A 6.1 nW Wake-Up Receiver Achieving −80.5 dBm Sensitivity via a Passive Pseudo-Balun Envelope Detector

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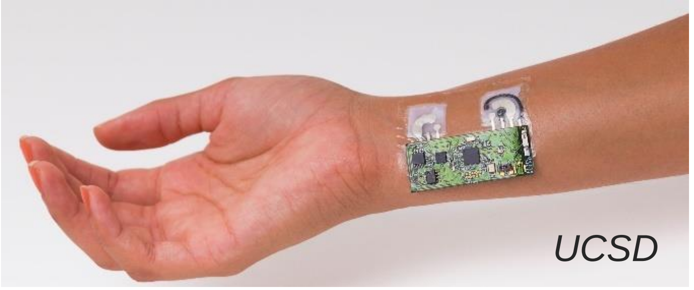
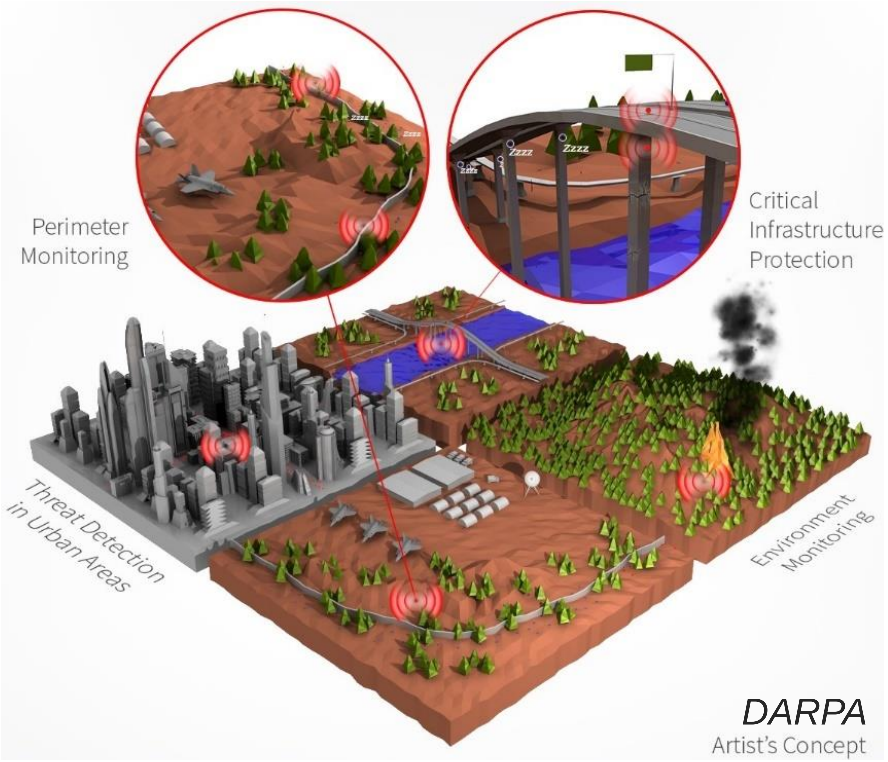
Motivation – Low-Power Wide-Area Networks (LPWAN)

Wearables/Medical



Unattended ground sensors



Smart Meters

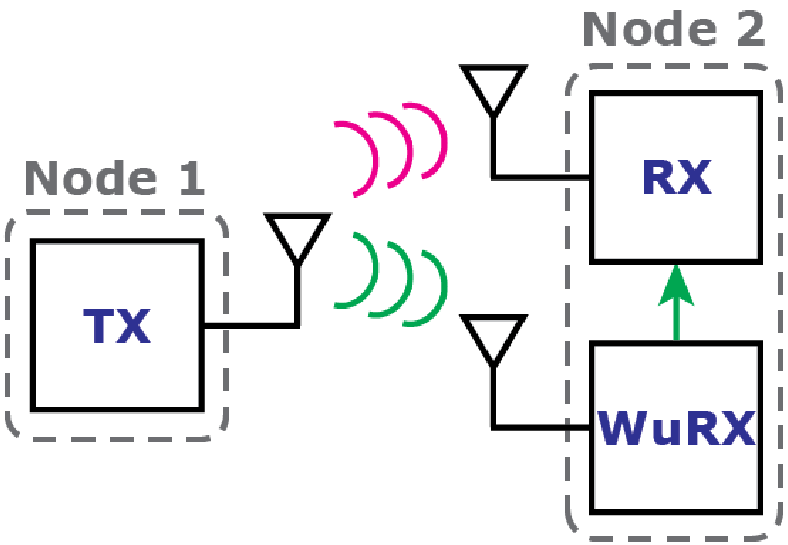
The age of Internet of Everything (IoE)

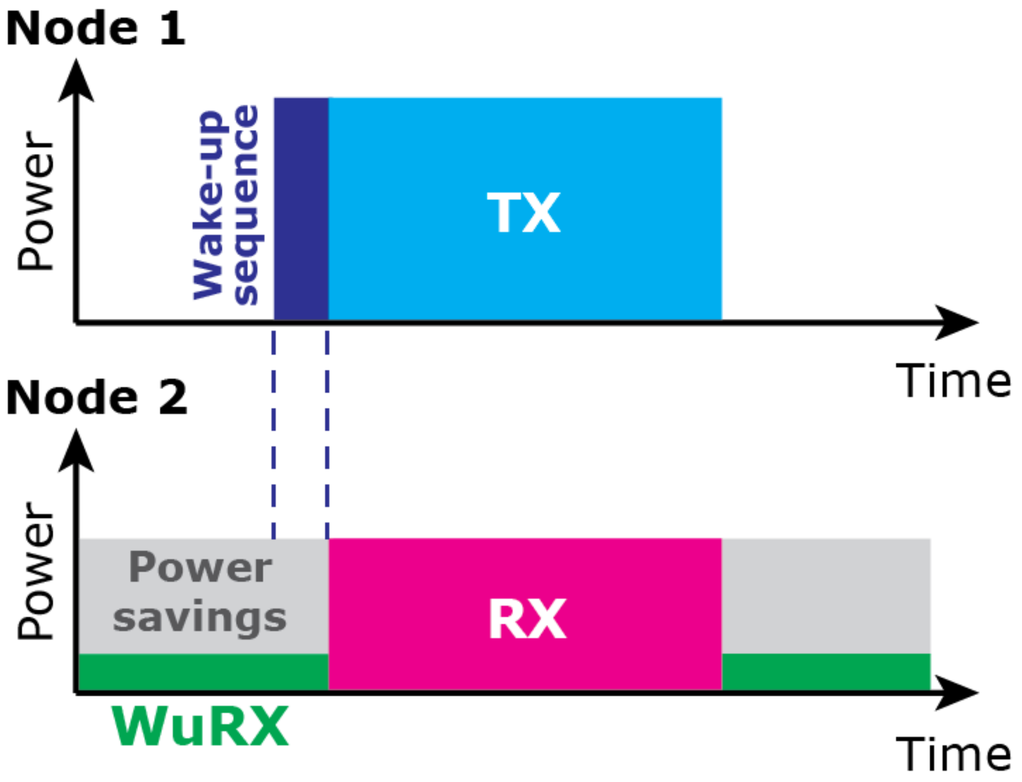
- 500 billion connected devices before 2030 [Cisco, 2014]

Event-driven applications focuses on lifetime and range

- Low power and high sensitivity are the main targets

Wake-up Receiver (WuRX)

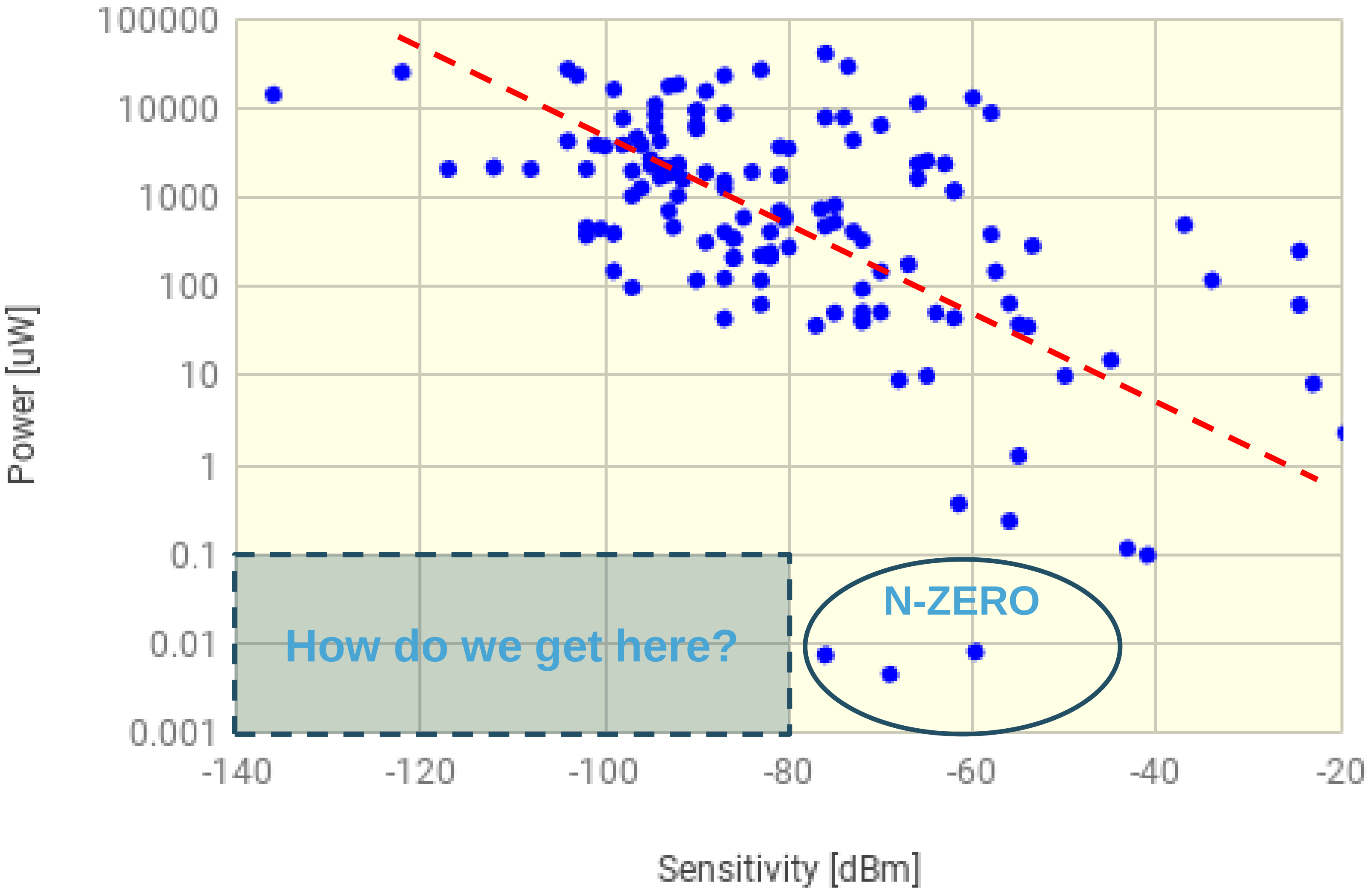




For infrequent event-driven networks:

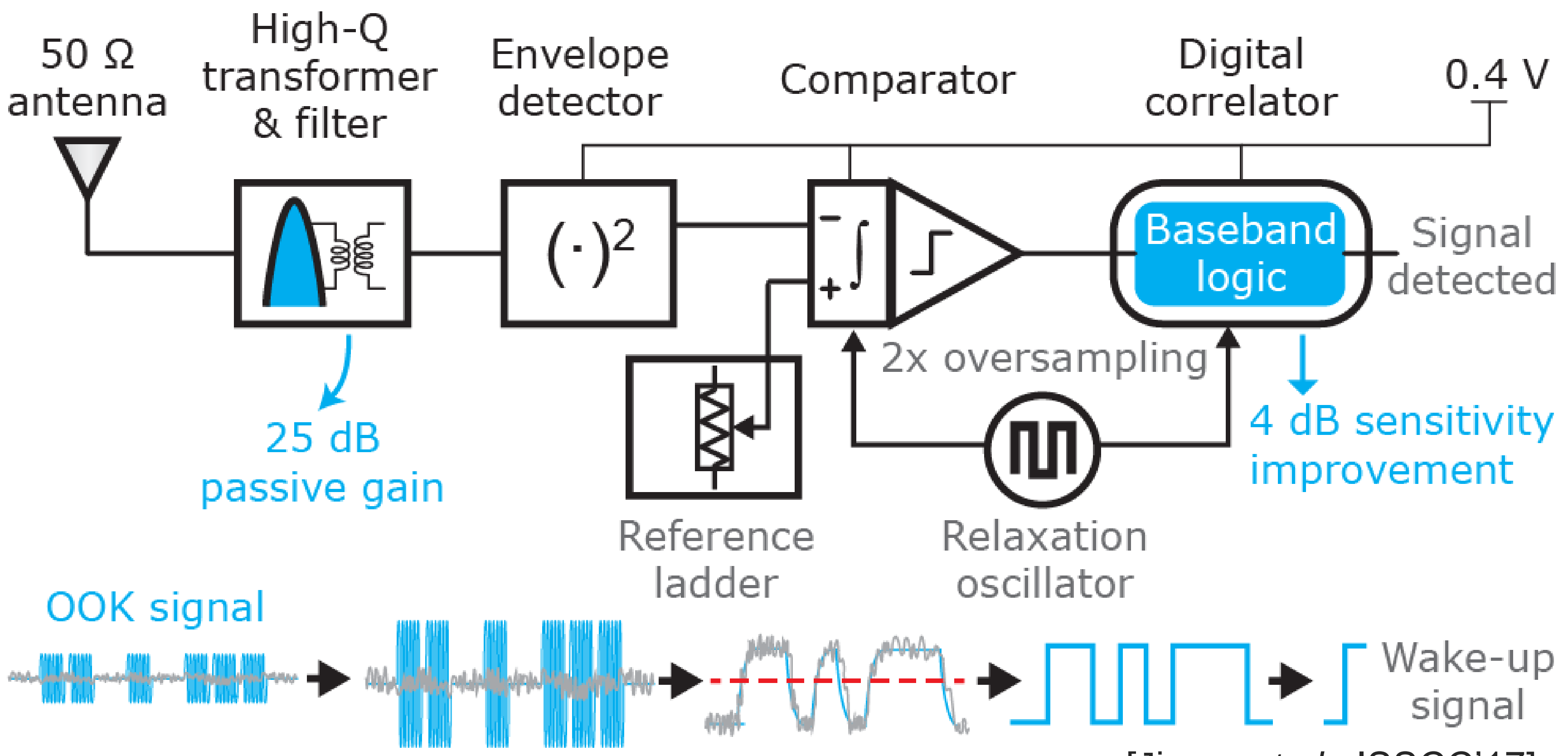
- Always-ON WuRX extends the system lifetime
- WuRX sensitivity should be comparable with the main RX

The Current State-of-the-Art



David D. Wentzloff, “Low Power Radio Survey,” [Online]. www.eecs.umich.edu/wics/low_power_radio_survey.html

Direct ED nW WuRX Architecture

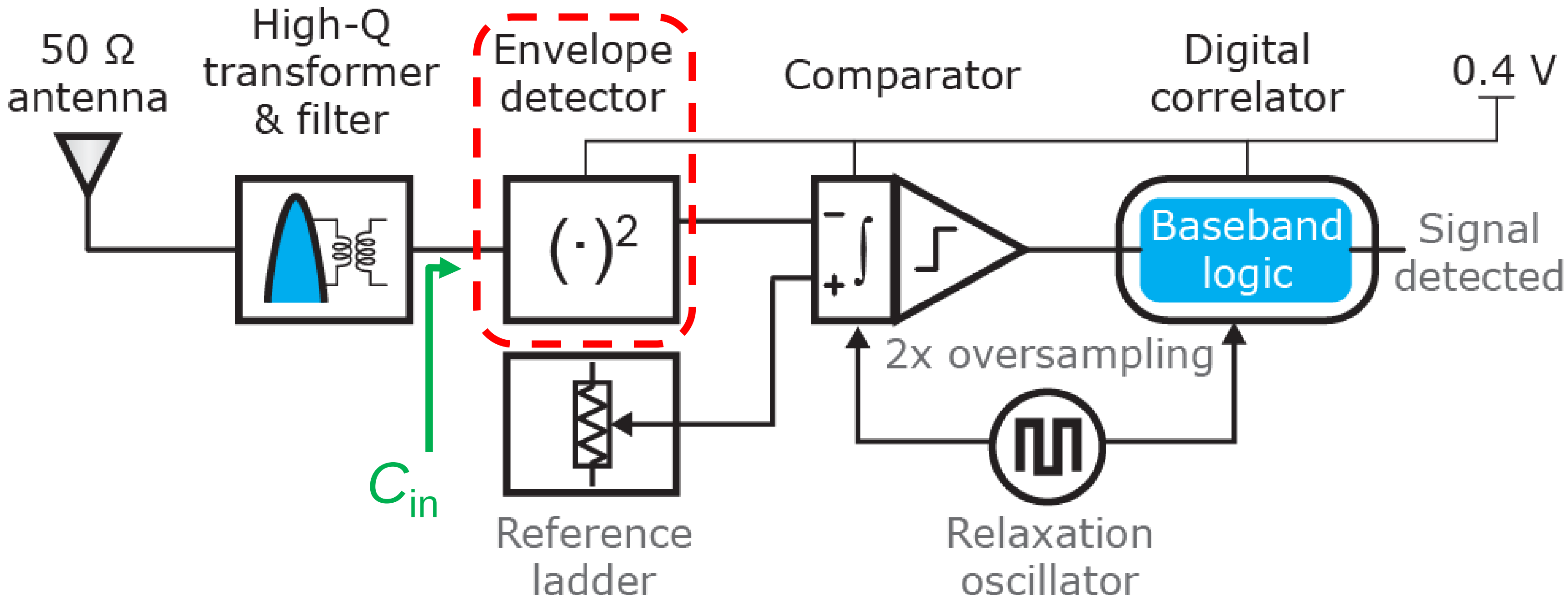


[Jiang, *et al.*, ISSCC'17]

The combination of passive RF gain and a Direct ED architecture enables nW level WuRXs

Haowei Jiang, Po-Han Peter Wang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M Rebeiz, Drew A Hall, and Patrick P Mercier, "A 4.5nW Wake-Up Radio with -69dBm Sensitivity," ISSCC, 2017.
Po-Han Peter Wang, Haowei Jiang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M. Rebeiz, Patrick P. Mercier, and Drew A. Hall, "A Near-Zero-Power Wake-up Receiver Achieving −69 dBm Sensitivity," JSSC, 2018.

Problem 1: High Input Capacitance ED



High C_{in} ED limits carrier frequency and passive gain

Haowei Jiang, Po-Han Peter Wang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M Rebeiz, Drew A Hall, and Patrick P Mercier, “A 4.5nW Wake-Up Radio with -69dBm Sensitivity,” ISSCC, 2017.
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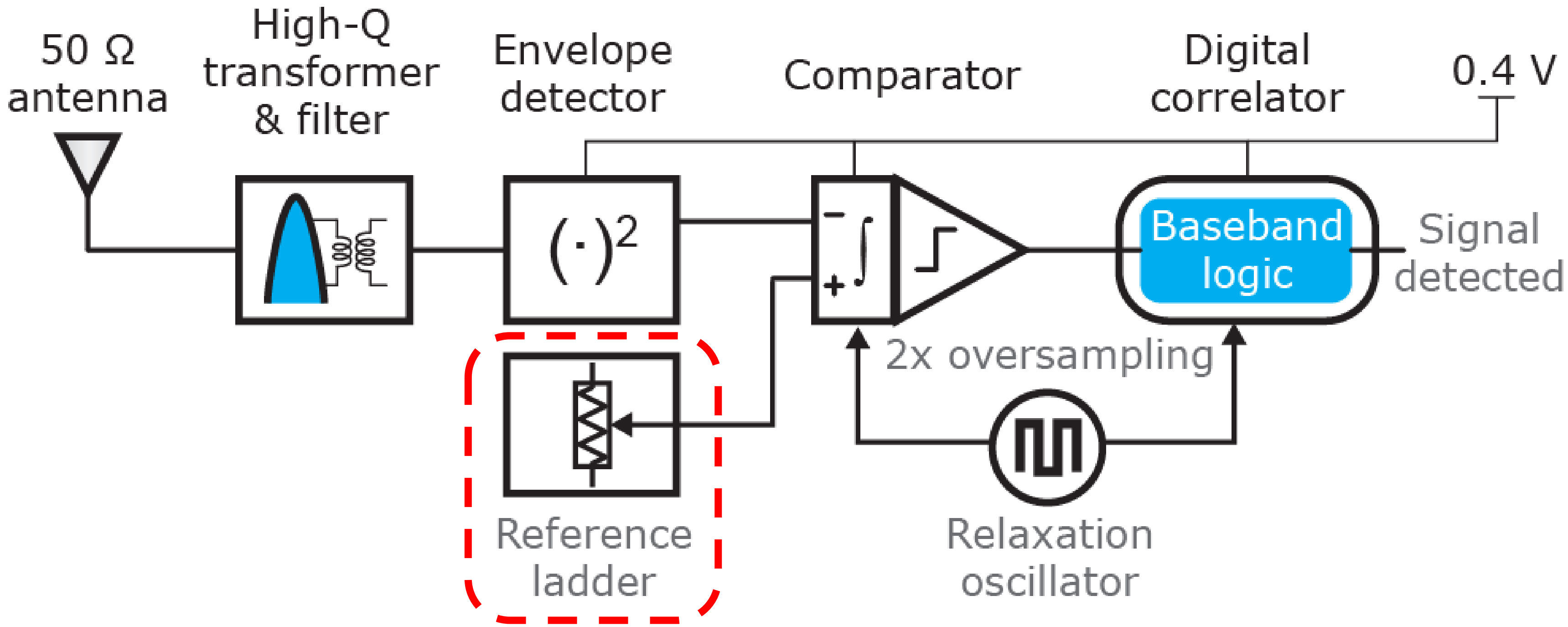
Problem 2: Single-ended Output ED



- Needs extra reference circuit for comparator
  - Extra tuning required for DC variation from PVT
  - Reference circuit is an additional noise source
- Could we eliminate the need for a reference circuit?

Haowei Jiang, Po-Han Peter Wang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M Rebeiz, Drew A Hall, and Patrick P Mercier, “A 4.5nW Wake-Up Radio with -69dBm Sensitivity,” ISSCC, 2017.
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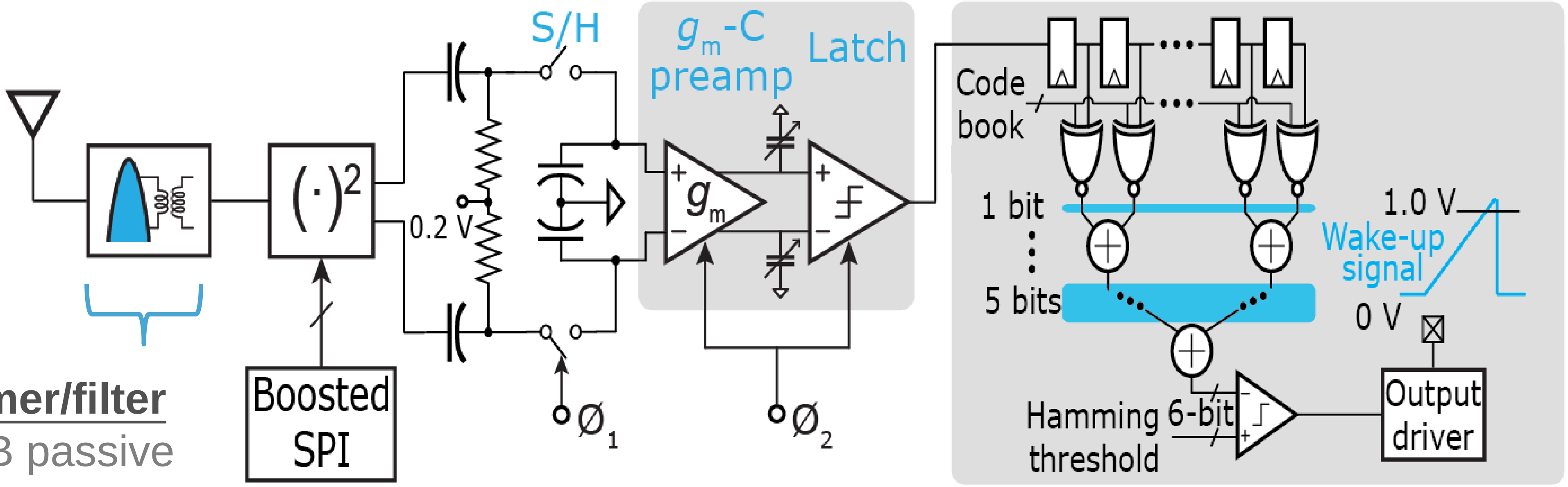
Proposed WuRX Architecture



Transformer/filter

- 30.6 dB passive gain @ 110 MHz

Active pseudo-balun ED

- Single-ended input to pseudo-differential output
- Boosted SPI for super cut-off switches

S/H stage and comparator

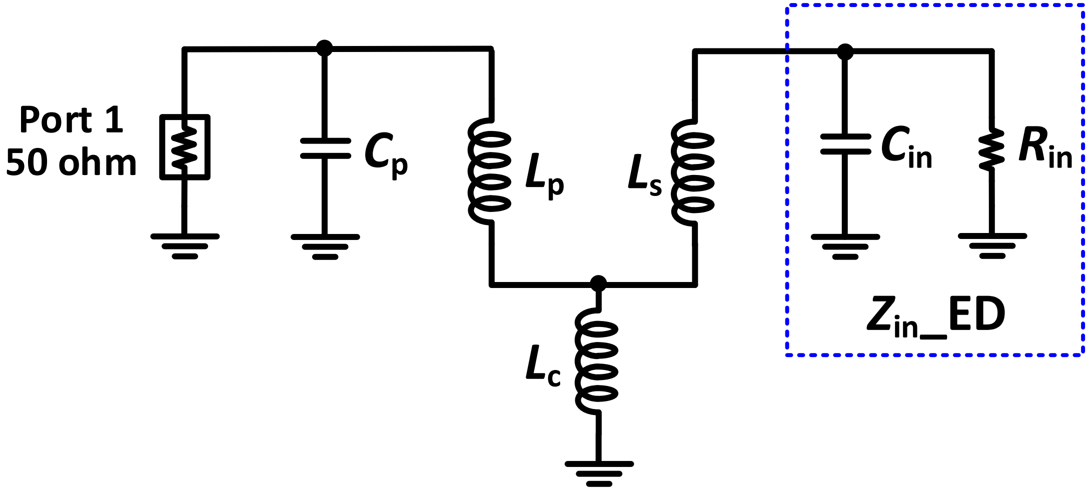
- S/H stage to handle asymmetric comparator kickback during ø2

Digital correlator

- 6× oversampling to overcome clock asynchronization and average low frequency noise
- 2.5 dB coding gain

Po-Han Wang, Haowei Jiang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M. Rebeiz, Patrick P. Mercier, and Drew A. Hall, “A 400 MHz 4.5 nW -63.8 dBm Sensitivity Wake-Up Receiver Employing an Active Pseudo-Balun Envelope Detector,” ESSCIRC, 2017.
Po-Han Wang, Haowei Jiang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M. Rebeiz, Patrick P. Mercier, and Drew A. Hall, “A 6.1 nW Wake-Up Receiver Achieving −80.5 dBm Sensitivity via a Passive Pseudo-Balun Envelope Detector,” SSCL, 2018.

110 MHz Transformer



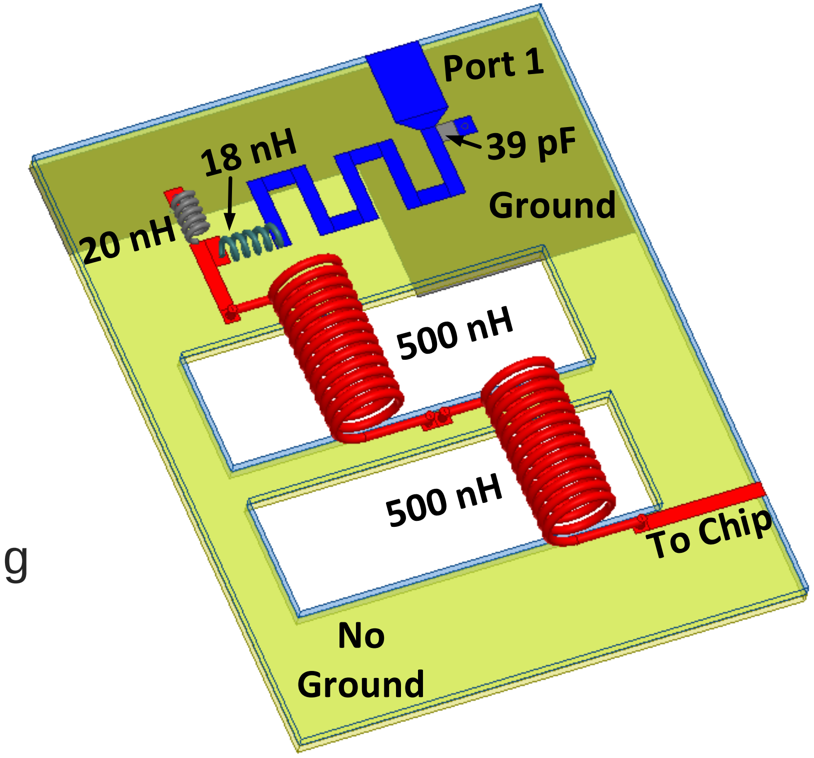
Transformer Structure

- Two stage LC to realize impedance transformation as well as filtering
- L_c is used to control the bandwidth and input matching

$$Gain_{\max} = \sqrt{R_L/R_S}$$

$$R_L = R_P || R_{in} = Q\omega L_S || R_{in}$$

- To achieve high gain, L_s and Q should be large
- To get large L_s, no additional cap is used in the secondary stage
- To get large Q, the inductor underneath the ground and substrate were removed

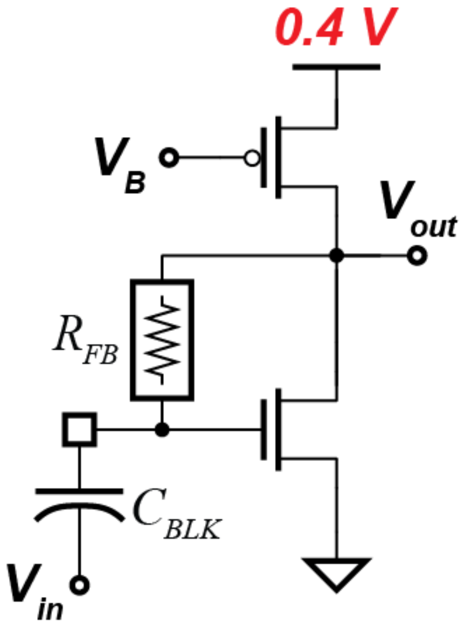


Transformer 3-D Model

Po-Han Wang, Haowei Jiang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M. Rebeiz, Patrick P. Mercier, and Drew A. Hall, "A 6.1 nW Wake-Up Receiver Achieving −80.5 dBm Sensitivity via a Passive Pseudo-Balun Envelope Detector," SSCL, 2018.

Active vs. Passive ED (w/ the same BW)

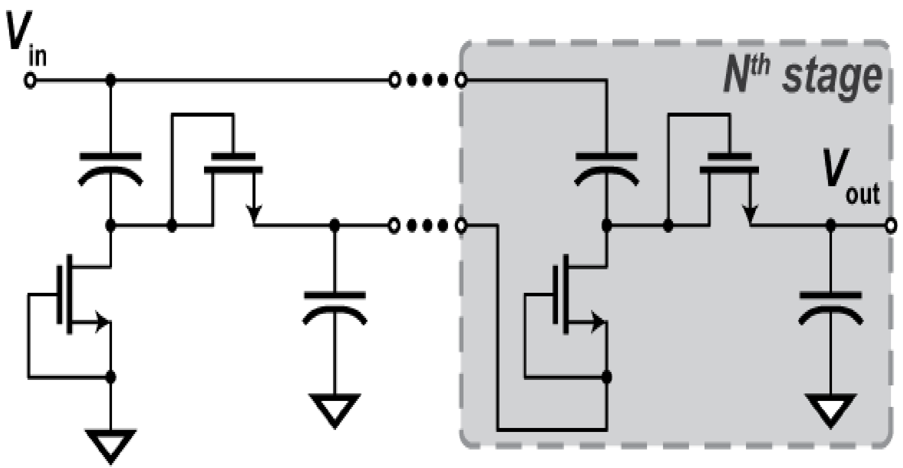
Active ED



Pros: high R_{in}
high conversion gain

Cons: high C_{in}
low SNR
non-zero power

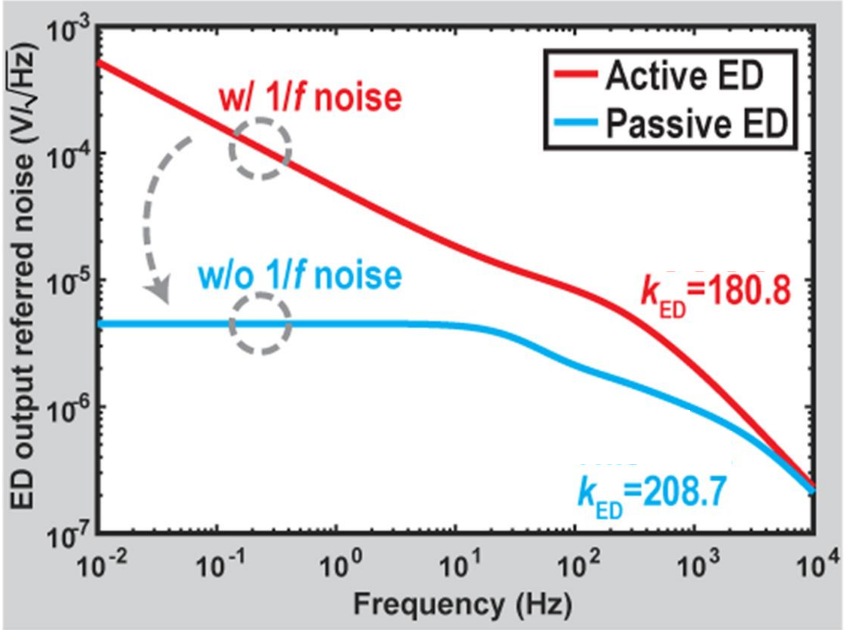
Passive ED



Pros: low C_{in}
high SNR
zero power

Cons: low R_{in}
low conversion gain

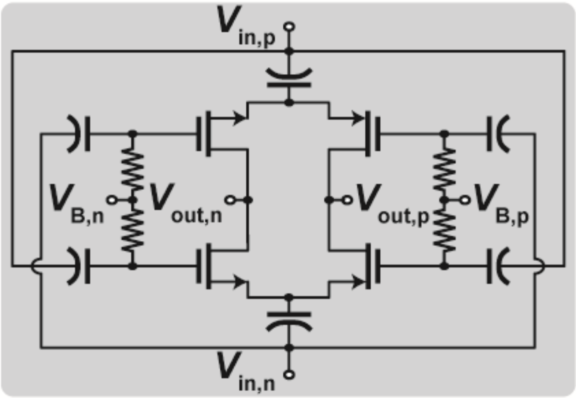
SNR



Passive ED has no 1/*f* noise compared to active ED

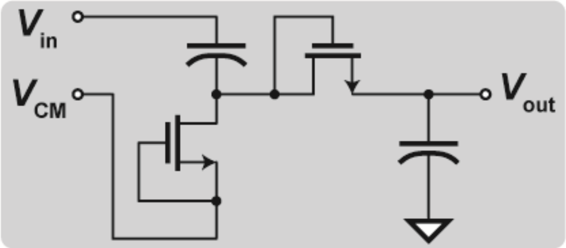
Proposed Passive Pseudo-balun ED

Differential input unit cell



Problem 1: extra loading @ RF for biasing
Problem 2: differential input requires center-tapped transformer ⟶ *low Q; low passive voltage gain*

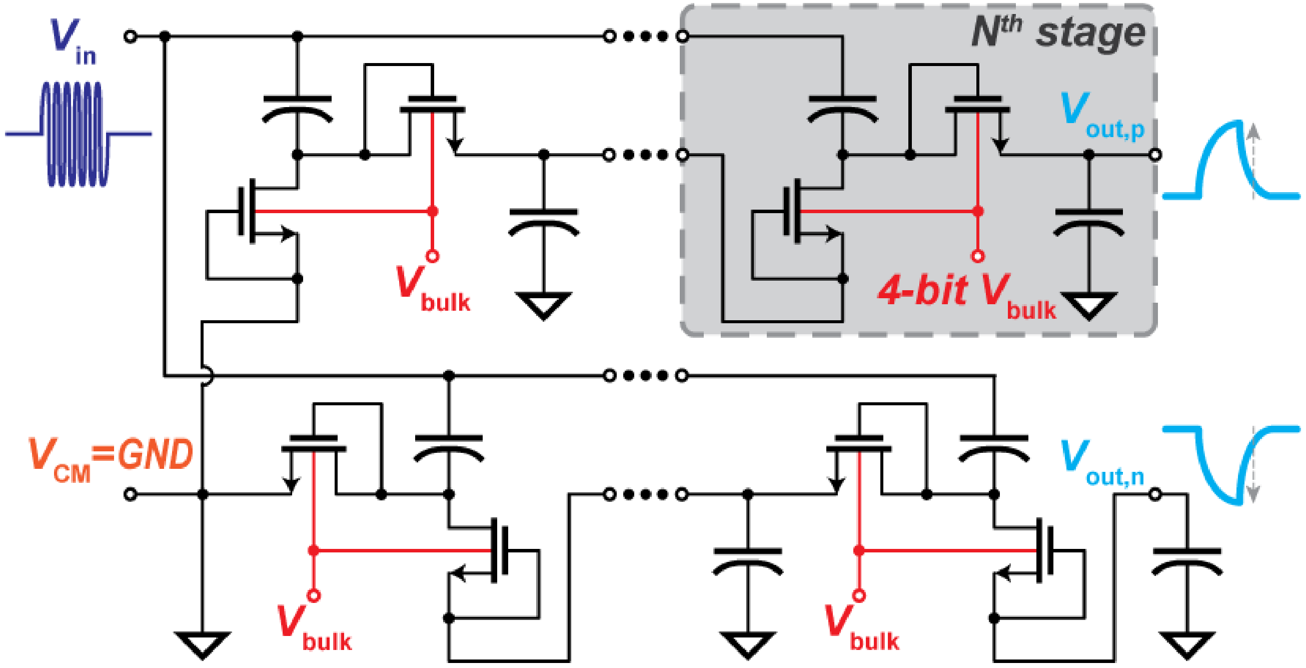
Single-ended input unit cell



Problem 1: no transistor tuning capability

Problem 2: single-ended output ED requires extra reference circuit with tuning for comparator

Proposed ED



Pseudo-balun ED

Benefit 1: 2X conversion gain w/o output bandwidth penalty
Benefit 2: 1.5 dB sensitivity improvement vs. single branch only

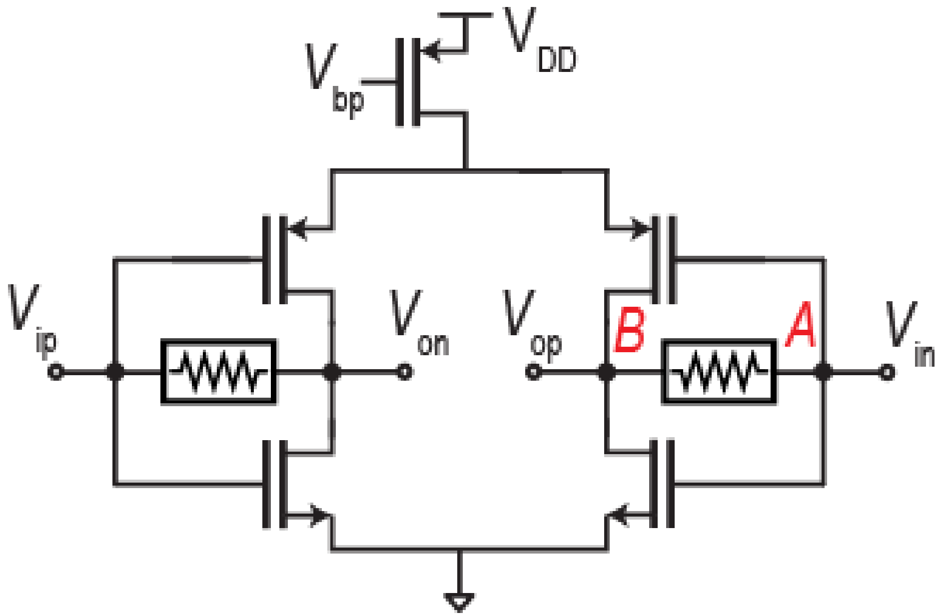
Bulk tuning unit cell

Benefit 1: tunable V_t for PVT or sizing for lower C_{in}
Benefit 2: no extra loading @ RF for biasing network

Baseband Amplifier

Design requirements:

- High input impedance to not degrade the ED gain & bandwidth
- High noise efficiency



2× current reuse reduces noise by 2×

Potential issue

- $Z_{\mathrm{in}} = \frac{R}{A_V+1} \parallel (A_V+1)(C_{\mathrm{gd,n}} + C_{\mathrm{gd,p}})$
- Low R_{in} and high C_{in} due to Miller effect

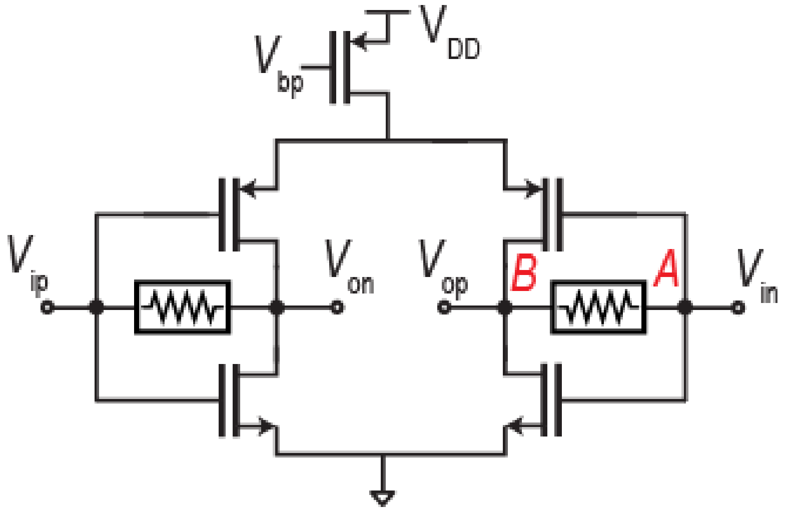
Solutions:

- Pseudo-resistor > 1TΩ
- Neutralization capacitors cancel Miller capacitance

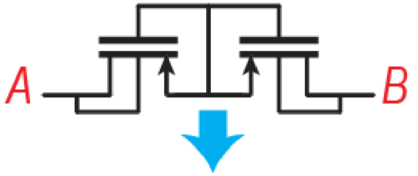
Achieves 9μV_{RMS} noise and an input impedance of 30GΩ || 0.4pF with only 3.4nW

Baseband Amplifier

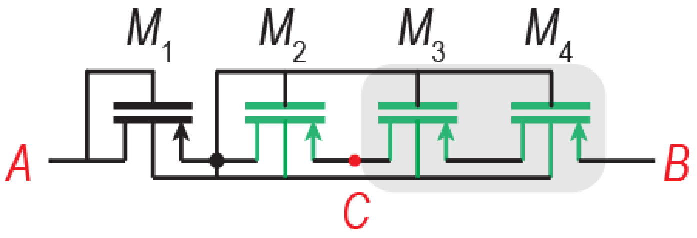
Current-reuse amplifier:



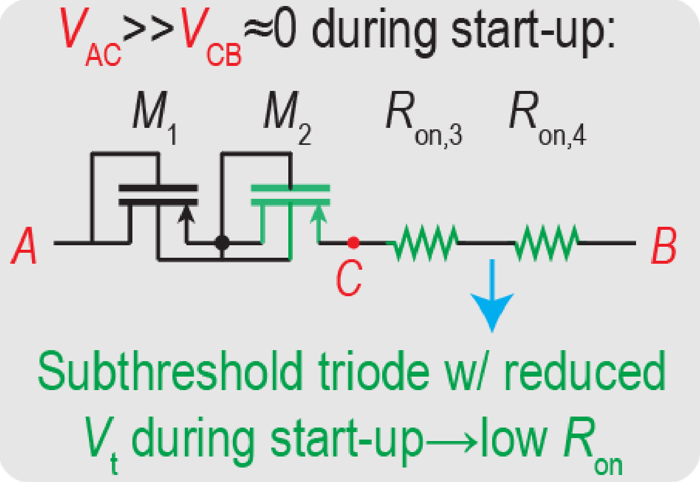
Conventional pseudo-resistor:

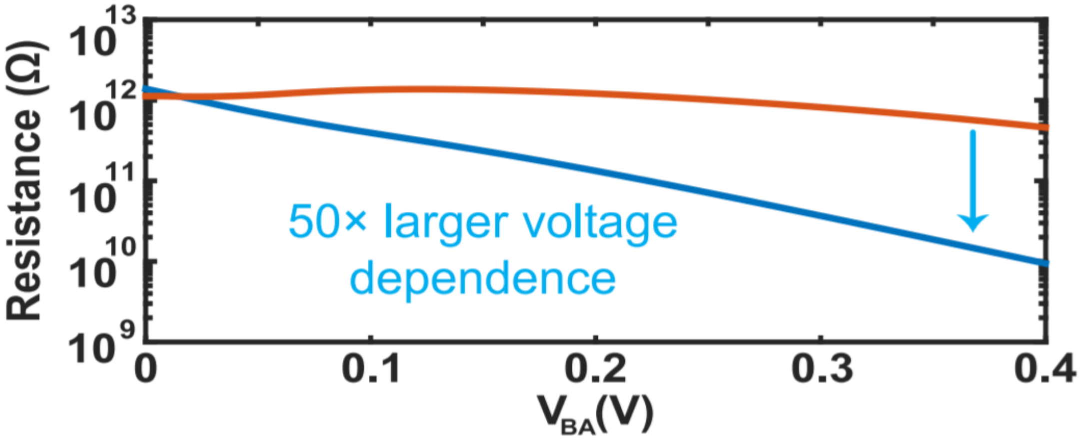


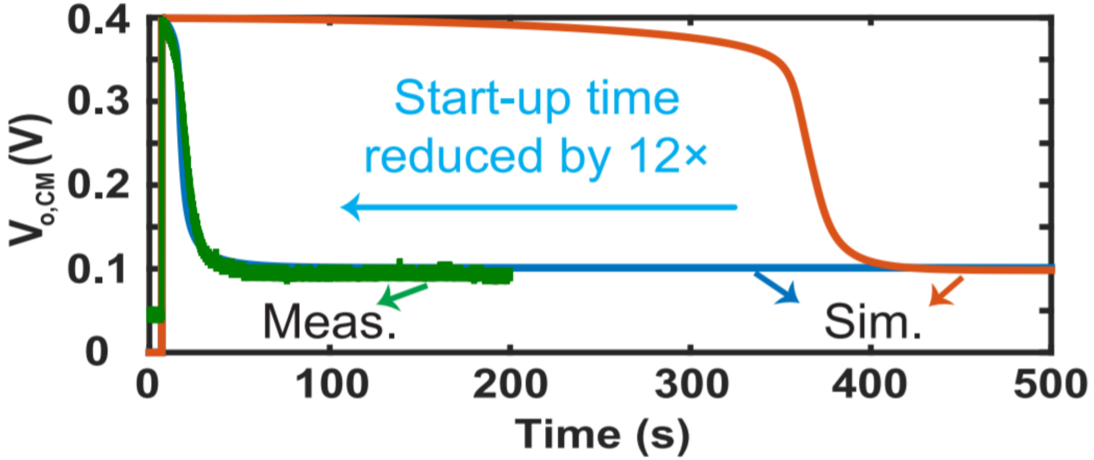
Fast start-up pseudo-resistor:



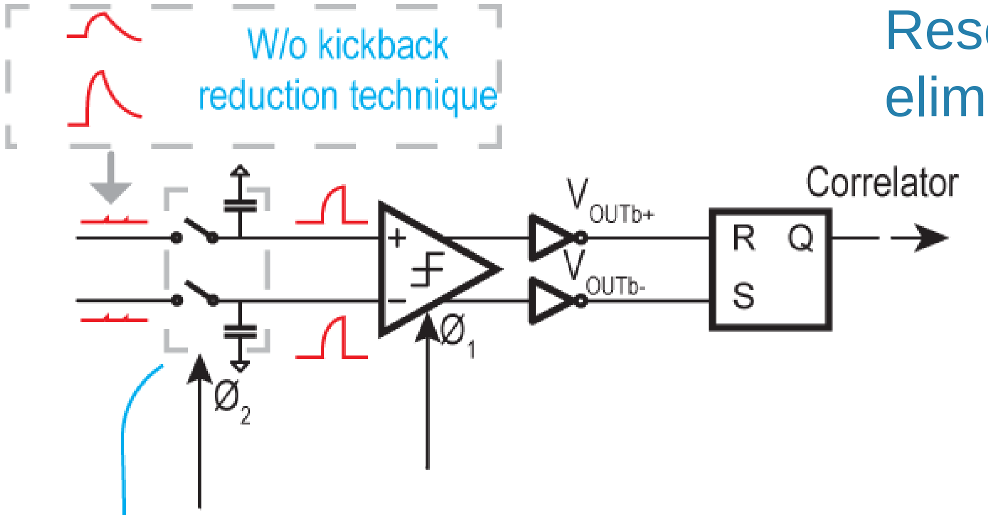
>400s)!





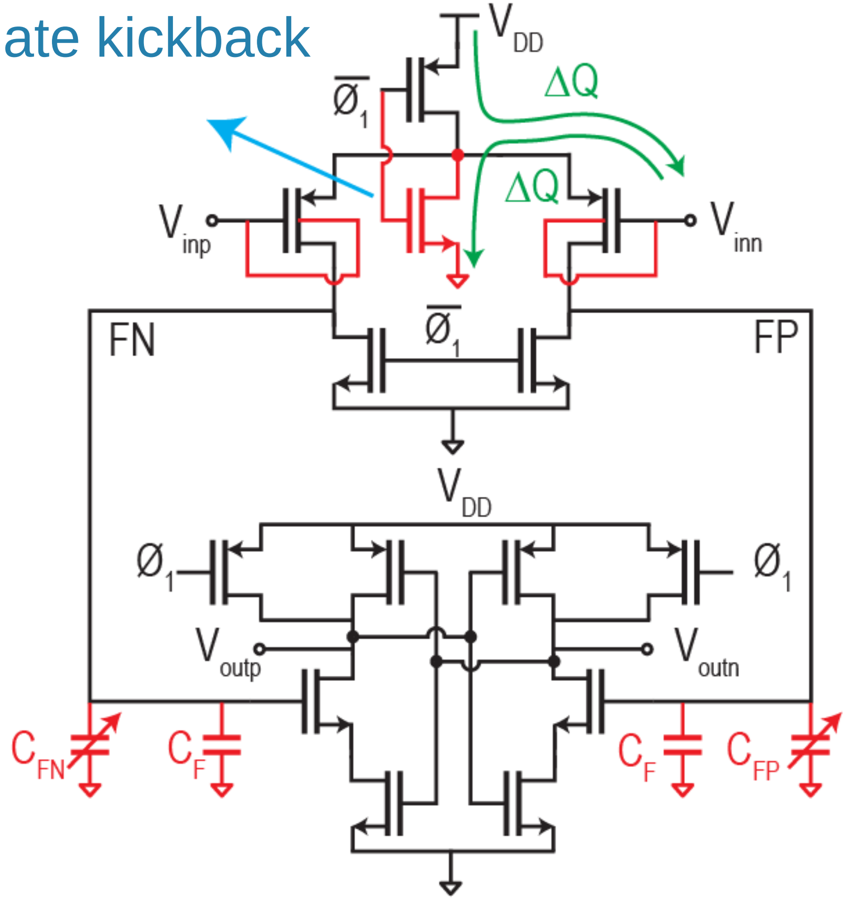


Utilizing asymmetric nonlinearity achieves 12× faster stat-up w/o compromising R_{in}



S/H to store kickback charge

Reset transistor to eliminate kickback



S&H: balanced impedances & stores kickback charge temporarily
Reset transistor: Purge kickback charge before next cycle

Haowei Jiang, Po-Han Peter Wang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M Rebeiz, Drew A Hall, and Patrick P Mercier, "A 4.5nW Wake-Up Radio with -69dBm Sensitivity," ISSCC, 2017.
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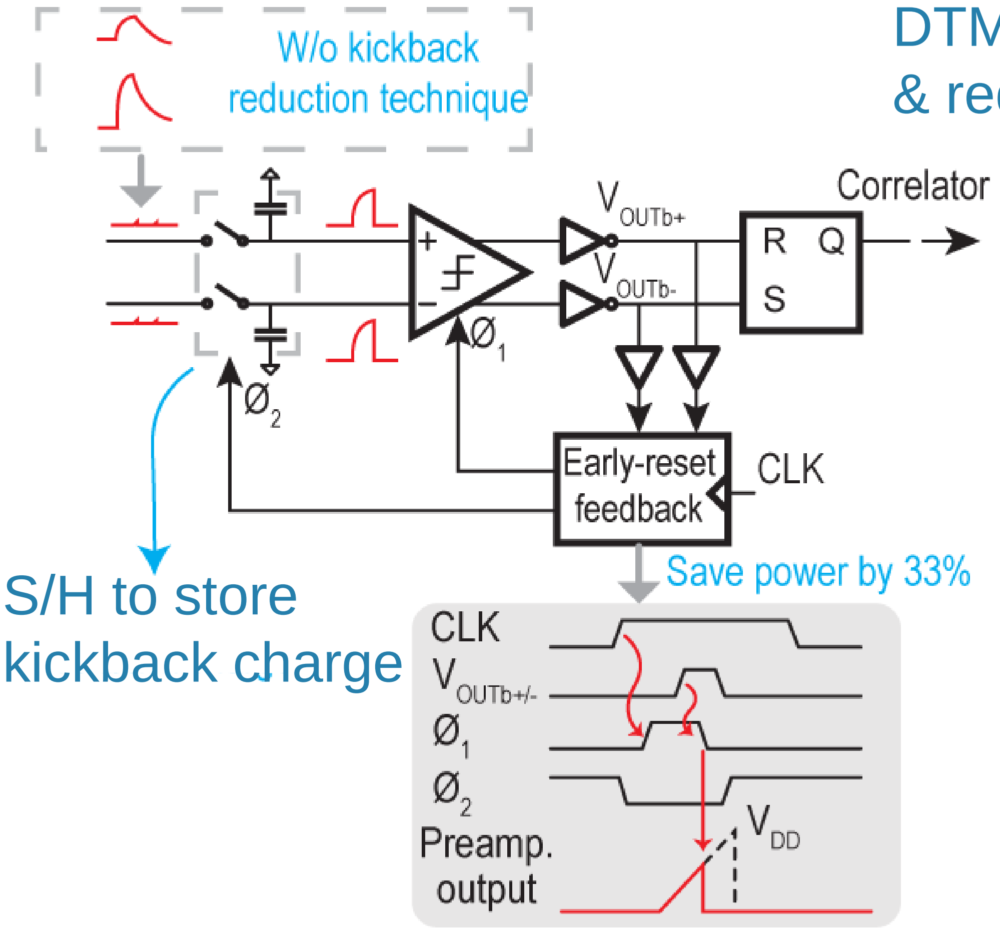
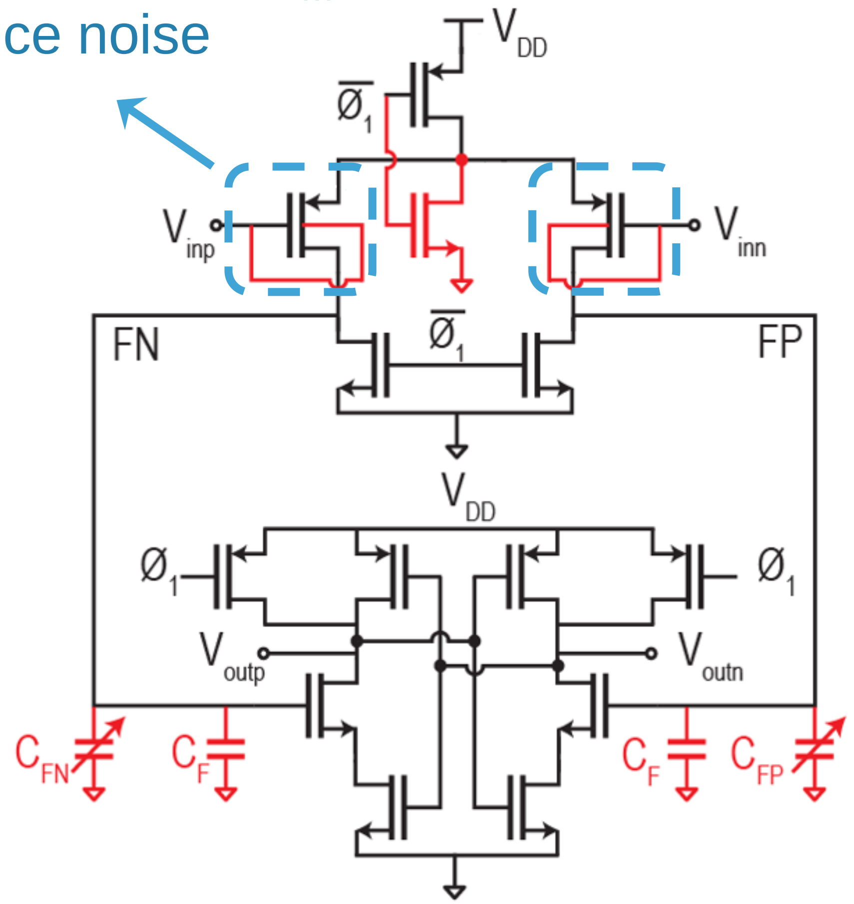
Comparator



S/H to store kickback charge

DTMOS to boost g_m & reduce noise



Early-reset: save dynamic power & generate non-overlapping clock

Haowei Jiang, Po-Han Peter Wang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M Rebeiz, Drew A Hall, and Patrick P Mercier, “A 4.5nW Wake-Up Radio with -69dBm Sensitivity,” ISSCC, 2017.
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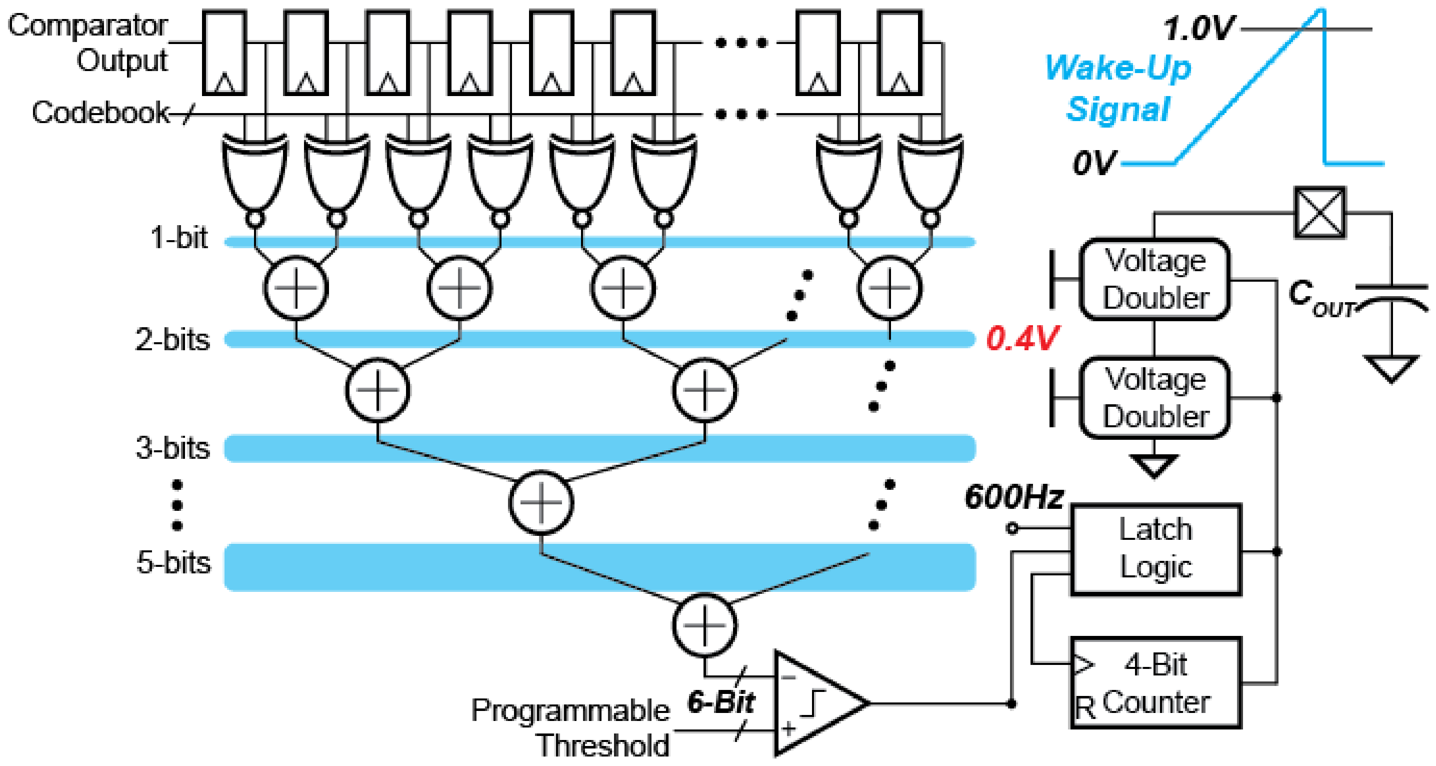
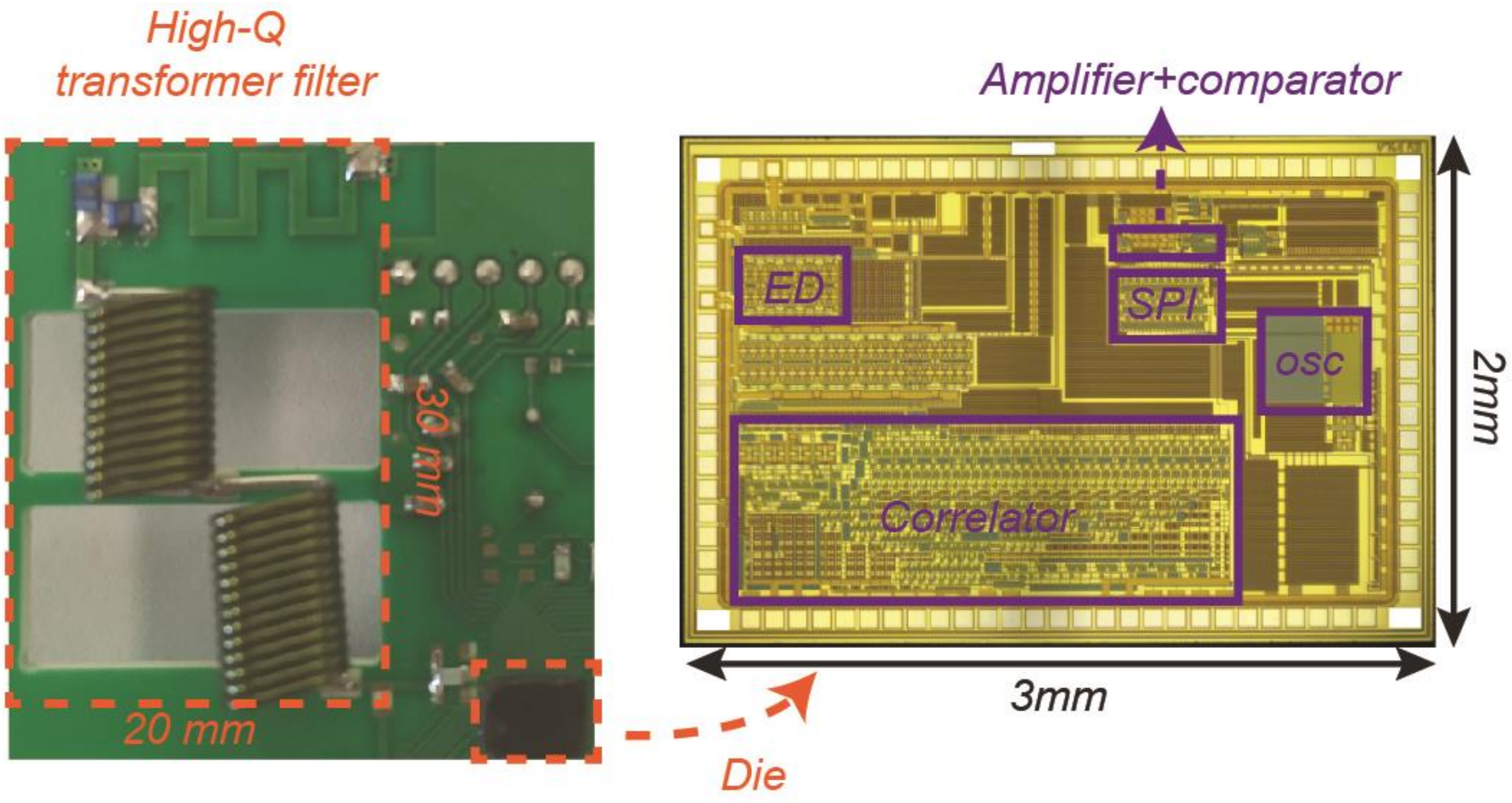
Coding and Digital Baseband



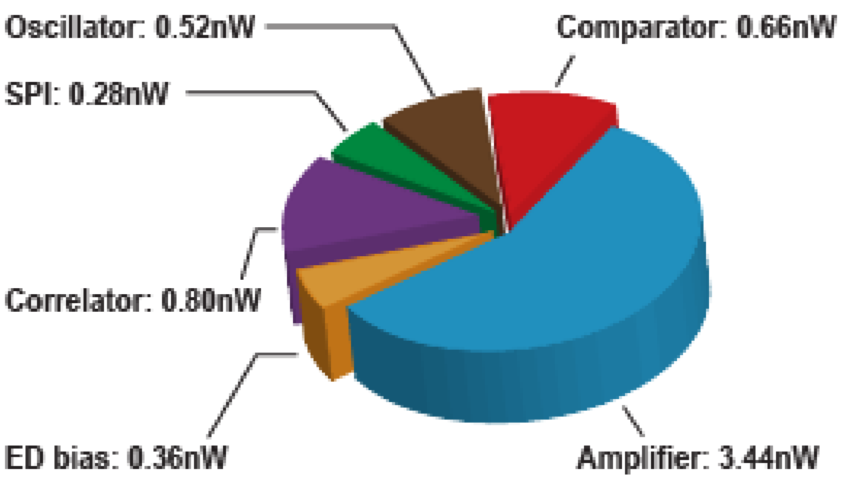
Optimal codeword improves SNR by 2.5 dB while consuming only 800 pW

Board and die photo

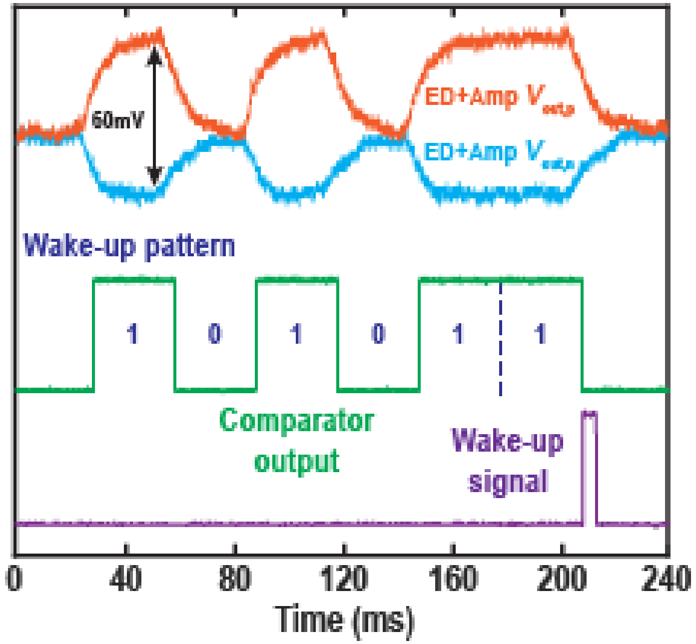


Measurement Results

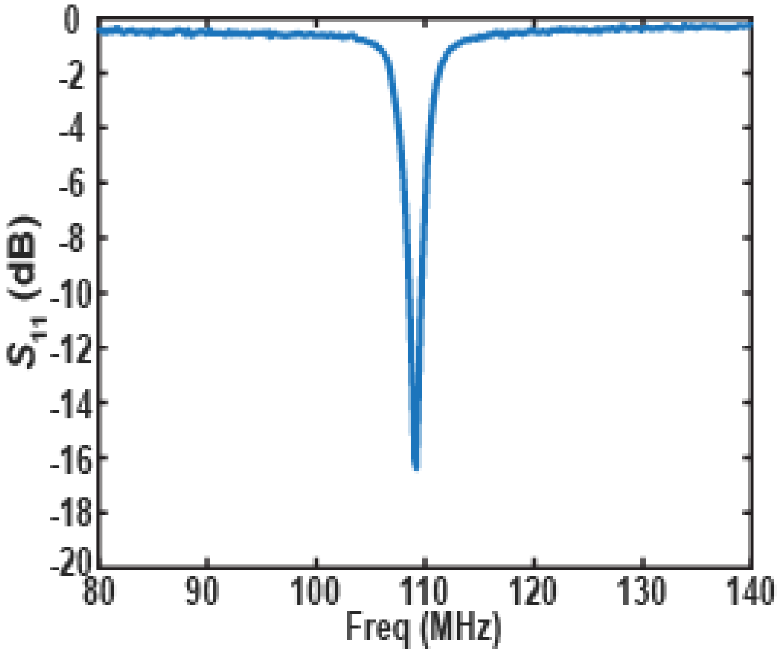
Power Breakdown



Transient Response



Input Matching

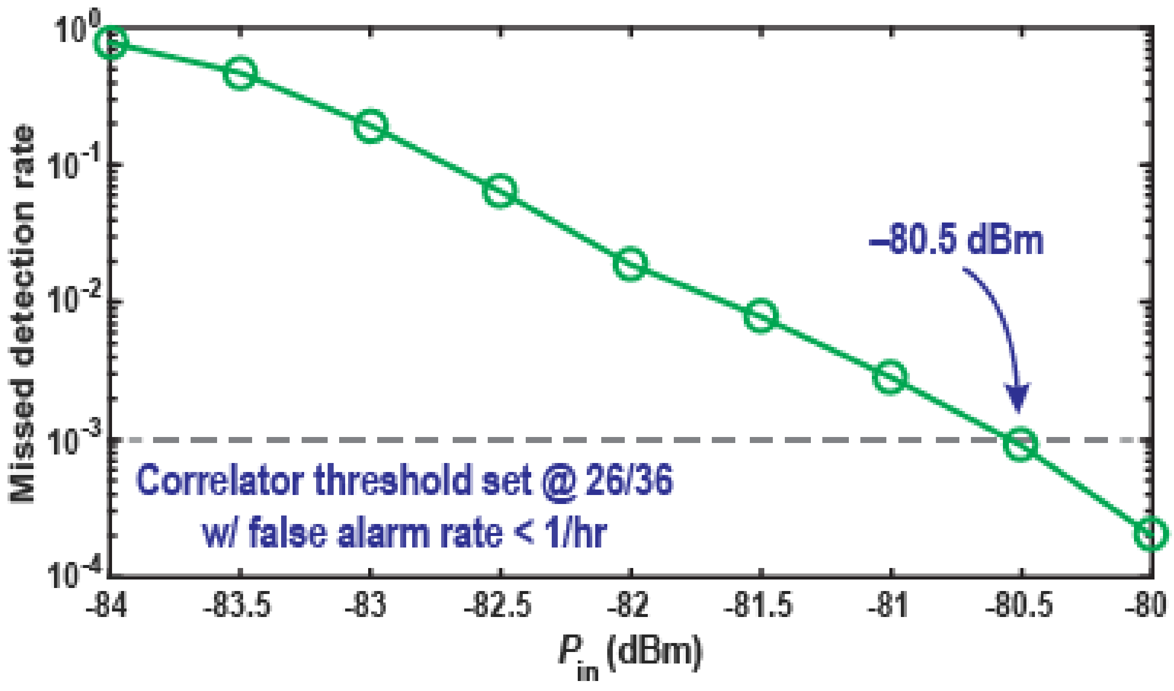


6.1 nW power consumption WuRX – Less than the leakage of a coin cell battery!

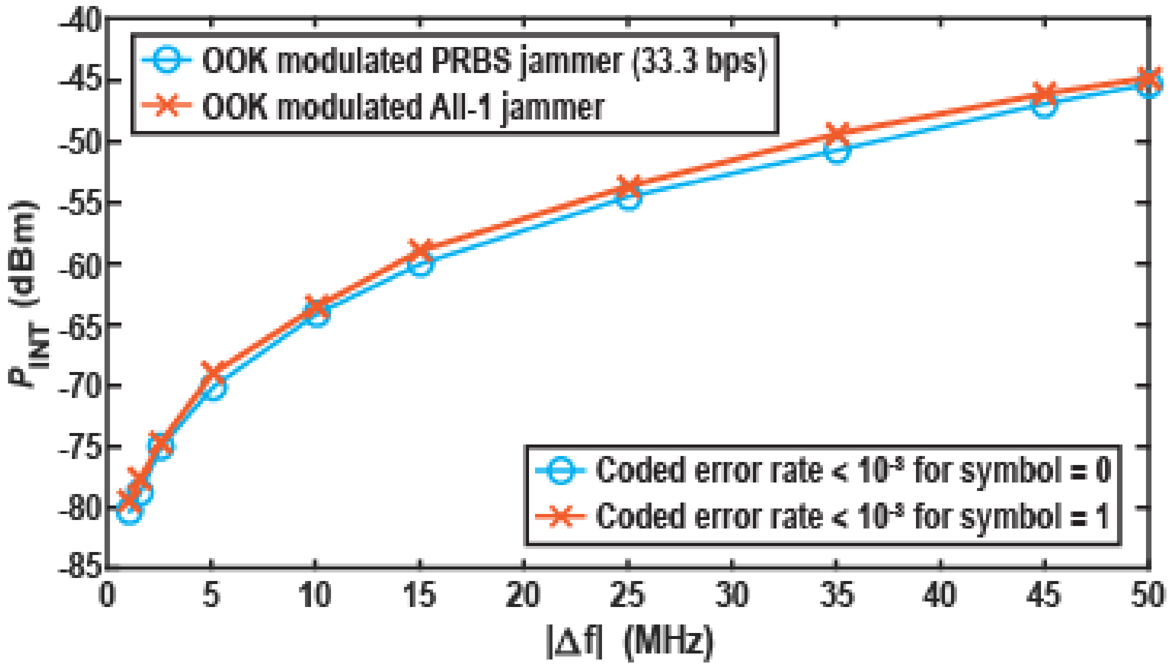
Po-Han Wang, Haowei Jiang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M. Rebeiz, Patrick P. Mercier, and Drew A. Hall, “A 6.1 nW Wake-Up Receiver Achieving −80.5 dBm Sensitivity via a Passive Pseudo-Balun Envelope Detector,” SSCL, 2018.

Measurement Results

Missed Detection Rate



Interference Sensitivity



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Comparison to the State-of-the-Art

	[1] CICC'13	[4] CICC'17	[7] ESSCIRC'17	[8] ISSCC'18	[2] ISSCC'17	[5] ISSCC'18	**This Work**
Technology	130 nm	130 nm	180 nm	65 nm	180 nm	130 nm	**180 nm**
Supply Voltage	1.2 / 0.5 V	0.5 V	0.4 V	0.5 V	0.4 V	1.0 / 0.6 V	**0.4 V**
Digital Correlator	31-bit	11-bit*	32-bit	3∼10-bit	32-bit	8-bit	**36-bit**‡
Clock	XTAL osc.	No	Relaxation osc.	Relaxation osc.	Relaxation osc.	Ring osc.	**Relaxation osc.**
Passive RF Voltage Gain	5 dB	27 dB$^{\triangleleft}$	18.5 dB	N.R.$^{\diamond}$	25 dB	27 dB	**30.6 dB**
Demodulator Type	Passive Dickson single-ended ED	Passive self-mixer	Active CG pseudo-balun ED	Active CS-CG single-ended ED	Active CS single-ended ED	Passive Dickson single-ended ED	**Passive Dickson pseudo-balun ED**
Carrier Frequency	403 MHz	550 MHz	405 MHz	57 kHz	113.5 MHz	151.8 MHz	**109 MHz**
Data Rate	12.5 kbps	400 kbps†	300 bps	336 bps	300 bps	200 bps	**33.3 bps**
Wake-Up Latency	2.48 ms	27.5 μs	53.3 ms	8.9∼29.8 ms	53.3 ms	>80 ms$^{\triangleright}$	**180 ms**
Sensitivity	−45 dBm	−56.4 dBm	−63.8 dBm	−60.1 dBm$^{\wr}$	−69 dBm	−76 dBm	**−80.5 dBm**
Sensitivity Normalized to 1/Latency$^{\circ}$	−58 dB	−79.2 dB	−70.2 dB	−68.5 dB$^{\wr}$	−75.4 dB	−81.5 dB	**−84.2 dB**
Power Consumption	116 nW	222 nW	4.5 nW	8 nW	4.5 nW	7.6 nW	**6.1 nW**

State-of-the-art performance: the highest sensitivity and the best sensitivity normalized to latency

Po-Han Wang, Haowei Jiang, Li Gao, Pinar Sen, Young-Han Kim, Gabriel M. Rebeiz, Patrick P. Mercier, and Drew A. Hall, "A 6.1 nW Wake-Up Receiver Achieving −80.5 dBm Sensitivity via a Passive Pseudo-Balun Envelope Detector," SSCL, 2018.

Conclusion

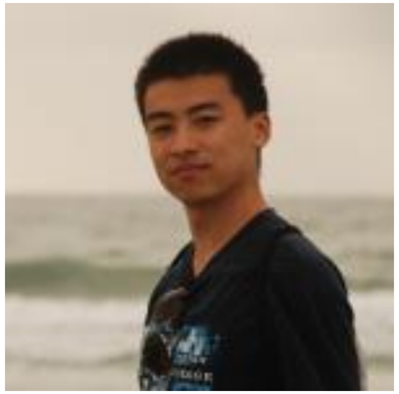
- For event-driven applications with low-average throughput, WuRXs extend system lifetime
  - Design targets: Low power and high sensitivity
- The proposed design accomplishes this using:
  - Passive gain at RF with a high Q impedance transformer
  - Passive pseudo-balun ED with low C_{in}
  - A current-reuse baseband amplifier and two-stage integrating comparator
  - A low-power digital correlator with 6× oversampling
- **Result:** A 110 MHz, 6.1 nW, –80.5 dBm sensitivity WuRX

Acknowledgment

- This work is supported by the Defense Advanced Research Projects Agency (DARPA) under contract No. HR0011-15-C-0134

- Mentor Graphics for the use of Analog FastSPICE tool (AFS)

STUDENTS



Haowei Jiang

Li Gao

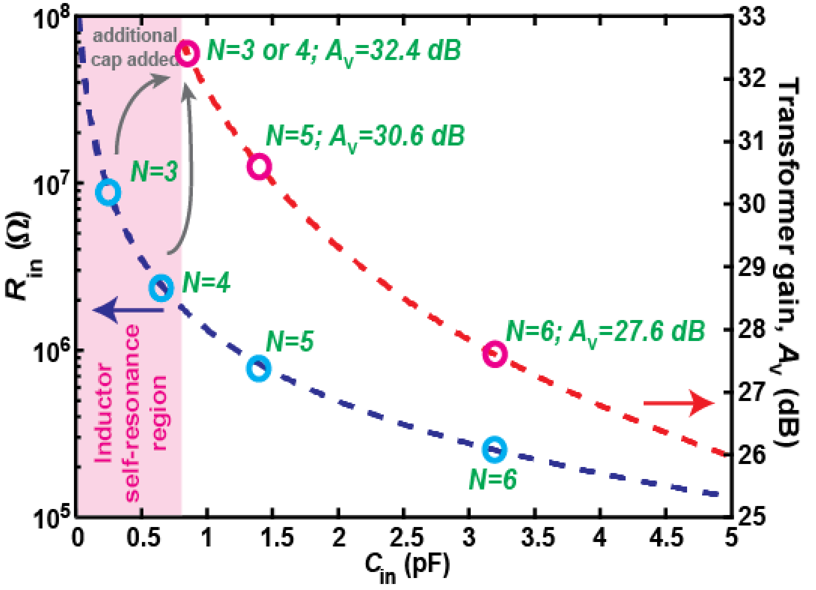
Po-Han Wang

Pinar Sen

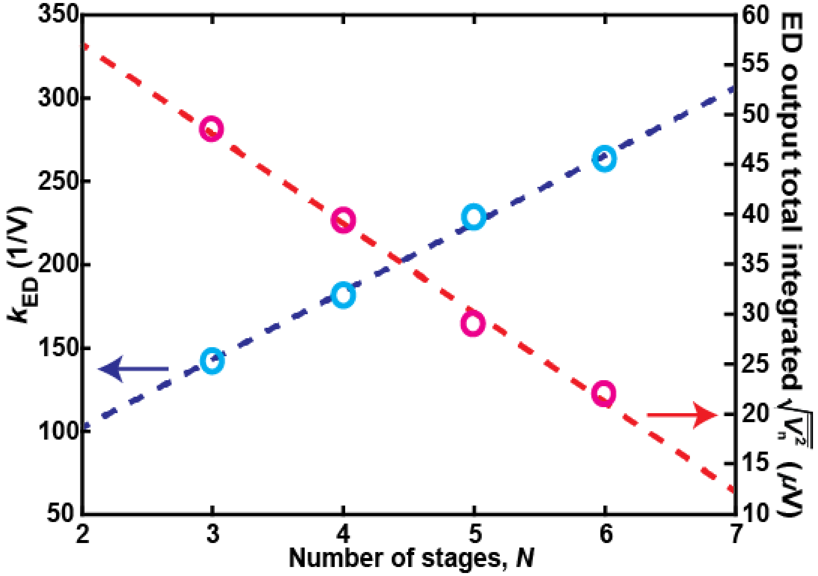
Backup

Passive ED Stage Optimization

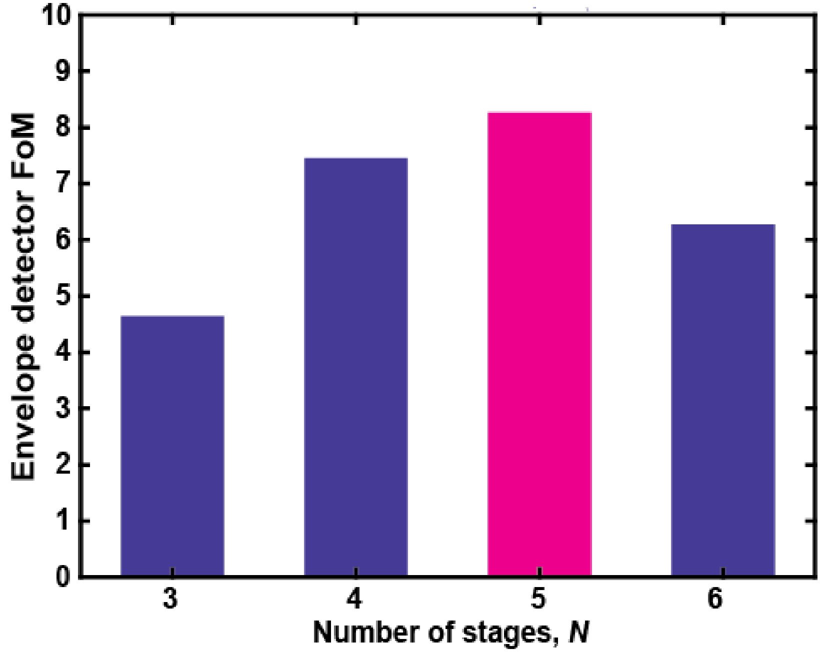
Transformer gain for different *N*



k_{ED} and noise for different *N*

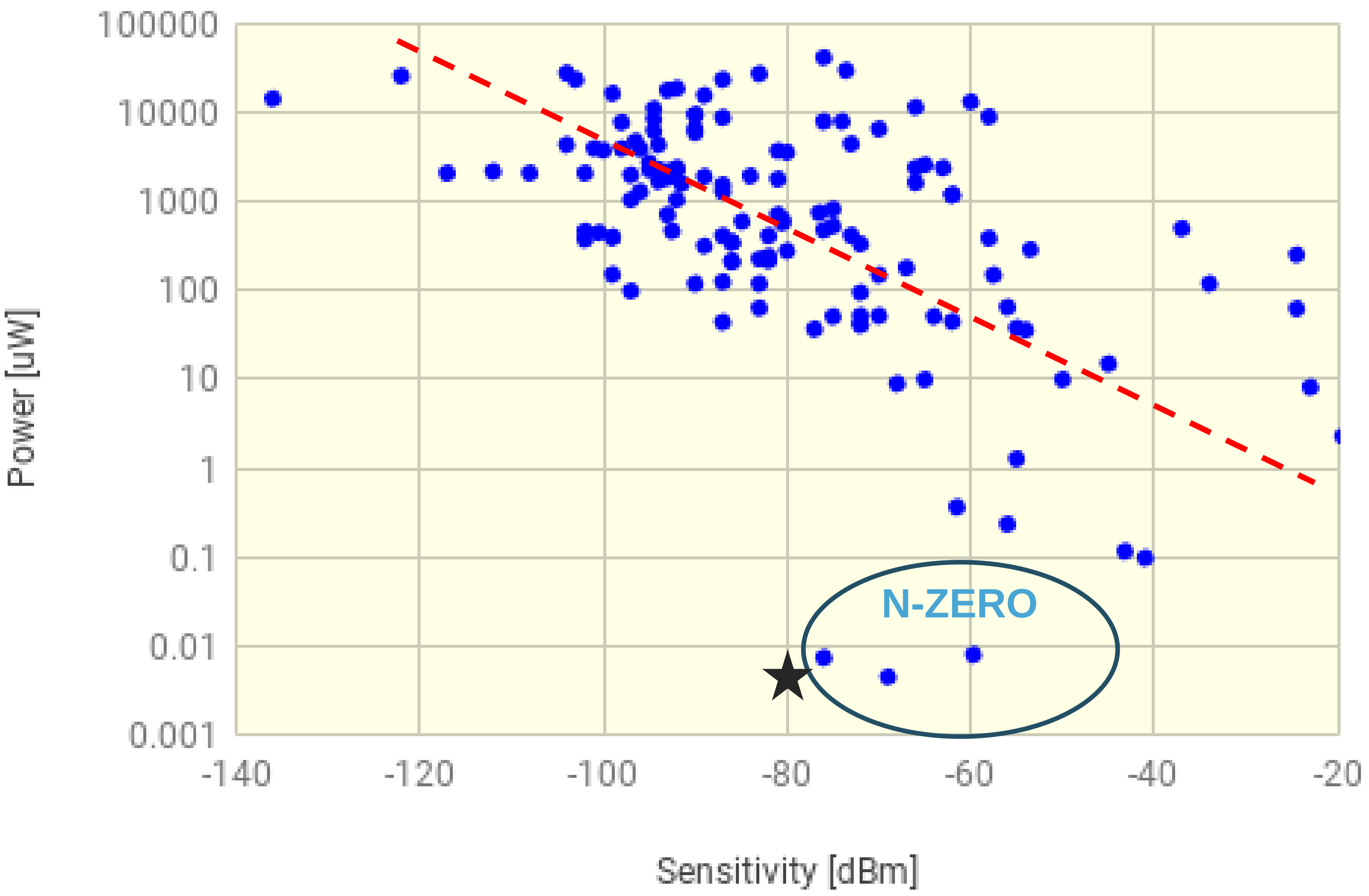


$$SNR_{ED,norm} = A_V^2 \cdot k_{ED} \Big/ \sqrt{\overline{V_n^2}} \cdot 10^{-9}$$



N=5 ED achieves the best *SNR*

The State-of-the-Art Landscape (Revised)



David D. Wentzloff, "Low Power Radio Survey," [Online]. www.eecs.umich.edu/wics/low_power_radio_survey.html