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

Human EEG, C3 Electrode

μV

-20

0

20

0

1

2

Seconds

EEG Electrodes
Clinical-Grade EEG

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/
Clinical-Grade EEG Challenges

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

Emotiv
- 84dB SNR
- 14 Channels
- 12 Hour Battery

Cognionics
- 112dB SNR
- 64 Channels
- 6 Hour Battery
Commercial Wireless EEG Challenges

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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

Power/Ground

Channel 1

Channel 2

Channel N

Active electrodes

N+3 wires

Gateway module

Warchall, et al. ISCAS 2016

PMU

ADC 1 >16

ADC 2 >16

Reference

ADC N >16
EXG – The Traditional Approach

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

Warchall, et al. ISCAS 2016
EXG – The Traditional Approach

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

- Long Wires in Baseband
  - Require Active Electrode

Power/Ground

Channel 1

Channel 2

Channel N

Active electrodes

N+3 wires

Gateway module

EXG – The Traditional Approach

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

- Long Wires in Baseband
  - Require Active Electrode

- N ADCs
  - High ENOB
  - High Power Consumption

Power/Ground

Channel 1

Channel 2

Channel N

Active electrodes

N+3 wires

Gateway module

PMU

ADC 1

ADC 2

ADC N

Reference

EXG – An FM-FDM Approach

FM-FDM:

Power/Ground

Channel 1

Channel 2

Channel N

FM-FDM bus

PMU

ADC

Reference

Gateway module

4 wires

Warchall, et al. *ISCAS 2016*
EXG – An FM-FDM Approach

FM-FDM: Minimizes Wire Count,

Warchall, et al. ISCAS 2016
EXG – An FM-FDM Approach

FM-FDM:
- Minimizes Wire Count,
- Mitigates Cable Sway,

Warchall, et al. ISCAS 2016
EXG – An FM-FDM Approach

FM-FDM:
- Minimizes Wire Count,
- Mitigates Cable Sway,
- Minimizes ADC Count

Warchall, et al. ISCAS 2016
Why FM Multiplexing?

Other Multiplexing Possibilities:

• Serial Digital (TDM, I2C, SPI, etc.)
  • Requires $N \sim 100\text{dB}$ DR ADCs for $N$ channels

• FDM Digital (OOK, BPSK, QPSK, etc.)
  • Still requires $N \sim 100\text{dB}$ DR ADCs

• AM-FDM
  • Requires one $\sim 100\text{dB}$ DR ADC

Warchall, et al. ISCAS 2016
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- FM-FDM
  - Single low bit depth high sample rate ADC
  - Leverages oversampling converter efficiency
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• FM-FDM
  • Single low bit depth high sample rate ADC
  • Leverages oversampling converter efficiency

FM-FDM Also **Reduces** ADC Complexity, Maintains **High DR**
A Rugged Wearable Modular ExG Platform
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A Rugged Wearable Modular ExG Platform

Active Electrode Integrated Circuit

- EEG Electrode
- Coupling Network
- Sinusoidal VCO
- Tuned Amplifier

ExG Band
0 Hz - 250 Hz
A Rugged Wearable Modular ExG Platform

Active Electrode Integrated Circuit

EEG Electrode Coupling Network Sinusoidal VCO Tuned Amplifier

To FM Bus

ExG Band
0 Hz - 250 Hz

FDM Bus

Ch. 1 Ch. 2 Ch. 3 Ch. N

Subject

N Active Electrodes Rugged 4-Wire Bus

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A Rugged Wearable Modular ExG Platform

Gateway Integrated Circuit

Active Electrode Integrated Circuit

- EEG Electrode
- Coupling Network
- Sinusoidal VCO
- Tuned Amplifier

From FM Bus
- SAR ADC
- Serializer / Coder
- TX Antenna
- UWB Pulsed Oscillator

ExG Band
- 0 Hz - 250 Hz

FDM Bus
- Ch. 1
- Ch. 2
- Ch. 3
- Ch. N

FM Band Plan
A Rugged Wearable Modular ExG Platform

Gateway Integrated Circuit

FM Band Plan

ExG Band 0 Hz - 250 Hz

Ch. 1, Ch. 2, Ch. 3, Ch. N

FDM Bus

To FM Bus

Tuned Amplifier

Sinusoidal VCO

Coupling Network

EEG Electrode

Active Electrode Integrated Circuit

Subject

Reference

N Active Electrodes Rugged 4-Wire Bus

Battery

From FM Bus

SAR ADC

Serializer / Coder

Pulse Shaper

UWB Pulsed Oscillator

TX Antenna
Bandwidth Expansion

ExG Bands

FDM Bus with $N \times M$ KHz Bands

Ch. 1  Ch. 2  Ch. 3  Ch. $N$

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

$$D = \frac{M \text{ KHz}}{250\text{Hz}}$$

$$SNR_{FM,MAX}^* = 10 \log_{10}(3D^2(D+1)) + CNR$$

- **ExG Bands**
- **FDM Bus with N M KHz Bands**
- **FM Band Plan**

**Bandwidth Expansion**

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Bandwidth Expansion

ExG Bands

FDM Bus with $N M$ KHz Bands

Ch. 1  Ch. 2  Ch. 3  Ch. $N$

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

$SNR_{FM, MAX} = 10 \log_{10}(3D^2(D + 1)) + \text{CNR} \approx 134 \text{dB}$

FM Coding Gain

Gateway

SAR SNR

50KHz FM Channels
Bandwidth Expansion

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

\[
SNR_{FM,\text{MAX}} = 10 \log_{10}(3D^2(D + 1)) + \text{CNR} \approx 134\text{dB}
\]

FM Coding Gain

Gateway SAR SNR

50KHz FM Channels

ExG Bands

FDM Bus with \(N\) \(M\) KHz Bands

Ch. 1  Ch. 2  Ch. 3  Ch. \(N\)

Really?
Phase Noise in FM VCO

500Hz
Test Sine

Phase
Noisy
Sine
VCO

Ideal
FM
Demod
Phase Noise in FM VCO

Low VCO Phase Noise Maintains High System SNR
Active Electrode Design

Diagram showing a circuit with:
- On-chip Varactor Diodes
- High Q Off-chip Inductor
- Switching Active Core
- $V_{in,EEG}$
- $V_{out,osc}$
- $R_{tail}$
- $V_{DD}$
Active Electrode Design

Low Phase Noise Maintains High SNR

Diagram showing a circuit with labeled components including:
- $V_{in,EEG}$
- On-chip Varactor Diodes
- High Q Off-chip Inductor
- Switching Active Core
- $R_{tail}$
- $V_{DD}$
- $V_{out,osc}$
Active Electrode Design

- Low Phase Noise maintains High SNR
- Low Power

Diagram:
- On-chip Varactor Diodes
- Off-chip Inductor
- Switching Active Core
- $V_{i\text{n,EEG}}$
- $V_{\text{out,osc}}$
- $R_{\text{tail}}$
- $V_{\text{DD}}$
Active Electrode Design

Low Phase Noise Maintains High SNR

Low Power
Active Electrode Design

Nonlinear V-to-C Relationship!

Low Phase Noise Maintains High SNR

Low Power
Active Electrode Nonlinearity

Electrode Input  System Output
Active Electrode Nonlinearity

Electrode Input

System Output

Derive Polynomial Transform
Active Electrode Nonlinearity

Electrode Input

System Output

With Calibration:

Derive Polynomial Transform

Calibration Gains

~20dB SNDR!
Gateway Power Saving

Nyquist Sampling

FM Channels Higher Frequency → Lower Varactor Nonlinearity
Gateway Power Saving

Nyquist Sampling

Wasted Spectrum

Ch. 1  Ch. 2  Ch. 3  Ch. N
Gateway Power Saving

Nyquist Sampling

Wasted Spectrum

\[ f_s \approx 30 \text{ MHz} \]

Sampling Power: 3 Milliwatts
Gateway Power Saving

Nyquist Sampling

Wasted Spectrum

Bandpass Sampling

Baseband Aliases of FM Channels

\[ f_s \approx 30 \text{ MHz} \quad \rightarrow \quad \text{Sampling Power: 3 Milliwatts} \]
Gateway Power Saving

Nyquist Sampling

Wasted Spectrum

\[ f_s \approx 30 \text{ MHz} \]

Sampling Power: 3 Milliwatts

Bandpass Sampling

Baseband Aliases of FM Channels

\[ f_s \approx 1 \text{ MHz} \]

Sampling Power: 100 Microwatts

Sampling Power:

- Nyquist Sampling: 3 Milliwatts
- Bandpass Sampling: 100 Microwatts
Gateway Power Saving

Nyquist Sampling

Wasted Spectrum

\[ f_s \approx 30 \text{ MHz} \rightarrow \text{Sampling Power: } 3 \text{ Milliwatts} \]

Bandpass Sampling

\[ f_s \approx 1 \text{ MHz} \rightarrow \text{Sampling Power: } 100 \text{ Microwatts} \]

Baseband Aliases of FM Channels

Bandpass Sampling Reduces Sampling Power by \( \sim 30x \)
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

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Single Channel Measurement Results

Full-Scale
10mVpp 10Hz
Sine Test Message
Probed at VCO Output

FM Carrier
~50KHz BW

Magnitude (dB)

Frequency (MHz)
Single Channel Measurement Results

Full-Scale
10mVpp 10Hz
Sine Test
Message

After FM
Demodulation

Demodulated Message Signal

SNR = 101dB

Magnitude (dB)
-200
-150
-100
-50
0

Frequency (Hz)
0
50
100
150
200
250
Single Channel Measurement Results

Various Amplitude Sine Test Messages After FM Demodulation

101dB max SNR 84dB max SNDR
Single Channel Measurement Results

Single Channel Input Step Test

After FM Demodulation

![Graph showing single channel measurement results](image-url)
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

Six FM Channels

Magnitude (dB)

-150  -125  -100  -75  -50  -25


Frequency (MHz)
Multi-Channel Measurement Results

Six Message Signals After Demodulation

Magnitude (dB)

0  -50  -100  -150

Frequency (Hz)

0  50  100  150  200  250
Biopotential Measurement Results

FM-ExG (μV)

OpenBCI (μV)

At Rest In Motion

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

10 Hz Target SSVEP EEG Spectrum

Target Peak
UWB TX Measurement Results

PSD (dBm/MHz)

RBW = 1MHz
VBW = 1MHz

FCC Spectral Mask

-41.3 dBm/MHz

Measured Pulse

11pJ/pulse

Marker 1 4.2457600000000 GHz

10 dB/div Ref 0.00 dBm

3.5 ns

-90
-70
-50
-30
-10
0
10
20
30
40
50
60
70
80
90

Frequency (GHz)

Subject

Gateway Integrated Circuit

From FM Bus

SAR ADC

12

Serializer / Coder

Pulse Shaper

TX Antenna

UWB Pulsed Oscillator

Battery

Rugged 4-Wire Bus

N Active Electrodes

Active Electrode ICs

Active Electrode ICs
# Table of Comparison

<table>
<thead>
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<th>Design</th>
<th>Rieger, TCAS-I 2018</th>
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<tr>
<td>Process [nm]</td>
<td>180</td>
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<td>Calculated Wireless TX Power* per Channel [µW]</td>
<td>4.93</td>
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<td>FOM = Usable DR [dB] + 10 log10(BW [Hz]) / Total Power per Channel [W]</td>
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*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: