A Rugged Wearable Modular ExG Platform Employing a Distributed Scalable Multi-Channel FM-ADC Achieving 101dB Input Dynamic Range and Motion-Artifact Resilience

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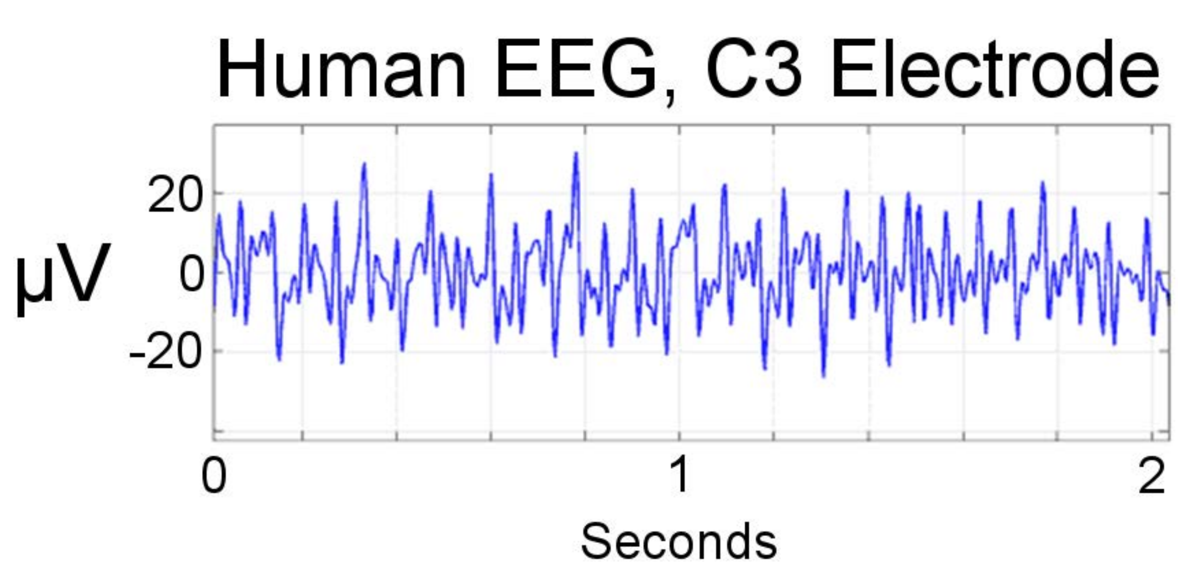
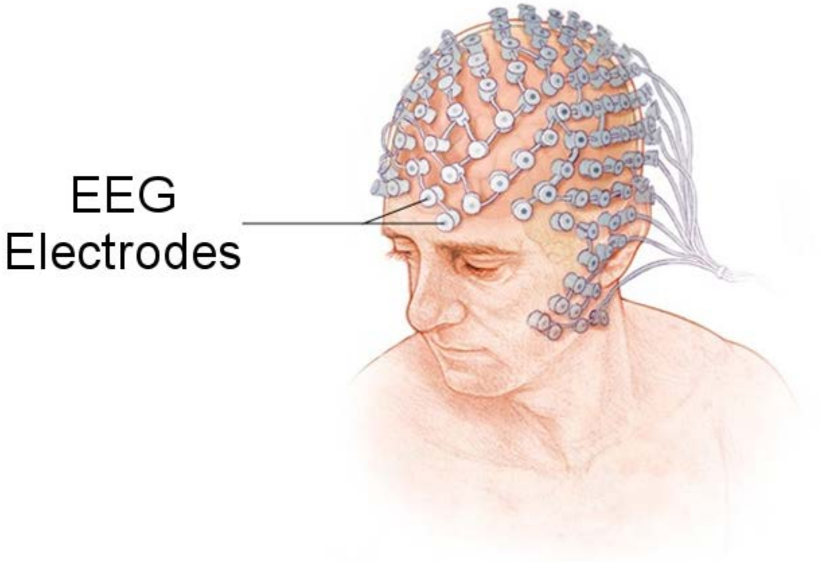
Clinical-Grade EEG





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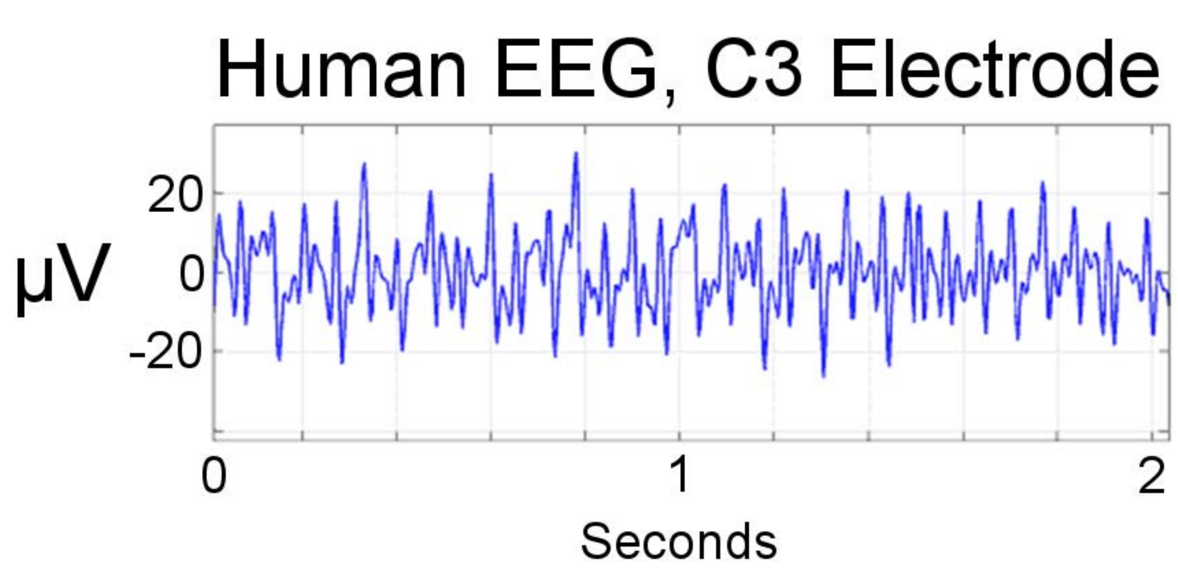
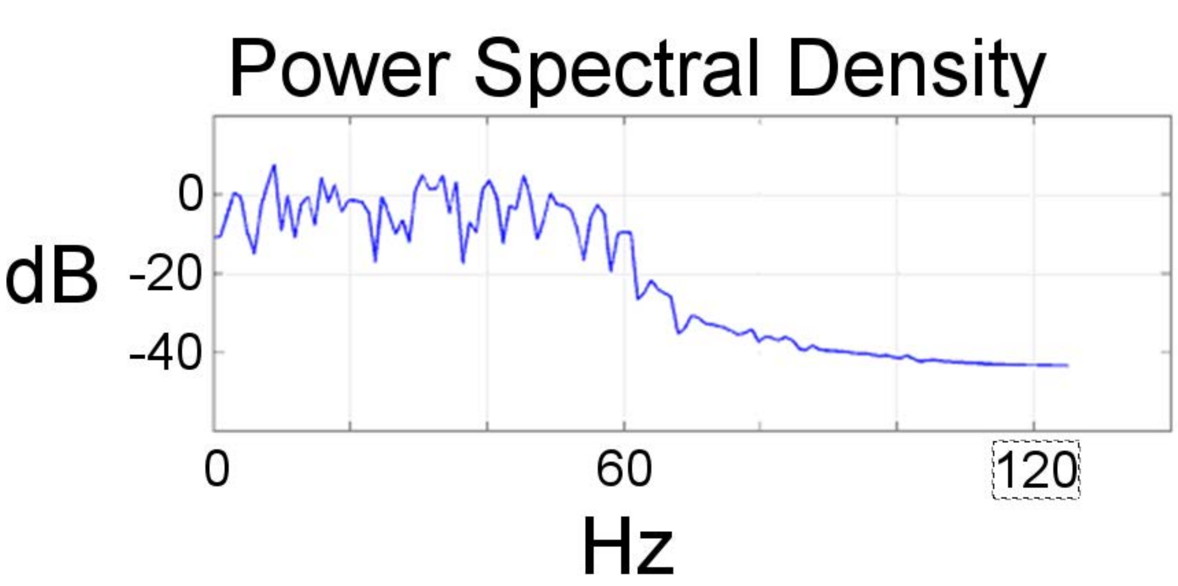
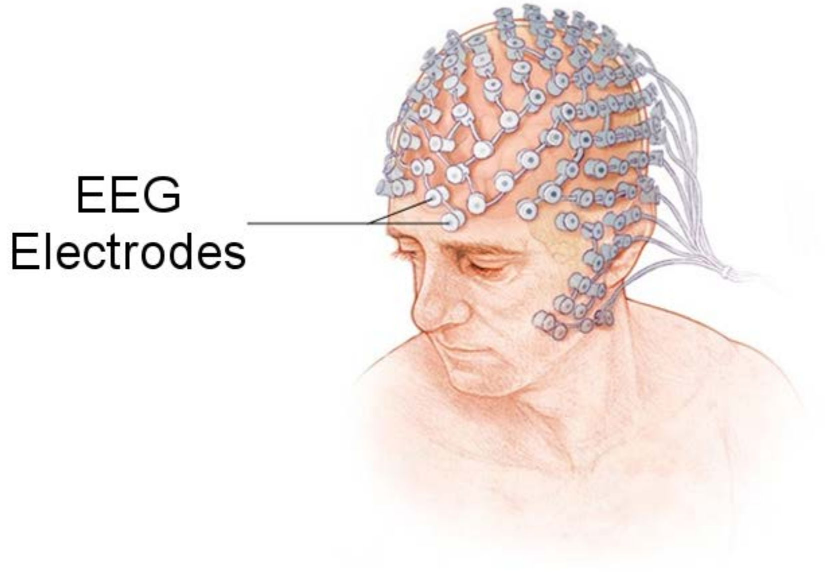




Data from https://jp.mathworks.com/



Range (with Motion):
1 μV ↔ ~100 mV
100 dB DR
Bandwidth:
0.5Hz ↔ ~250Hz

Clinical-Grade EEG Challenges

http://people.brandeis.edu/~sekuler/

https://www.cne.psychol.cam.ac.uk/

https://tragicoptimist.wordpress.com/

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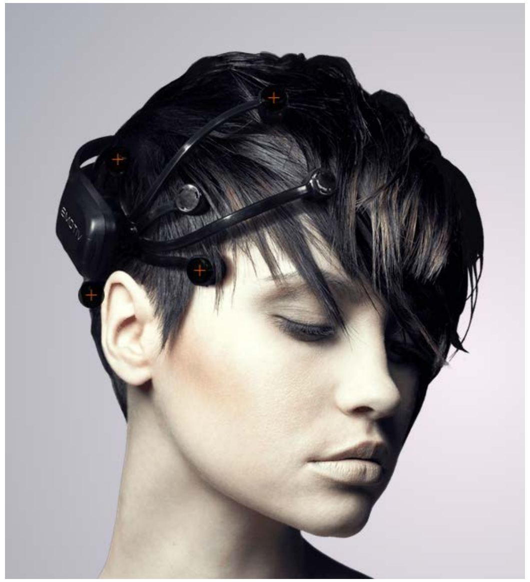
Lots of Wiring – Fragile and Bulky
Cable Sway Introduces Motion Artifacts

Commercial Wireless EEG Challenges

IMEC

Emotiv



Cognionics

Commercial Wireless EEG Challenges

IMEC

63dB SNR
8 Channels
96 Hour Battery

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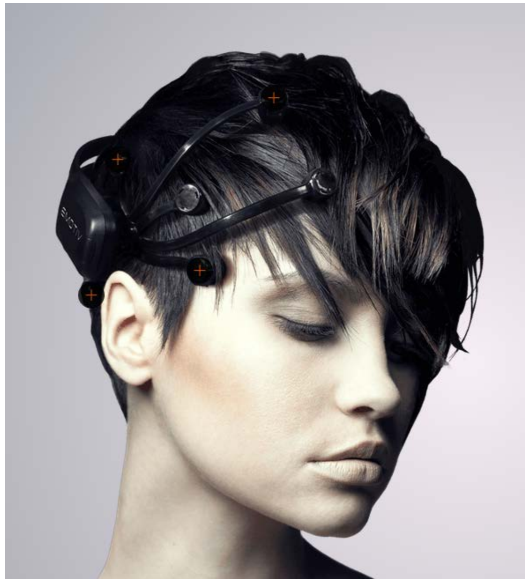

84dB SNR
14 Channels
12 Hour Battery

Cognionics

112dB SNR
64 Channels
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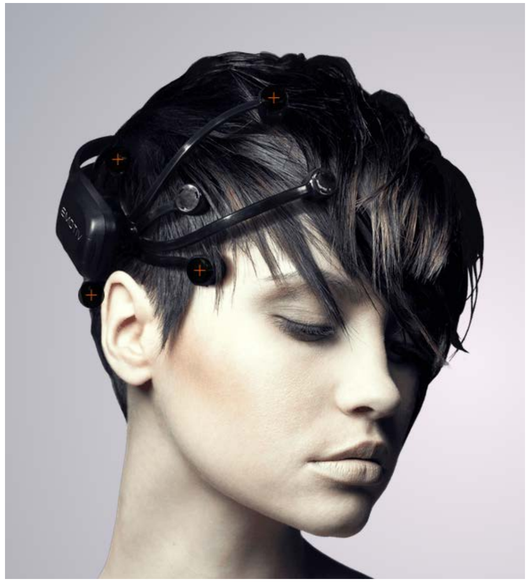

84dB SNR
14 Channels
12 Hour Battery

Cognionics

112dB SNR
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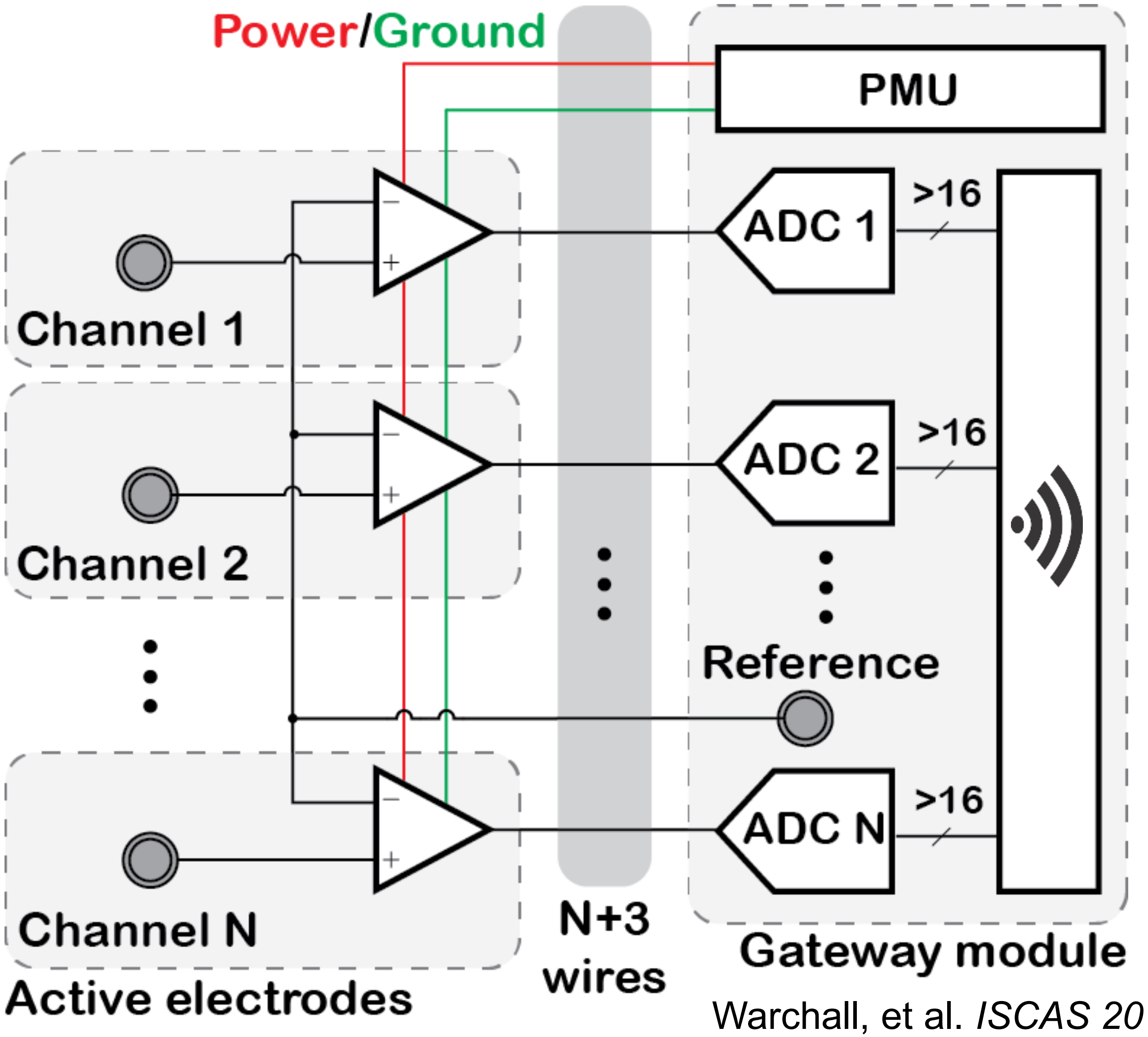
Choose: Long Battery Life OR High Fidelity/Density

Presentation Outline

1. **Motivation**
   - Increase Battery Life and Ruggedness for EXG
   - Maintain High Dynamic Range and High Density
2. **Approach**
   - A Scalable Multi-Channel FM-FDM Sensor Network
   - Integrated Gateway with ADC and UWB TX
3. **Measurement Results**
   - Single Channel Measurements
   - Multi-Channel Measurements
   - Biopotential Measurements
   - UWB Performance

EXG – The Traditional Approach



Warchall, et al. *ISCAS 2016*

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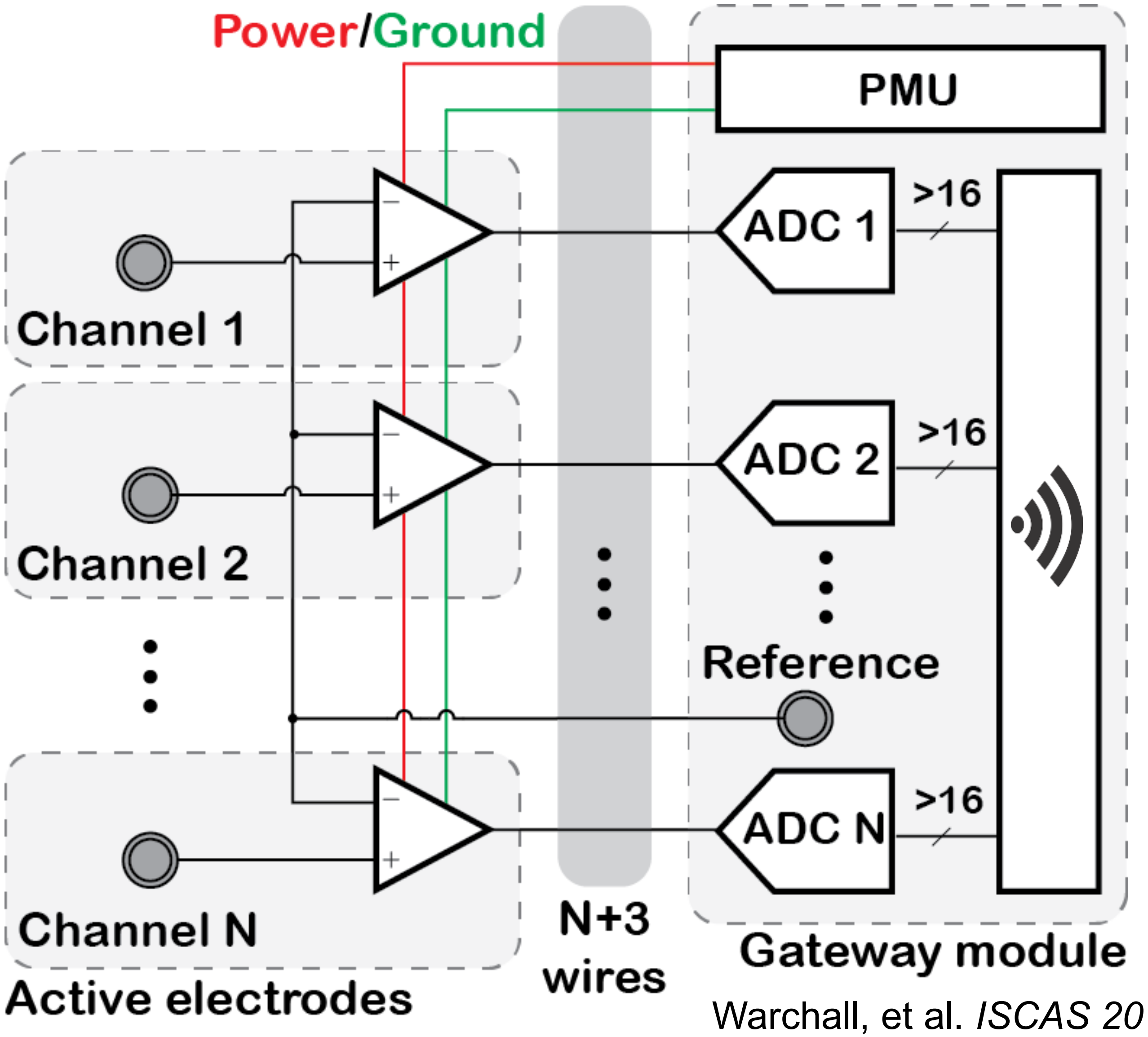

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- N wires for N Channels
  - Fragile and Bulky
  - Exacerbate Motion Artifacts

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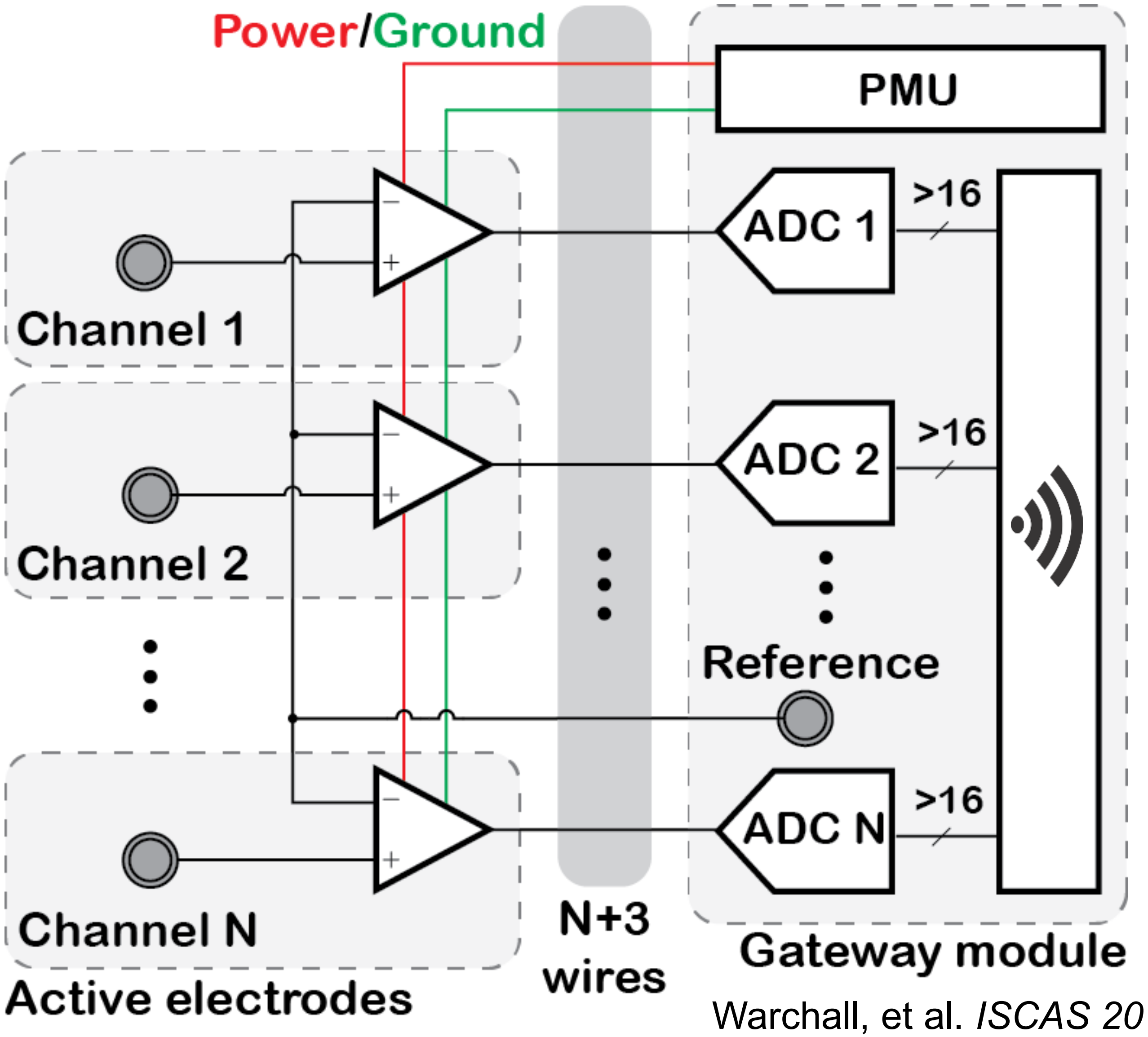

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- Long Wires in Baseband
  - Require Active Electrode

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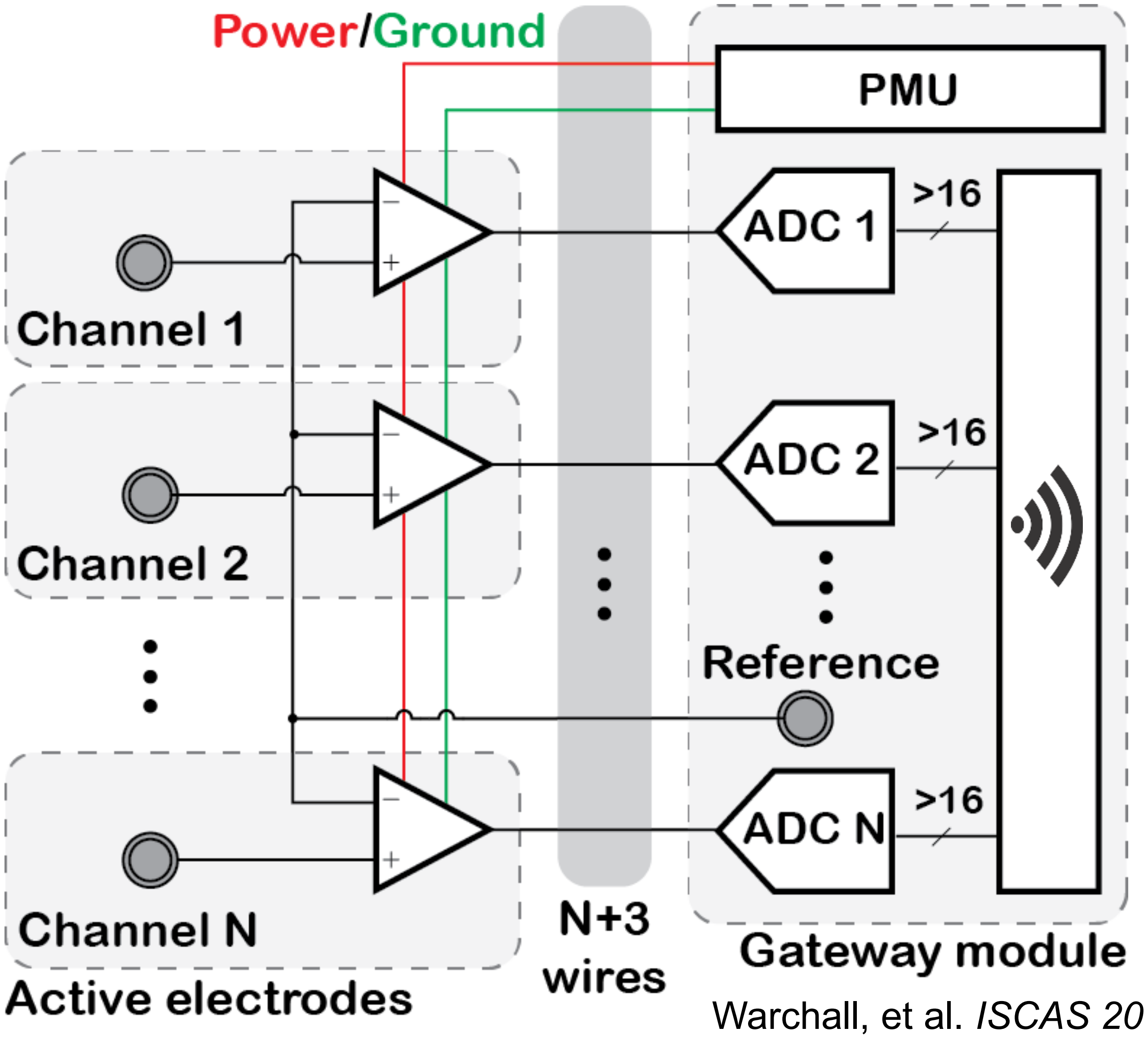

Warchall, et al. *ISCAS 2016*

- N wires for N Channels
  - Fragile and Bulky
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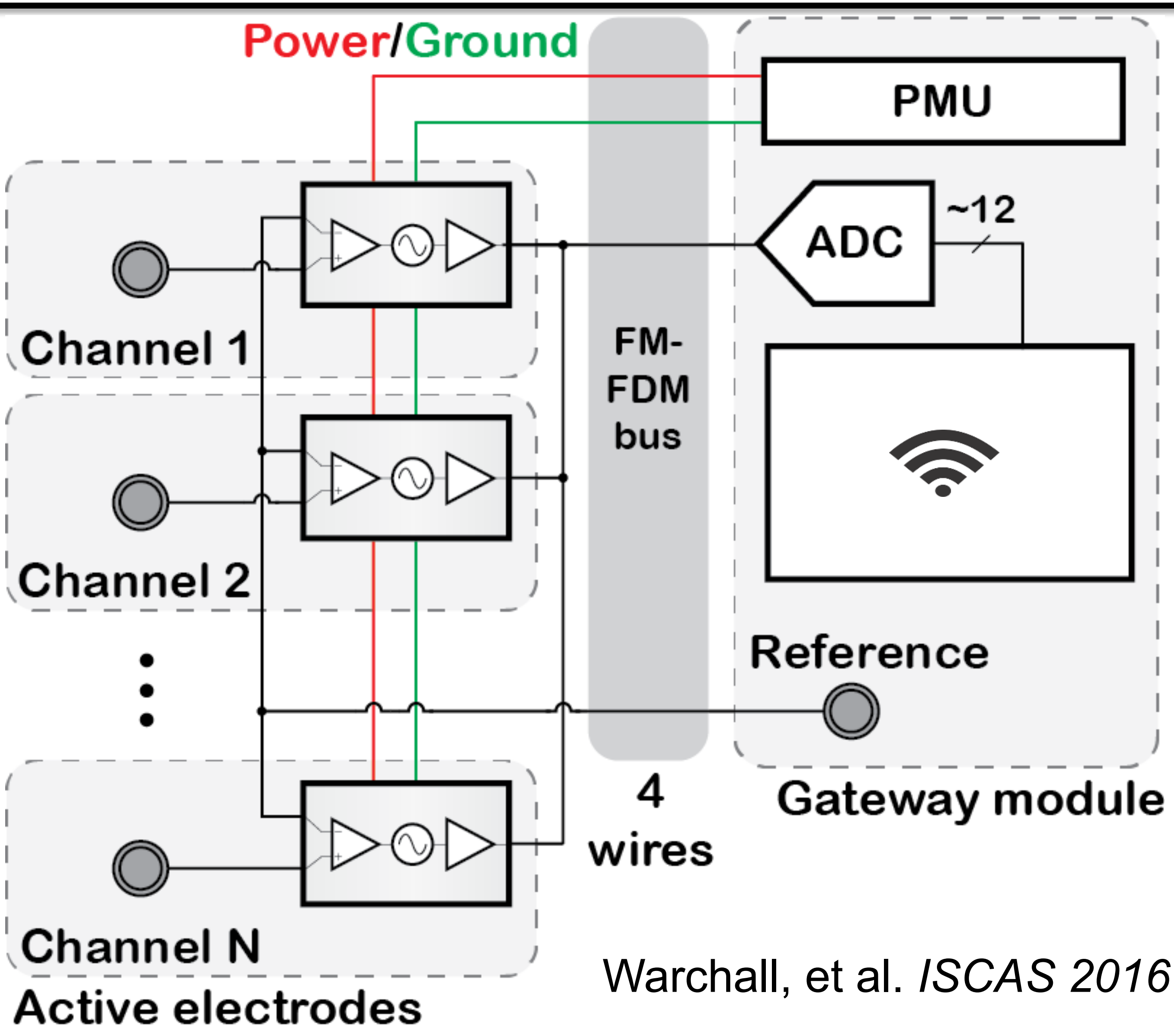
- Long Wires in Baseband
  - Require Active Electrode
- N ADCs
  - High ENOB
  - High Power Consumption

EXG – An FM-FDM Approach



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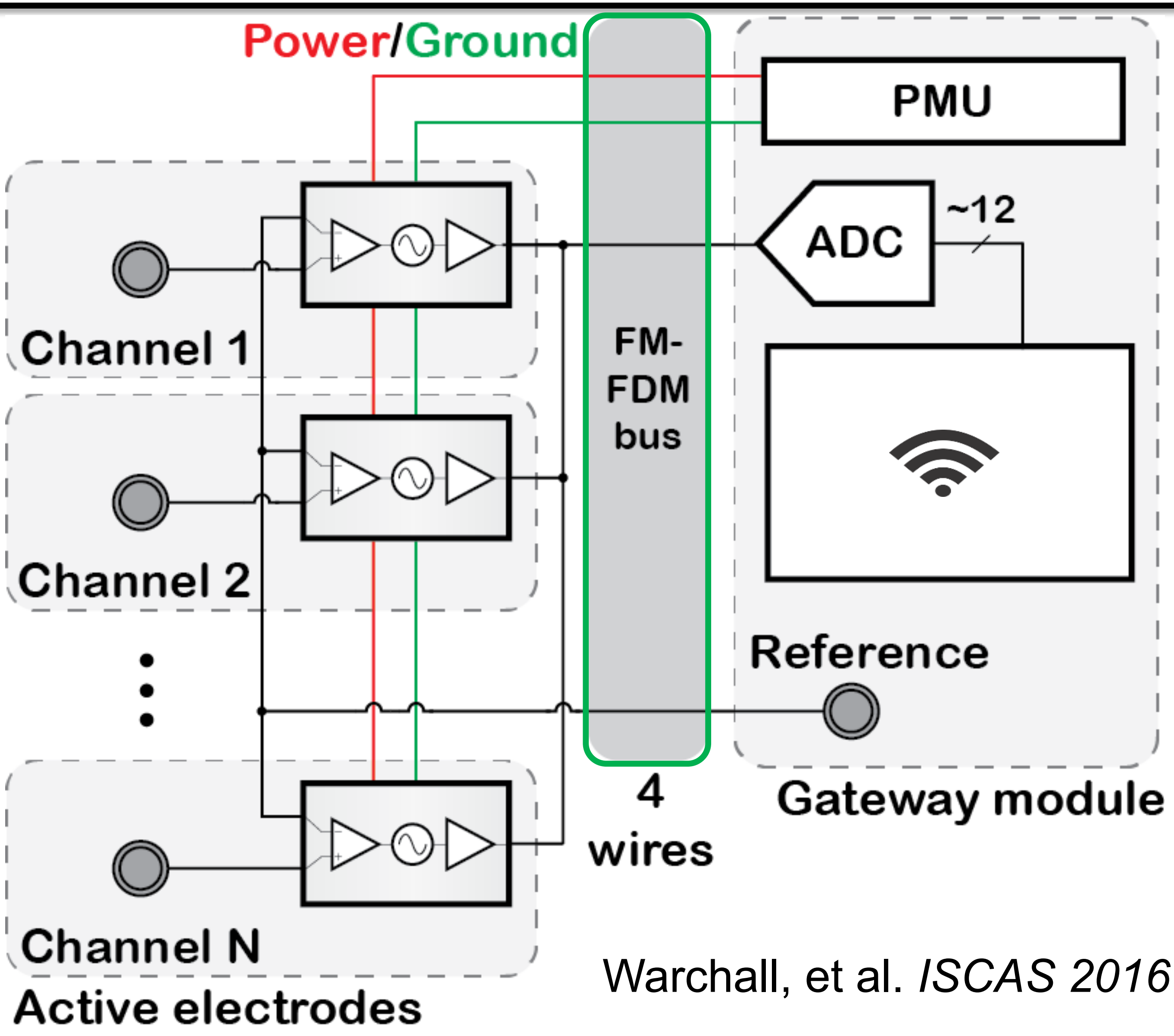
FM-FDM:

EXG – An FM-FDM Approach



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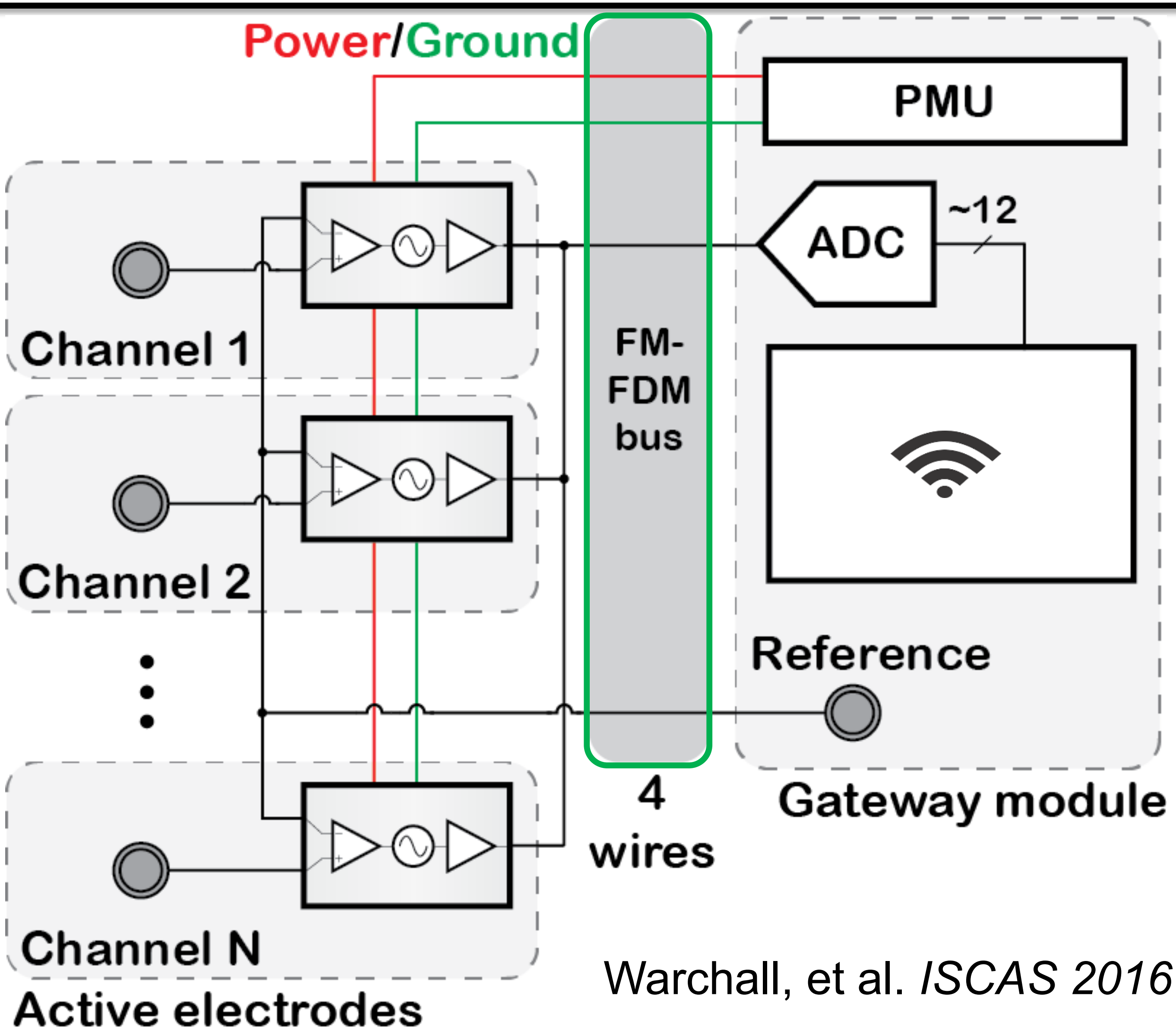
FM-FDM:

Minimizes Wire Count,

EXG – An FM-FDM Approach



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Minimizes Wire Count,

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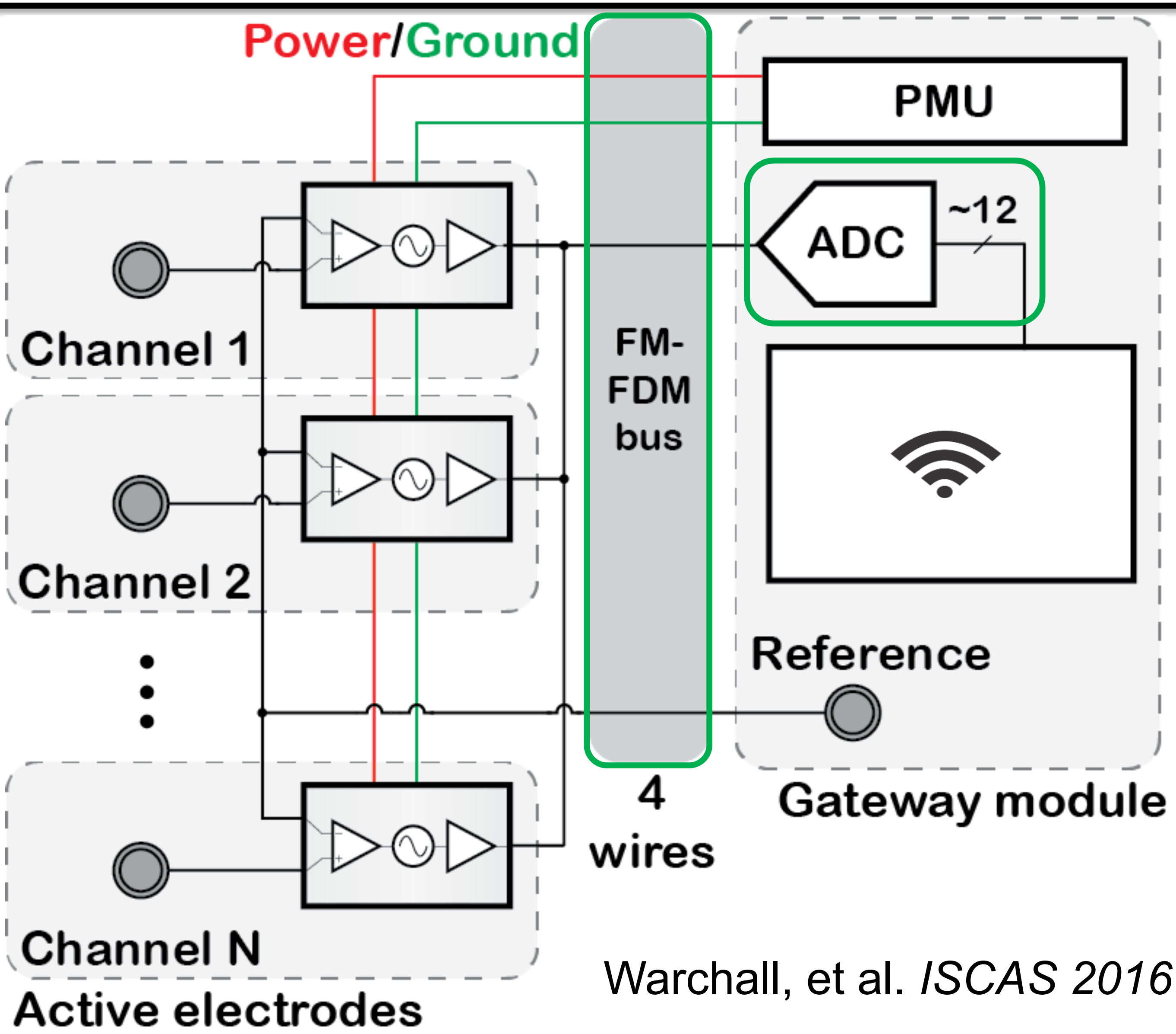

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FM-FDM:

Minimizes Wire Count,

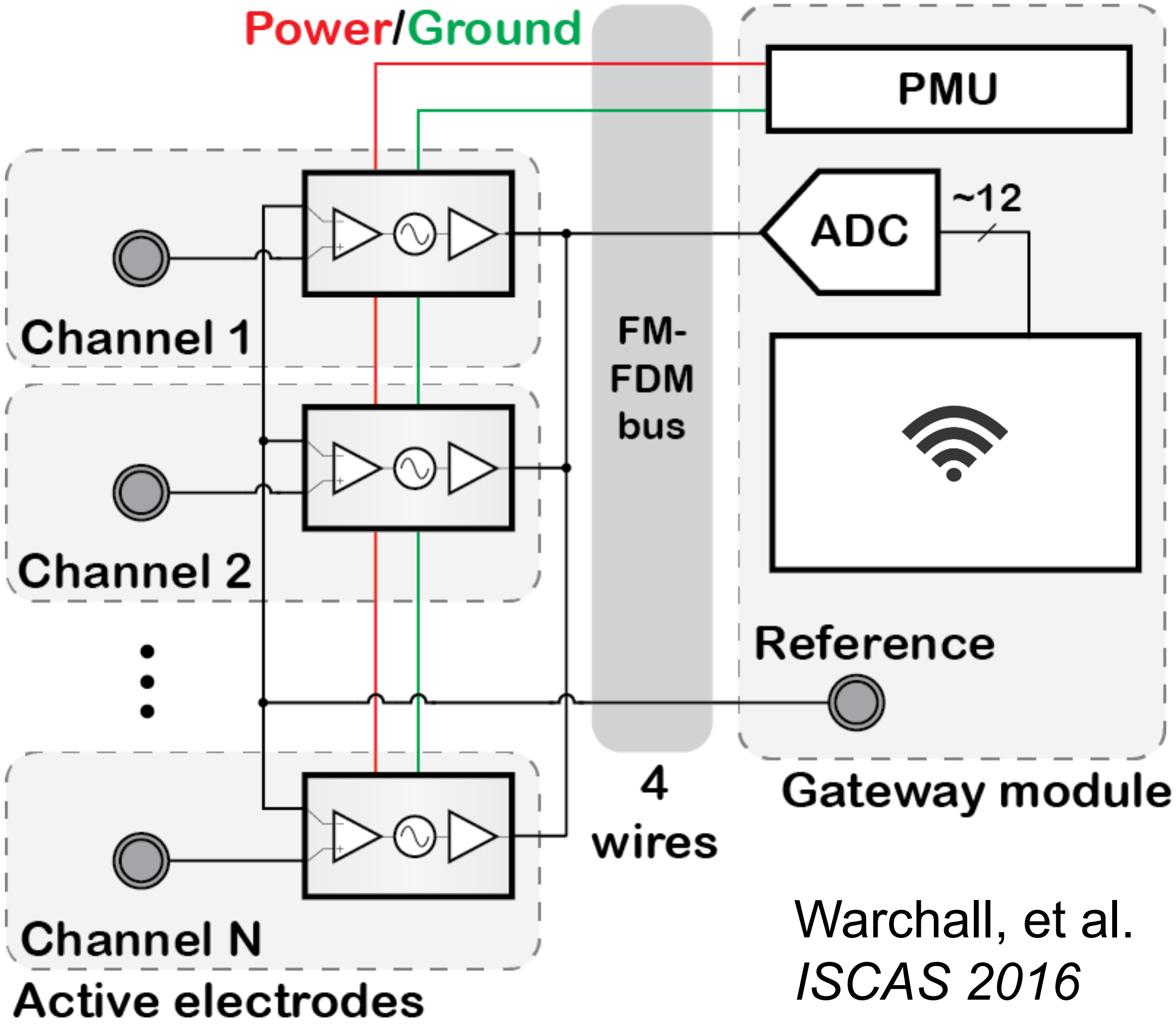
Mitigates Cable Sway,

Minimizes ADC Count

Why FM Multiplexing?

Other Multiplexing Possibilities:

- Serial Digital (TDM, I2C, SPI, etc.)
  - Requires *N* ~100dB DR ADCs for *N* channels
- FDM Digital (OOK, BPSK, QPSK, etc.)
  - Still requires *N* ~100dB DR ADCs
- AM-FDM
  - Requires one ~100dB DR ADC



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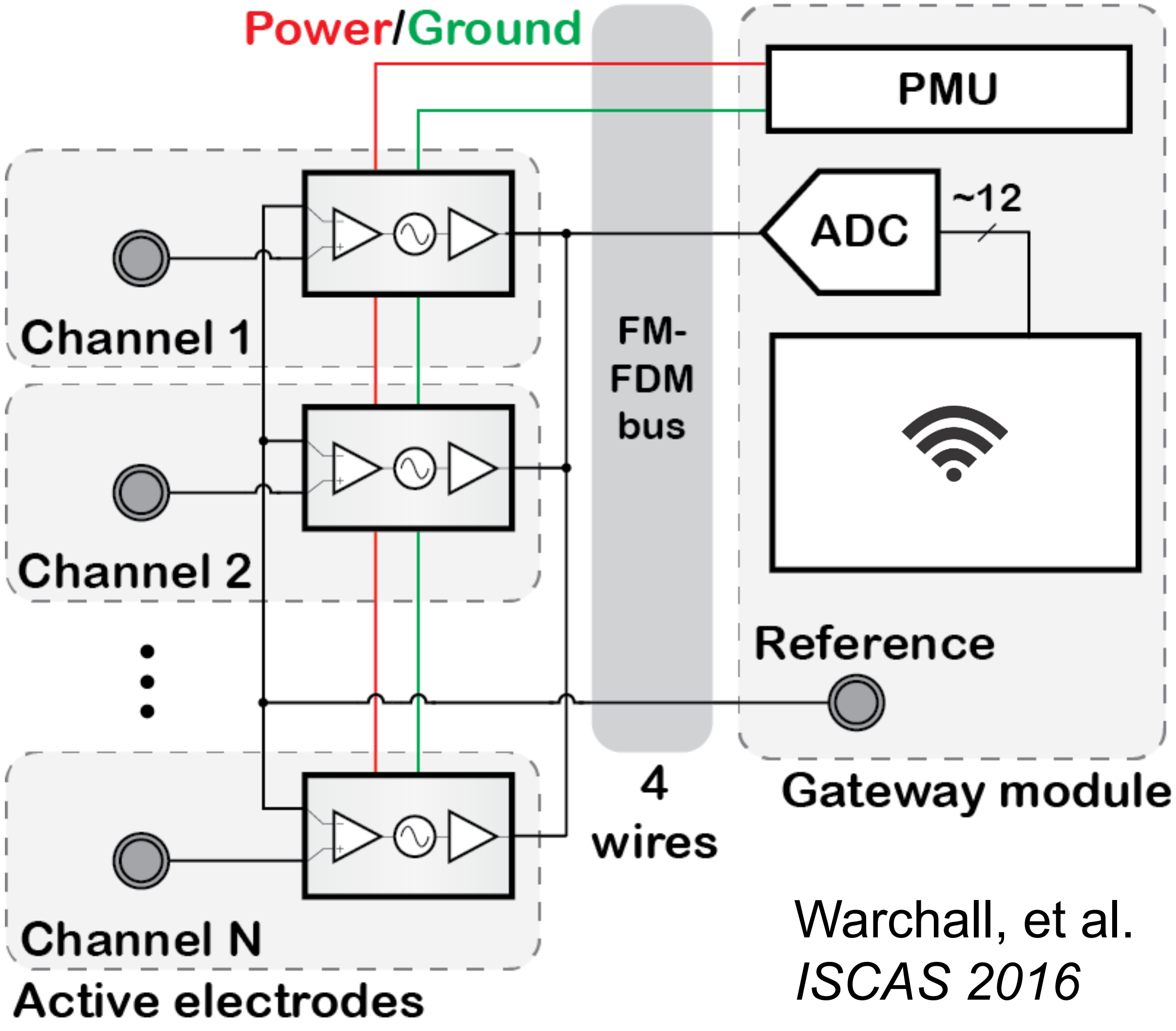
  - Single low bit depth high sample rate ADC
  - Leverages oversampling converter efficiency



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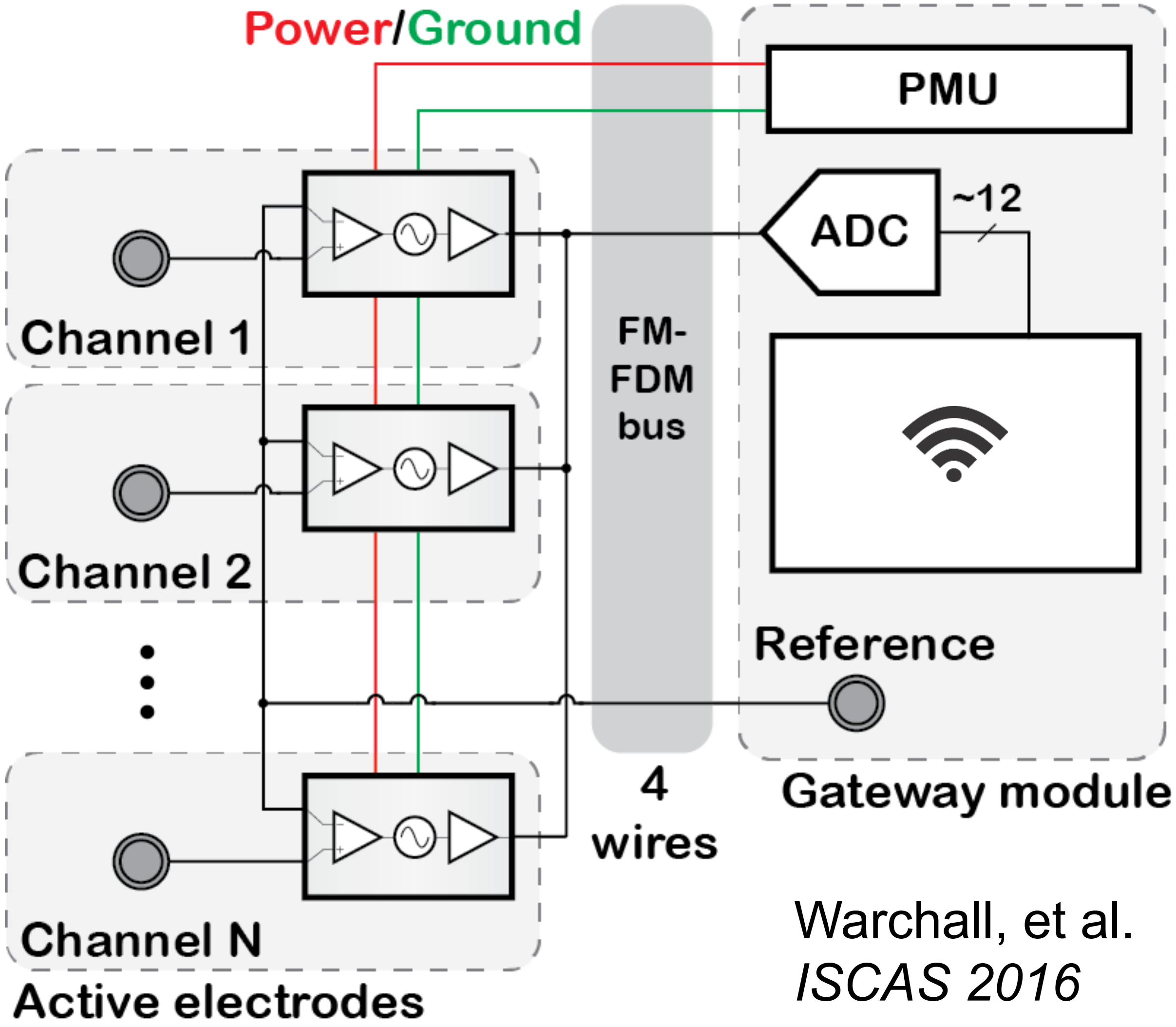

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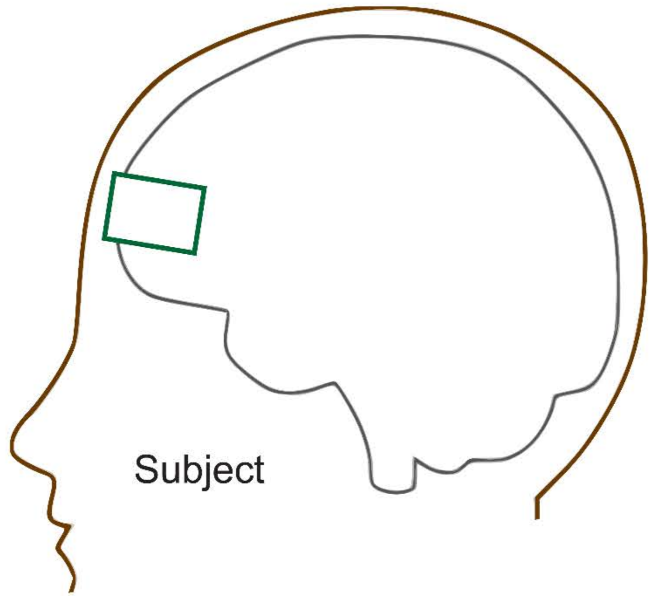
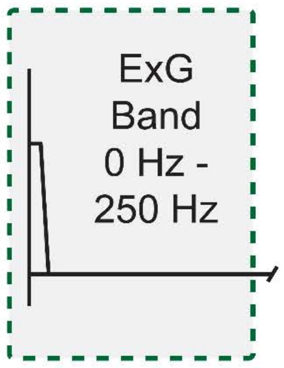
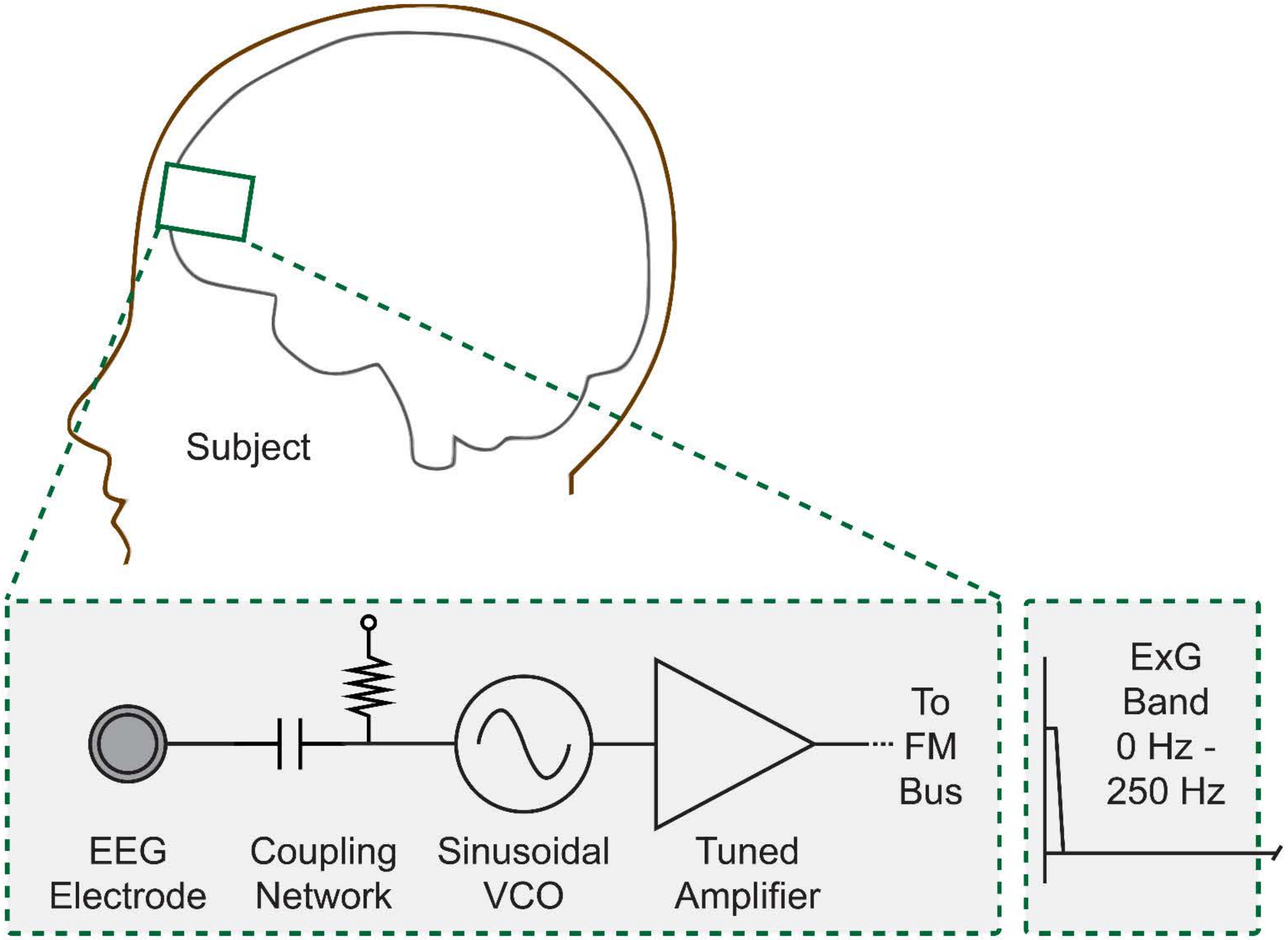
FM-FDM Also Reduces ADC Complexity, Maintains High DR

A Rugged Wearable Modular ExG Platform



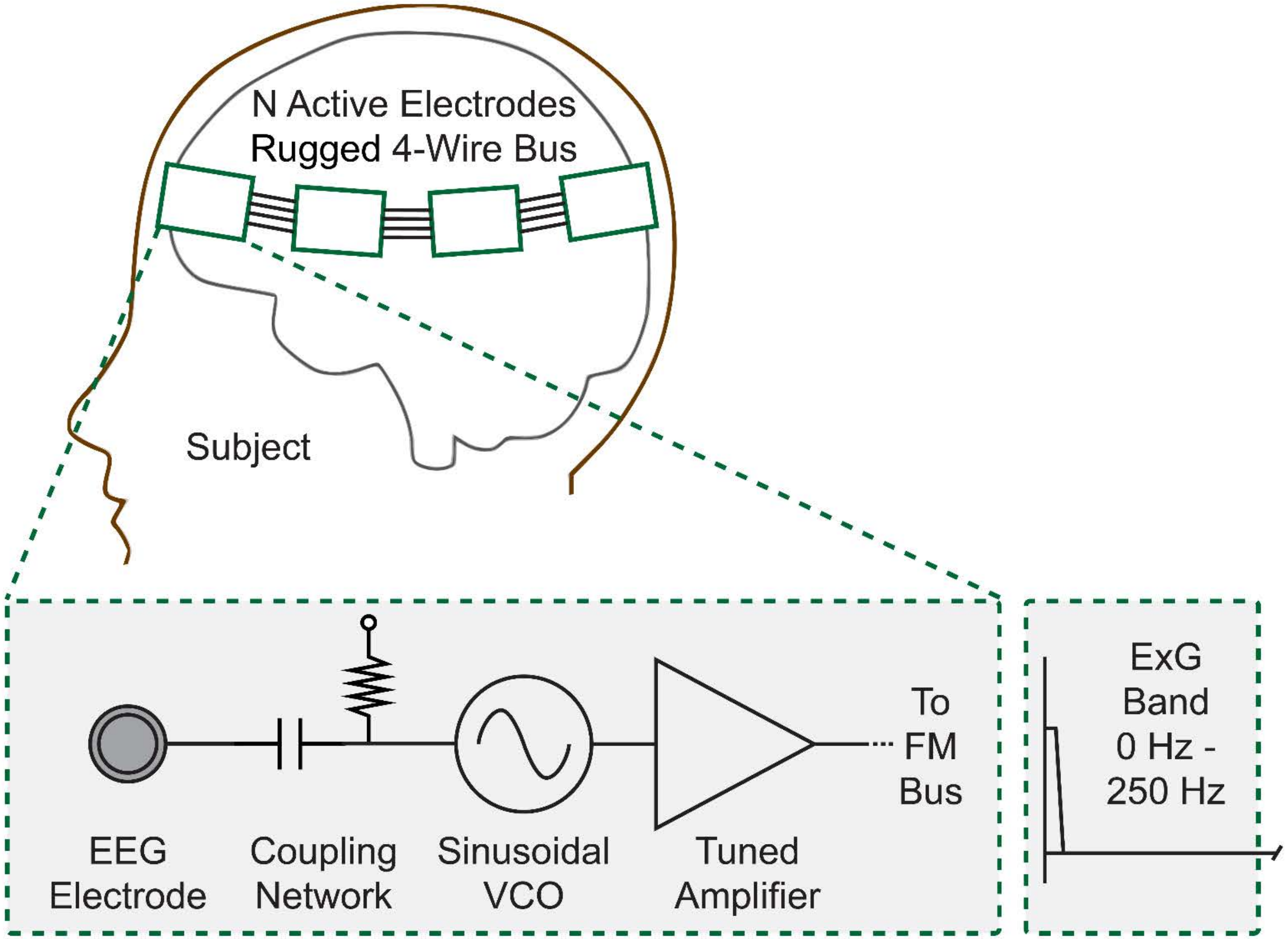


A Rugged Wearable Modular ExG Platform



Active Electrode Integrated Circuit

A Rugged Wearable Modular ExG Platform



Active Electrode Integrated Circuit

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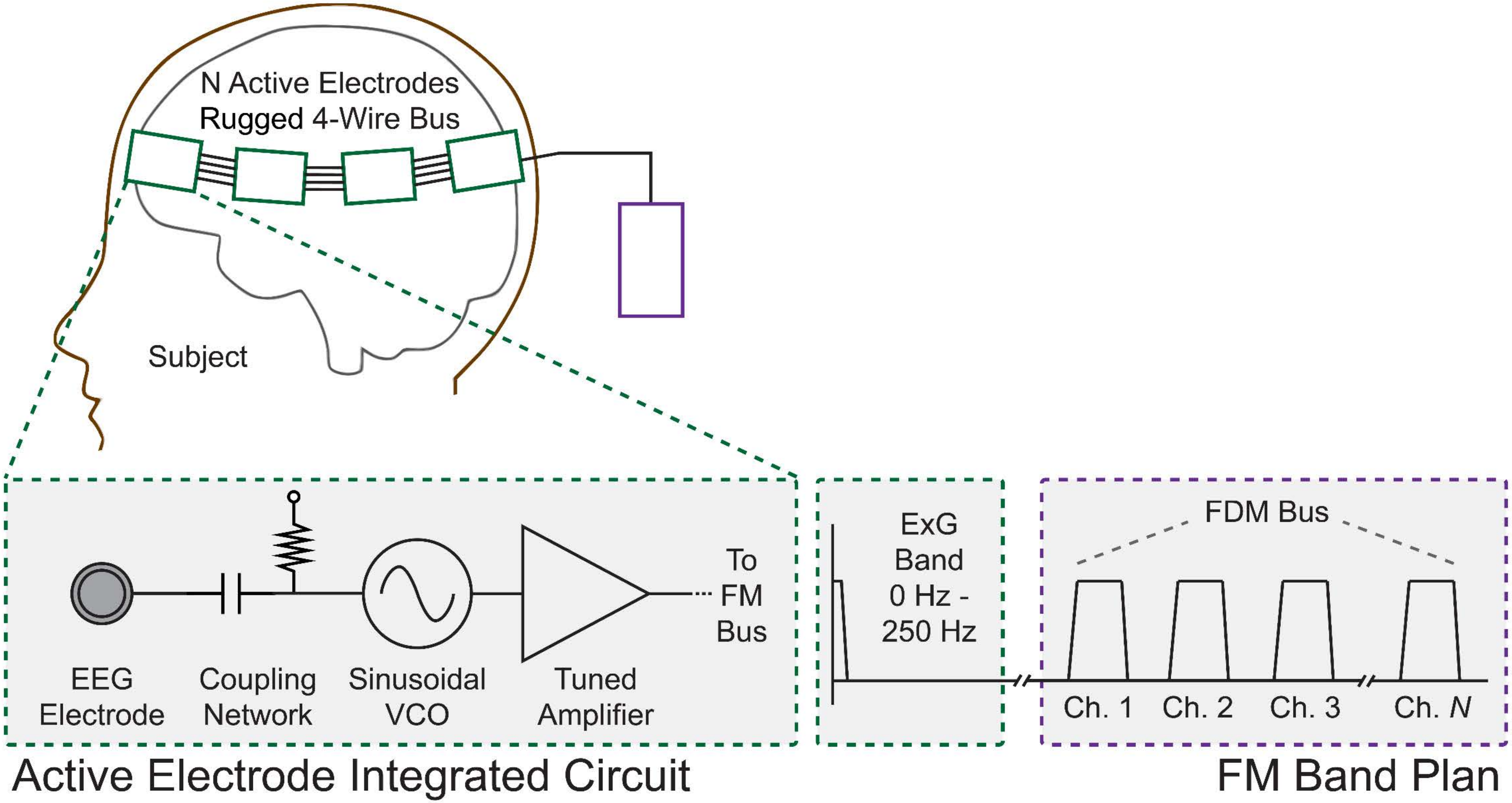

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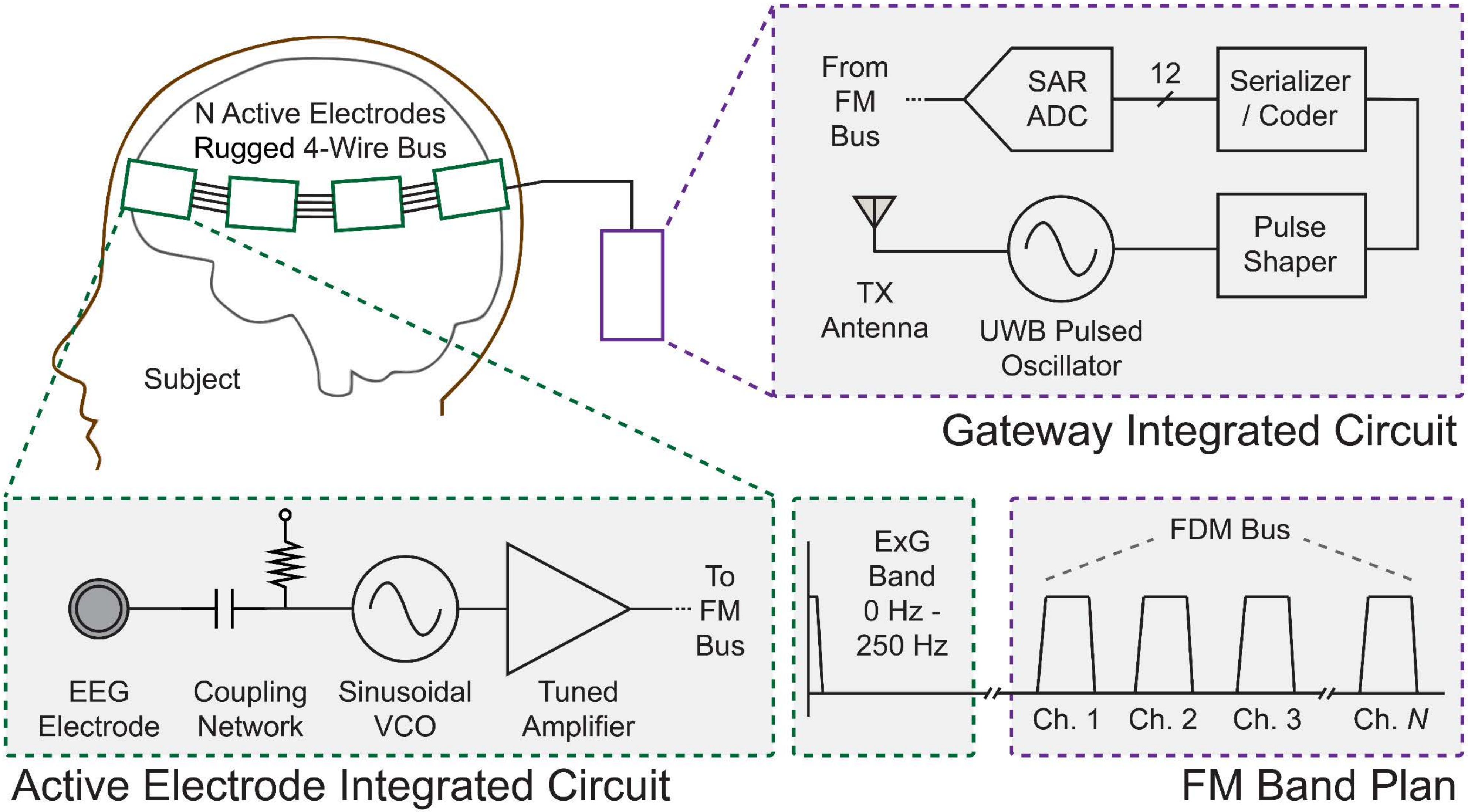

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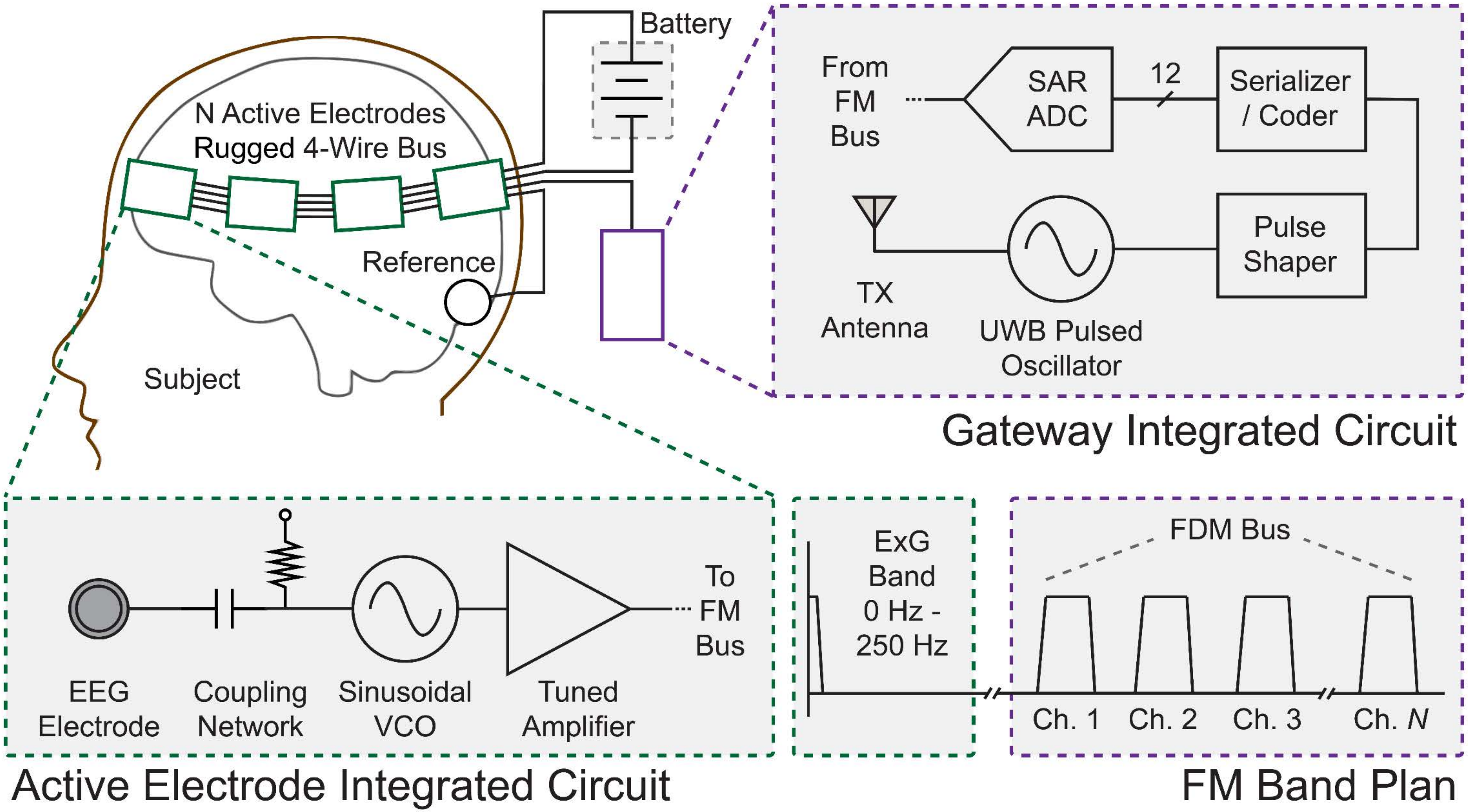
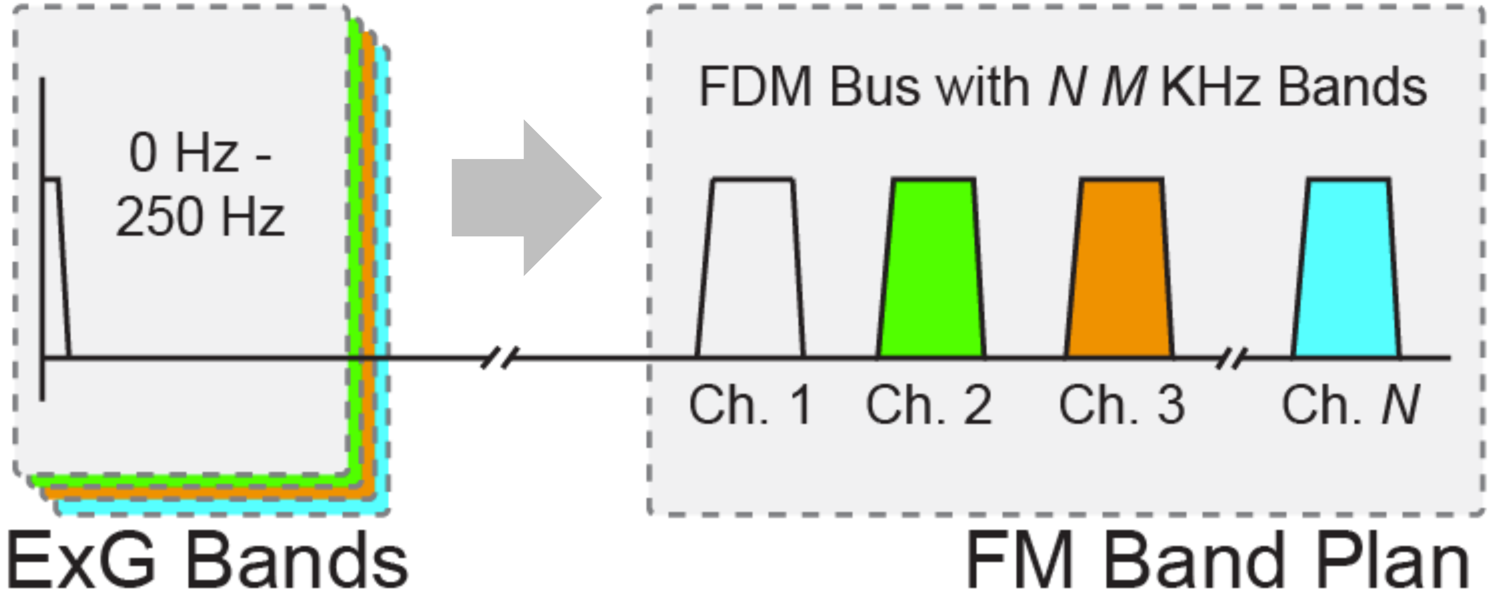
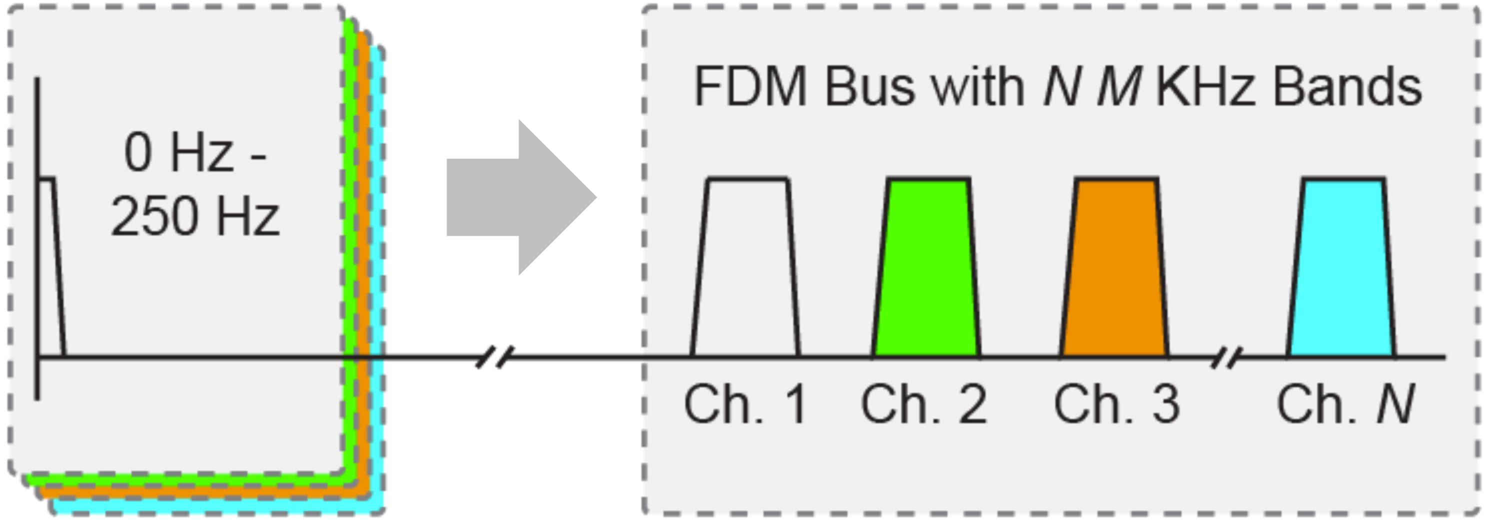


Bandwidth Expansion



$$\text{Bandwidth Expansion } D \approx \frac{M\ \text{KHz}}{250\text{Hz}}$$

Bandwidth Expansion



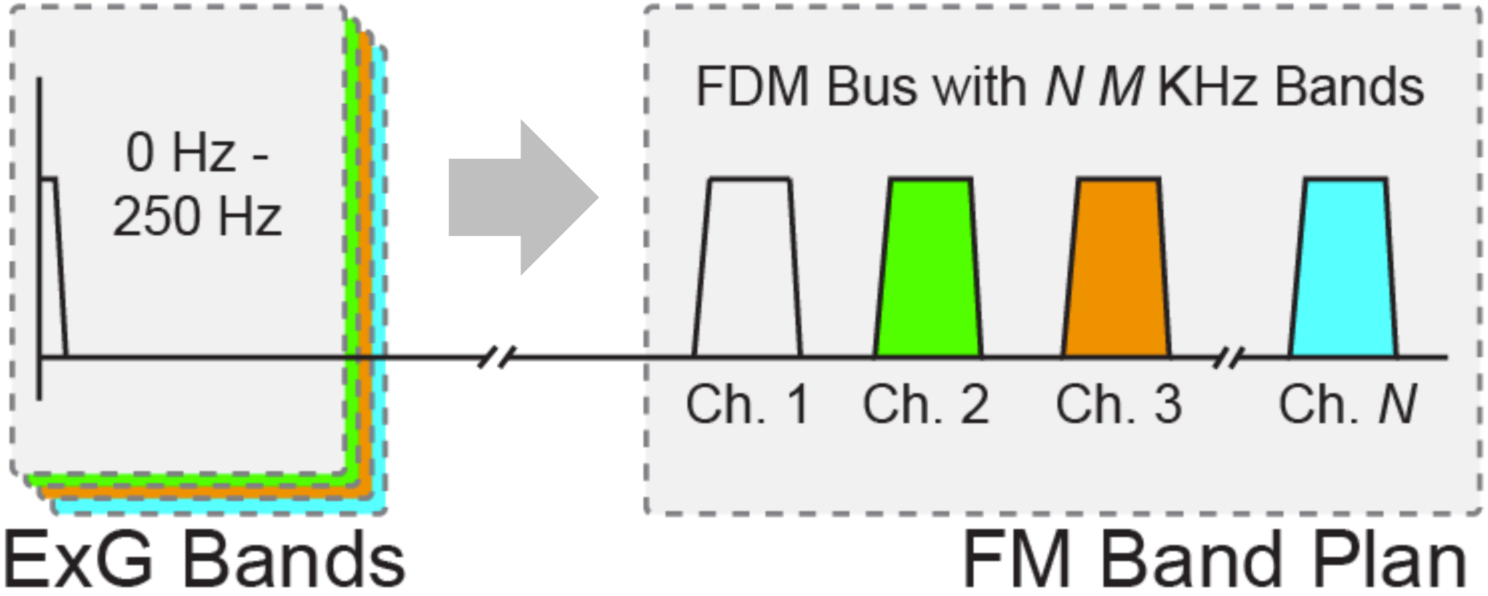
ExG Bands

FM Band Plan

$$\text{Bandwidth Expansion } D \approx \frac{M\ \text{KHz}}{250\text{Hz}}$$

$$SNR_{FM,MAX^*} = \underbrace{10\ log_{10}(\ 3D^2\,(D+1)\ )}_{\text{FM Coding Gain}} + \underbrace{CNR}_{\text{Gateway SAR SNR}}$$

Bandwidth Expansion



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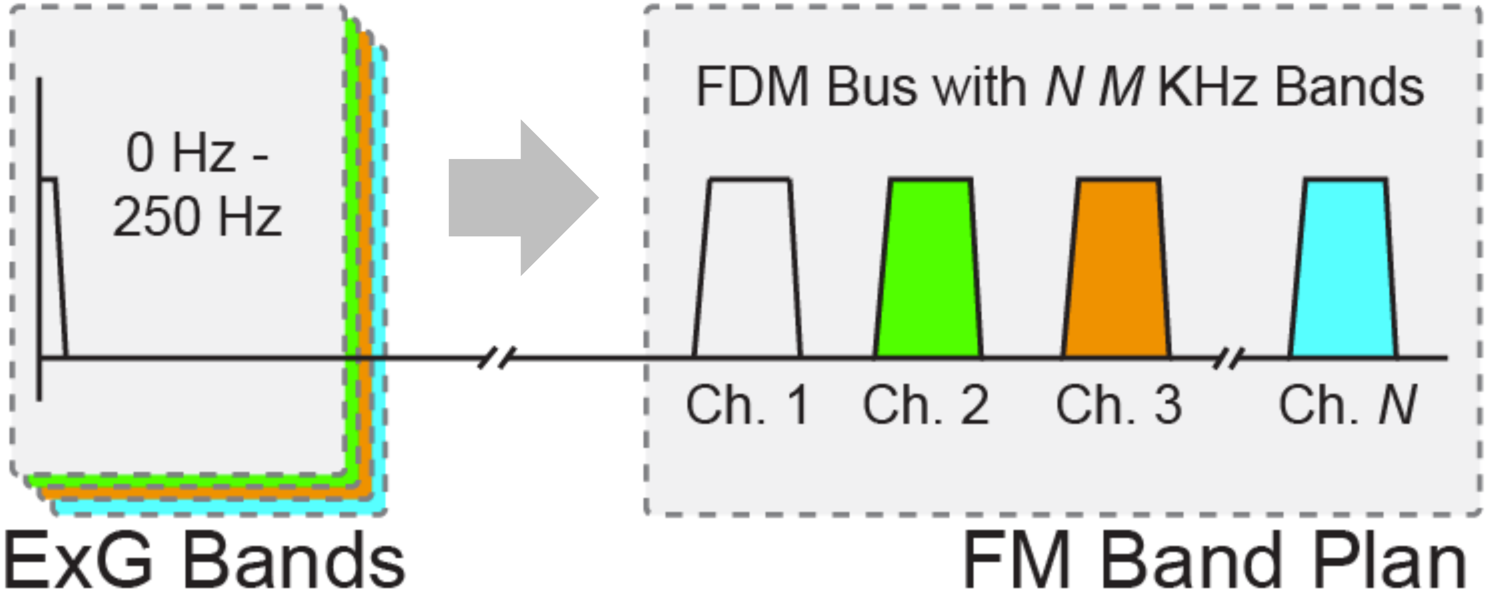

Really?

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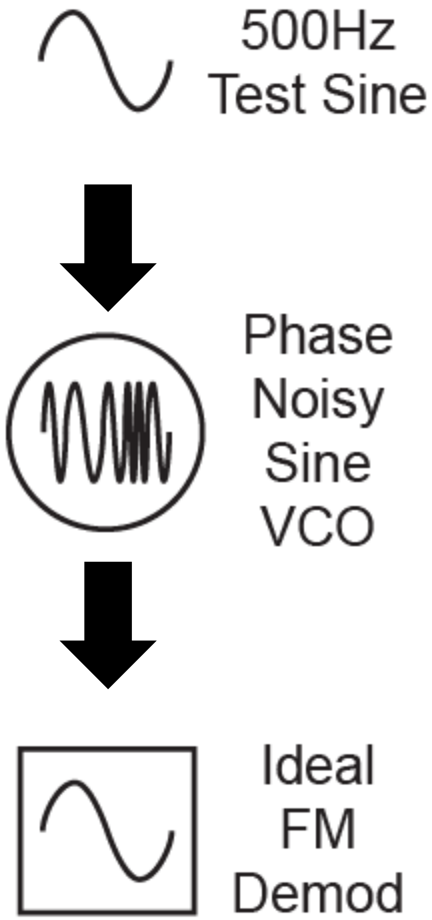
Phase Noise in FM VCO



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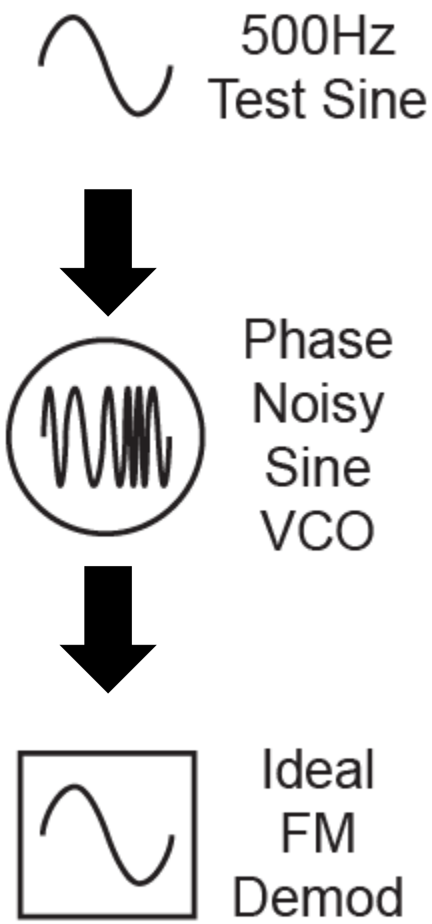
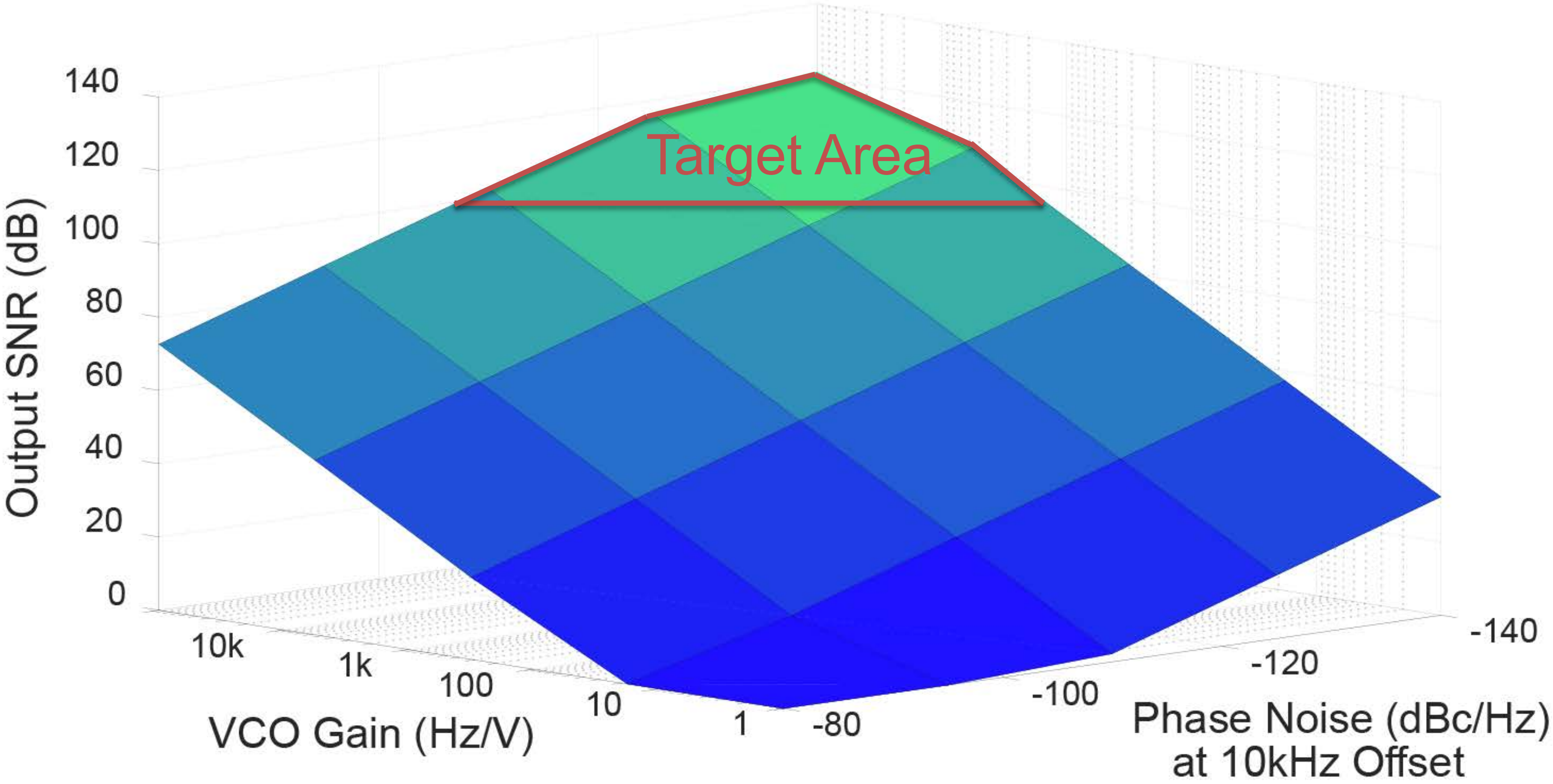
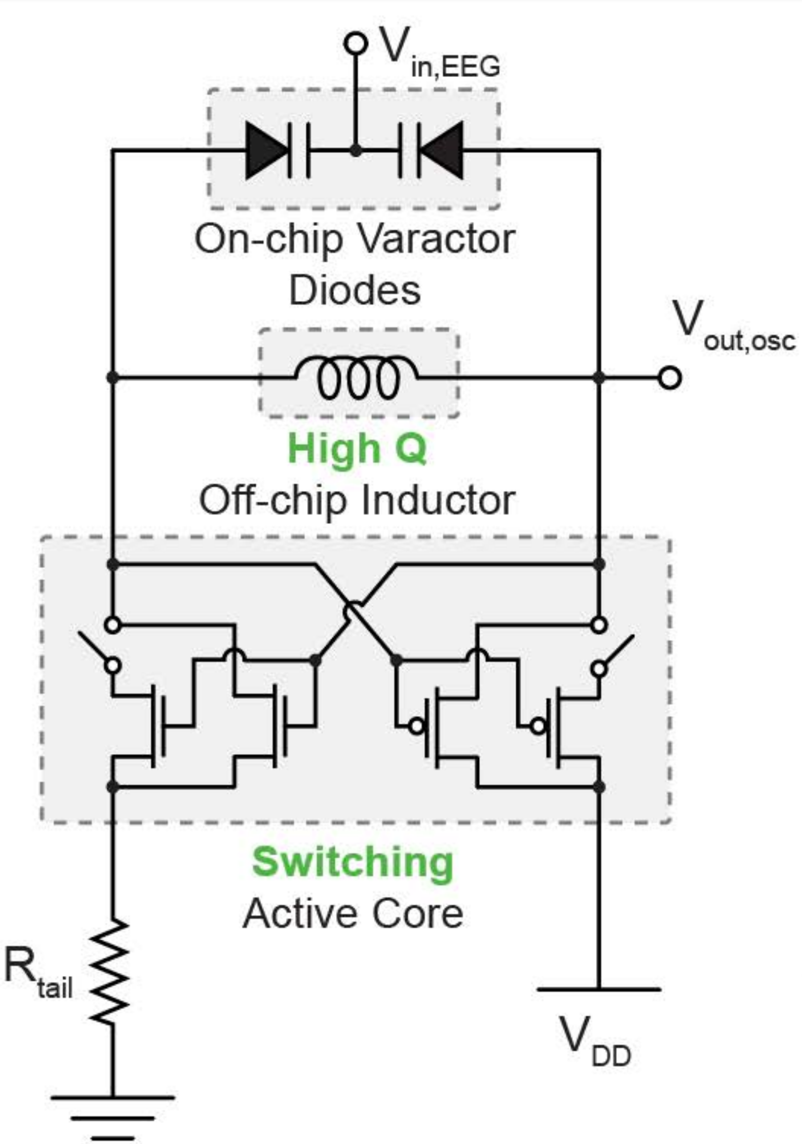




Low VCO Phase Noise Maintains High System SNR

Active Electrode Design



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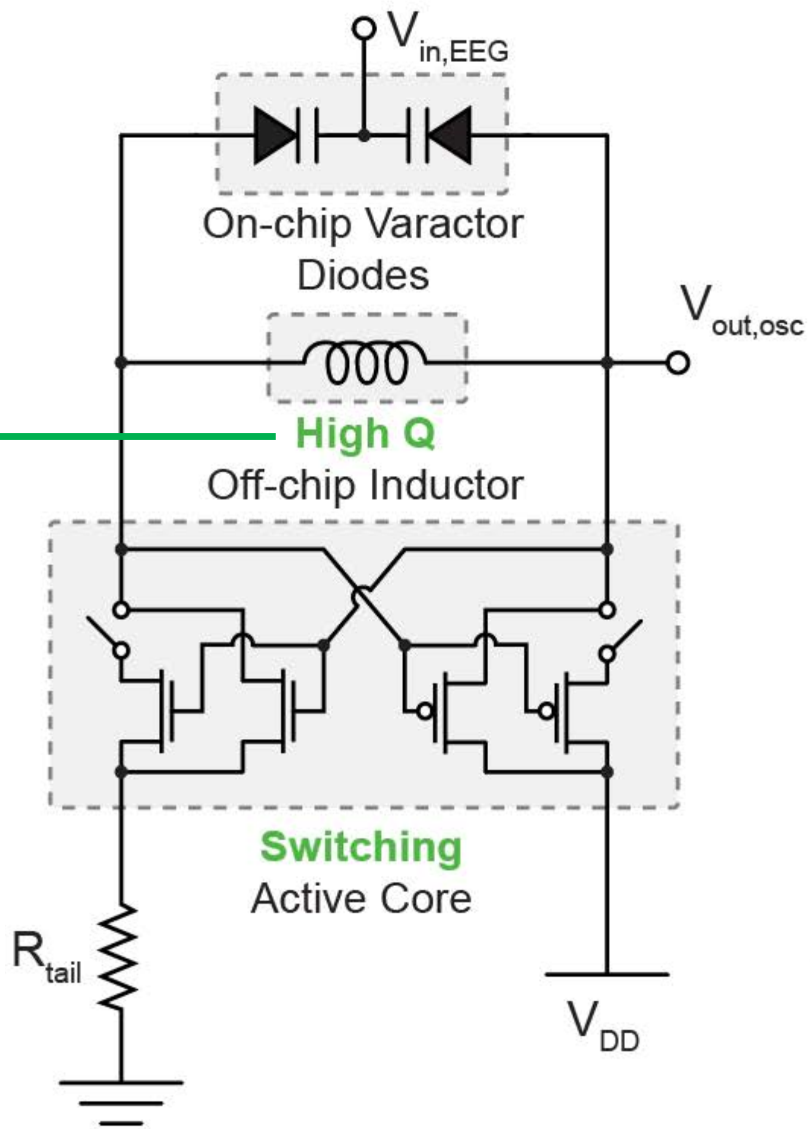

Low Phase Noise
Maintains High SNR

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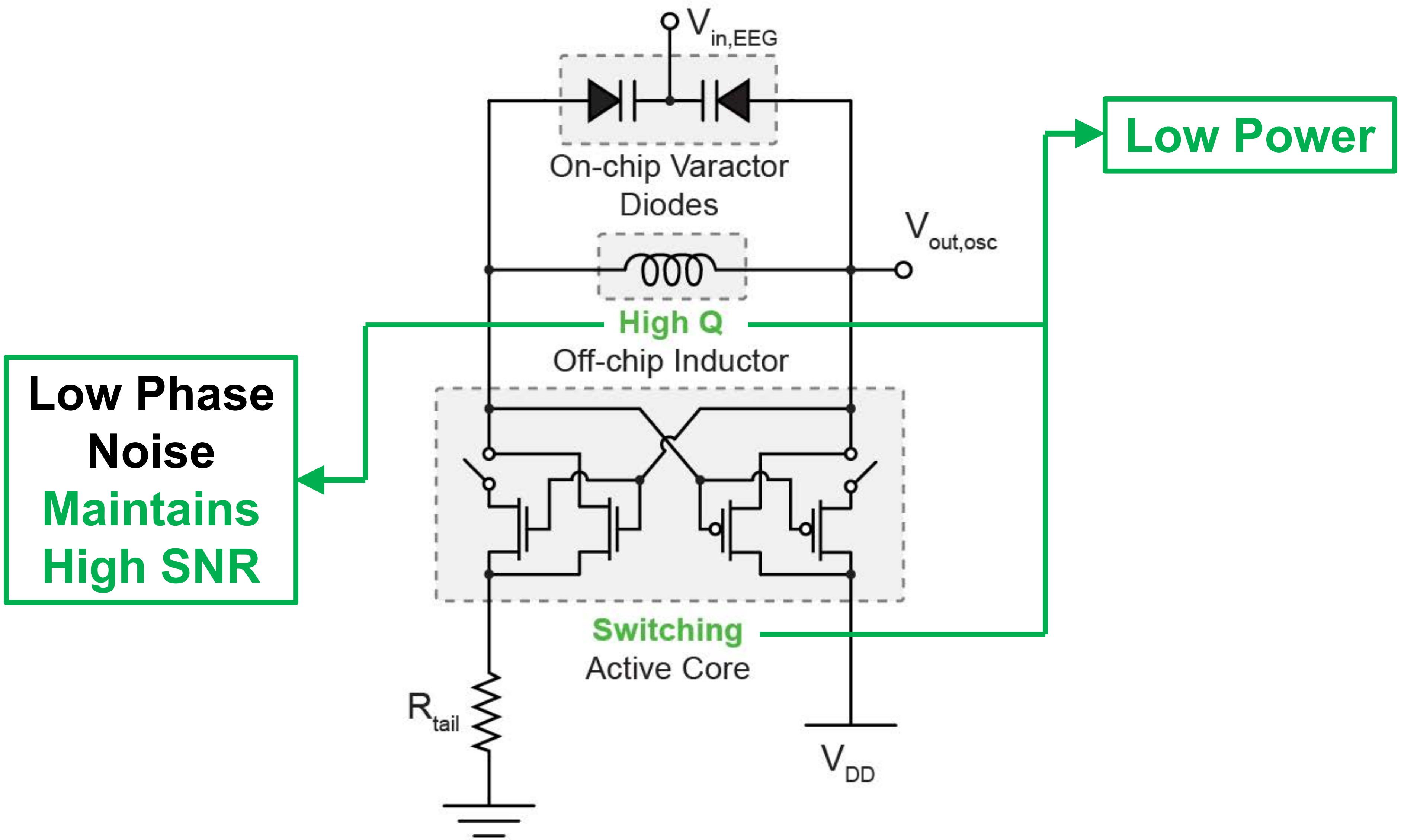

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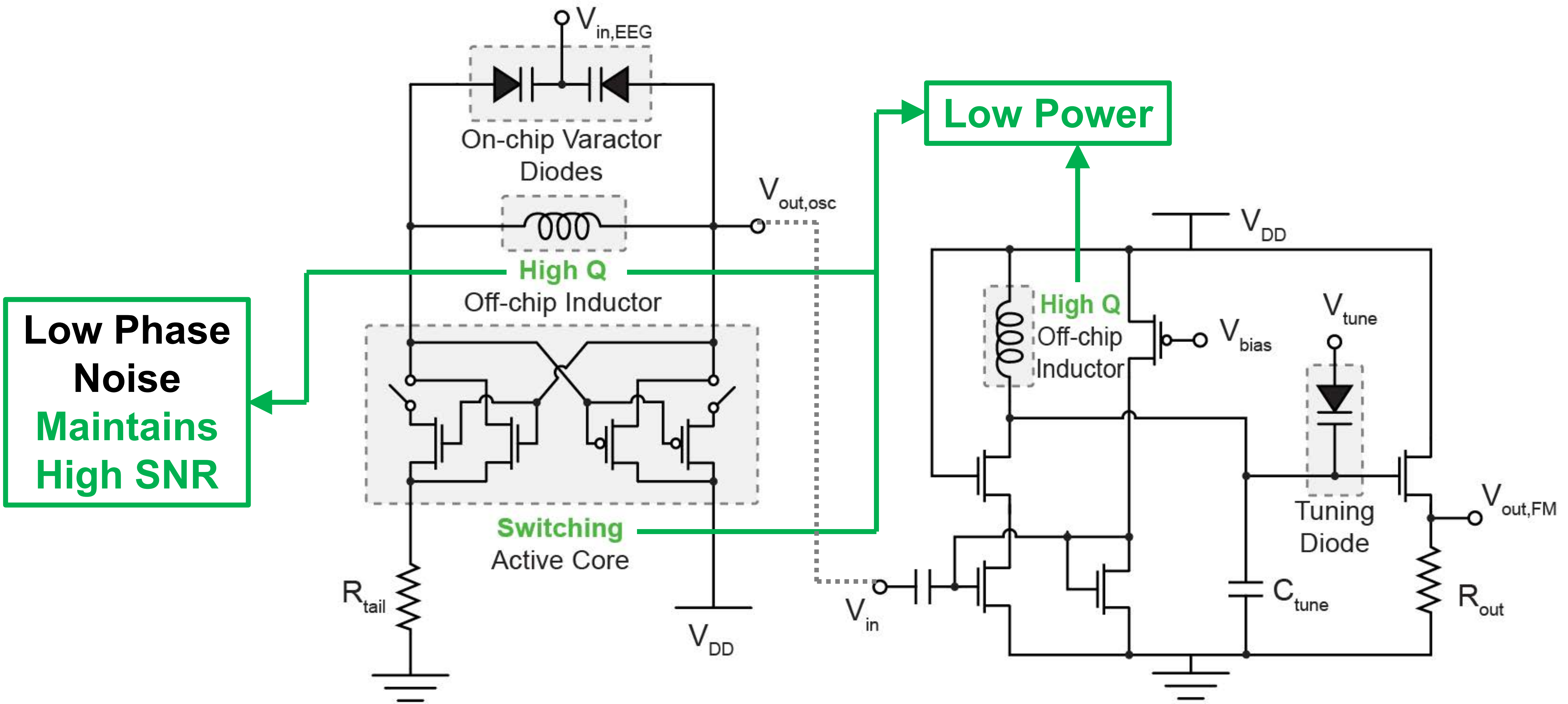

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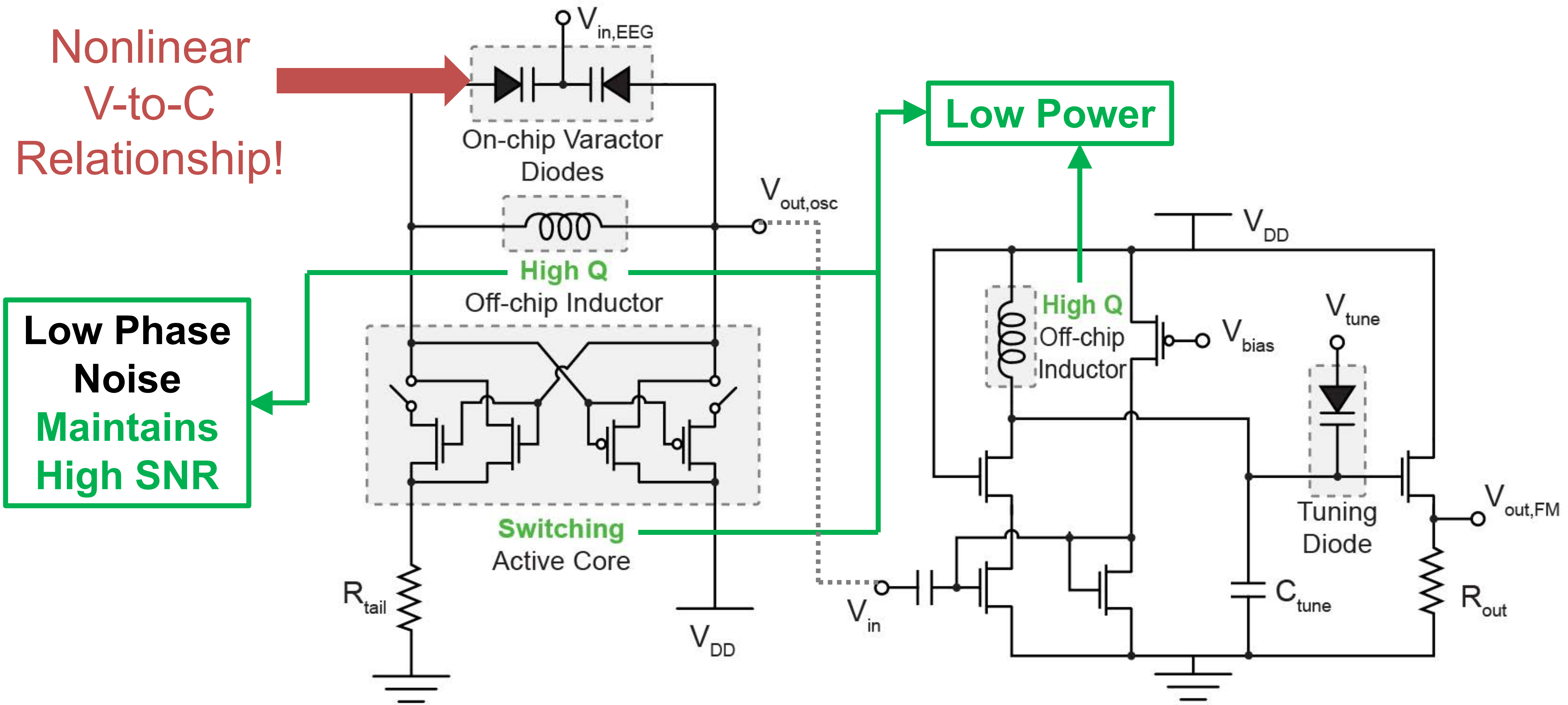
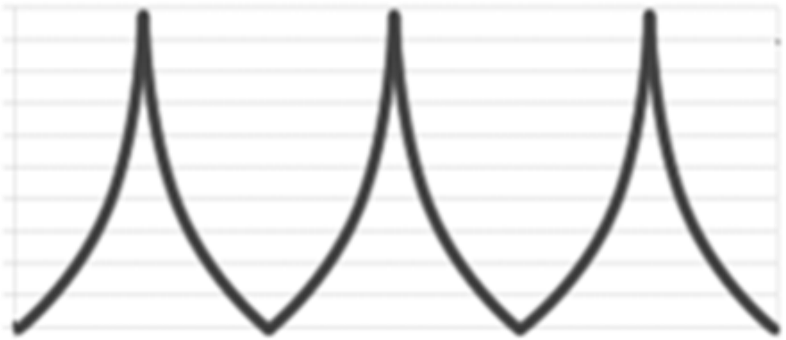


Active Electrode Nonlinearity

Electrode Input

System Output



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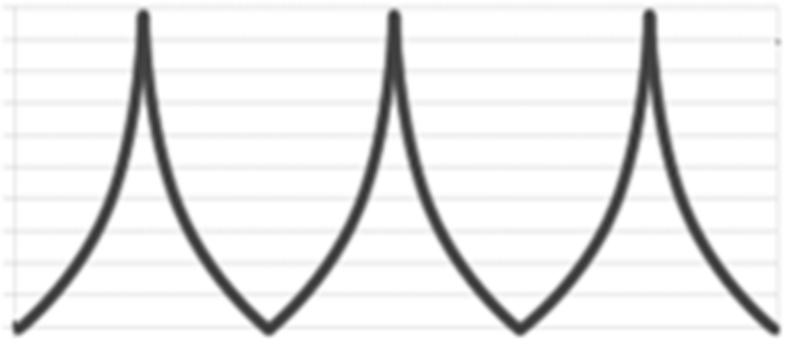

Derive Polynomial Transform

Active Electrode Nonlinearity

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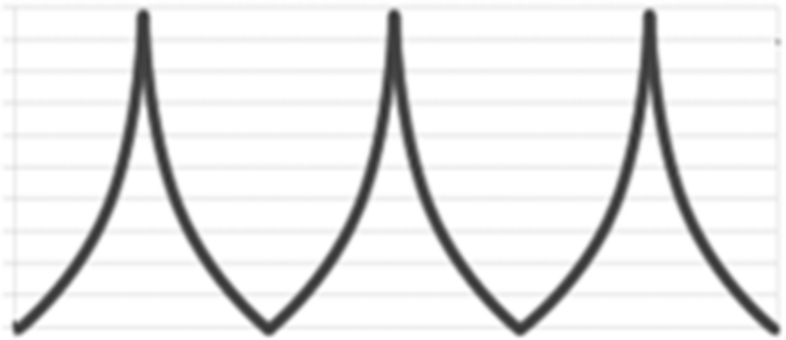
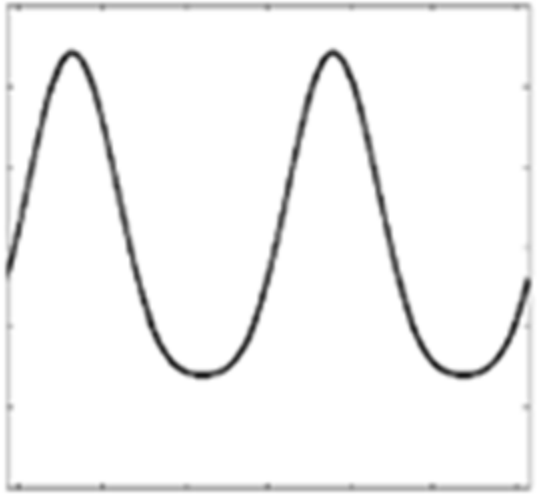
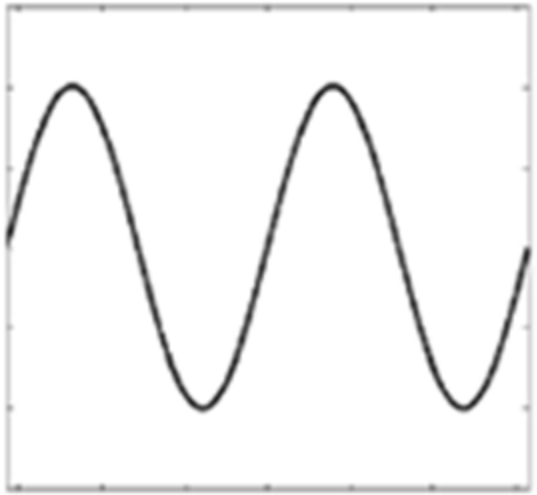


Derive Polynomial Transform

With Calibration:

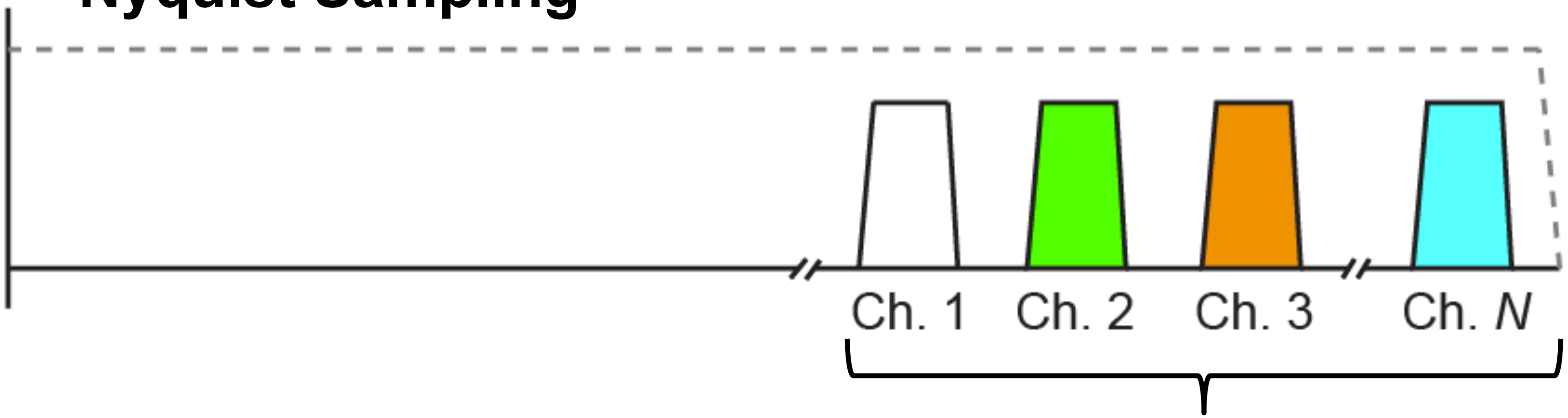




Calibration Gains ~20dB SNDR!

Gateway Power Saving

Nyquist Sampling

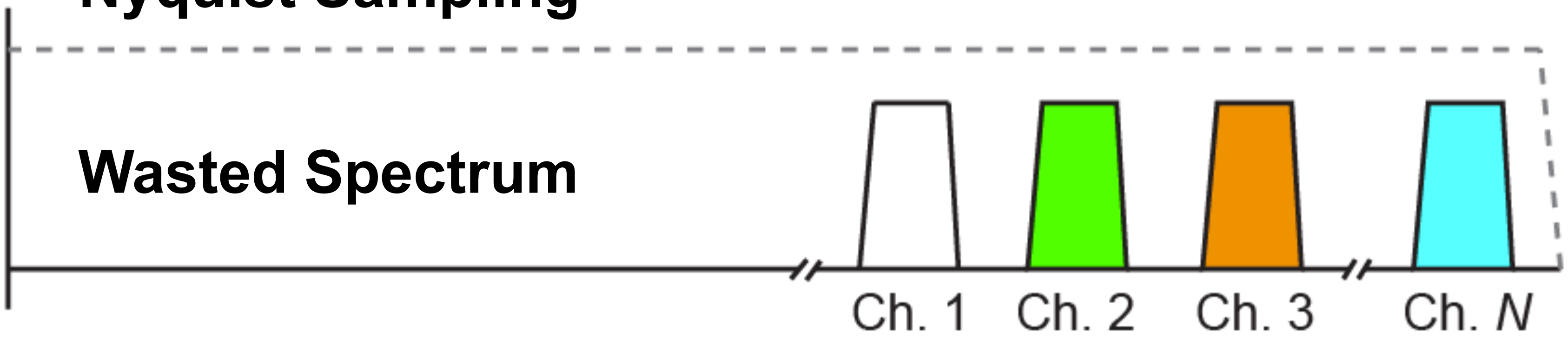


FM Channels Higher Frequency
→ Lower Varactor Nonlinearity

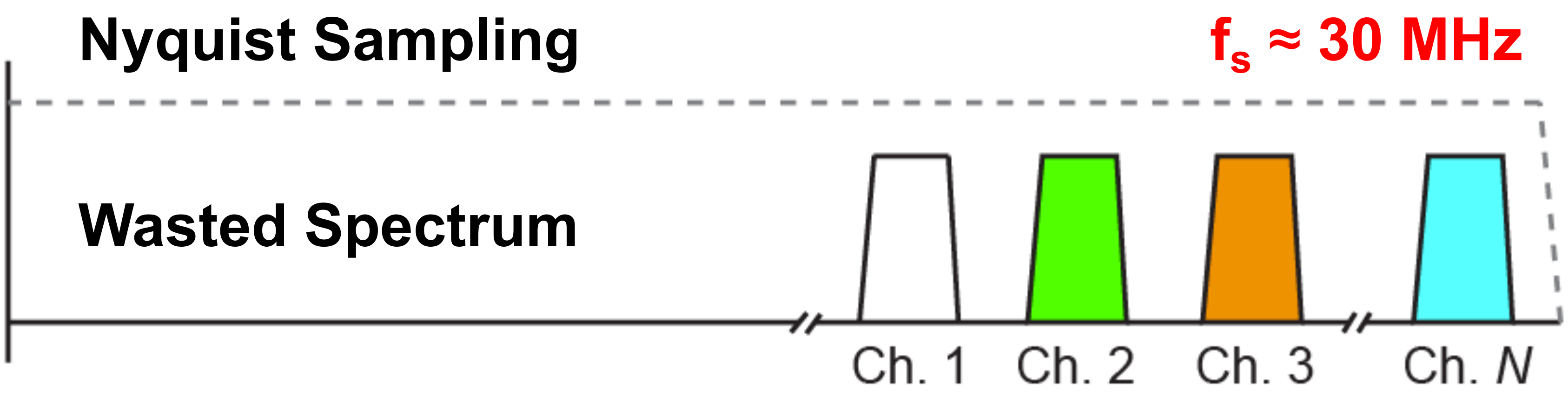
Gateway Power Saving

Nyquist Sampling

Wasted Spectrum



Gateway Power Saving

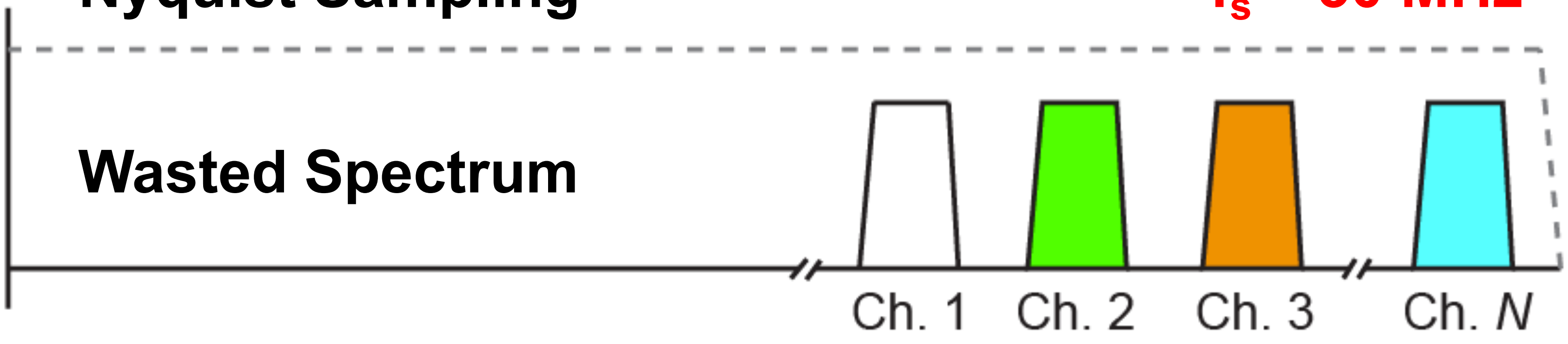


$f_s \approx 30$ MHz ➡ Sampling Power: 3 Milliwatts

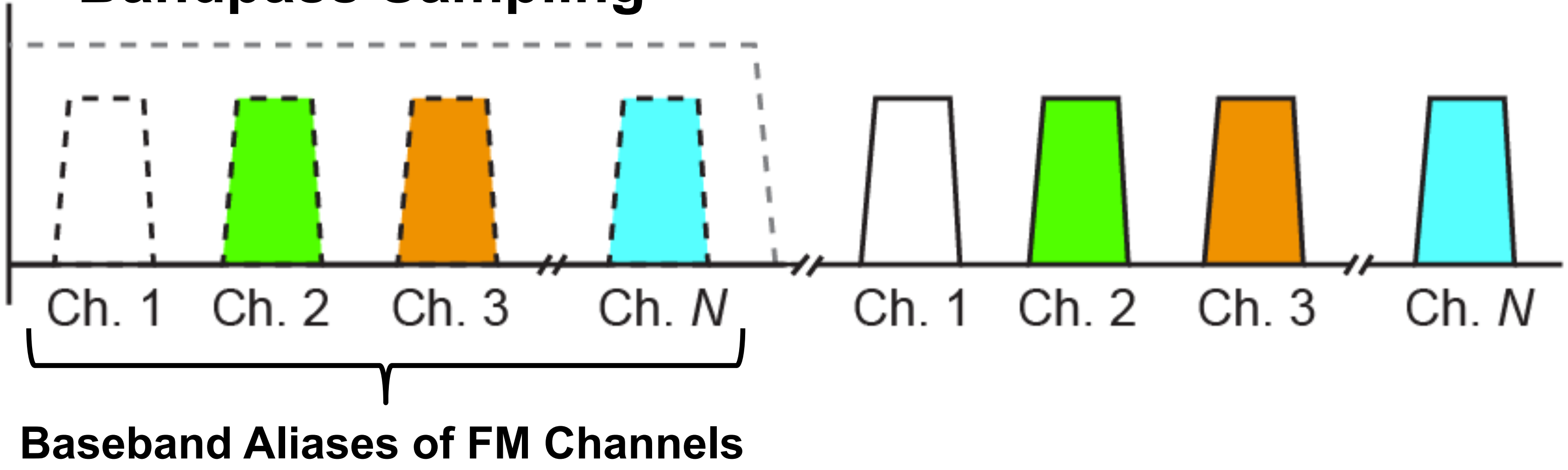
Gateway Power Saving

Nyquist Sampling

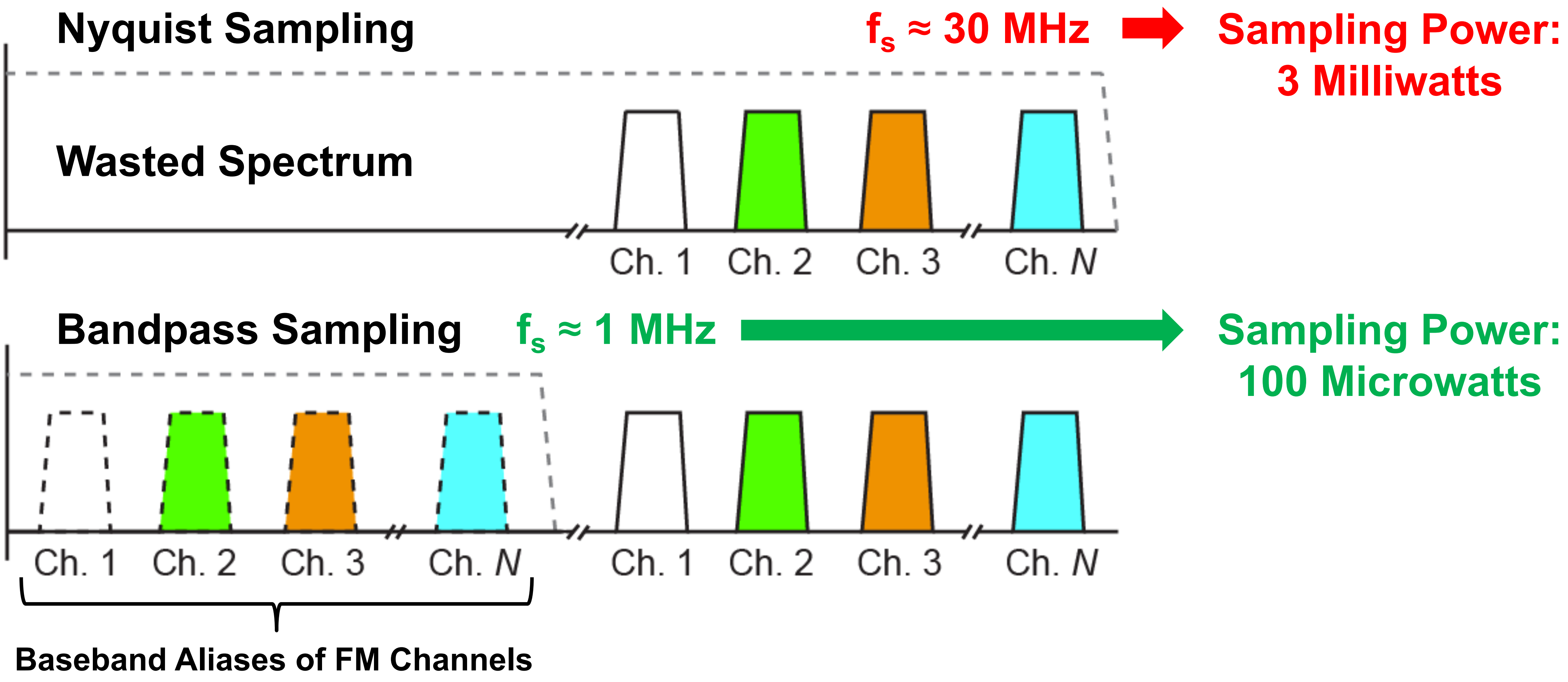
$f_s \approx 30$ MHz ➡ **Sampling Power: 3 Milliwatts**



Bandpass Sampling



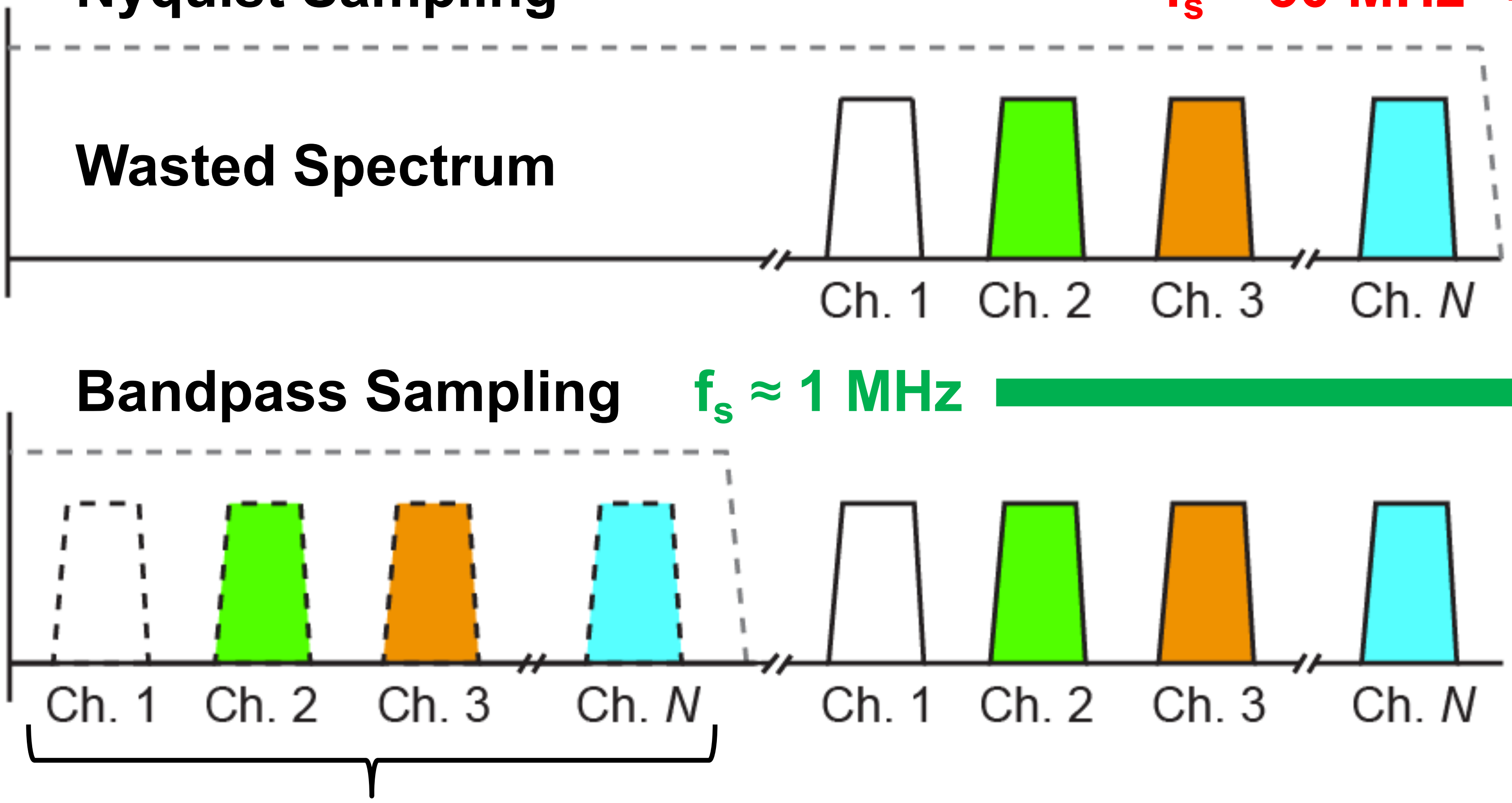
Gateway Power Saving



Gateway Power Saving

Nyquist Sampling $f_s \approx 30$ **MHz** → **Sampling Power: 3 Milliwatts**

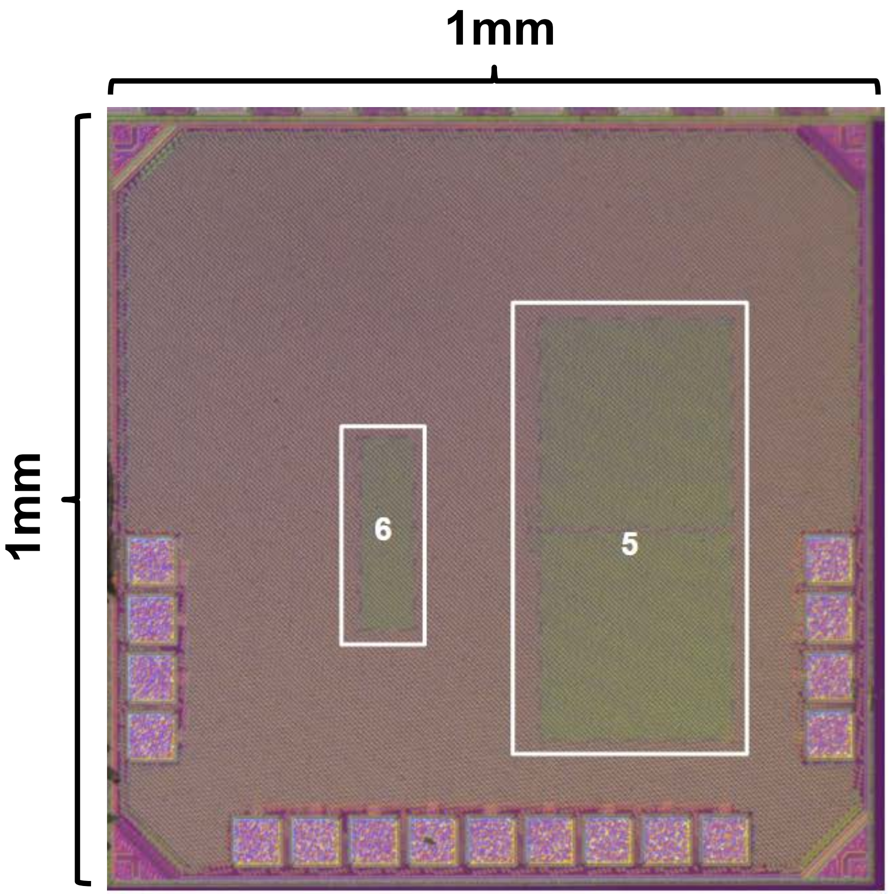
Bandpass Sampling $f_s \approx 1$ **MHz** → **Sampling Power: 100 Microwatts**

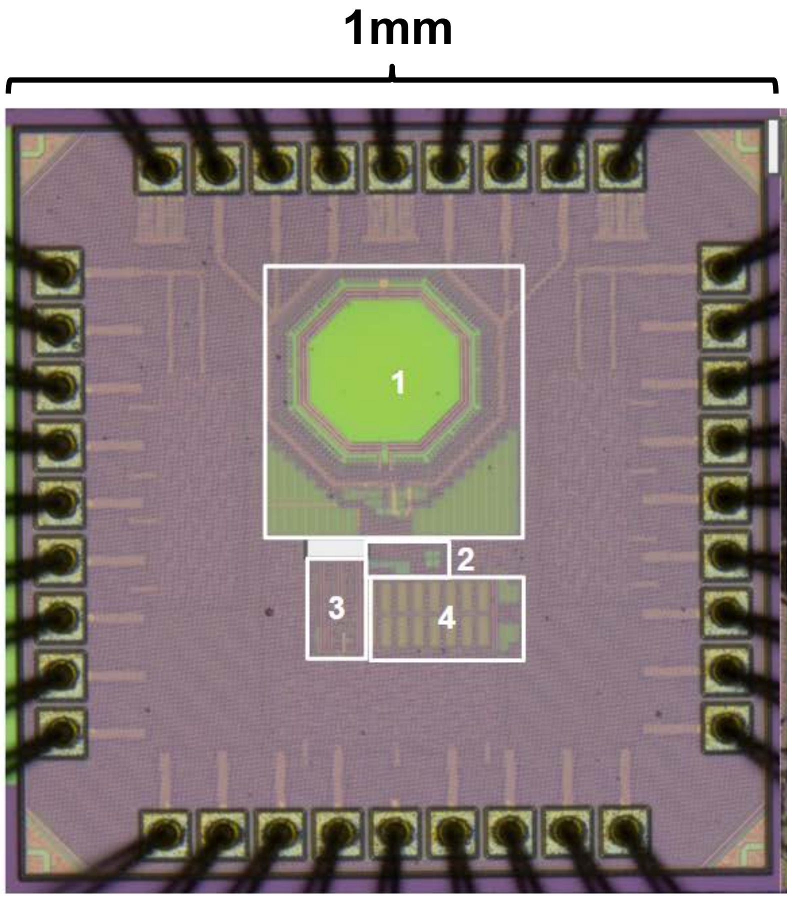


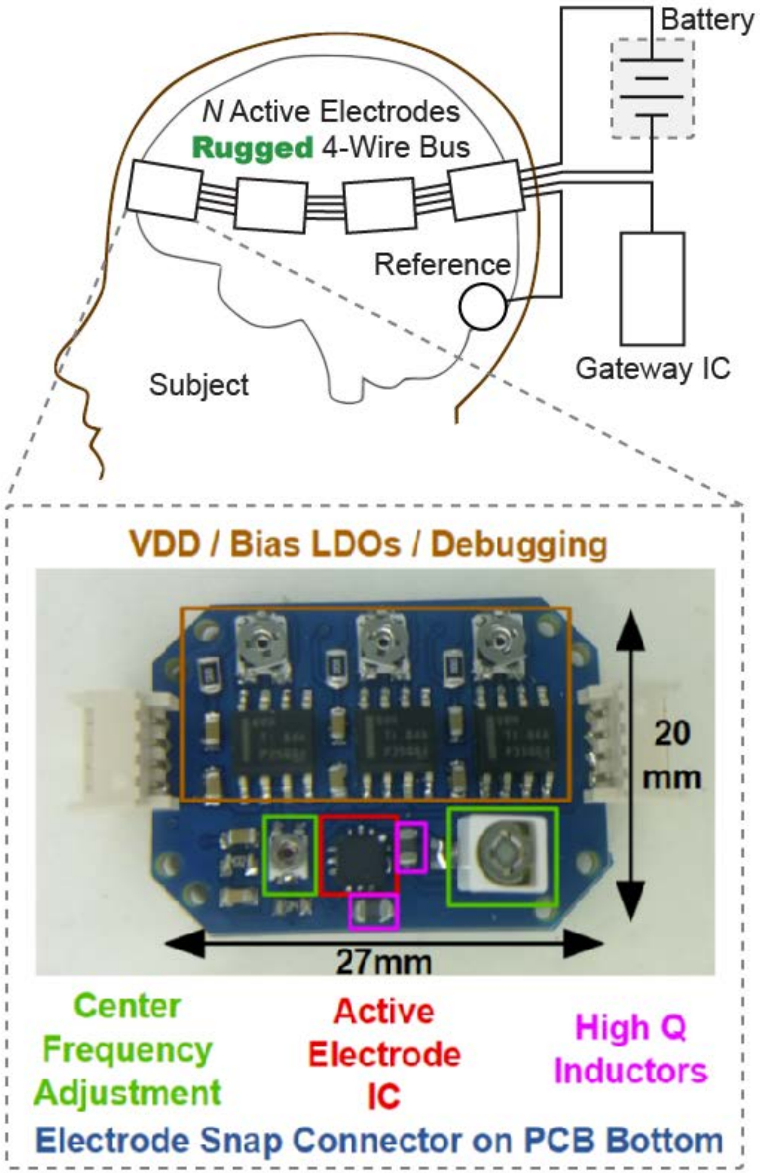
Baseband Aliases of FM Channels

Bandpass Sampling Reduces Sampling Power by ~30x

Two Chip System Implementation







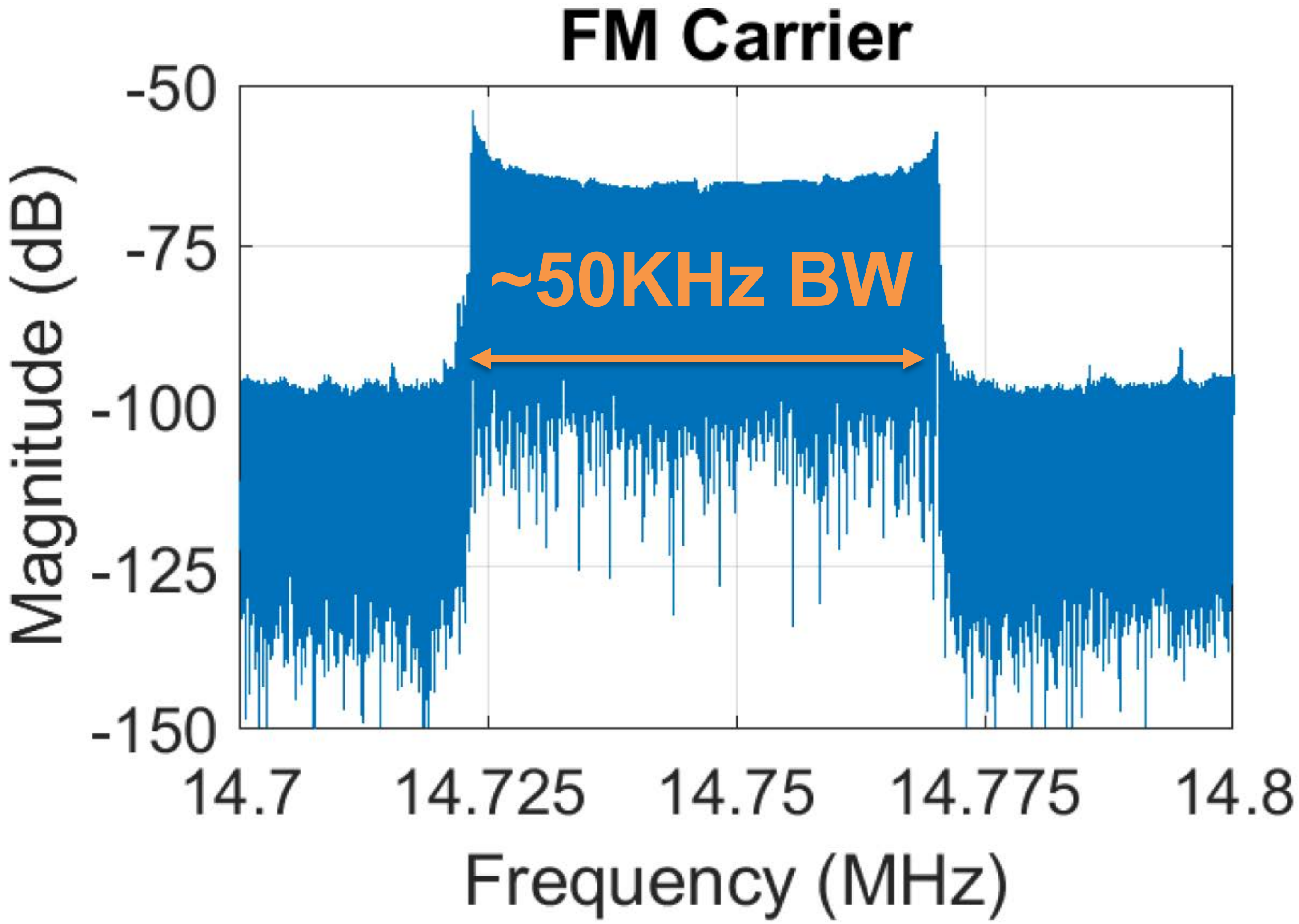
Active Electrode IC
5 – VCO
6 – Tuned Drive Amplifier

Gateway IC
1 – UWB TX
2 – Pulse Shaper
3 – Serializer/Coder
4 – SAR ADC

Single Channel Measurement Results

Full-Scale 10mVpp 10Hz Sine Test Message

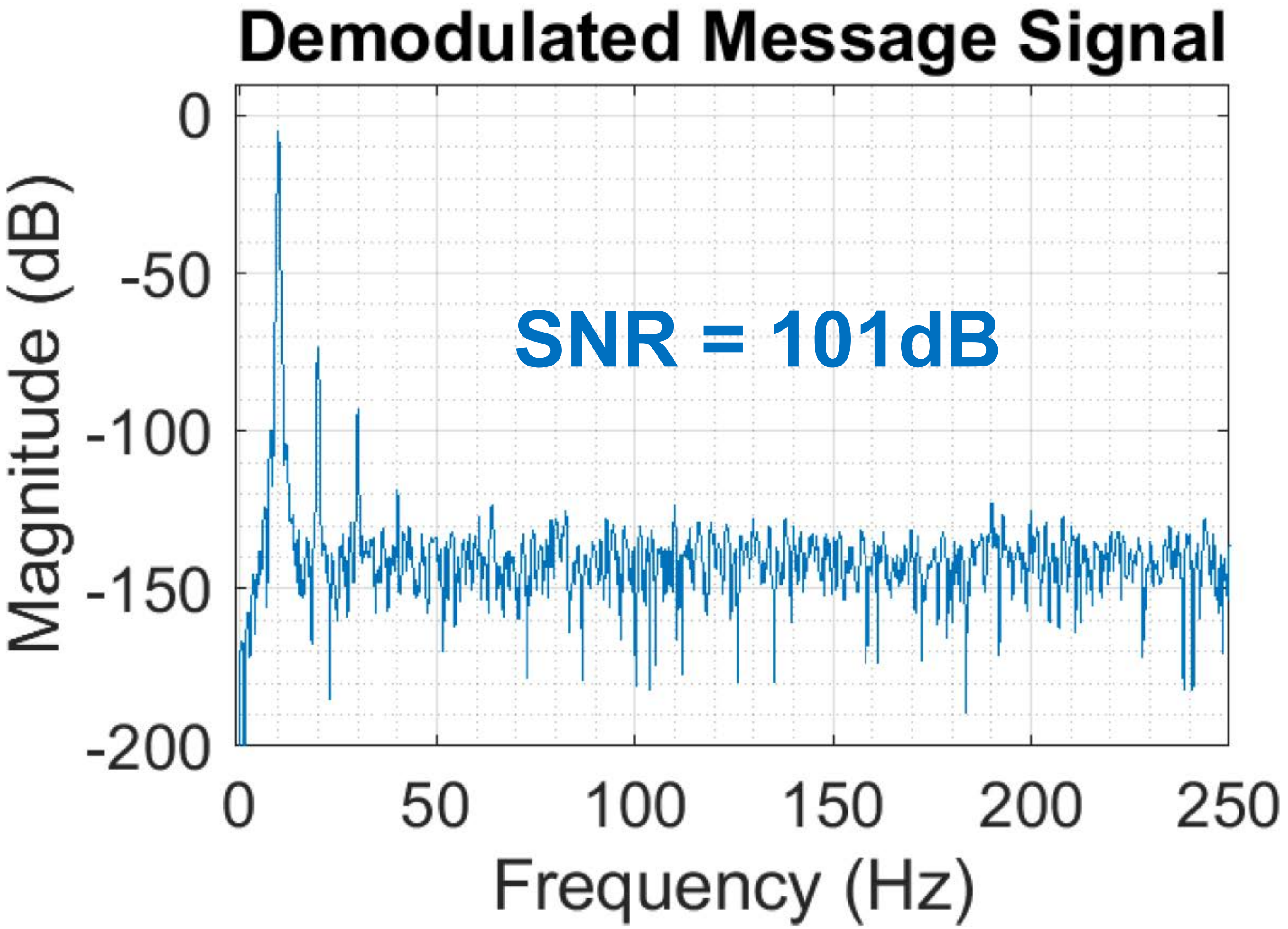
Probed at VCO Output



Single Channel Measurement Results

Full-Scale 10mVpp 10Hz Sine Test Message

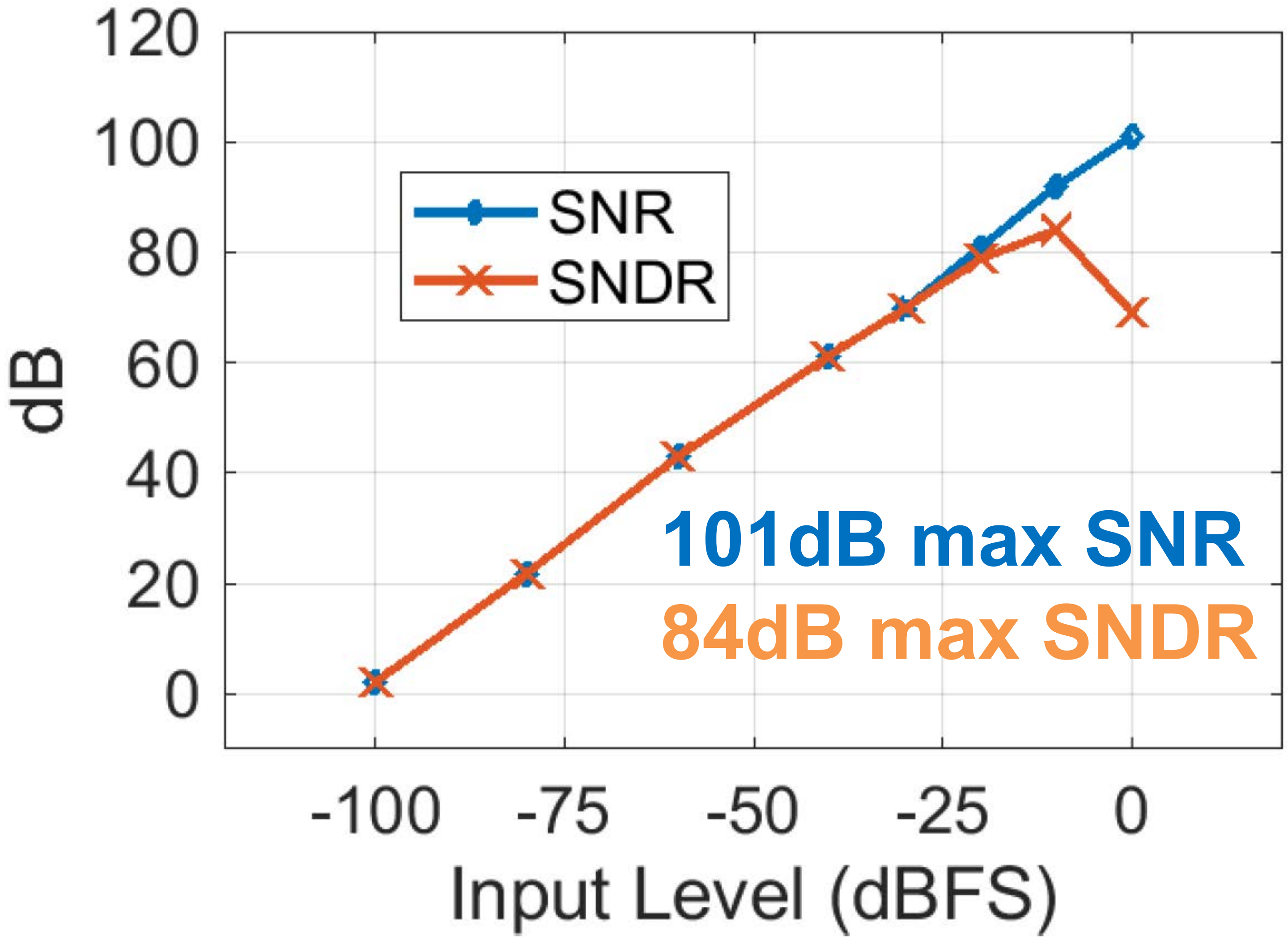
After FM Demodulation



Single Channel Measurement Results

Various Amplitude Sine Test Messages

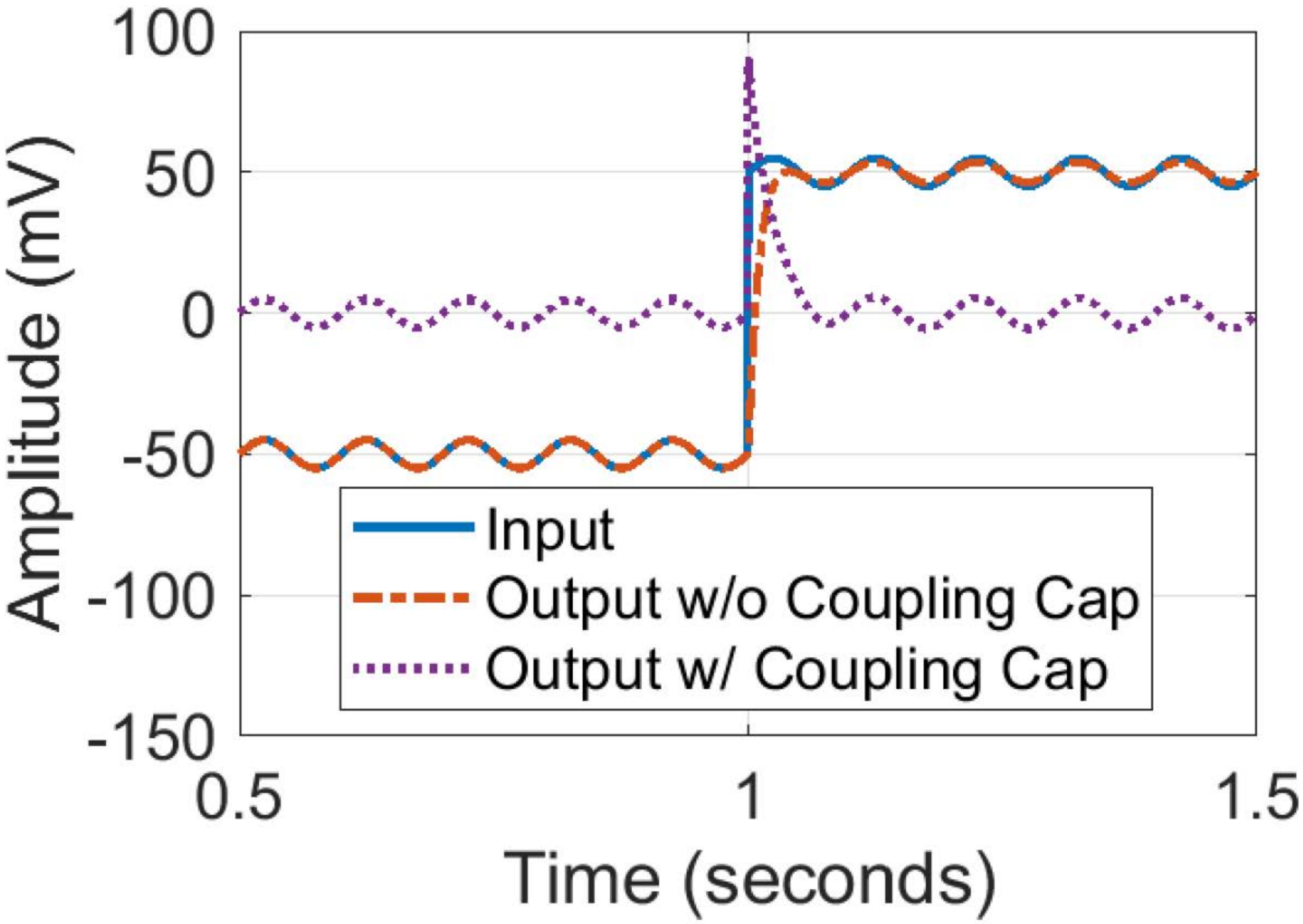
After FM Demodulation



Single Channel Measurement Results

Single Channel Input Step Test

After FM Demodulation

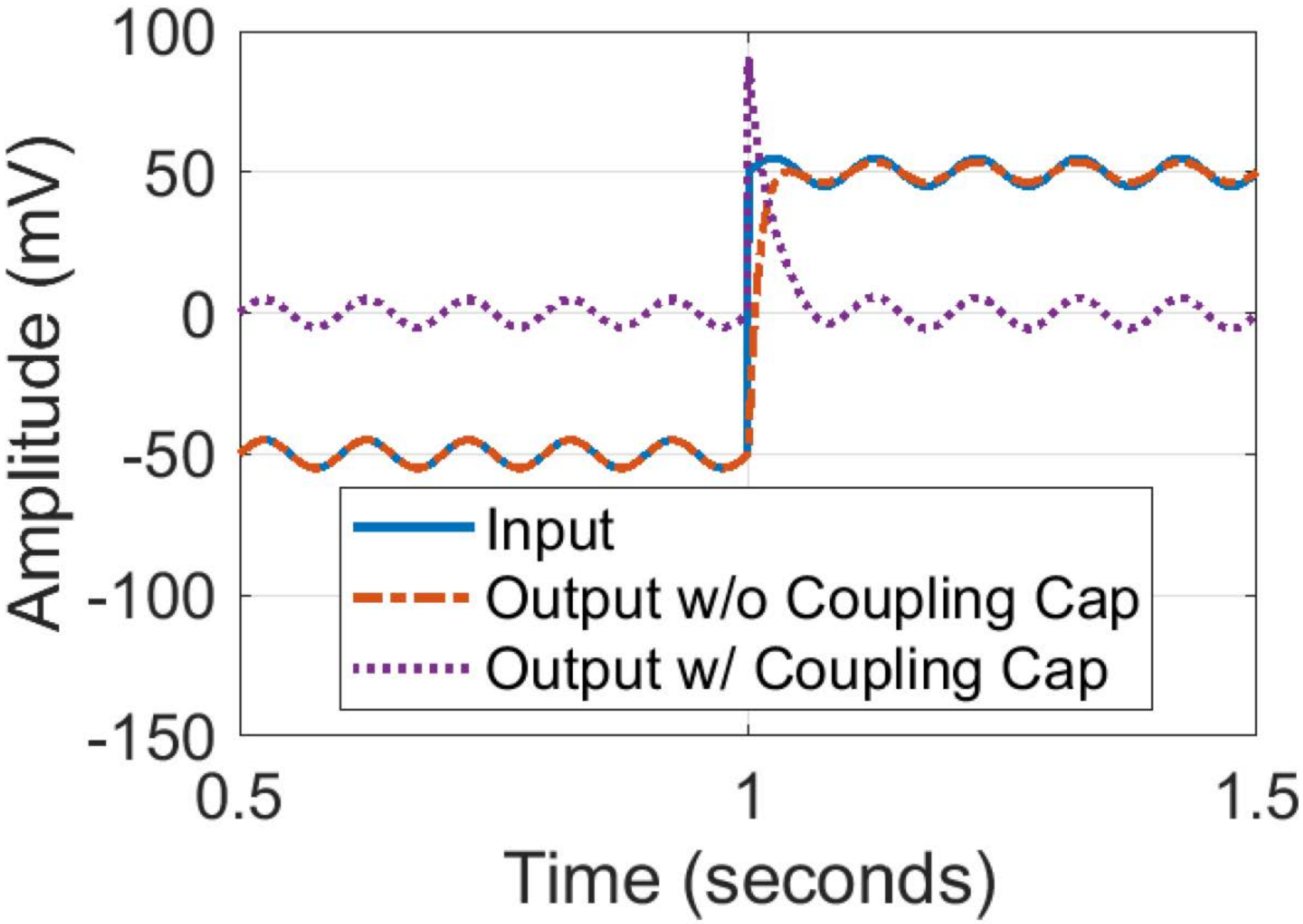


Single Channel Measurement Results

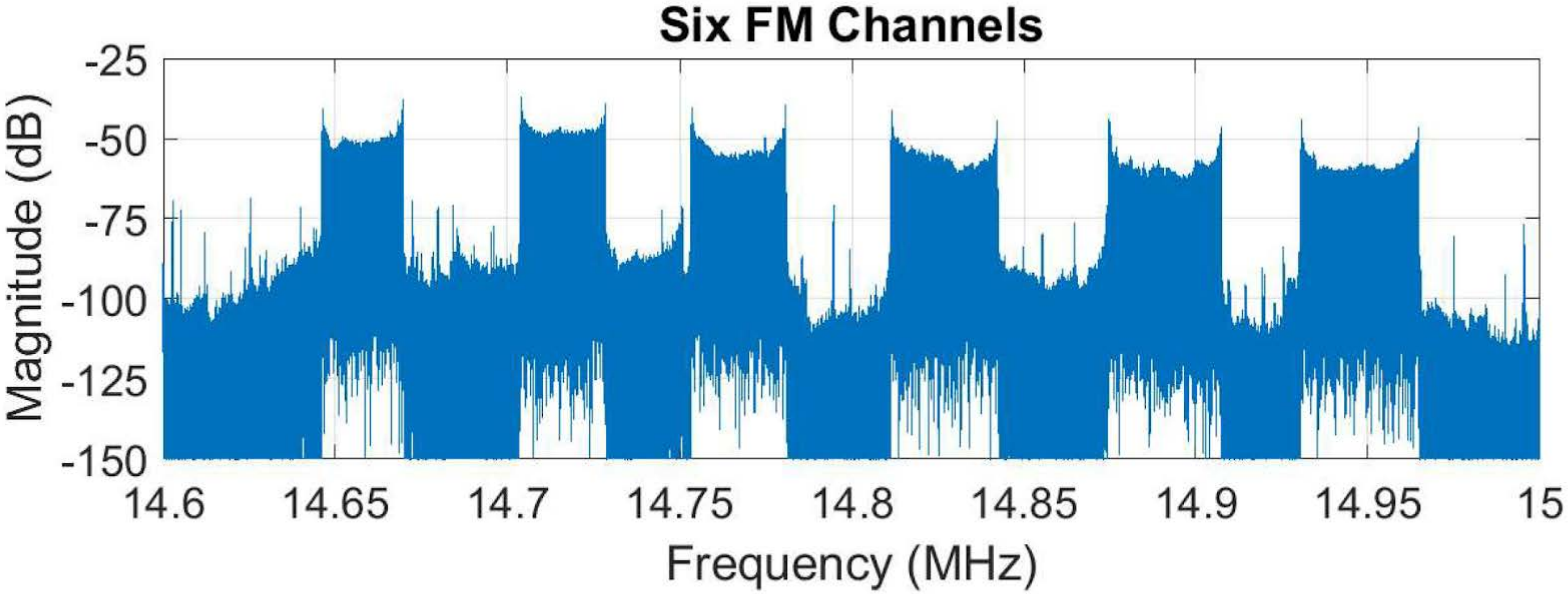
Single Channel Input Step Test

After FM Demodulation

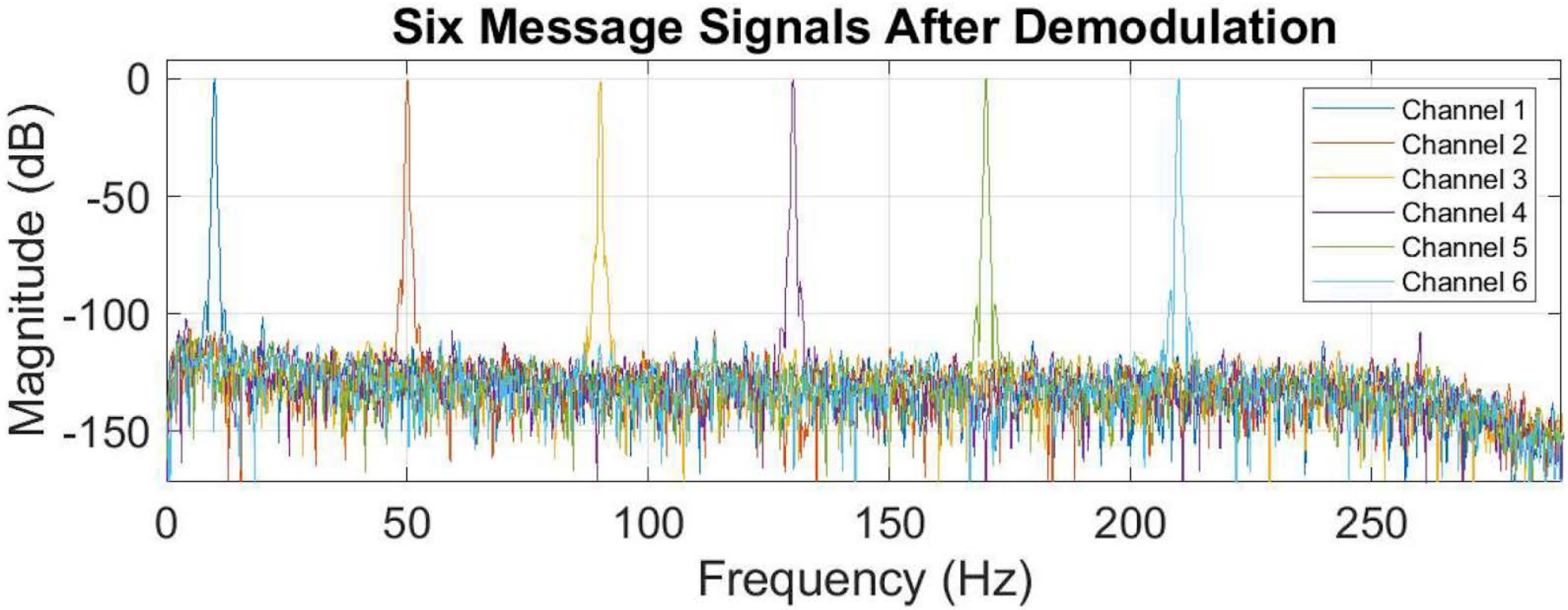
FM-ExG Active Electrodes Do Not Saturate For 10x Input Step



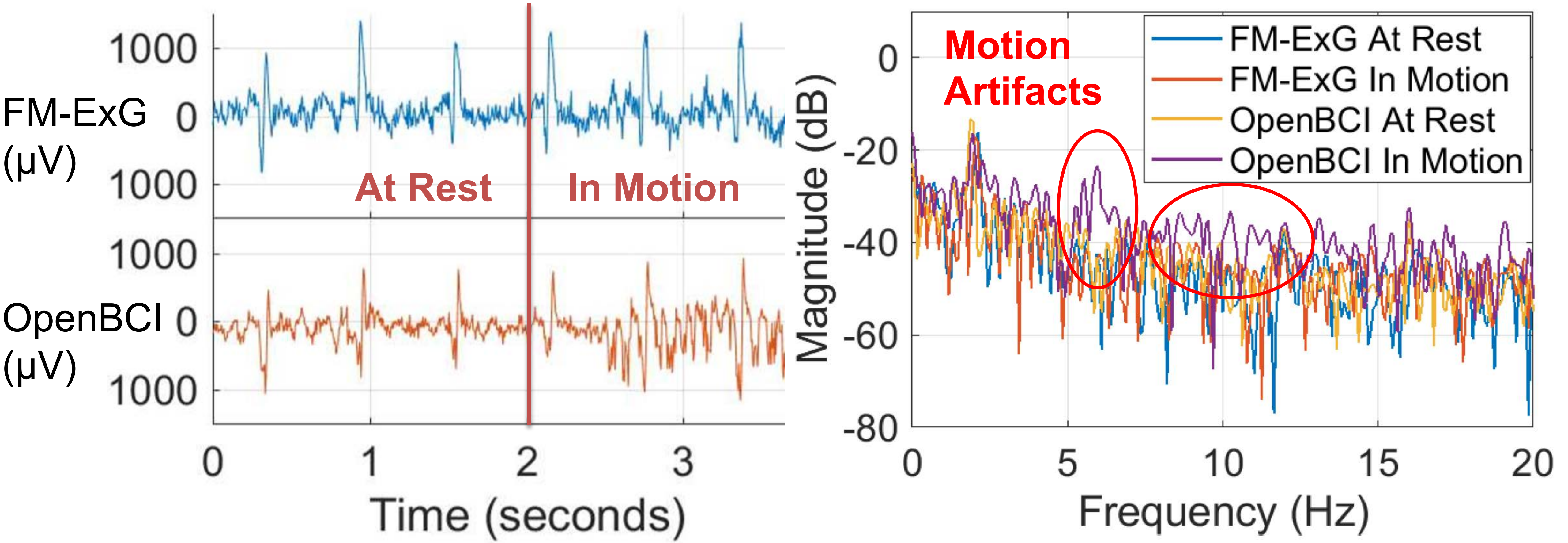
Multi-Channel Measurement Results



Multi-Channel Measurement Results

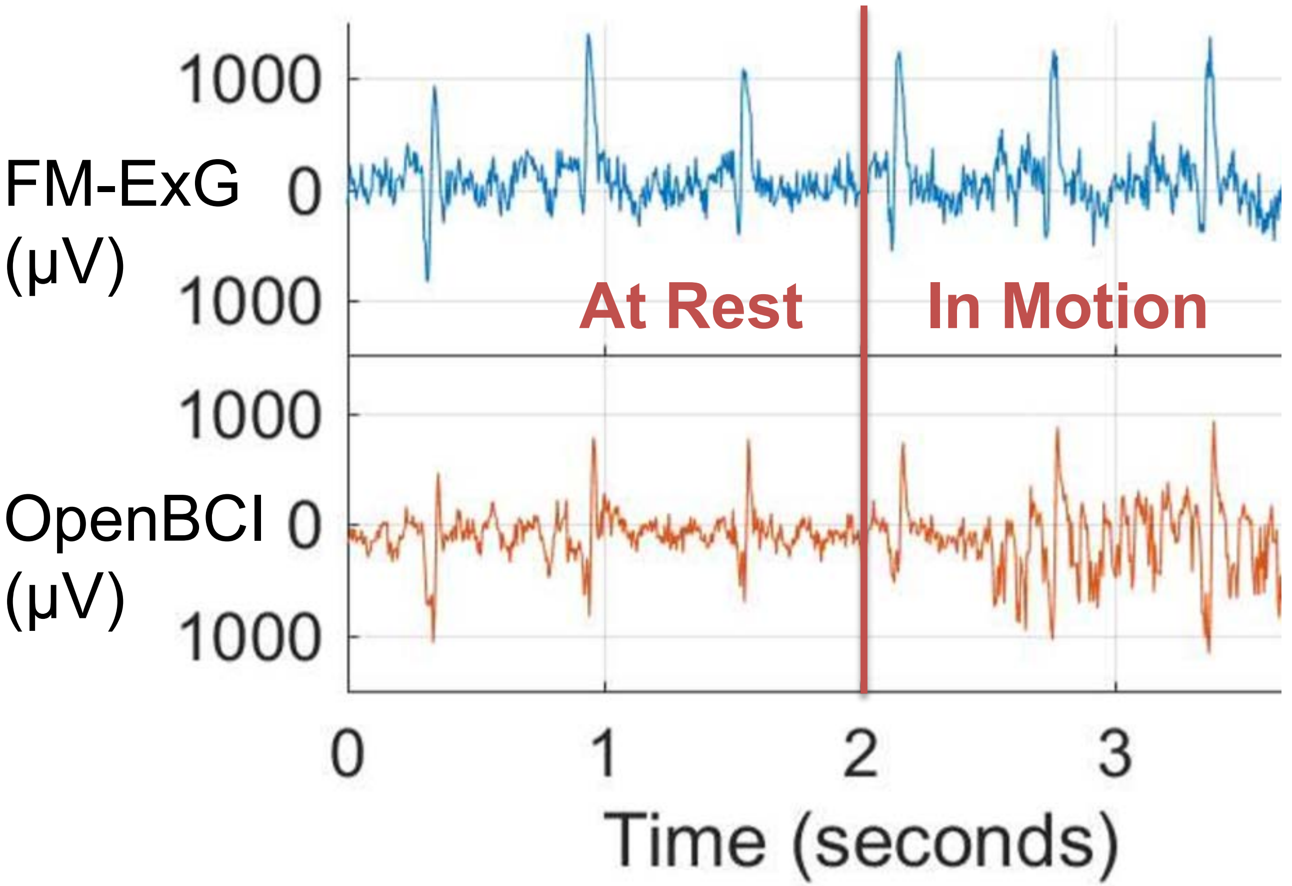


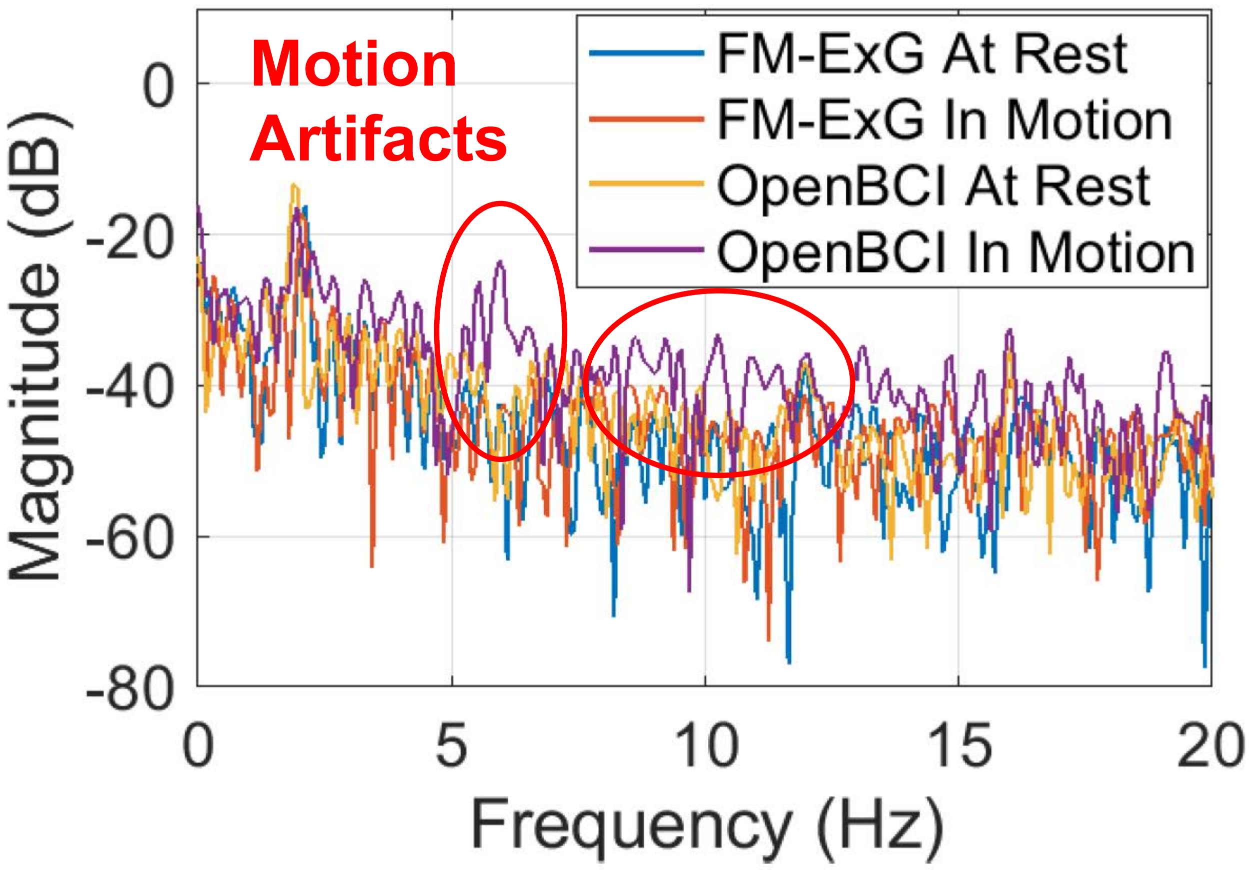
Biopotential Measurement Results



FM → Avoids In-Band Coupling
Fewer Wires → Reduced Electrode Inertia

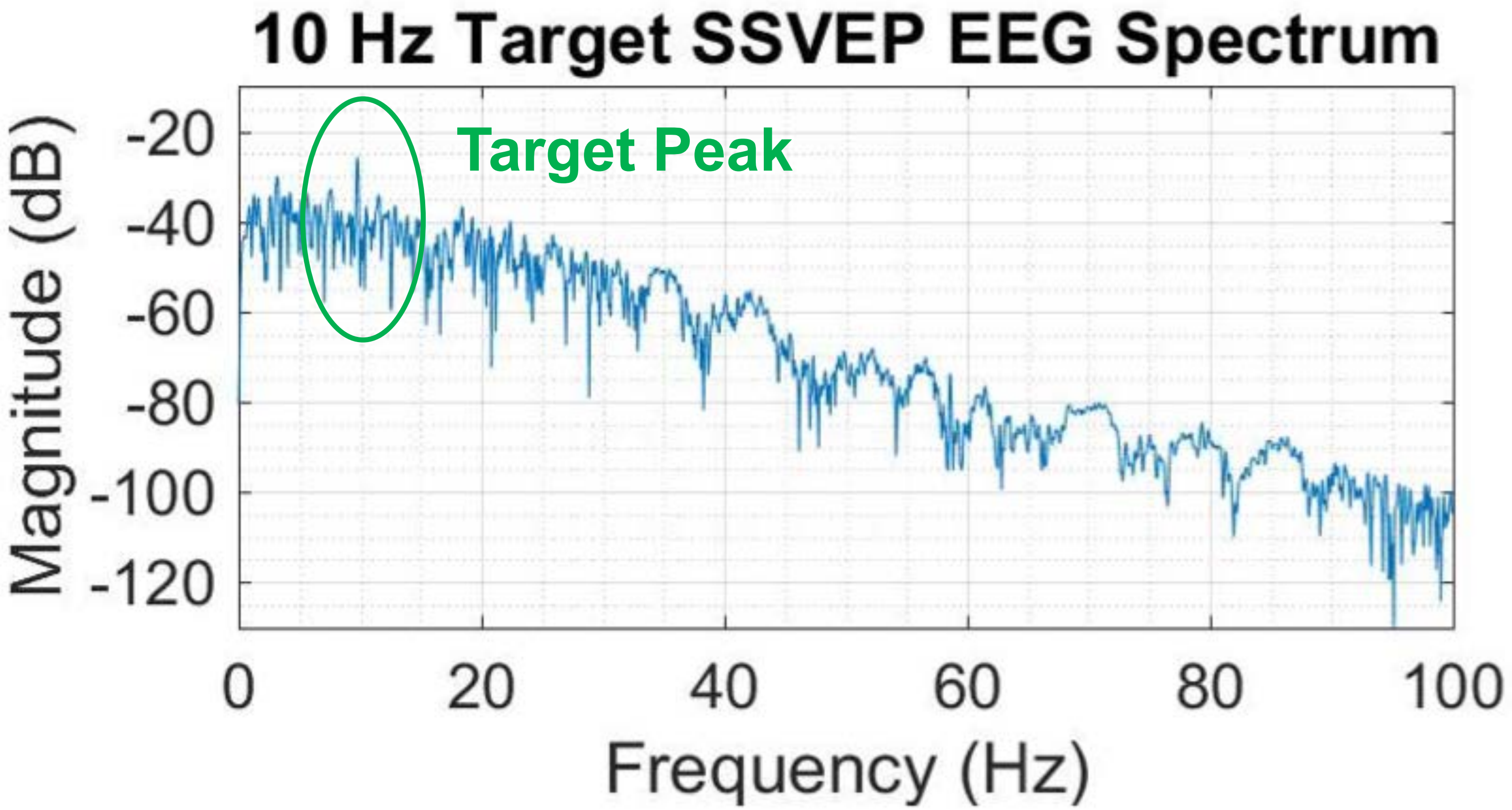
Biopotential Measurement Results



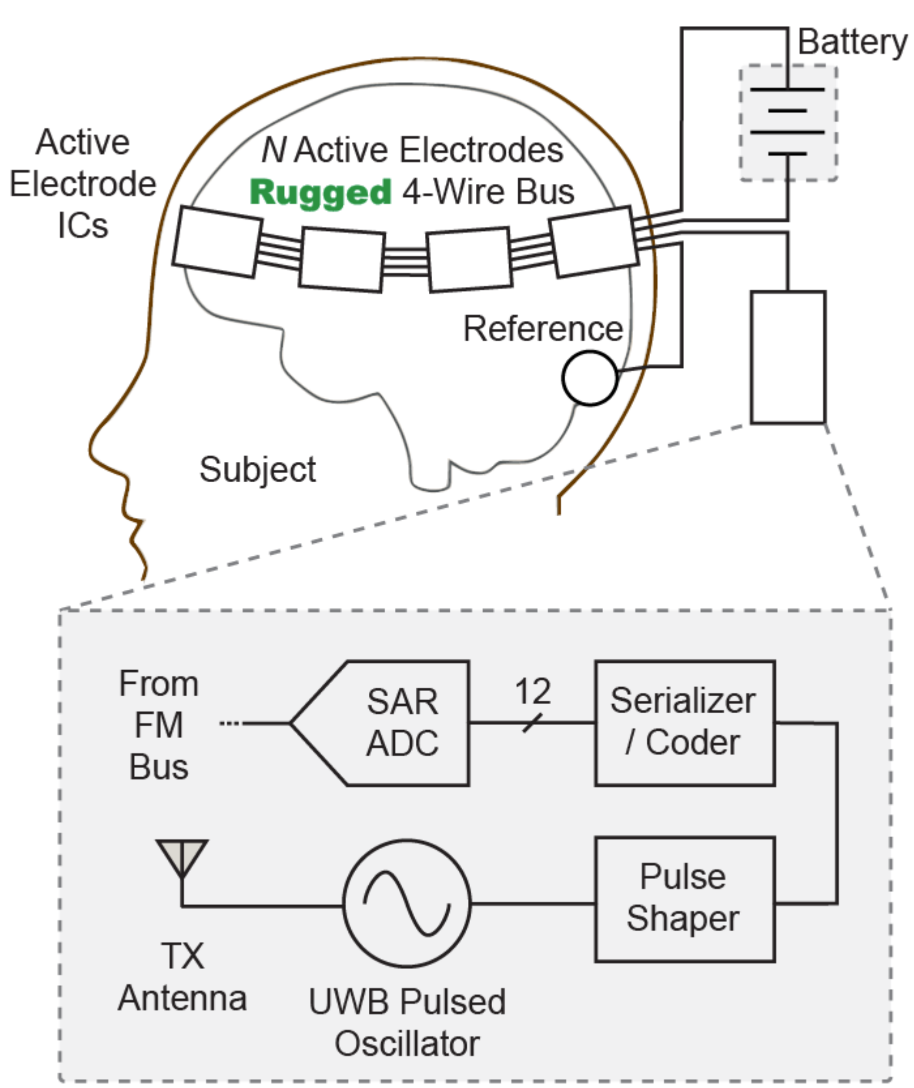


FM-EXG Reduces Motion Artifact Severity
In-Motion to At-Rest Peak MATLAB xcorr 2.9x Higher

Biopotential Measurement Results



UWB TX Measurement Results



Gateway Integrated Circuit

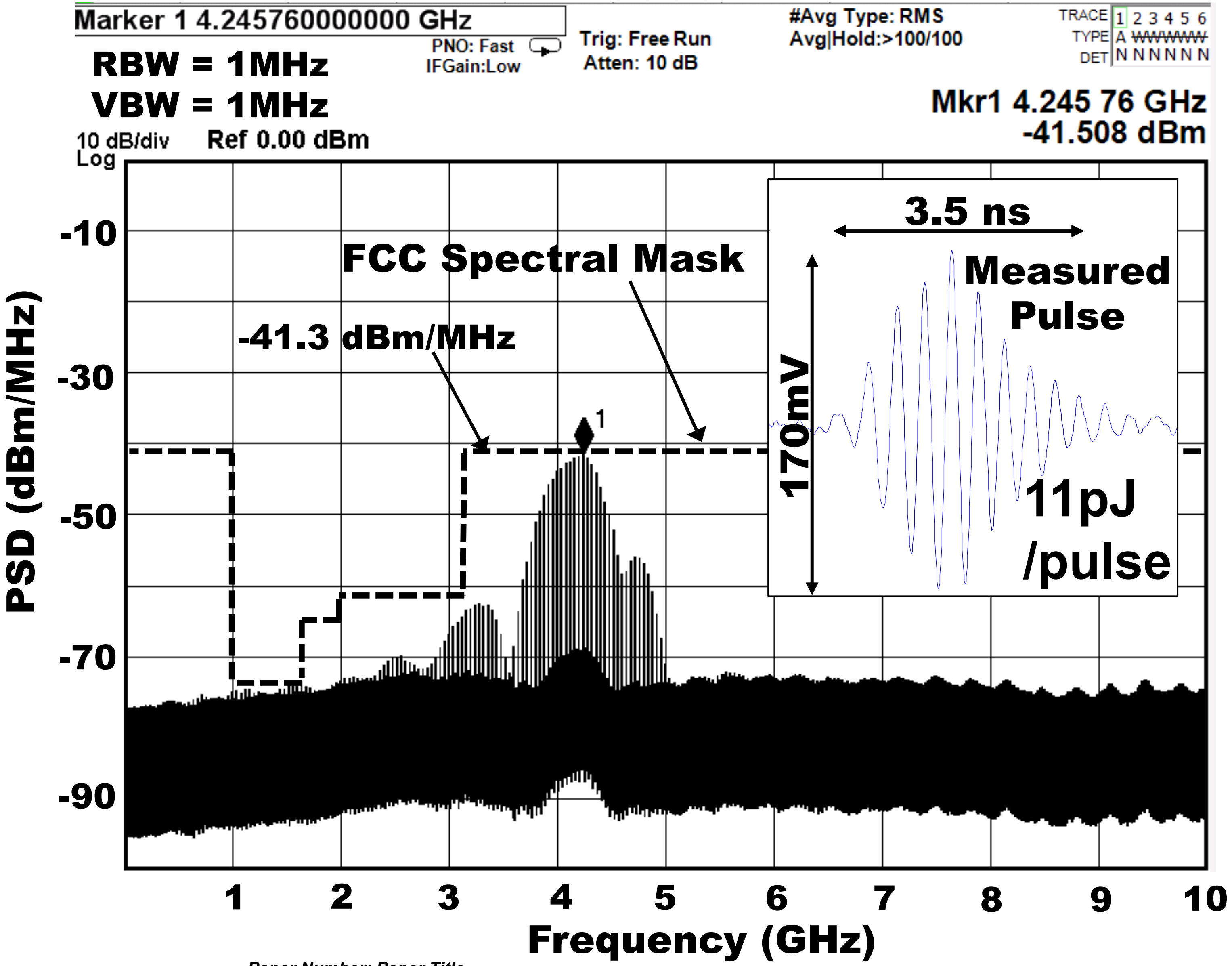


Table of Comparison

Design	Rieger, TCAS-I 2018	O'Leary, ISSCC 2018	Schönle, JSSC 2018	Xu, ISSCC 2014	This Work
Active Electrode?	No			Yes	
Process [nm]	180	130	130	180	**65**
Electrode Bus Drive Type	-	-	-	Digital I2C	**FDM via Tuned Amplifier**
Acquisition Bandwidth [Hz]	7000	500	4000	100	**250**
Usable DR at Input [dB]	~50 (8-bit)	70	~83 (13.5-bit)	~74 (12-bit)	**101**
Output Bit Rate per Channel [Hz]	56000	1000000	112000	2400	**1280000**
Acquisition Power per Channel [μW]	96.7	1.26	285	104.4	**228**
Calculated Wireless TX Power* per Channel [μW]	4.93	88	9.86	0.21	**112.6**
Total Power per Channel [μW]	101.63	89.26	294.86	104.61	**340.6**
FOM = Usable DR [dB] + 10 log10(BW [Hz] / Total Power per Channel [W])	128.4	137.5	154.3	133.8	**159.7**

*Calculated using 88 pJ/bit at digital output bit rate

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Highest FOM and Input DR Among Active Electrode Systems And Traditional AFEs

Conclusion

1. **Motivation**

   Increase Battery Life and Reduce Wiring Clutter for High Fidelity/Density EEG

2. **Approach**

   A Scalable Multi-Channel FM-FDM Sensor Network

   Integrated Gateway with ADC and UWB TX

3. **Results**

   Rugged

   Low Power

   Resilient to Motion

Thanks to our funding agencies: