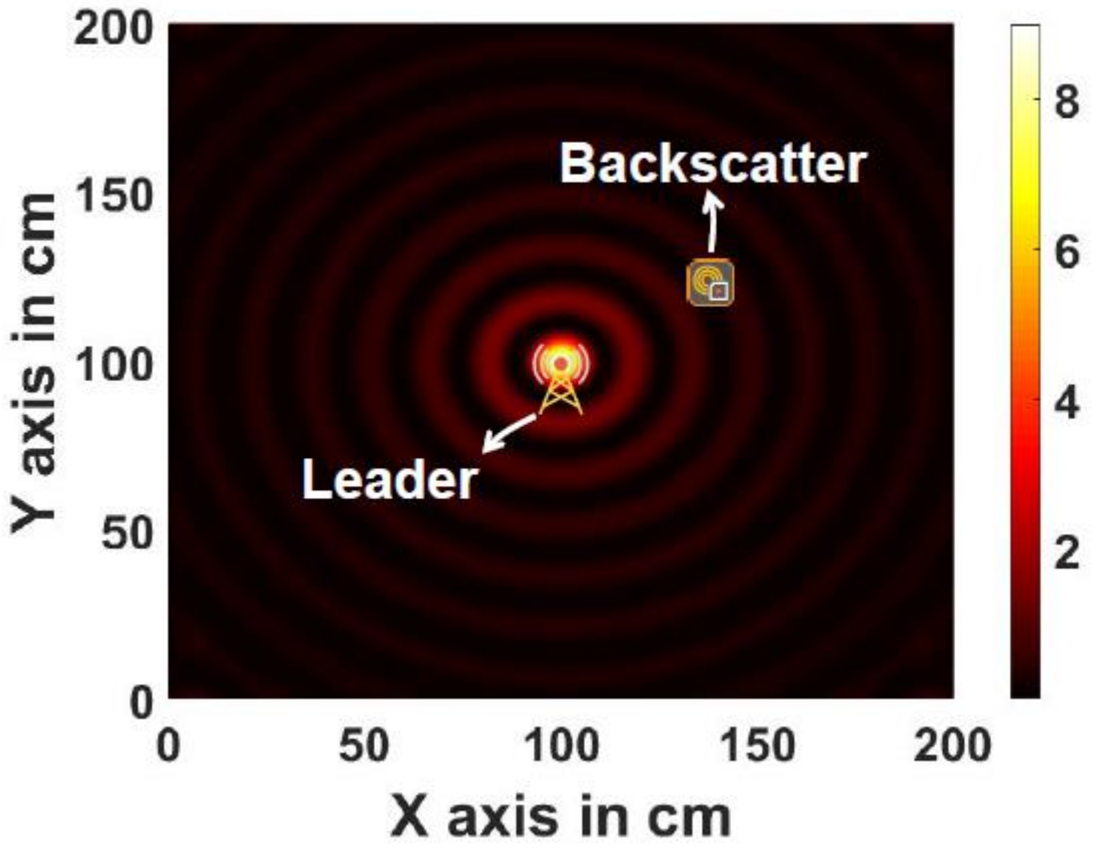
b $P_{CCS(0)}$ measurements

The increasing RSS trend is under the noise floor in time domain

The increasing RSS trend is clear after chirp decoding

Challenge 3: Bootstrap the Backscatter

Cold start is crucial – the inbody device might not have power at the first place



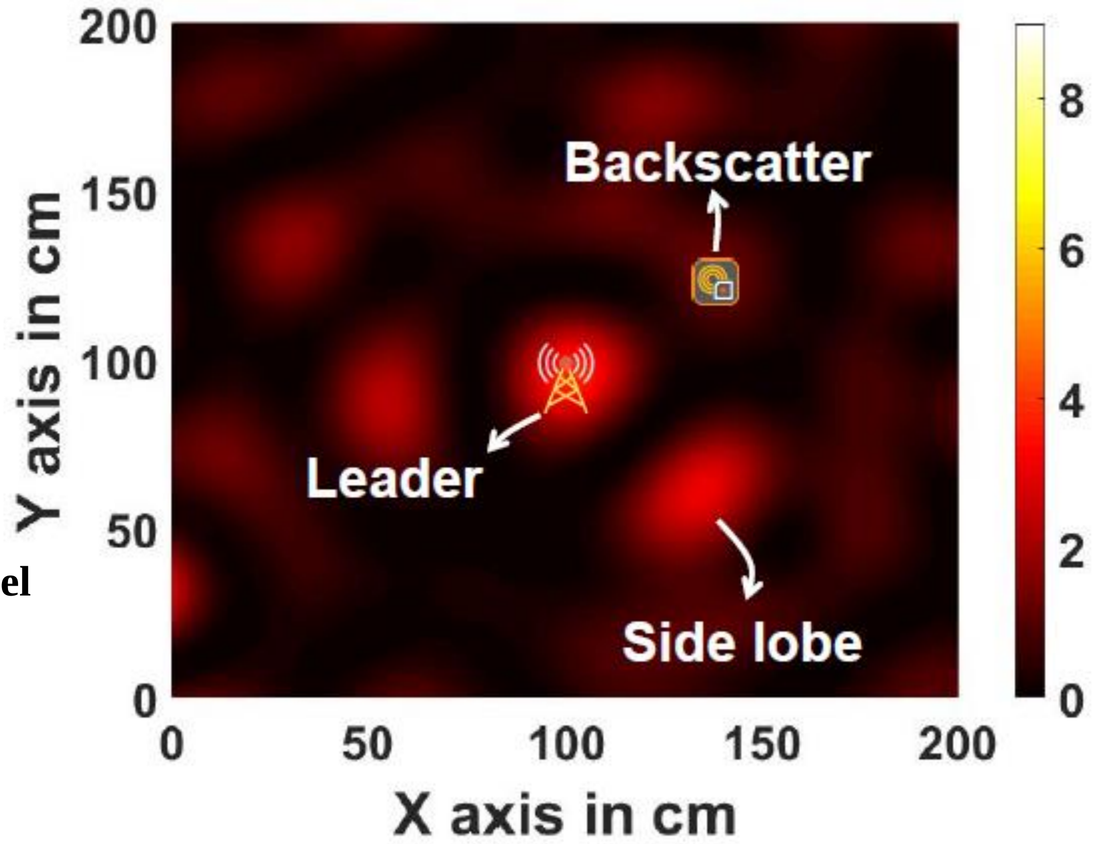
BF at the leader node first

Challenge 3: Bootstrap the Backscatter

Intentionally introduce phase noise to *enlarge* the 'Energy-Ball'

TX BF: 915MHz channel

Leader Monitoring: 935MHz channel



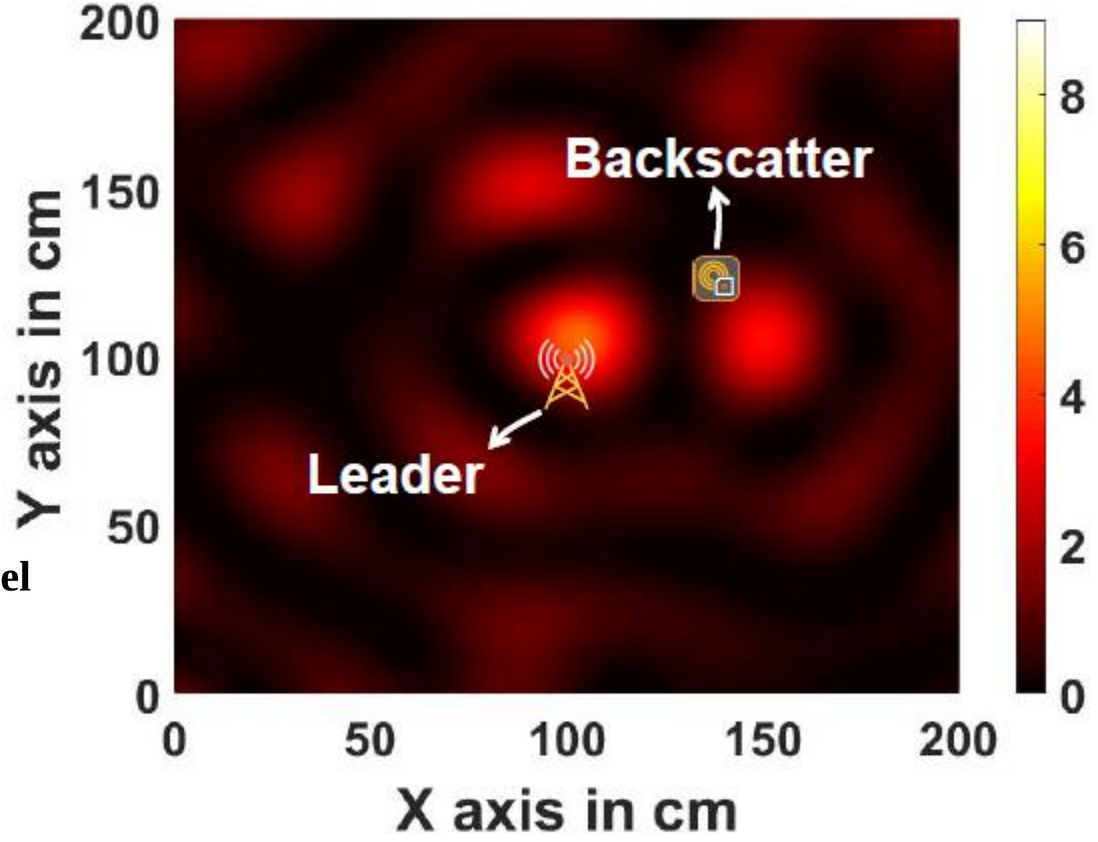
Phase perturbation 1: missed

Challenge 3: Bootstrap the Backscatter

Intentionally introduce phase noise to *enlarge* the ‘Energy-Ball’

TX BF: 915MHz channel

Leader Monitoring: 935MHz channel



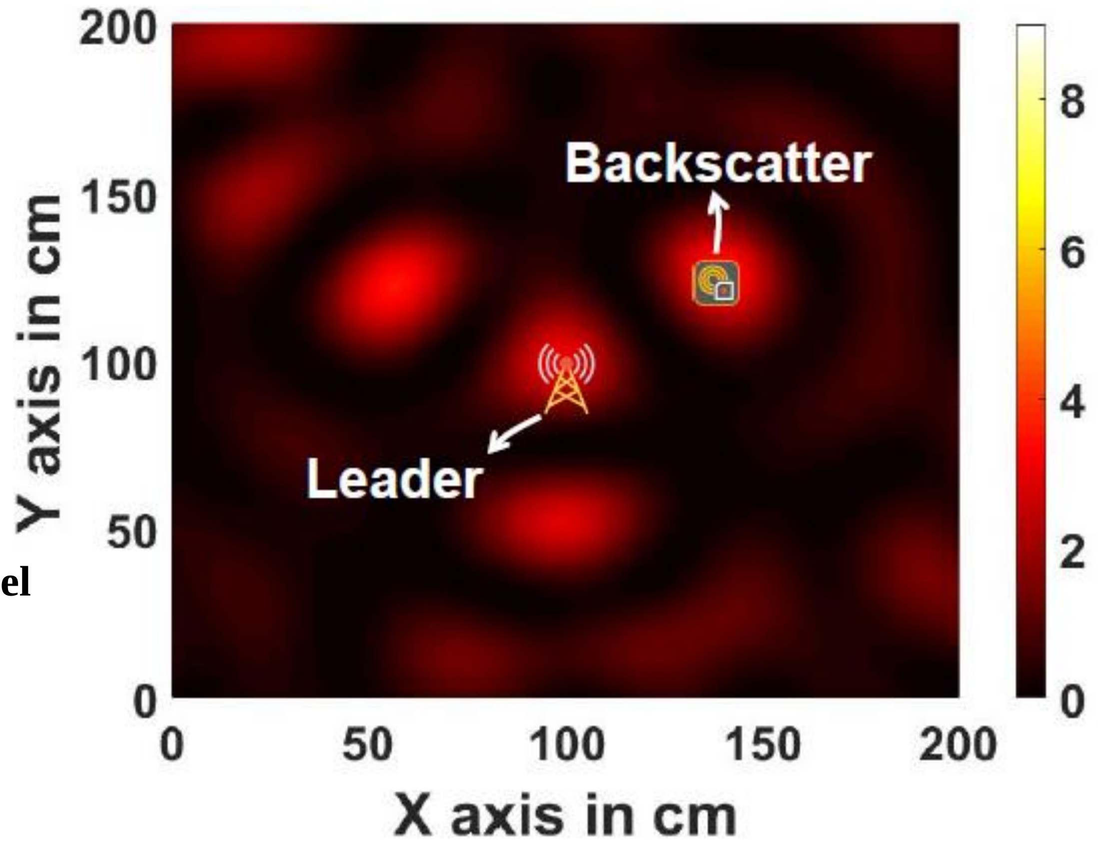
Phase perturbation 2: missed

Challenge 3: Bootstrap the Backscatter

Intentionally introduce phase noise to *enlarge* the ‘Energy-Ball’

