A 0.7cm^2 3.5GHz, -31 dBm sensitivity batteryless 5G energy harvester backscattering chip for asset identification in IoT-enabled warehouses

Deniz Umut Yildirim[1], Jaeyoung Jung[2], Amr Elsakka[3], Giuseppe Moschetti[3], Miguel Lopez[3], Jonas Hansryd[3], Tomás Palacios[1], Anantha Chandrakasan[1]

[1]Massachusetts Institute of Technology
[2]Analog Devices [3]Ericsson Research

Outline

- Motivation and Prior Work
- Compact Battery-free Backscattering Chip
  - System architecture
  - Antenna-rectifier co-design
  - On-chip clock generation
  - Data encoding, backscattering
- Measurement Results
- Conclusion

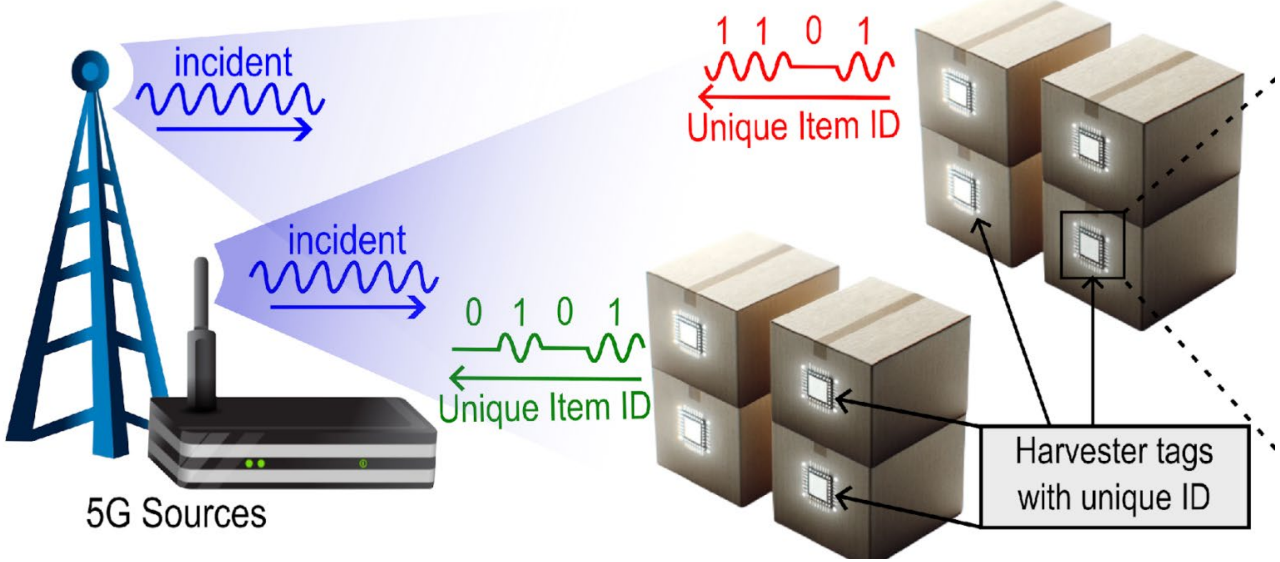
Outline

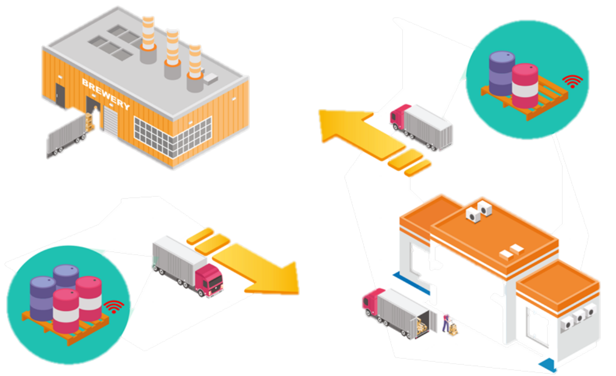
- **Motivation and Prior Work**
- Compact Battery-free Backscattering Chip
  - System architecture
  - Antenna-rectifier co-design
  - On-chip clock generation
  - Data encoding, backscattering
- Measurement Results
- Conclusion

RF Energy Harvesting – Power IoT Through Air

Unlocking ambient RF energy for a wireless, battery-free future in IoT connectivity.

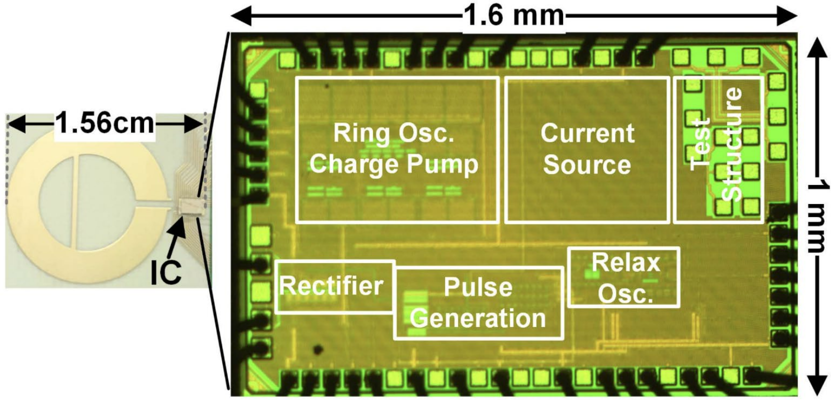
IoT - enabled Warehouses – Requirements for Tags



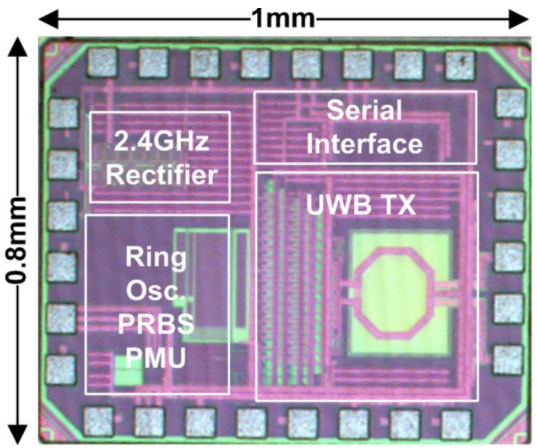


- Battery-free
- Highly sensitive (<-30dBm)
- Higher frequency of operation
  - < cm^2 dimensions
  - Compliant with 5G bands
- Ultra-low power communication
  - Quick start-up
  - Resilient data encoding

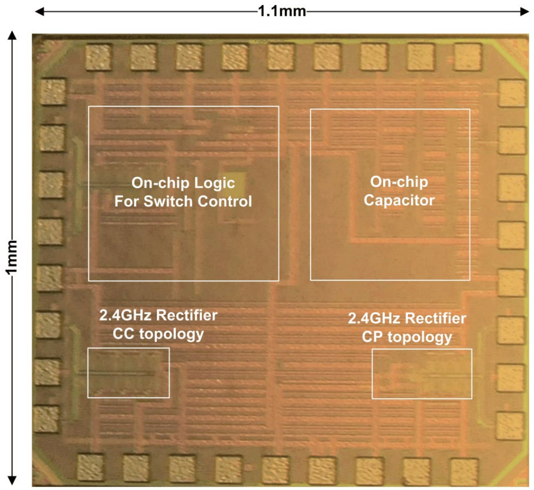
RF Energy Harvesting State-of-the-Art



[K. R. Sadagopan, ISSCC 2018]



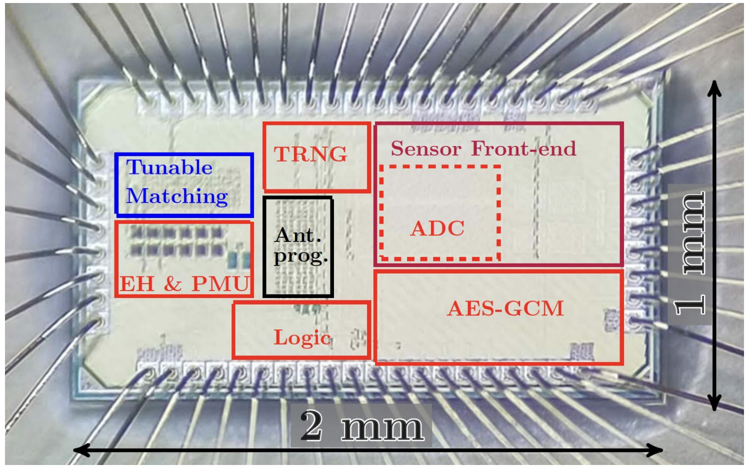
[J. Kang, RFIC 2015]



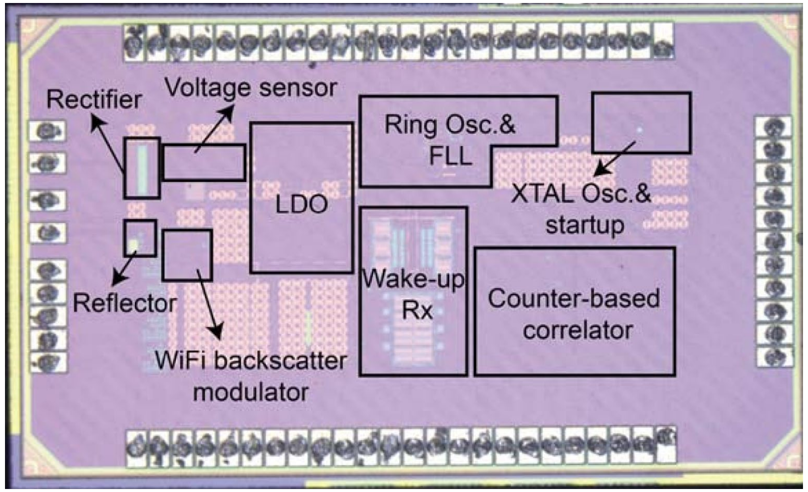
[J. Kang, T-MTT 2018]

- High sensitivity
  - Co-designed antenna – rectifier
  - Inductive boost converter
  - Negative gm-cell
- > 1cm^2 size
- Power-hungry communication

RF Energy Harvesting State-of-the-Art



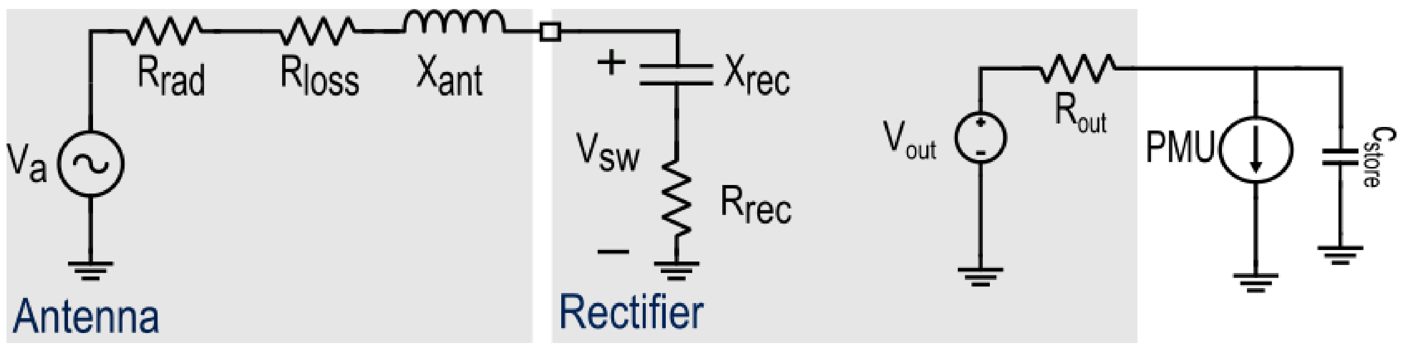
[M. R. Hamid, CICC 2022]



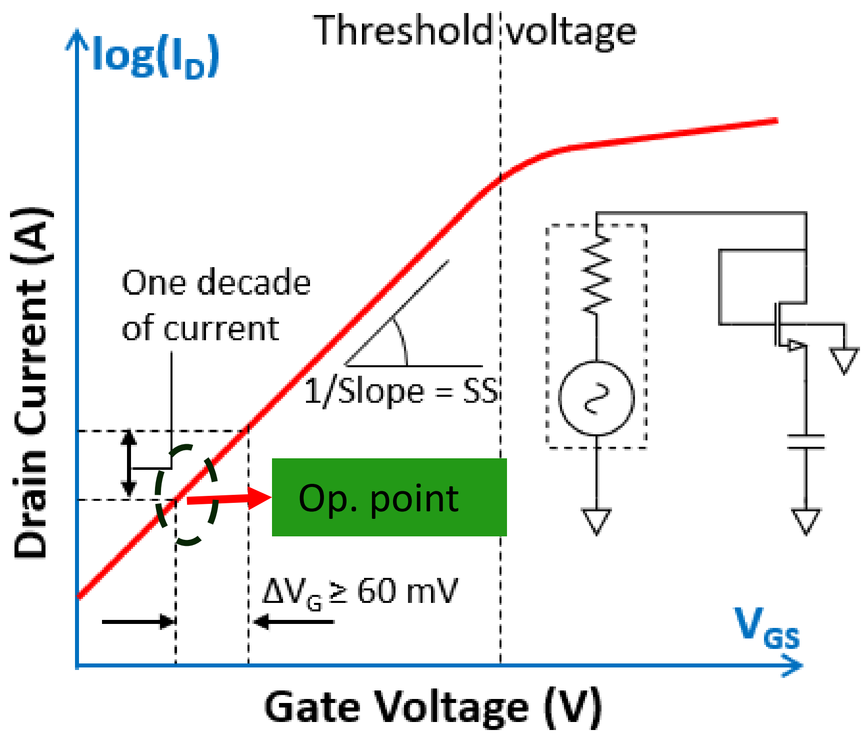
[Kuo, ISSCC 2023]

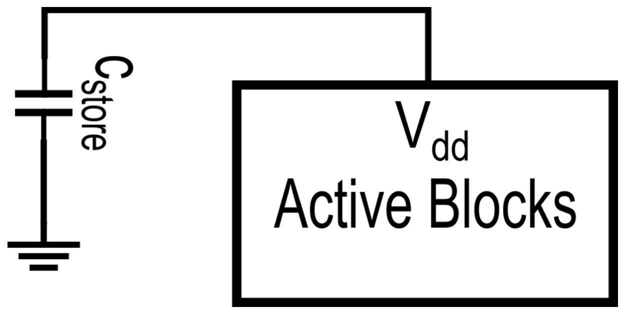
- Low sensitivity/ continuous mode operation
- Advanced data-processing, backscattering
  - Data conversion
  - Security
  - QPSK
- Long start-up time

Downlink and Uplink Limitations

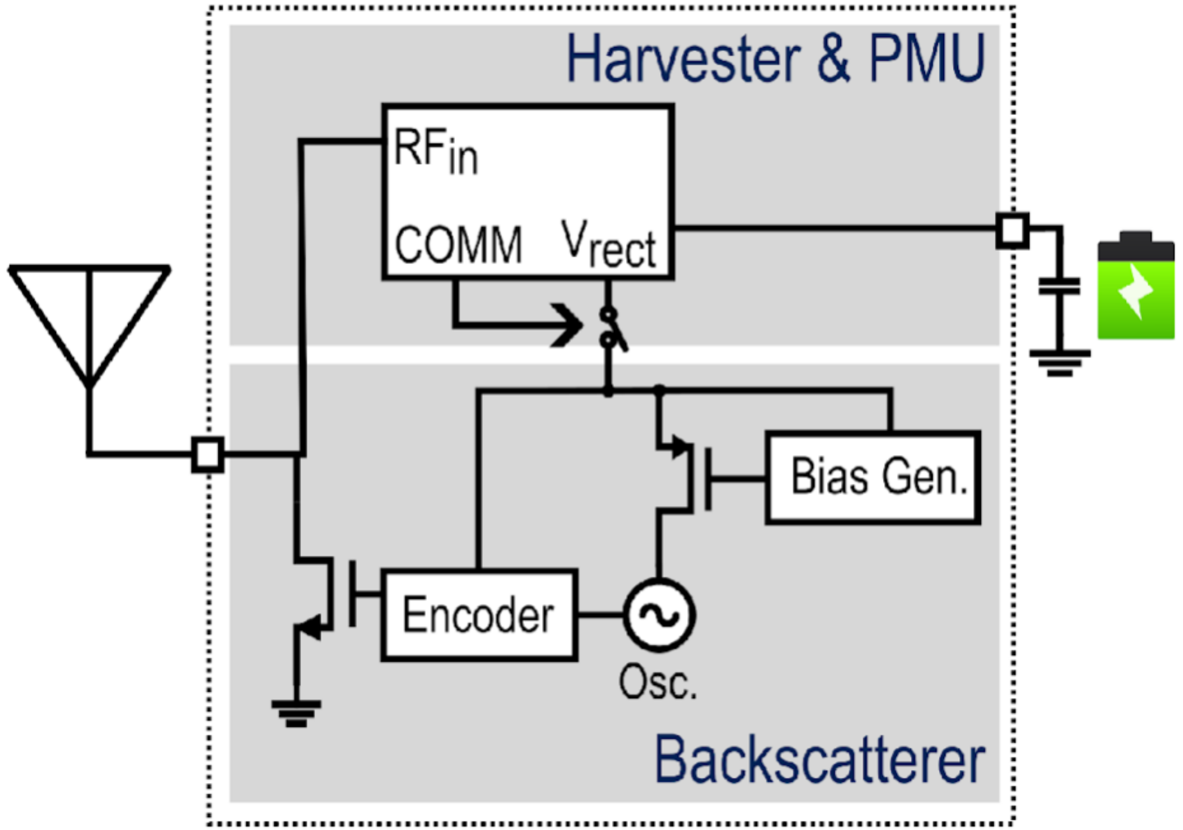


- Rectifier transistors @ deep subthreshold region
- Large R_{out} (10-100MΩ), limited power-conv. efficiency, long charging time of c_{store}
- Need ultra low-power (1-2nW) PMU
- <1min start-up time = minimalistic backscattering





This Work



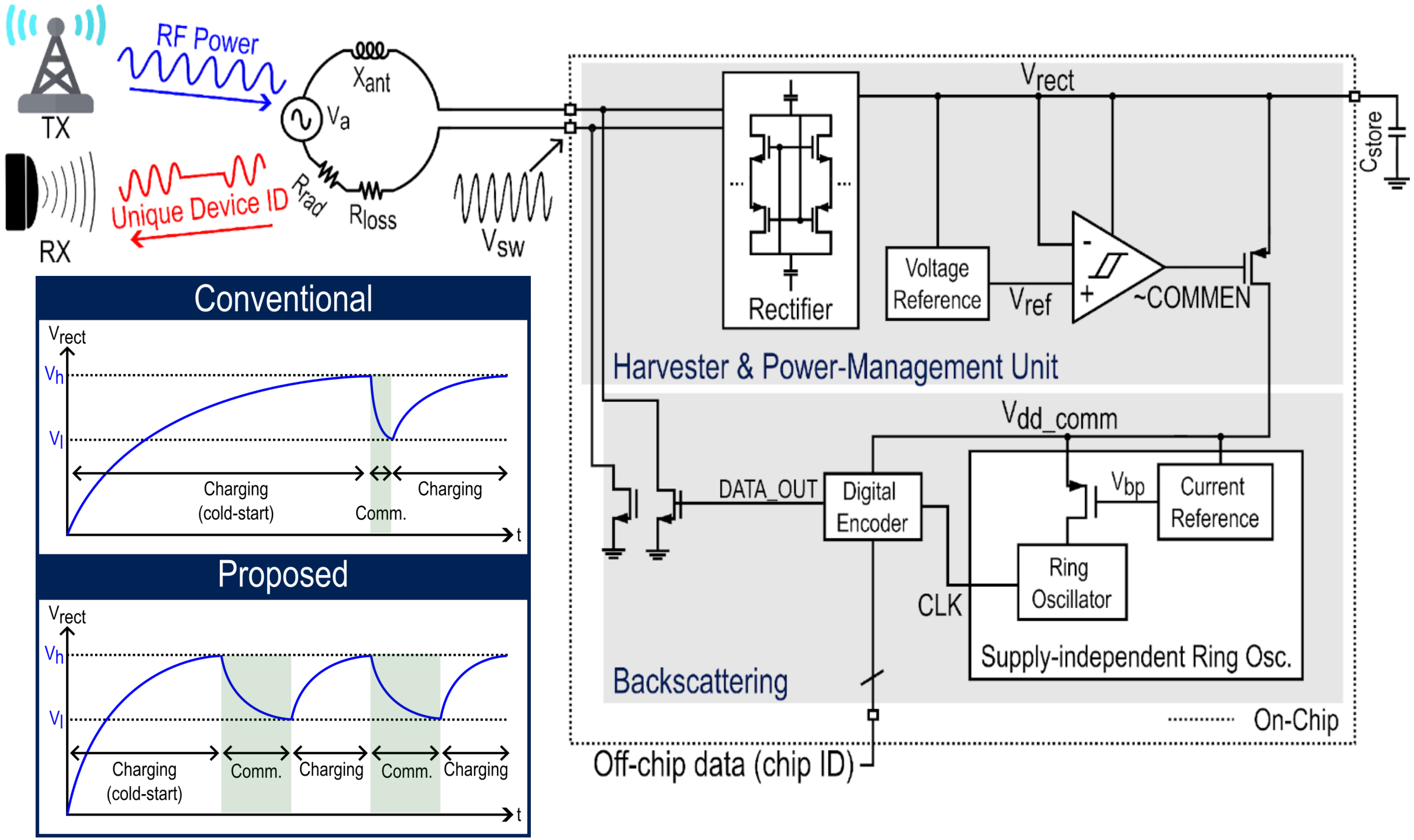
Key Features

- Battery-free
- 3.5GHz operation
  - -31dBm sensitivity
  - 0.7 cm^2 area
- 20sec cold-start time
  - 0.12 μW backscattering power
- Frequency synchronized with receiver through self-clocking

Outline

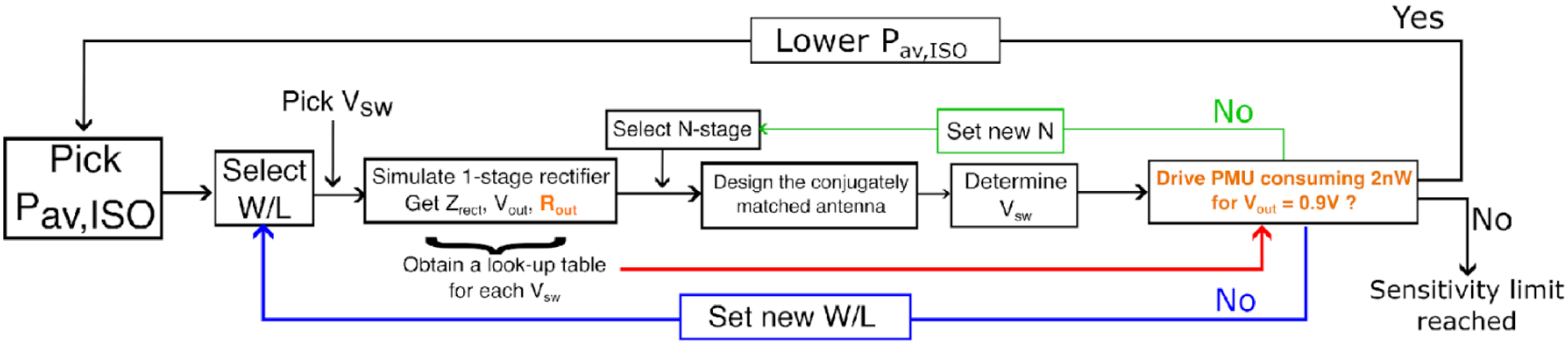
- Motivation and Prior Work
- **Compact Battery-free Backscattering Chip**
  - System architecture
  - Antenna-rectifier co-design
  - On-chip clock generation
  - Data encoding, backscattering
- Measurement Results
- Conclusion

System Architecture



- Power Management
  - Voltage reference & hysteresis comparator
- Communication
  - Power-on-reset
  - Current-starved ring oscillator
  - Encoder & backscattering

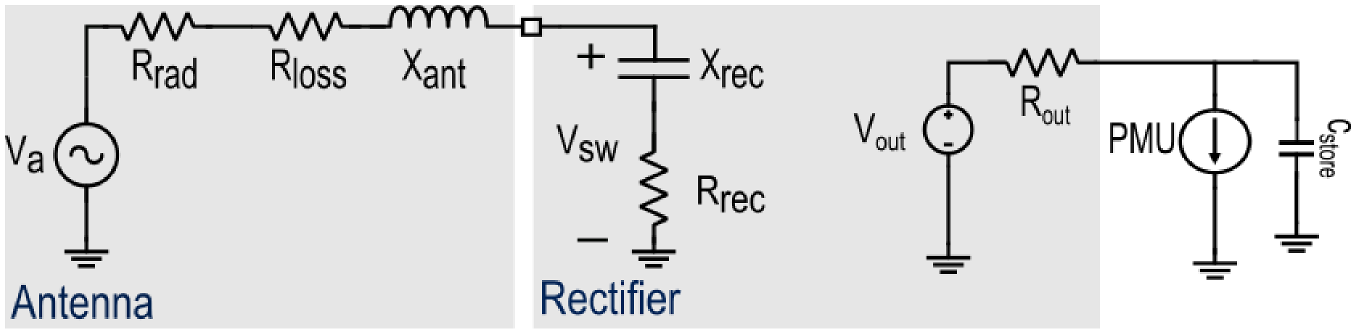
Antenna – Rectifier Co-design



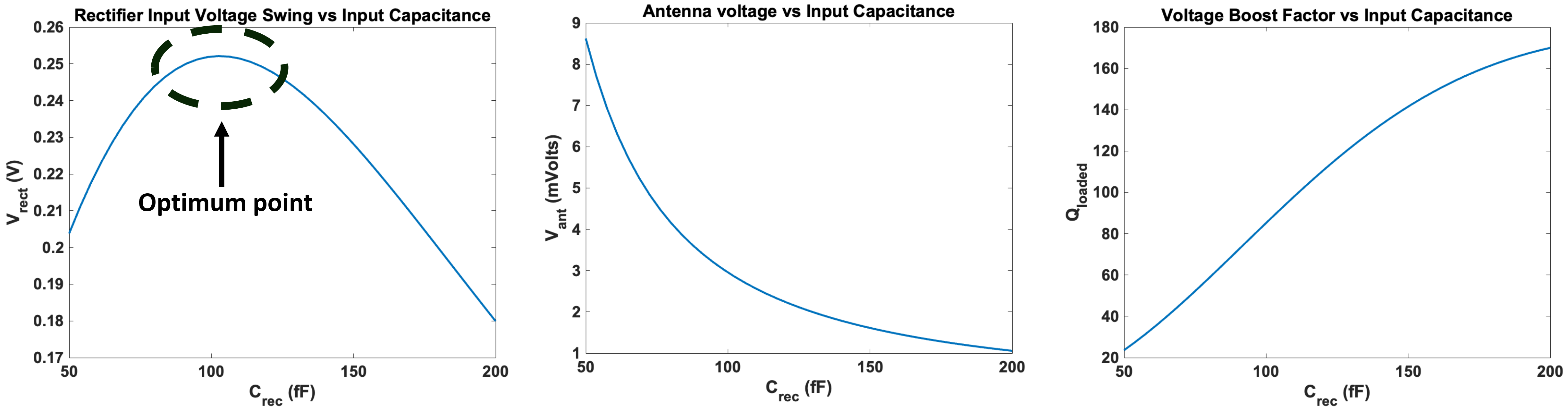
- Optimization metric:

$$V_{sw} = \sqrt{8 * R_{rad} * P_{av}} * \frac{X_{ant}}{R_{rad}+R_{loss}+R_{rec}}$$

- Particle-swarm searches the optimum number of stages, switch width

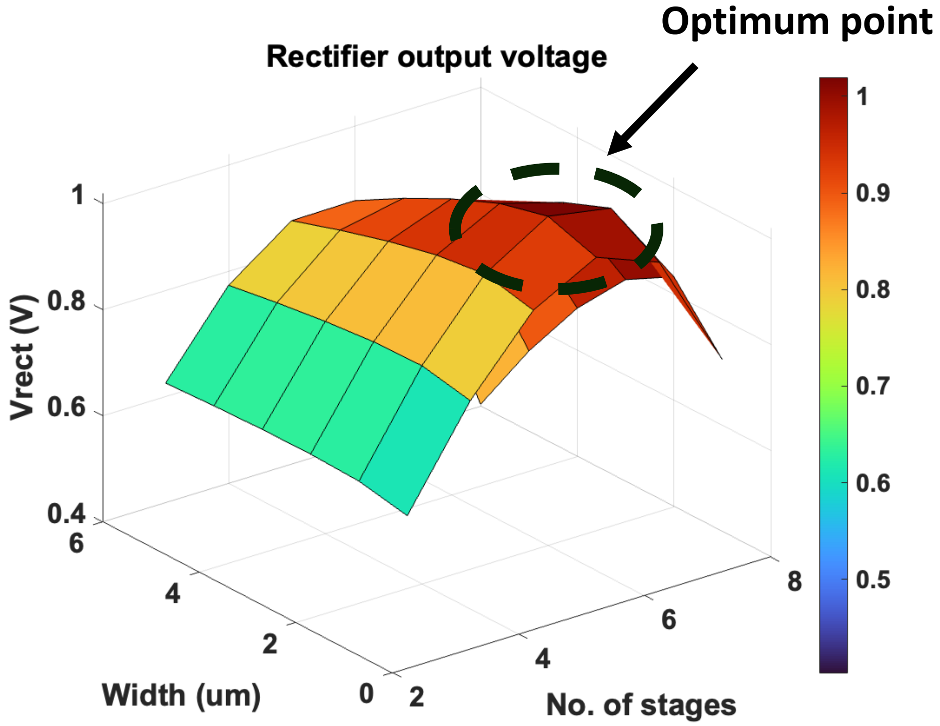


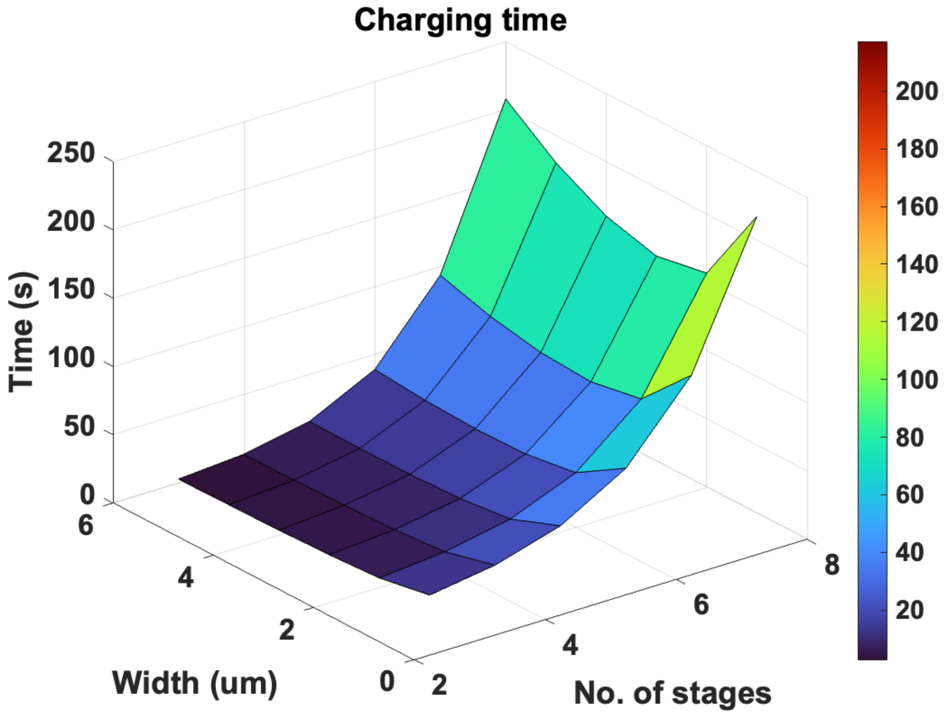
Antenna – Rectifier Co-design



- Small input capacitance (small W/L, few number of stages) necessitates a large antenna, quenches the voltage boost.
- Large input capacitance (large W/L, large number of stages) necessitates a small antenna, which is ineffective at capturing RF signals.

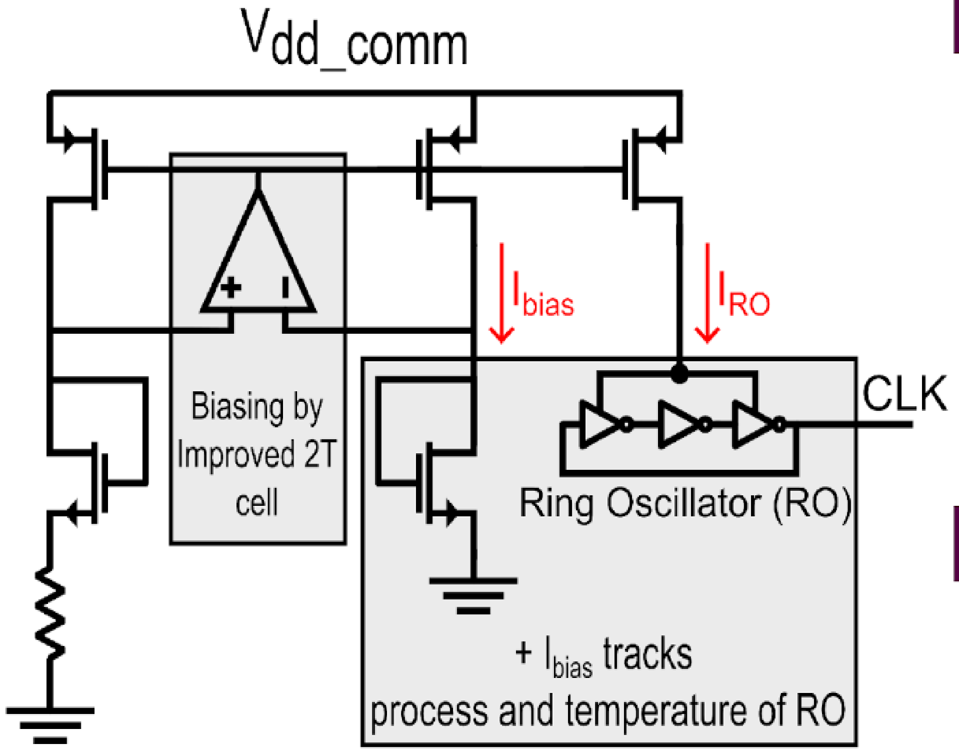
Antenna – Rectifier Co-design





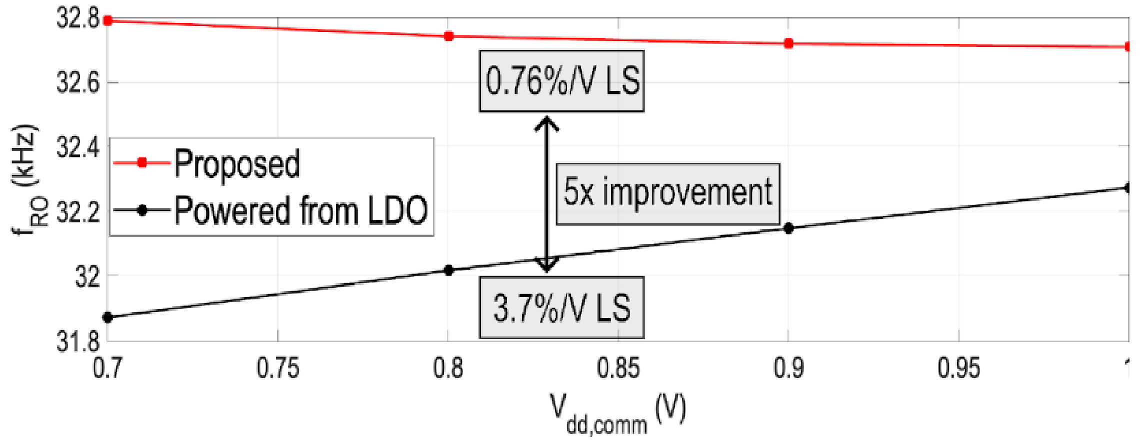
- Small input capacitance (small W/L, few number of stages) necessitates a large antenna, quenches the voltage boost, but charges fast
- Large input capacitance (large W/L, large number of stages) necessitate a small antenna, which is ineffective at capturing RF signals, plus charges slow

Supply - Independent Clock Generation

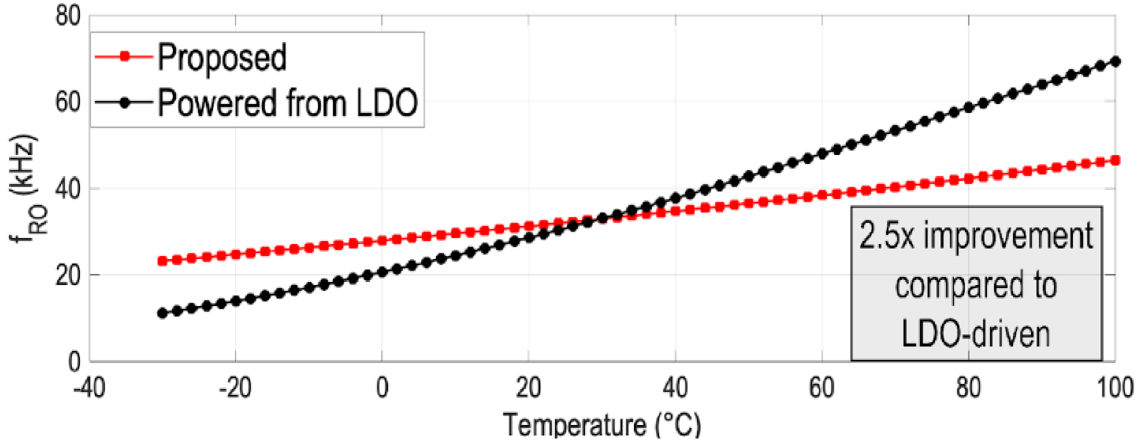


+ Lower - power solution
+ Reduced energy storage needed = faster charging
+ Better line-sensitivity, temp. insensitivity vs LDO-driven ring-osc.

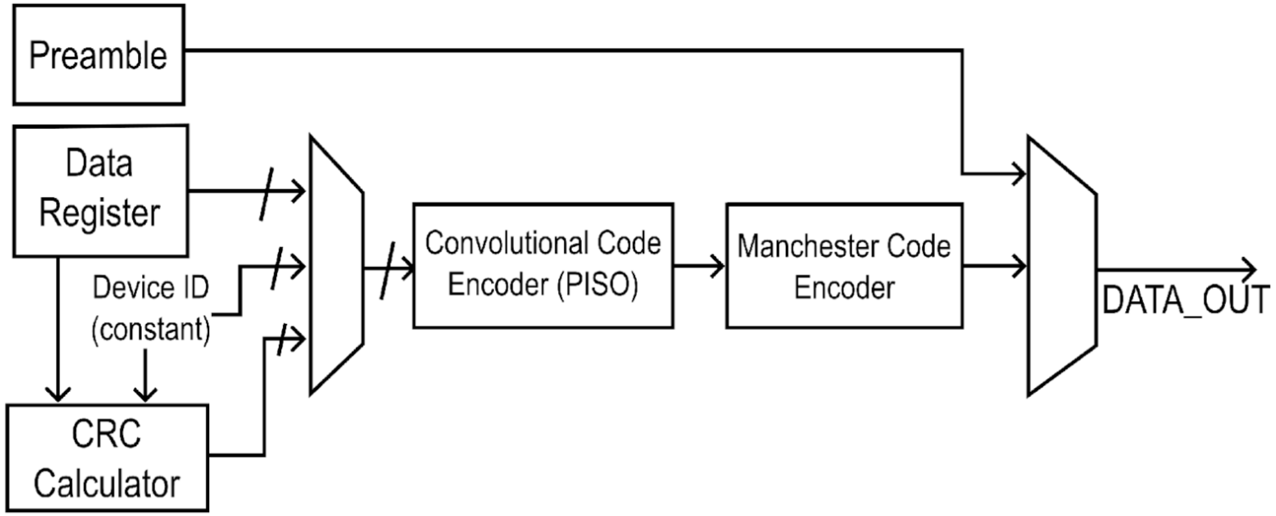
Simulation: Line-Sensitivity

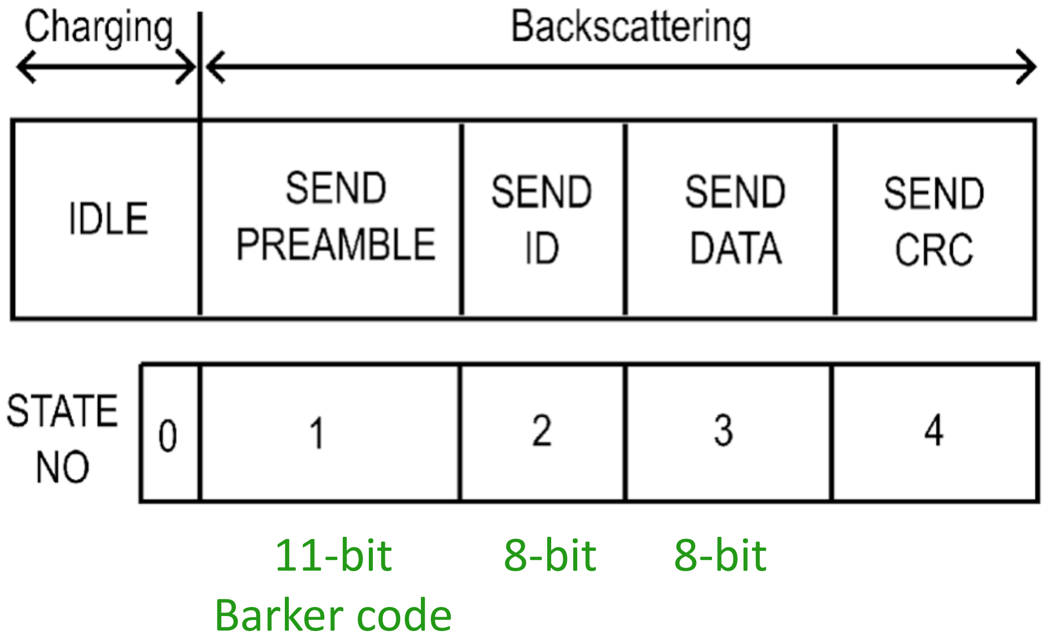


Simulation: Temperature Variation



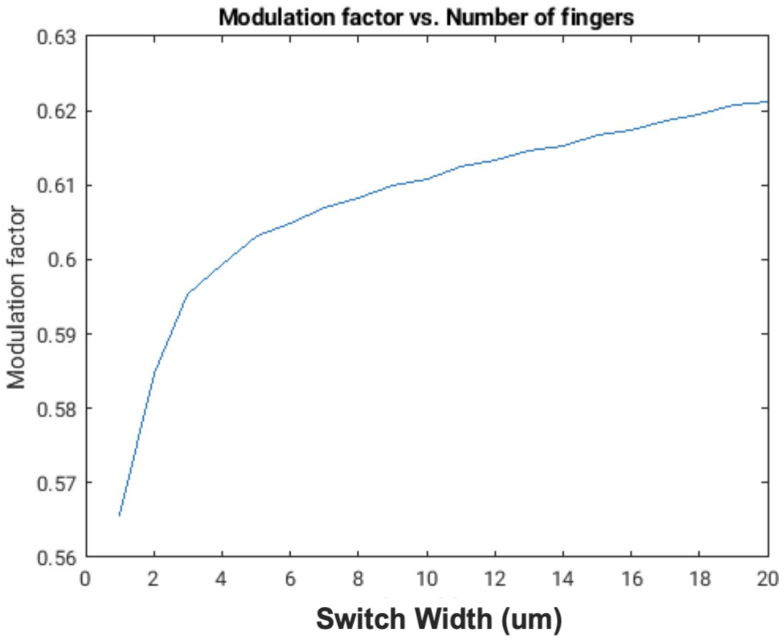
Data Transmission - Communication Protocol

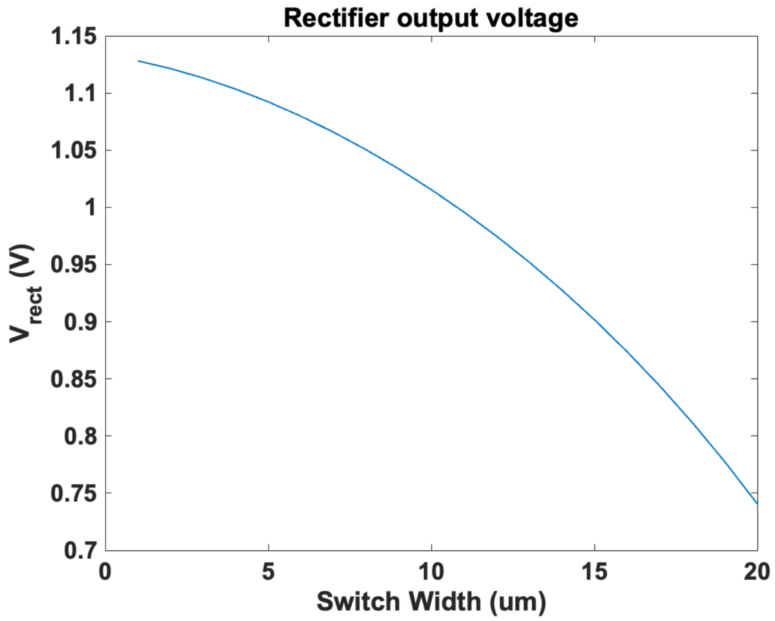


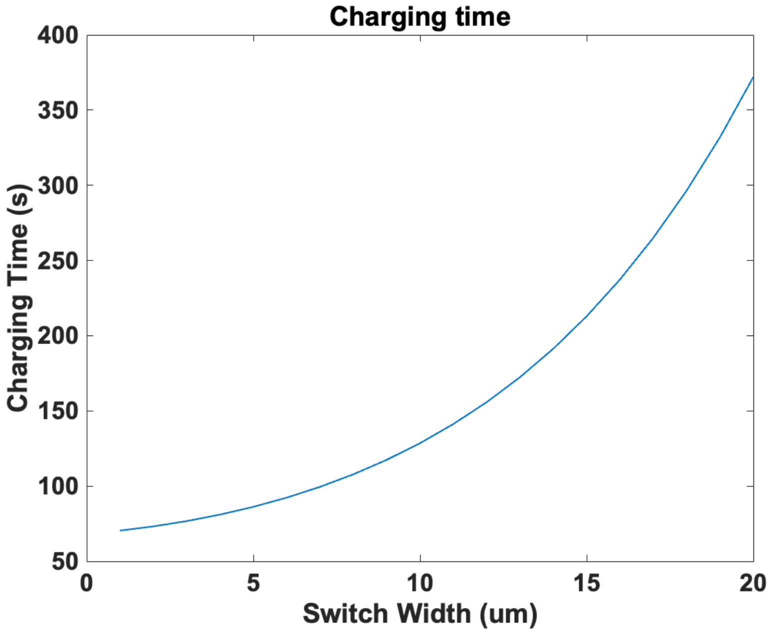


- ID, payload, and CRC are encoded with convolutional code and Manchester code
  - Convolutional code provides ~6dB gain over uncoded signal
  - Manchester code creates self-clocking signal, receiver can interpret without prior knowledge

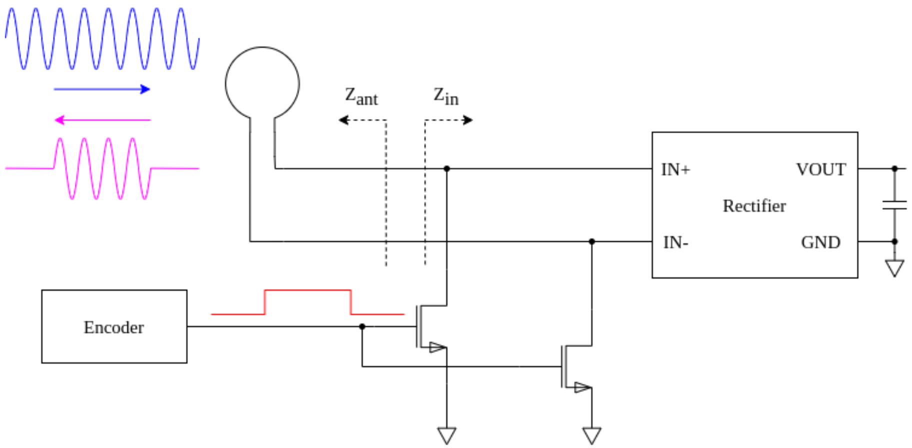
Backscattering - Sizing







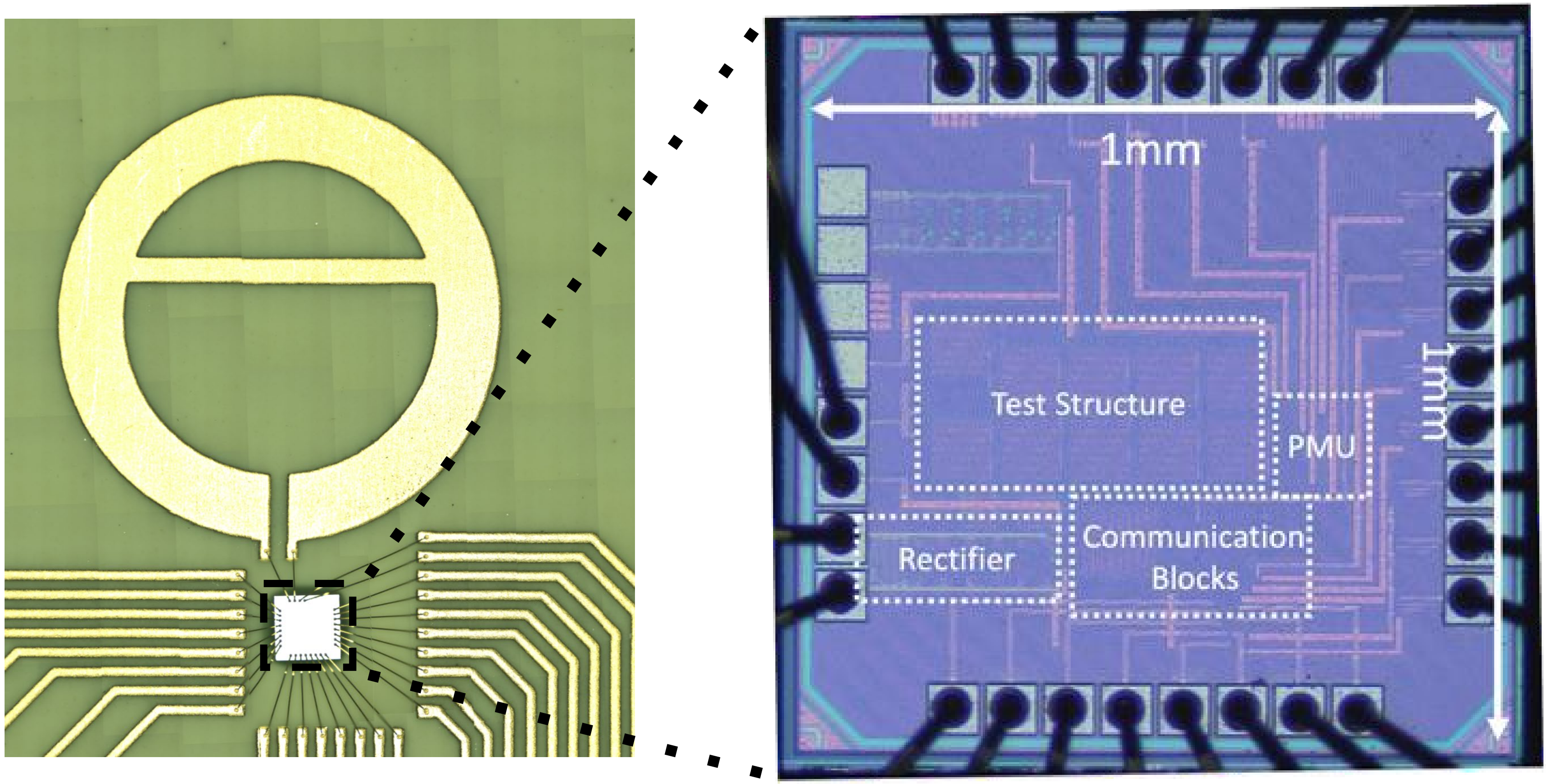
- Larger switch = Higher modulation factor, better uplink performance
- However, harvesting sensitivity suffers from parasitics



Outline

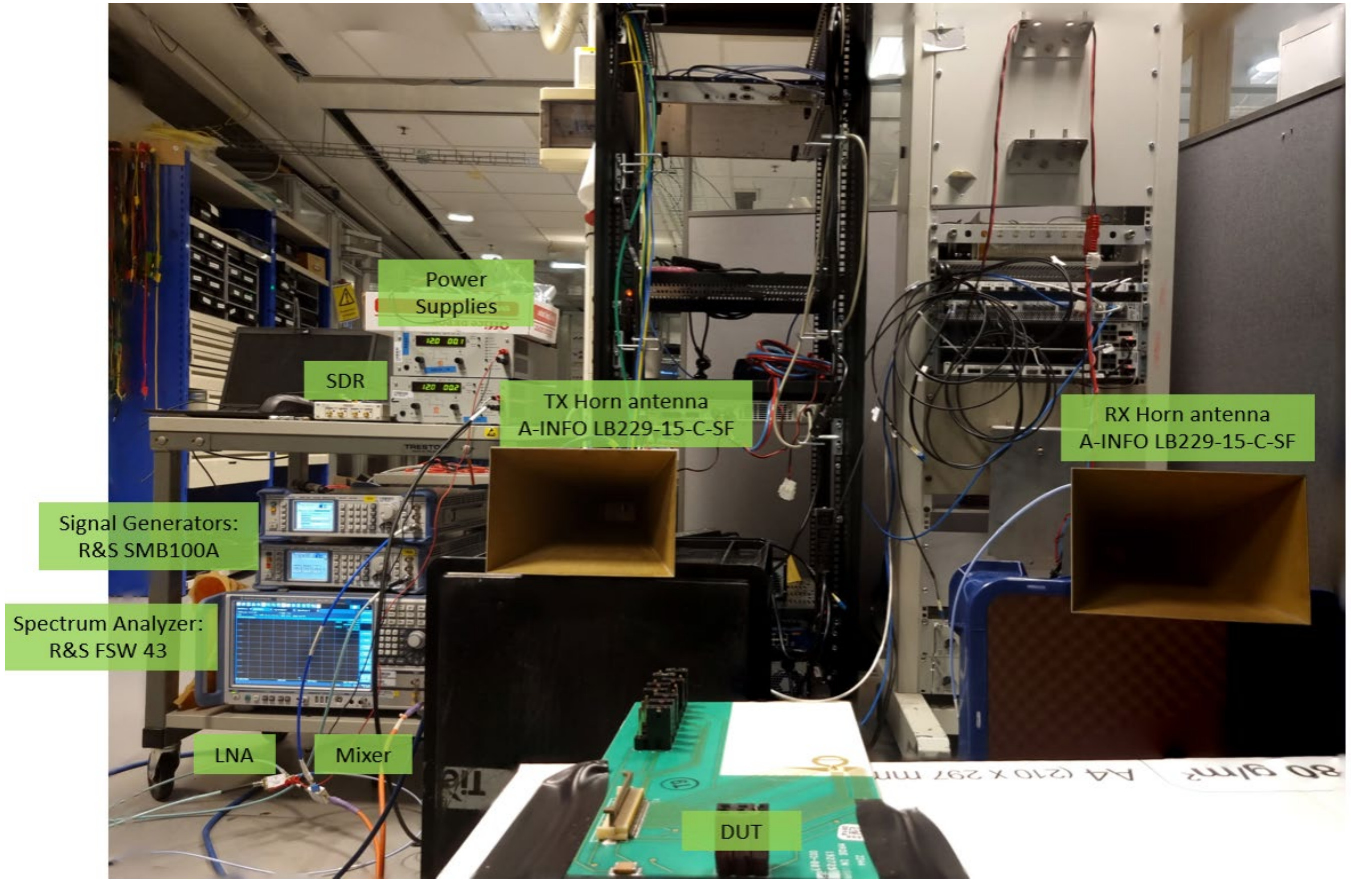
- Motivation and Prior Work
- Compact Battery-free Backscattering Chip
  - System architecture
  - Antenna-rectifier co-design
  - On-chip clock generation
  - Data encoding, backscattering
- **Measurement Results**
- Conclusion

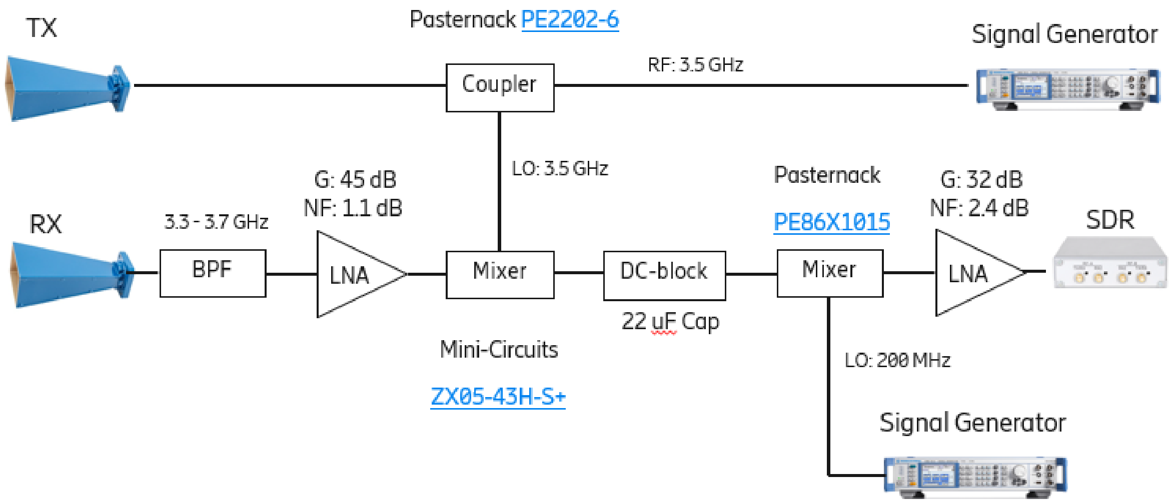
Antenna & Die Micrograph



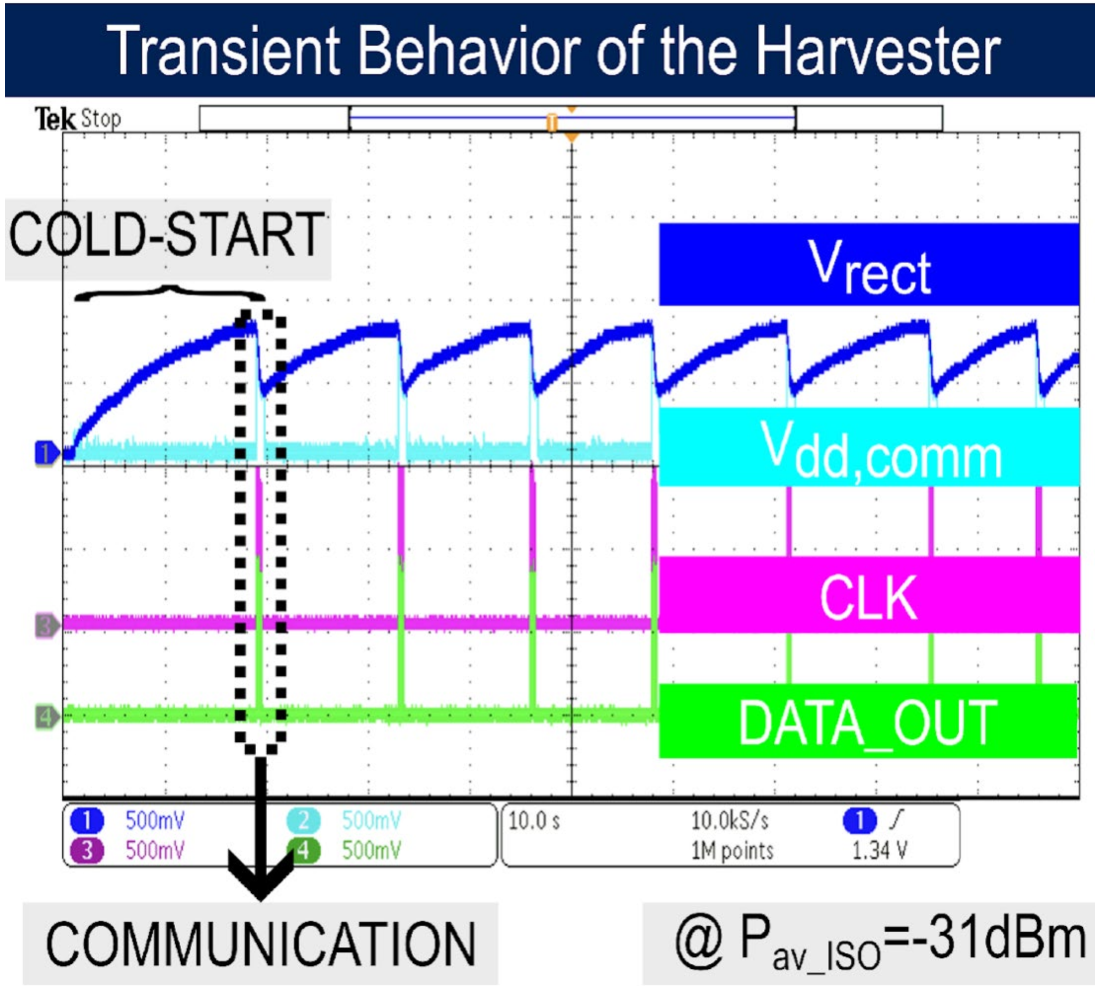
- Fabrication in 65nm CMOS technology
- Antenna area is the bottleneck

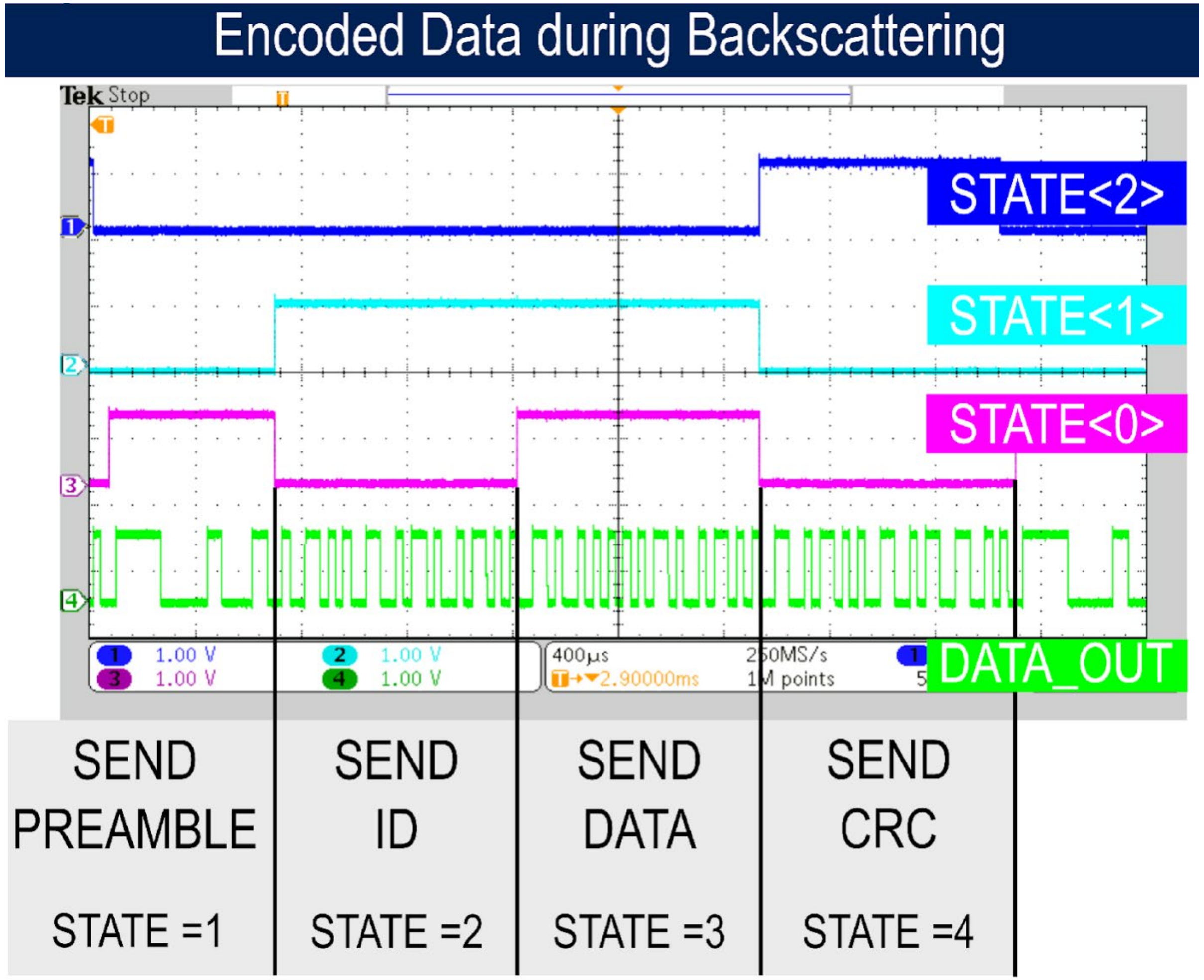
Measurement Setup





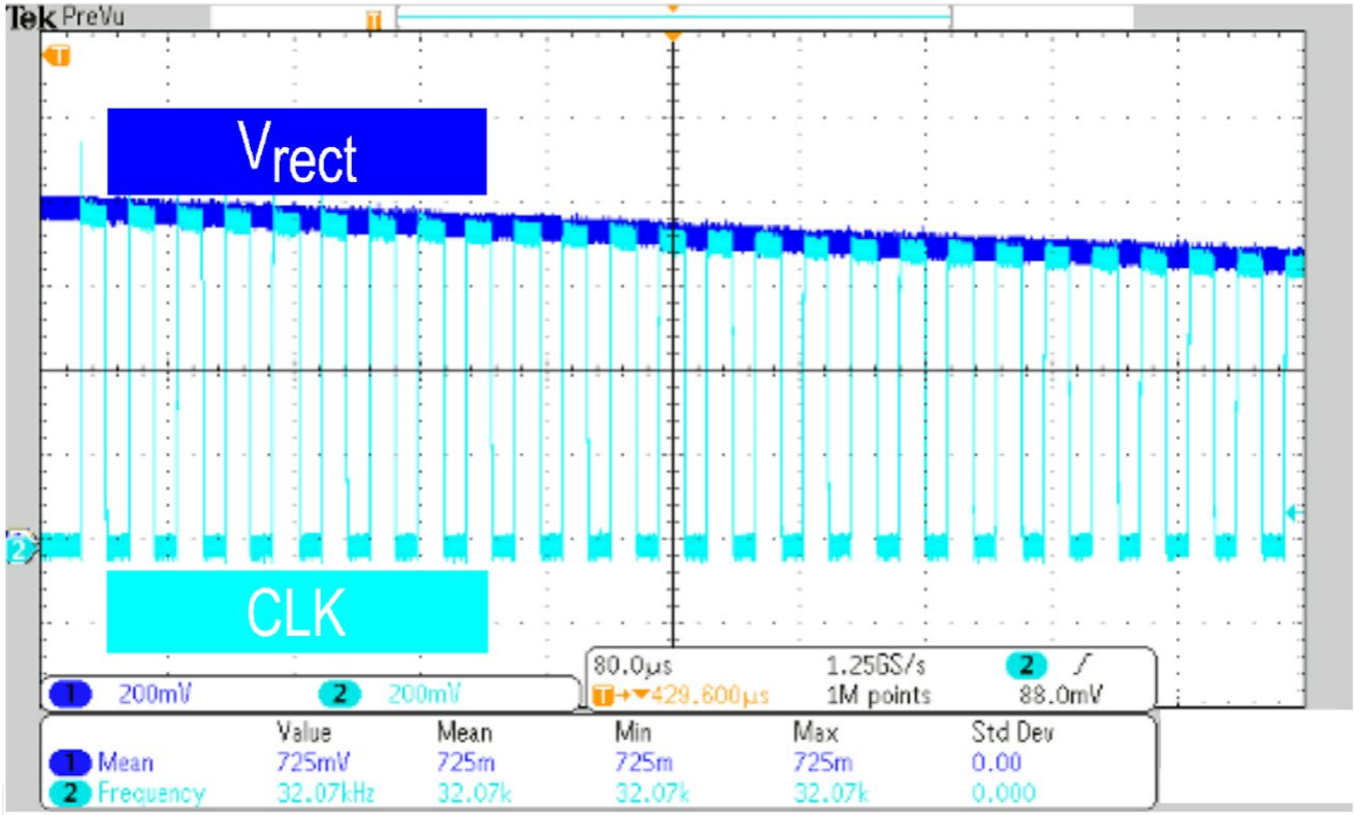
Measurement Results - Downlink



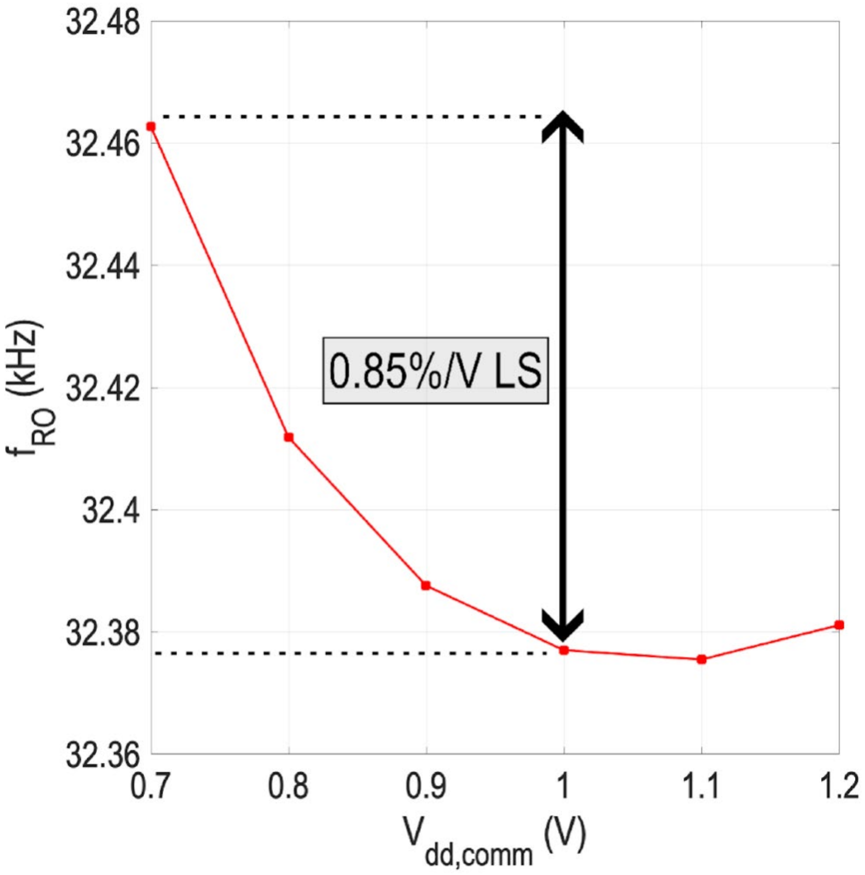


Measurement Results – Clock Generation

Clock Running on Discharging Cap

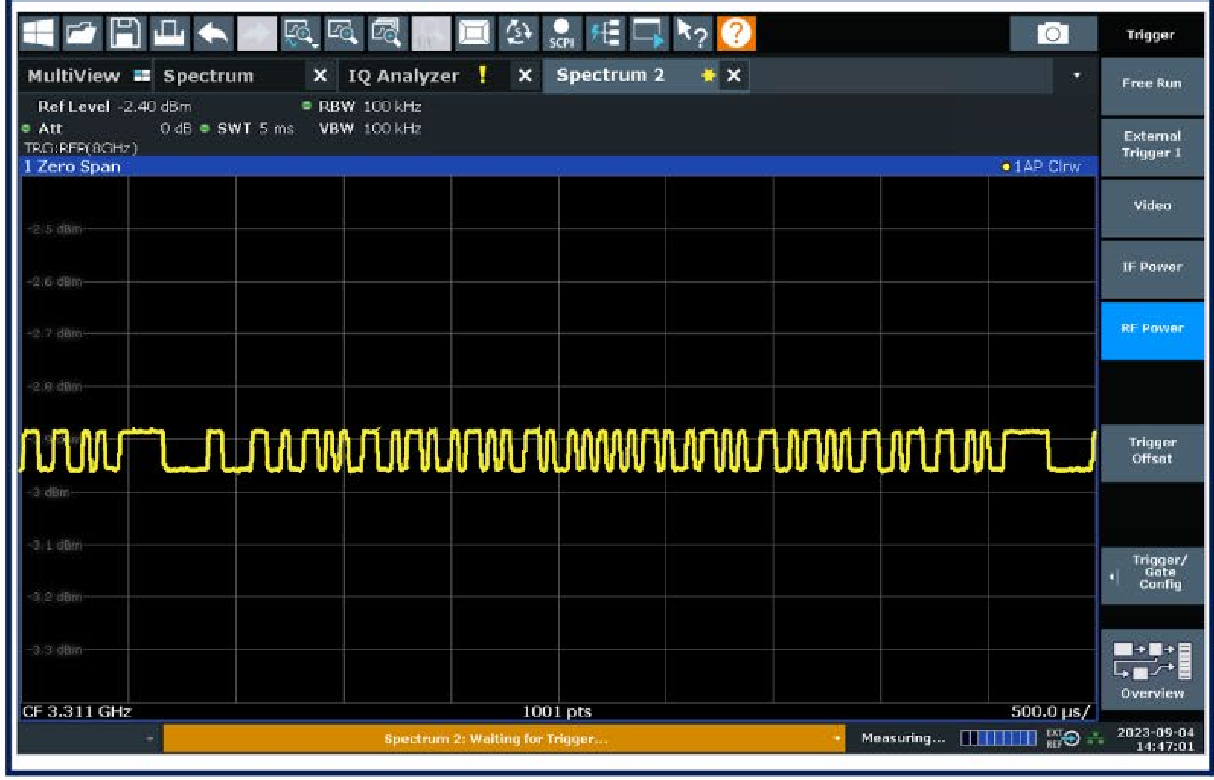


Measured Oscillator Line-Sensitivity

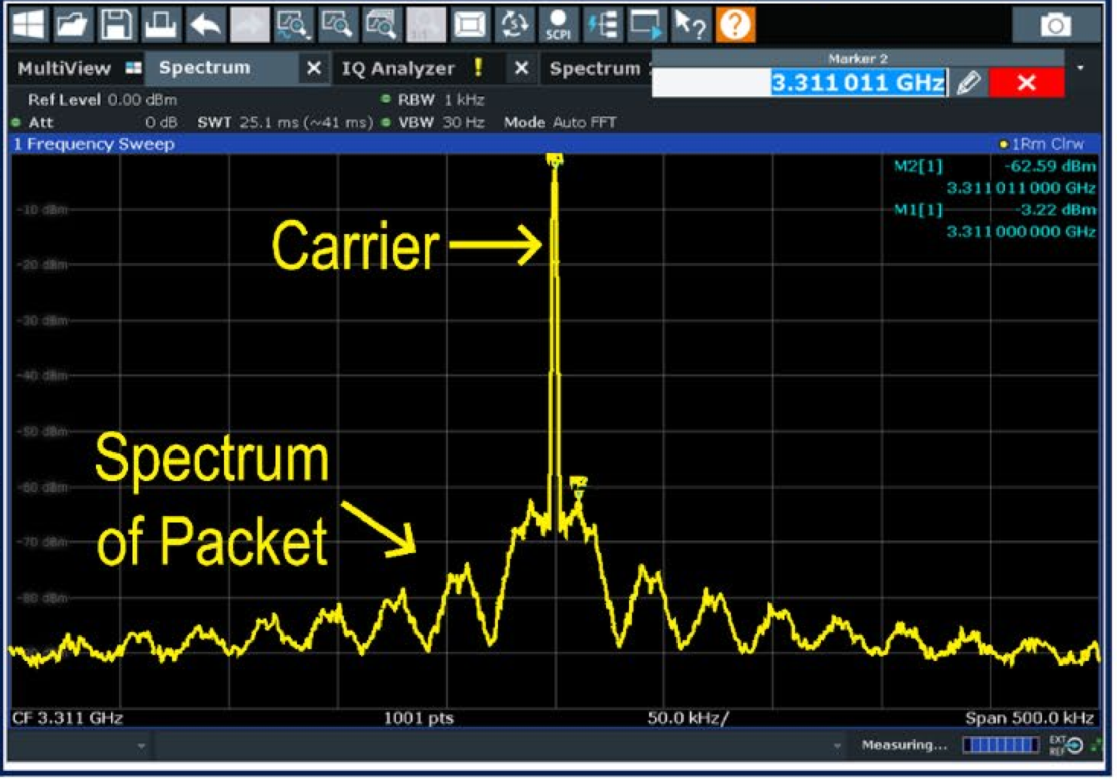


Measurement Results – Received Data

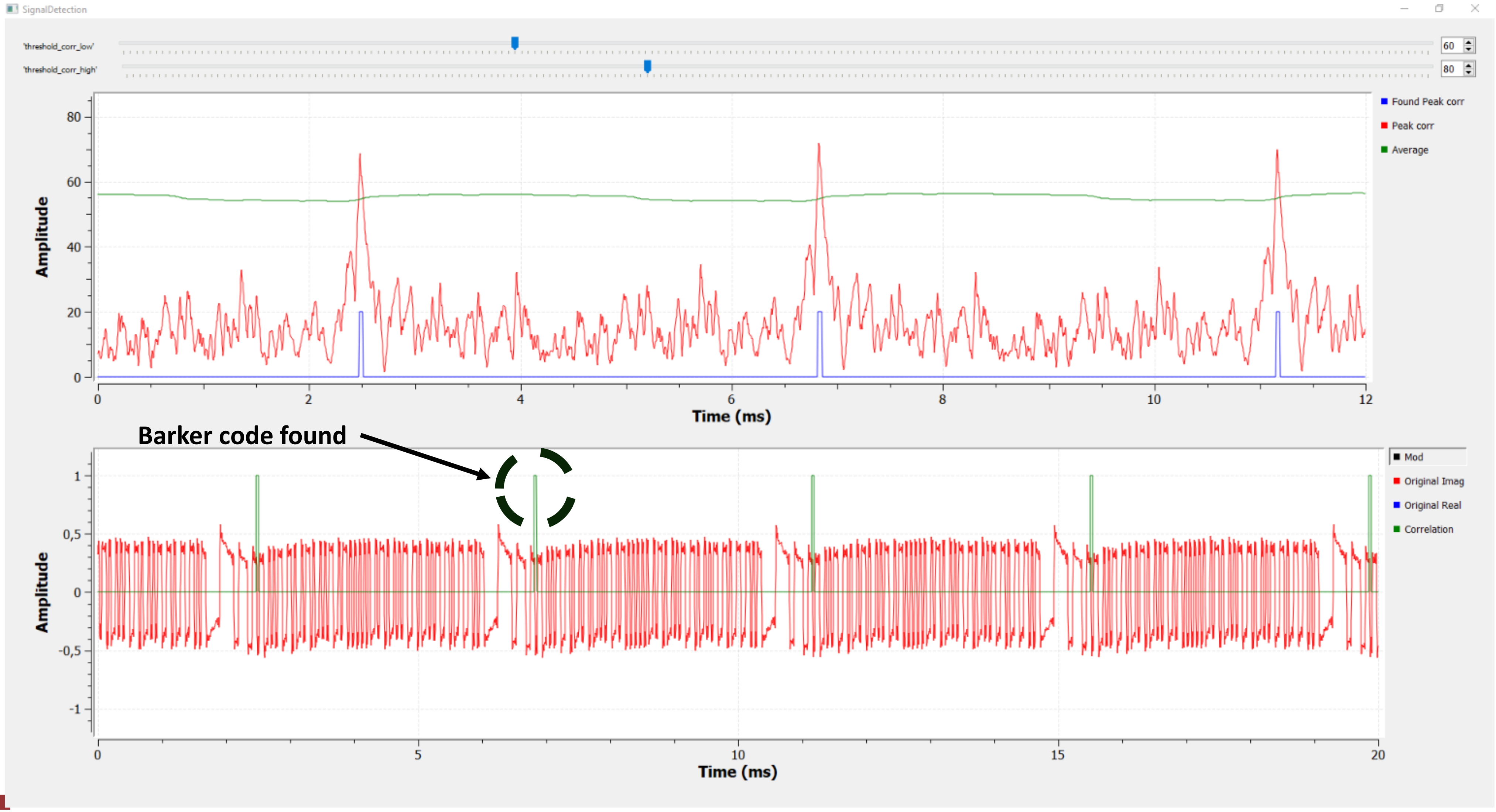
Measured packet @ RX - Transient



Measured packet @ RX - Spectrum



Barker Code Detection



Comparison to Prior Work

References	This Work	ISSCC 18 [2]	ISSCC 16 [3]	JSSC 14 [4]	MobiCom 20 [5]	ISSCC 23 [6]
Process	65nm	65nm	65nm	90nm	65nm	65nm
Freq.	**3.5GHz**	2.4GHz	2.4GHz	868MHz	900MHz	900MHz
Antenna Area (cm^2)	**0.7**	1.27	1.21	12	18.4	Commercial
Sensitivity (dBm) or Wake-up power	-31	-36	-34.5	-27	Not reported	4.5μW
V_{rect} (V), R_{load}/P_{load} at sensitivity	0.9 @1nW	1, ∞ load	1.6, 1.8MΩ	1, ∞ load	N/A	N/A
Cold-start charging time	18sec @ -31dBm	250sec @ -33dBm	Not reported	9sec @ -32dBm	Not reported	1sec @ -17dBm
Communcation Scheme	OOK	N/A	N/A	N/A	OOK	QPSK SSB
Communication Bitrate	2.5kbps	N/A	N/A	N/A	600kbps – 6Mbps	2Mbps
Communication Power @ V_{dd}	**0.12μW @ 0.9V**	N/A	N/A	N/A	11μW @ 0.5V	25μW @ 0.5V

- On-par sensitivity with the state-of-the-art at higher frequency
- Ultra-lightweight communication circuits for faster start-up

Outline

- Motivation and Prior Work
- Compact Battery-free Backscattering Chip
  - System architecture
  - Antenna-rectifier co-design
  - On-chip clock generation
  - Data encoding, backscattering
- Measurement Results
- **Conclusion**

Conclusion & Future Work

- Compact battery-free backscattering chip @ CBRS band
  - 0.7 cm^2 battery-free 5G energy harvester chip at 3.5GHz, with -31dBm sensitivity and 120nW active power consumption
  - Ultra-low power PMU
  - Supply-independent oscillator + self-clocking signal for resilient data encoding
  - Meter-range communication demo is shown
- Future Improvements
  - Implement data conversion for sensors
  - Implement PUF for unique tag IDs
  - Antenna-rectifier dynamic tuning

Acknowledgements

- This work is supported by Ericsson Research
- The authors thank members of the Energy Efficient Circuits and Systems Group at MIT, and researchers at Ericsson Research for their valuable discussion and feedback.

- Please reach out to ydeniz@mit.edu with any questions or feedback!