TX BF: 915MHz channel

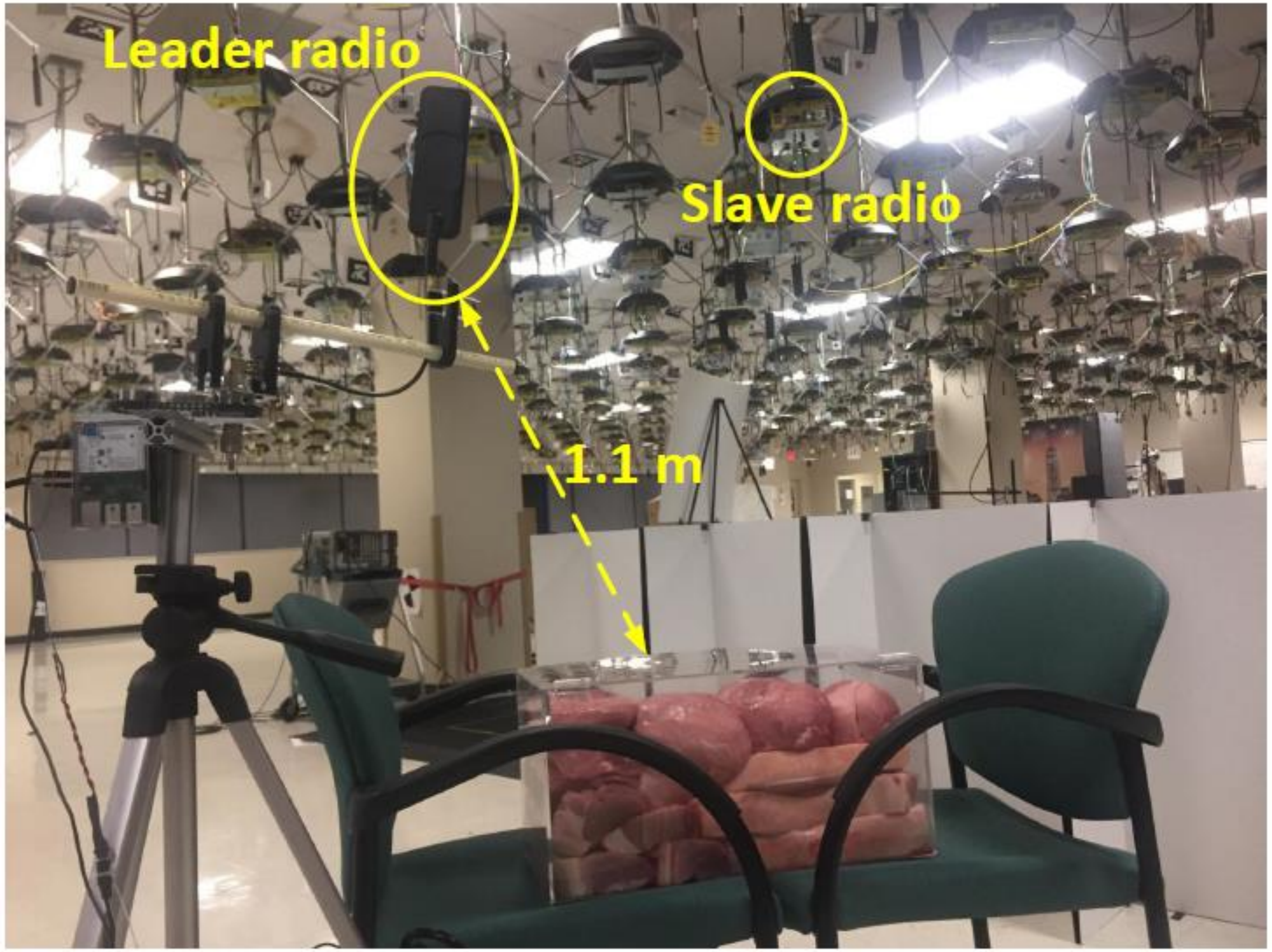
Leader Monitoring: 935MHz channel

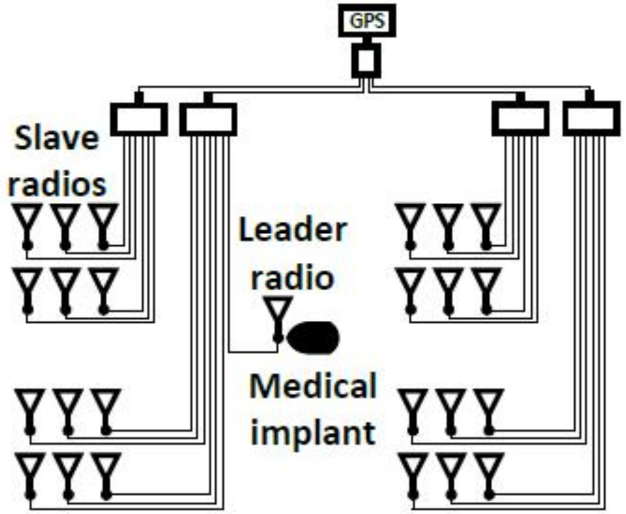


This cold start is a natural process by our default system design – bootstrap as long as the leader node observes the first *PCCS(0)* in the 935 MHz channel

Phase perturbation 3: hit

Experiment Setup

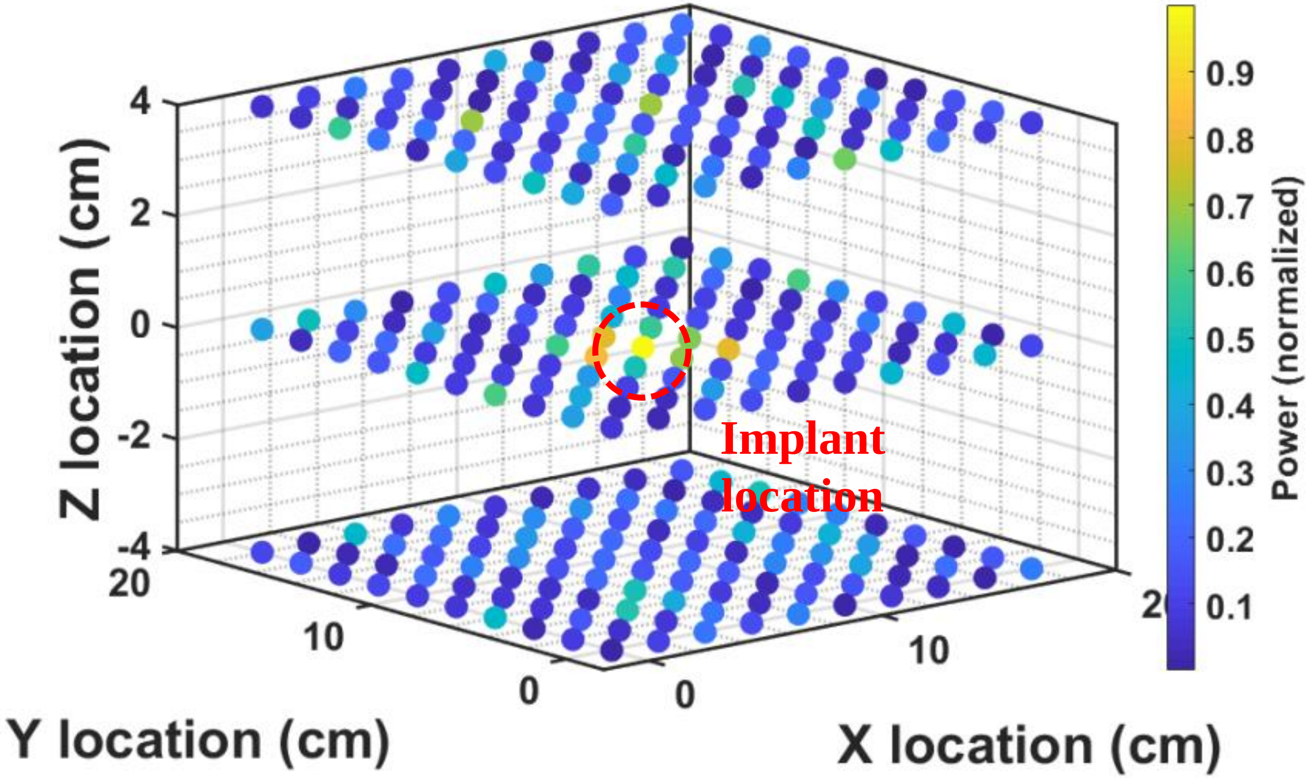




Power Delivering in 10 cm Tissues

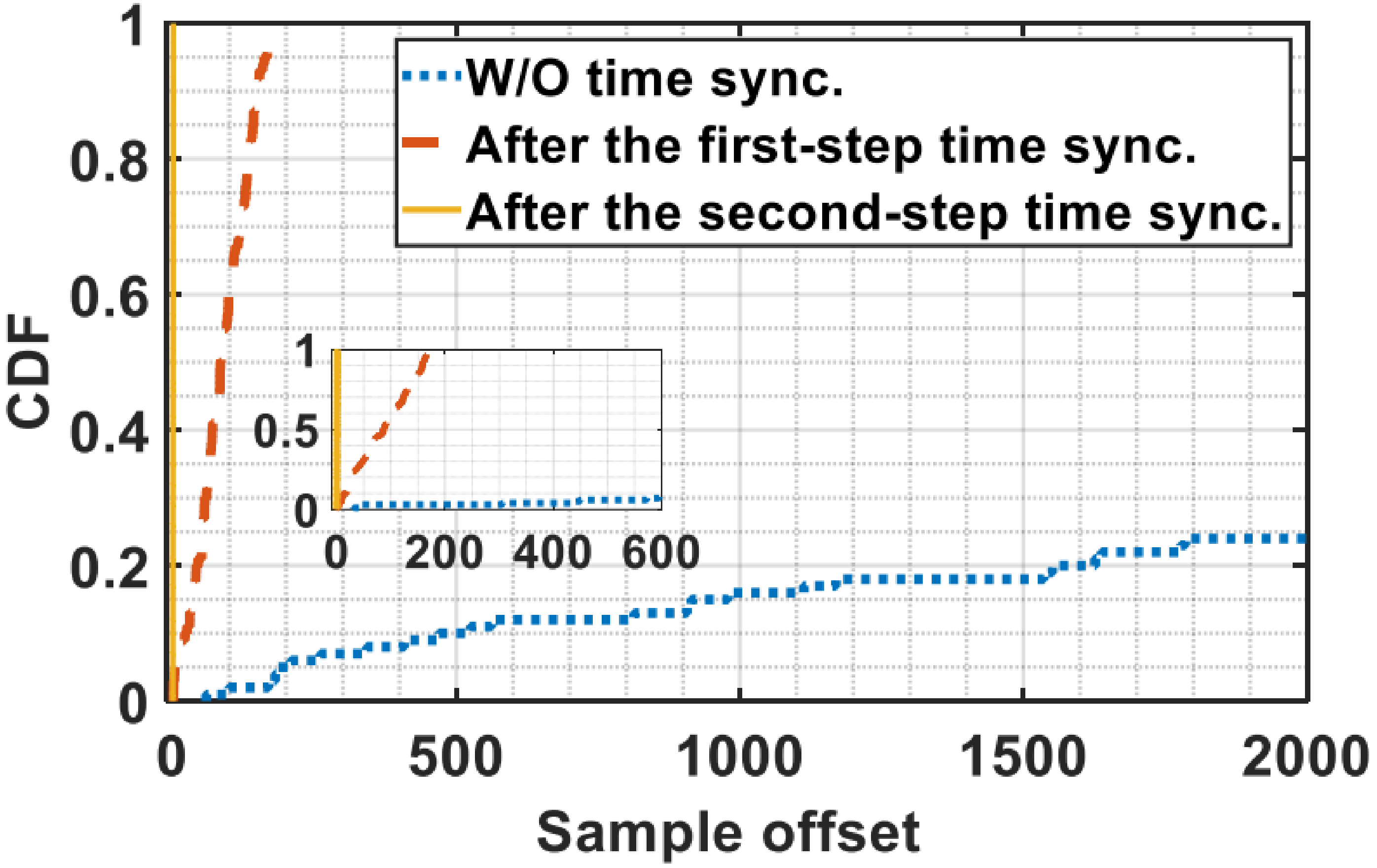
Device	Pacemaker	Cardiac defibrillator	neuro-stimulator	CIDR	In-N-Out
Power (μW)	10–100	25–250	40–500	100–800	372

In-N-Out Could achieve much higher power in actual room settings



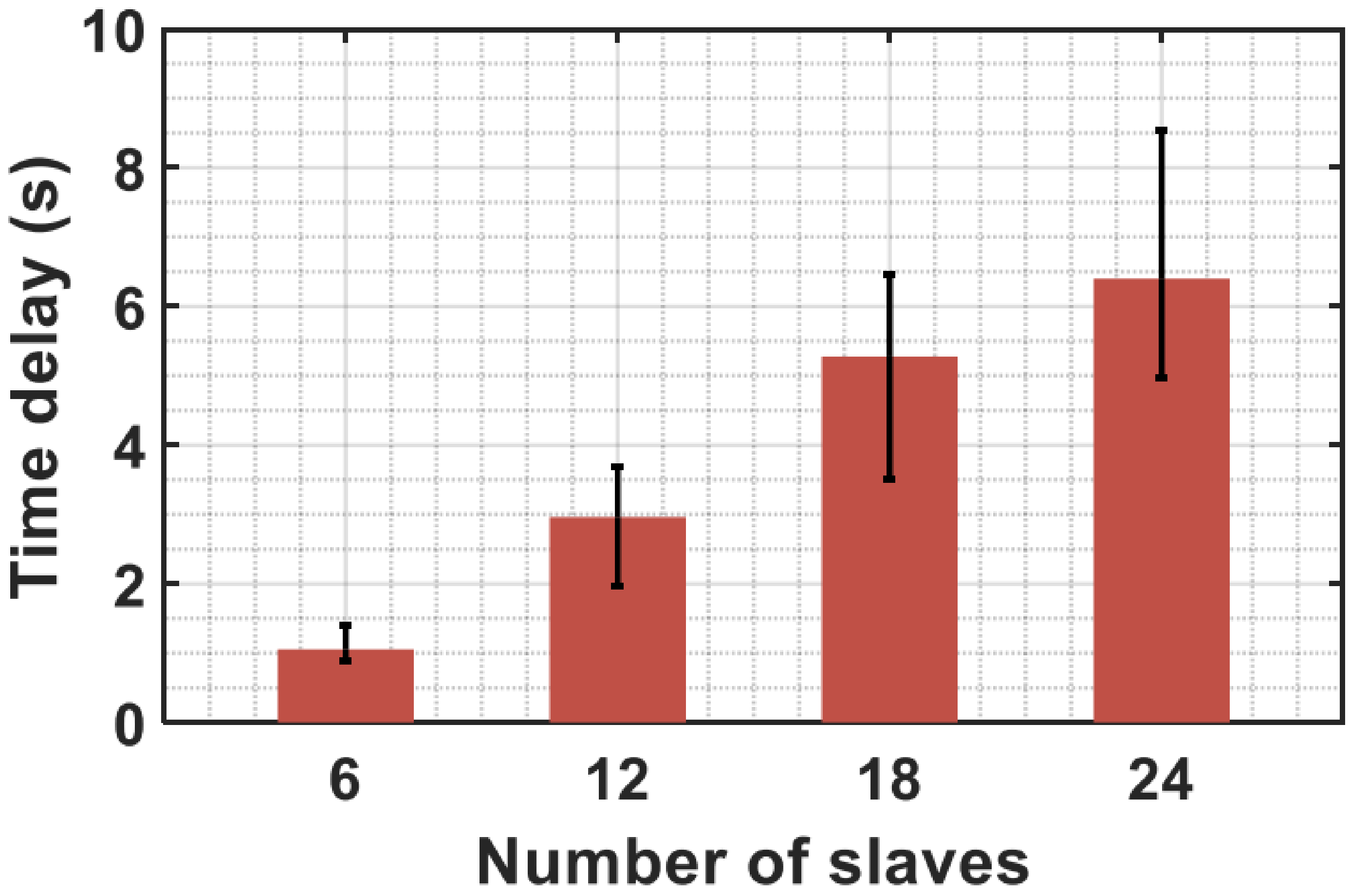
0.37 mW RF power delivered at 10 cm deep, achieves highly asymmetric energy distribution at the same time

Micro Benchmark Evaluations: Chirp Synchronization Accuracy



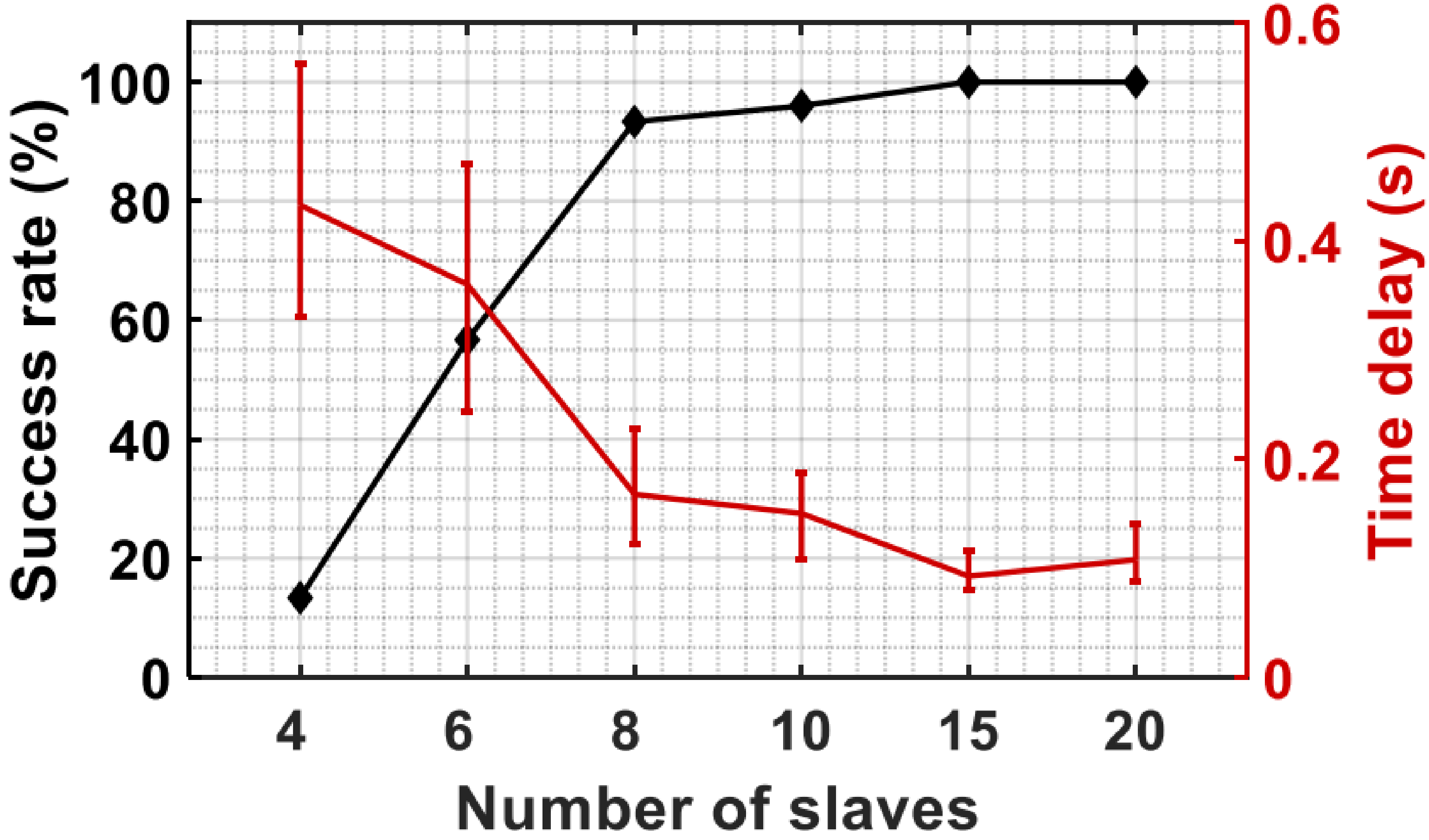
Residual time offset is minimized after two steps of chirp synchronization procedure

Micro Benchmark Evaluations: Sync Time Consumption



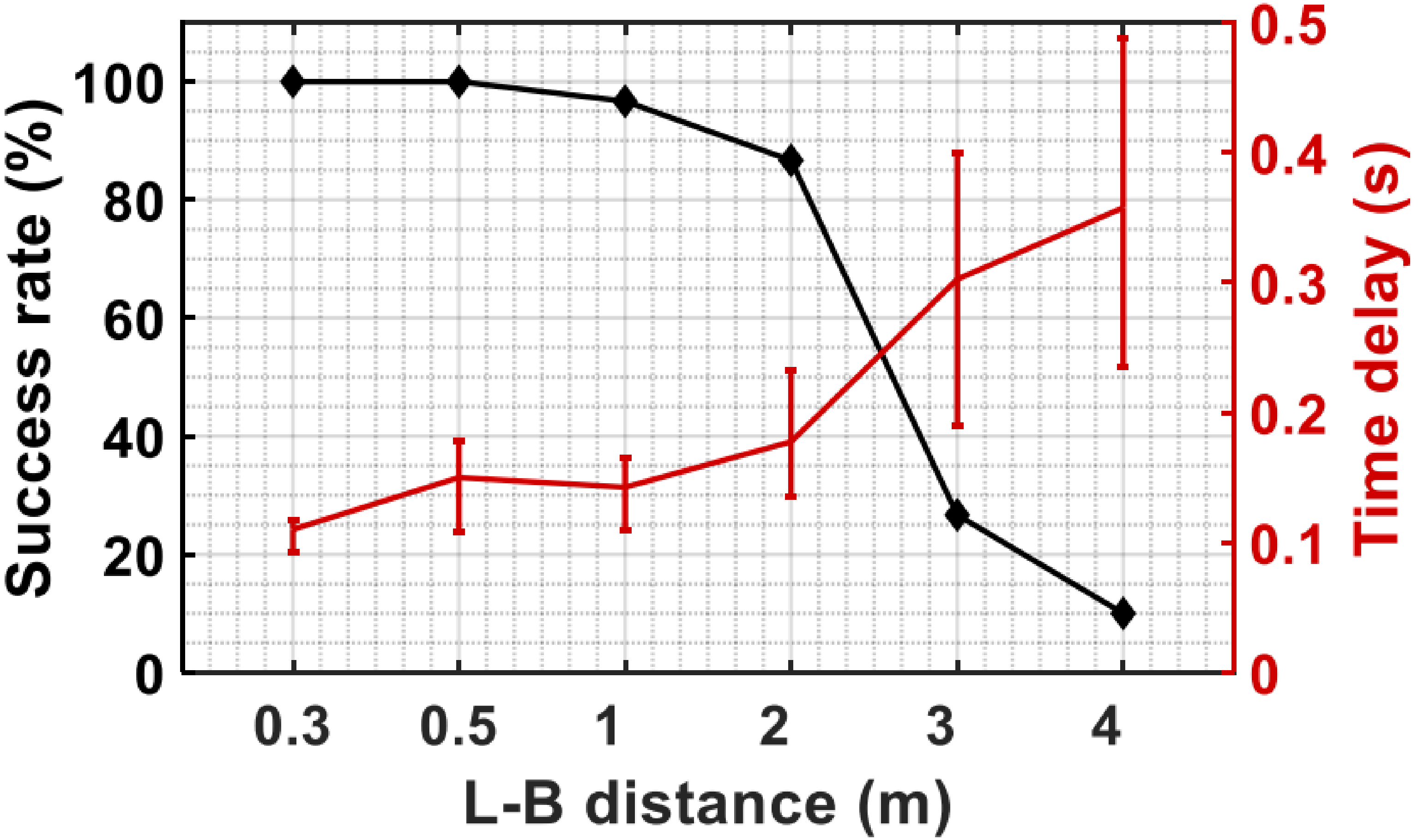
Time delay is quasi-linear to the number of transmitters, but this procedure only needs to be done once

Micro Benchmark Evaluations: Cold Start vs Number of TX



Cold start method has high (>92%) success rates with short (<0.6s) time delays when there are more than 8 TX

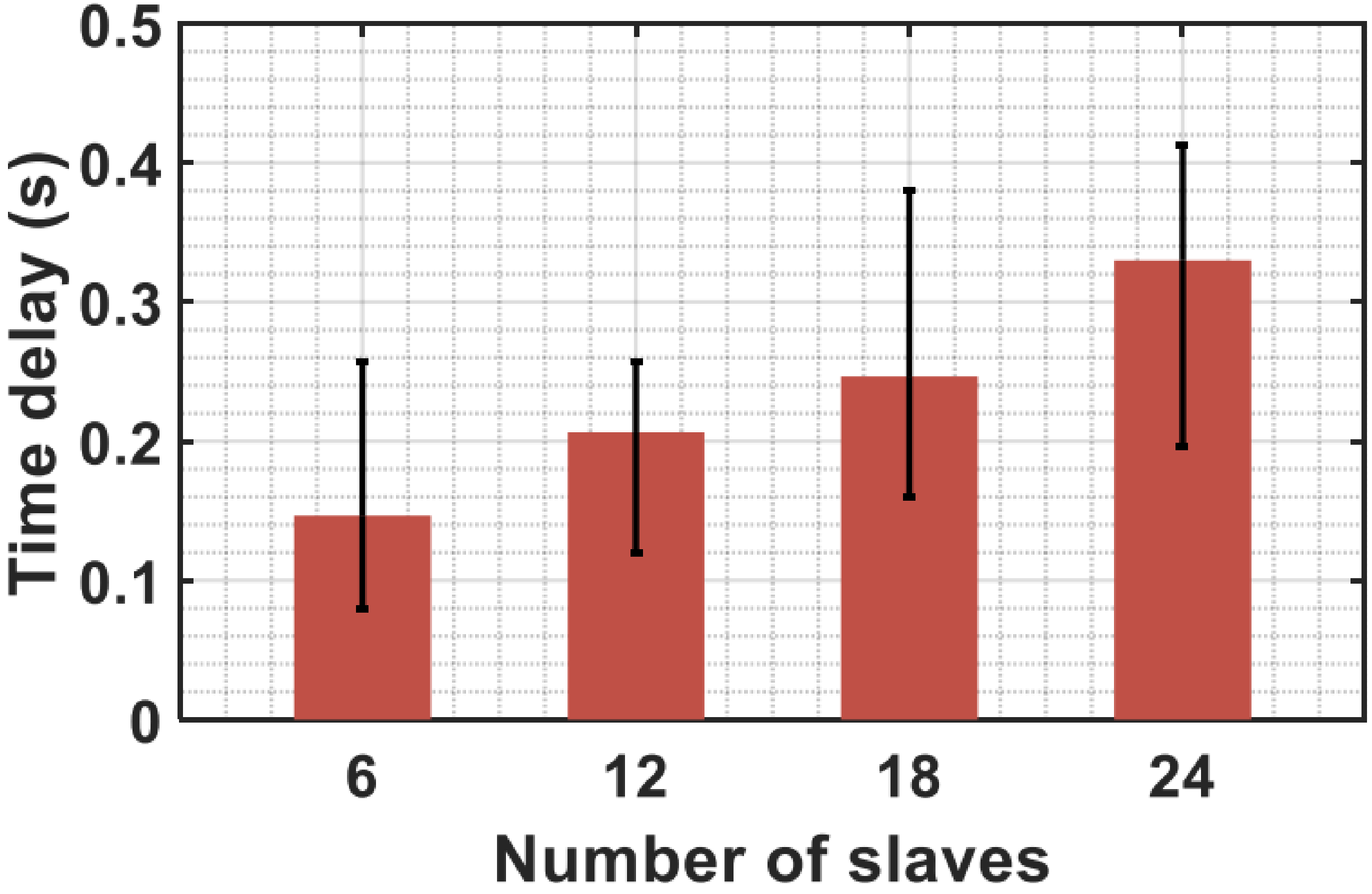
Micro Benchmark Evaluations: Cold Start vs L-B Distance



L-B distance: leader to backscatter distance

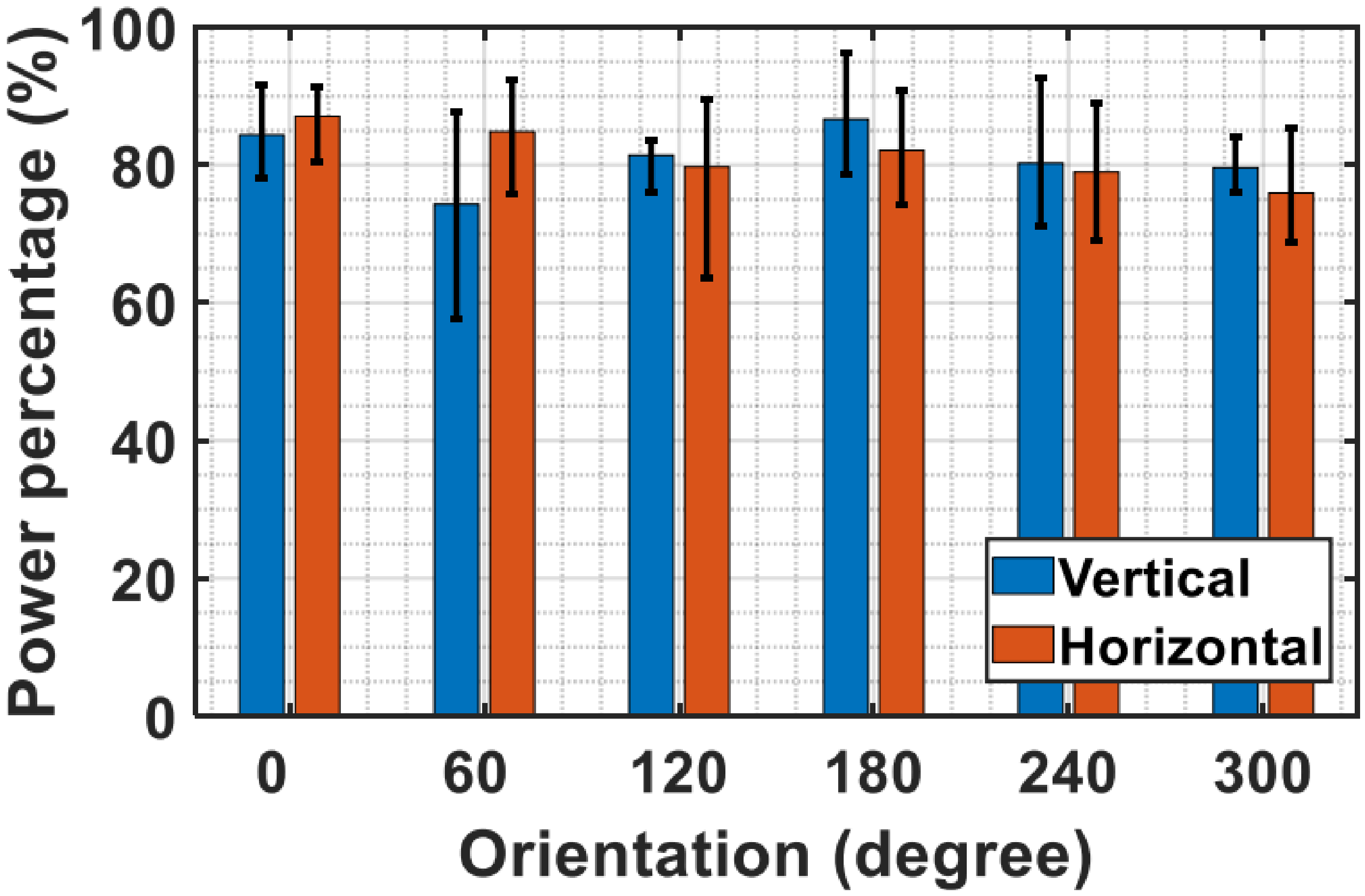
Cold start method performs well when L-B distance is less than 1 meter

Micro Benchmark Evaluations: Beamforming Time Consumption



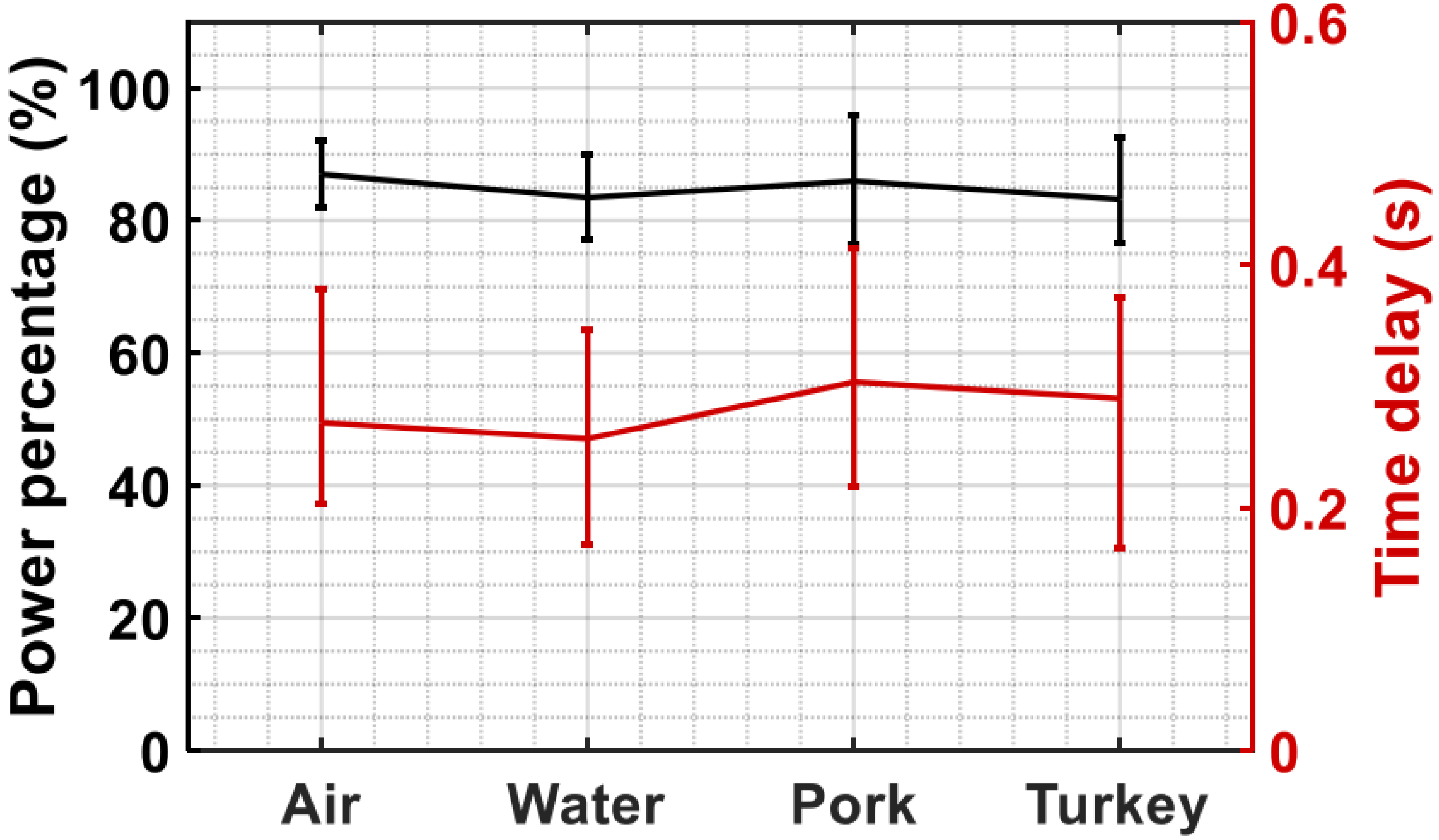
Establishing the Beamforming is fast (<0.4 s), the time consumption is quasi-linear to the # of TX

Micro Benchmark Evaluations: Backscatter Orientation



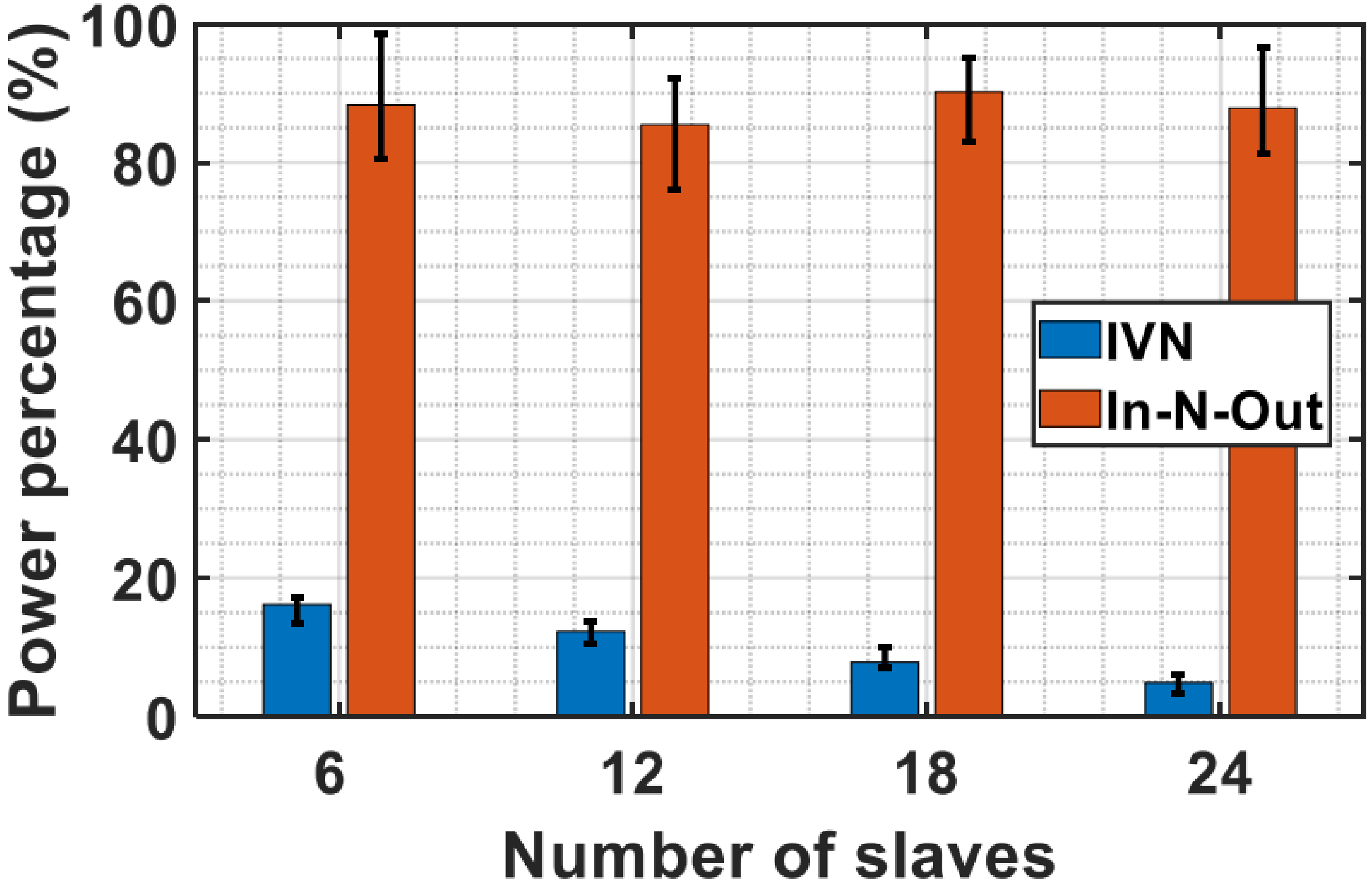
Power delivery is insensitive to the backscatter orientation (a big advantage)

Field Study: Beamforming Performance in Various Mediums

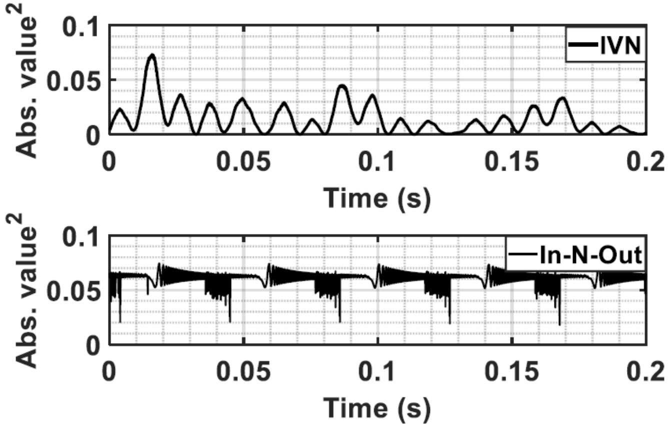


Our beamforming succeeds consistently in various wave propagation mediums (10 cm deep)

Field Study: BF Performance vs State of the Art (Stationary)



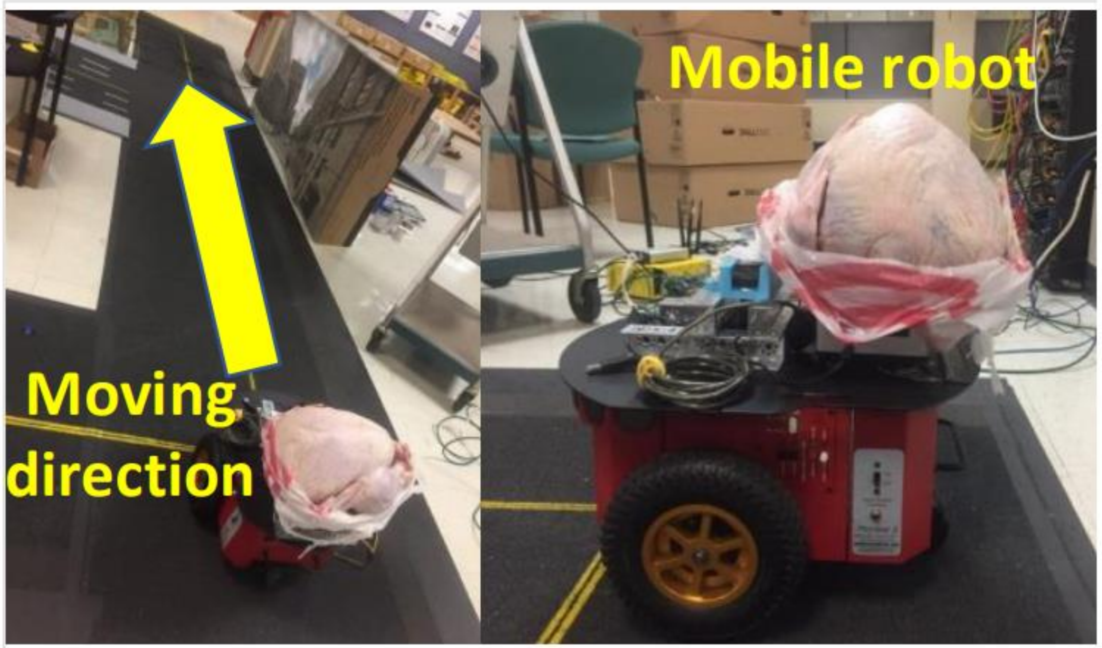
IVN is a multi-frequency multi-antenna blind beamforming design

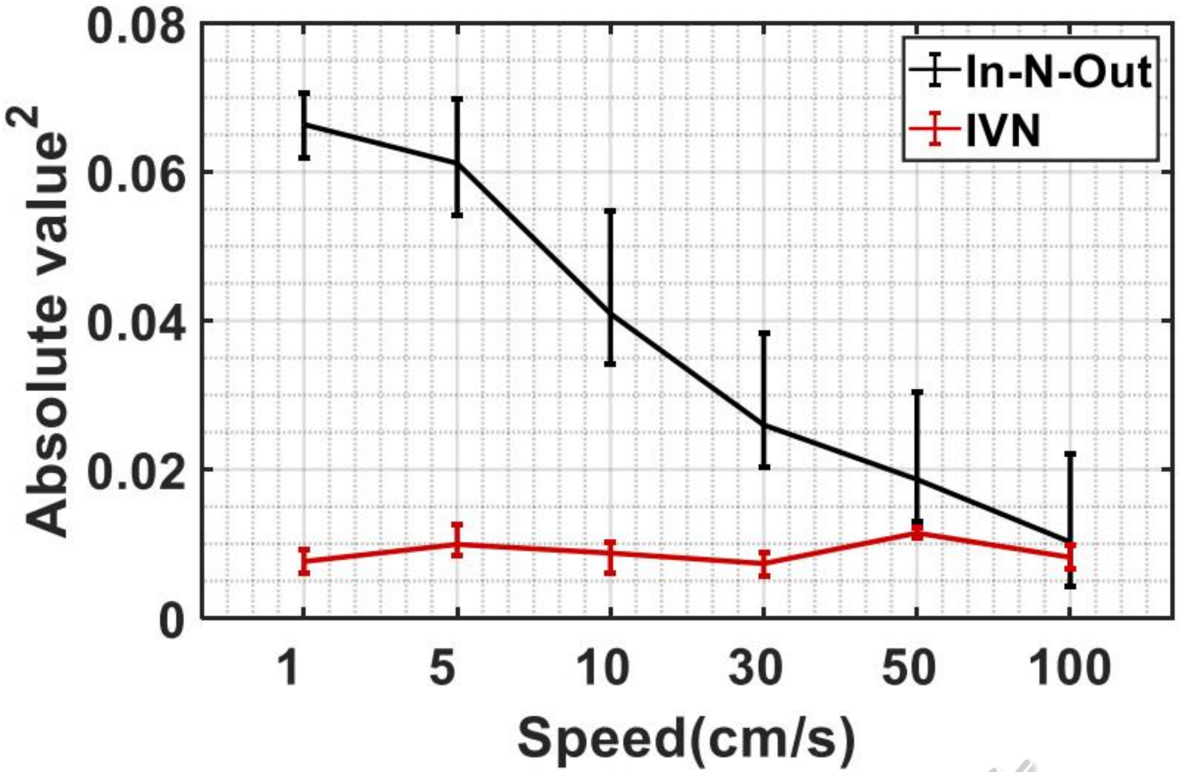


[1] Y. Ma et al. "Enabling deep-tissue networking for miniature medical devices." Proceedings of the 2018 Conference of the ACM SIGCOMM.

Our system delivers 18.1x power than IVN when there are 24 TX

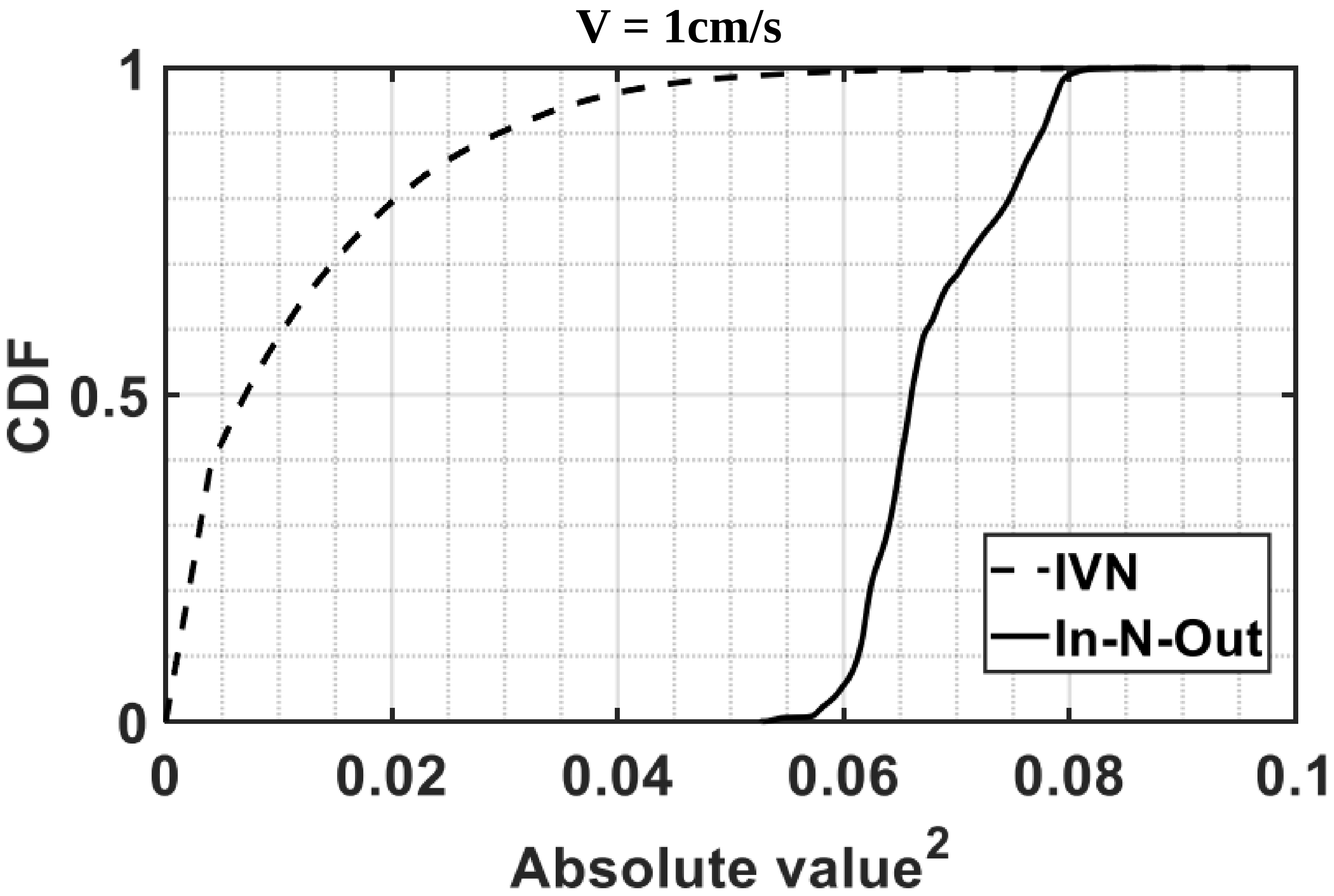
Field Study: BF Performance vs State of the Art (Mobile)





Our system outperforms IVN by 7.4× and 5.3× in relatively slow speed (1 cm/s and 5 cm/s)

Field Study: BF Performance vs State of the Art (Mobile)



Our system: lowest is 0.053, highest is 0.089

IVN: 90% points are smaller than 0.029

Our system delivers higher and more stable energy than IVN

In-N-Out Summary

- ❑ The first far-field distributed beamforming based wireless power transfer system charges deep tissue implants at a near-optimal power level
- ❑ Technical innovations including backscatter-leader-slave three-party beamforming without explicit CSI measurement, two-phase leader-slave chirp synchronization design and radio cold start through intentionally imperfect phase alignment
- ❑ Prototyping the system on software-defined radios with a monotonic backscatter PCB design, and conducting comprehensive evaluation of the system

Thank you!