Passive Wireless Multi-Sensor Technology –
Device and System Perspective

Don Malocha
Pegasense, LLC
dcmalocha@cfl.rr.com

Pegasus Professor Emeritus
University of Central Florida
donald.malocha@ucf.edu
http://caat.engr.ucf.edu/

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Pegasense, LLC – founded Oct. 2016

Svetlana Malocha, Ph.D. –30 years of industrial experience and Senior-MTS 22 years at Qorvo (formerly Triquint & Sawtek).
Solid state RF acoustics (SAW/BAW) theory, analysis, modeling and simulation tool development.

Don Malocha, Ph.D.- 40 years experience: UCF Pegasus Professor, with industrial experience at Texas Instruments, Sawtek, Motorola, and Piezo Technology, Inc.
Solid state devices and materials, RF communications, and sensor systems. SAW/BAW device RF system development.

Over 300 publications & 17 patents

Pegasense, LLC

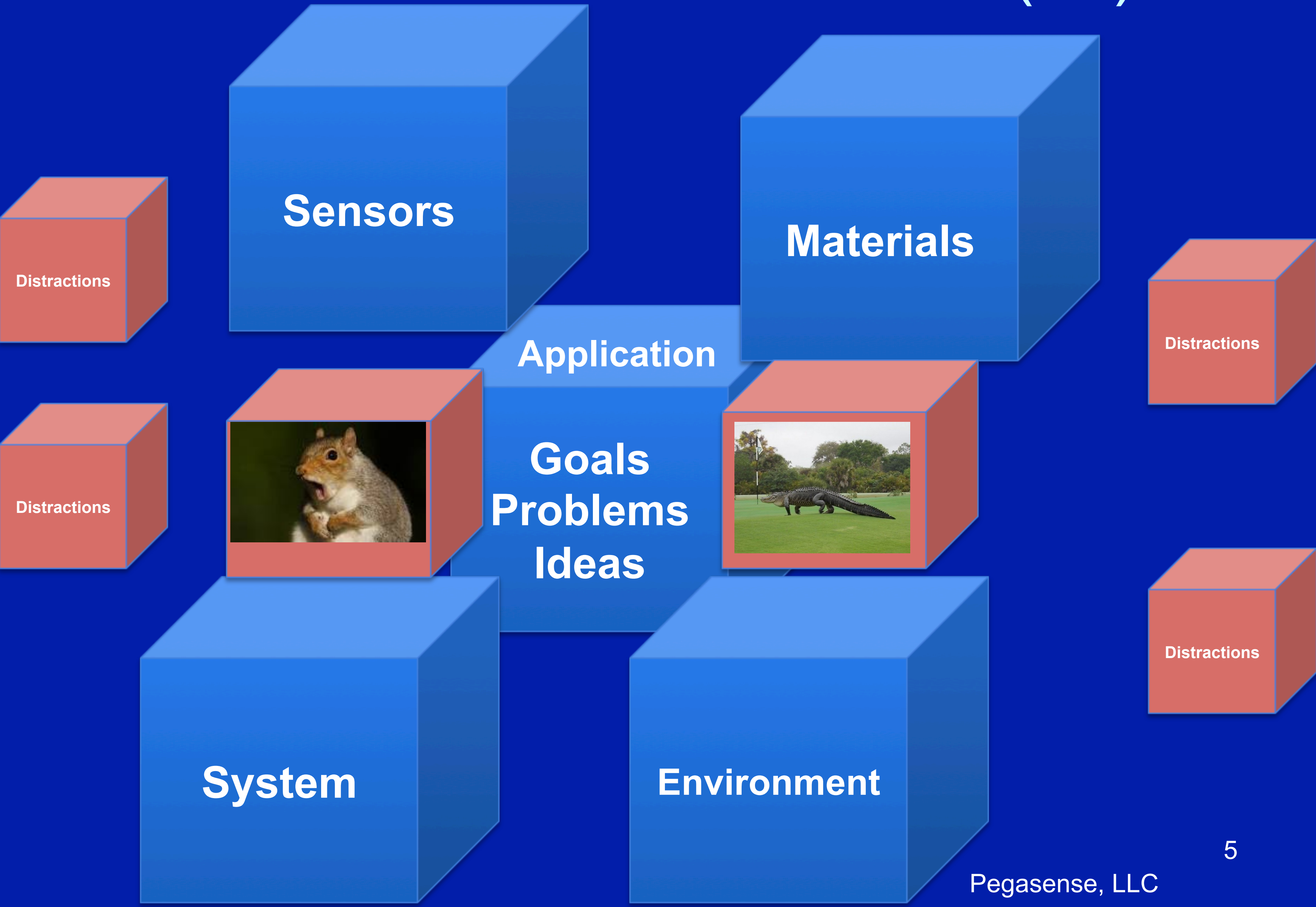
- *Consulting/partnering with industry, government and university groups in the technical areas of solid state devices and RF communications. Hardware and Software.*
- **Current Projects:**
- Signal Processing @ RF Frequencies
  - Low Loss RF Programmable Correlator (1GHz)
  - Acoustoelectric SAW Amplifier Filter: Gain & NF_{low}
- Sensor Systems – physical, gas, liquid
- Advanced Simulations: Device and RF Communications

Let's FLY!

- Dinosaurs, birds, bats, fish, squirrels, insects..........
- Leonardo da Vinci (1452-1519)
  - Presented novel ideas on human flight
  - Embodiments based on technology of the day
  - Built prototypes
  - Experimental verification
- Hot air balloon (1783)
  - The first free flight by humans was made by physicist Pilâtre de Rozier, and an army officer, the Marquis d'Arlandes.
- Wright Brothers 1st sustained, heavier-than-air, powered aircraft flight in 1903

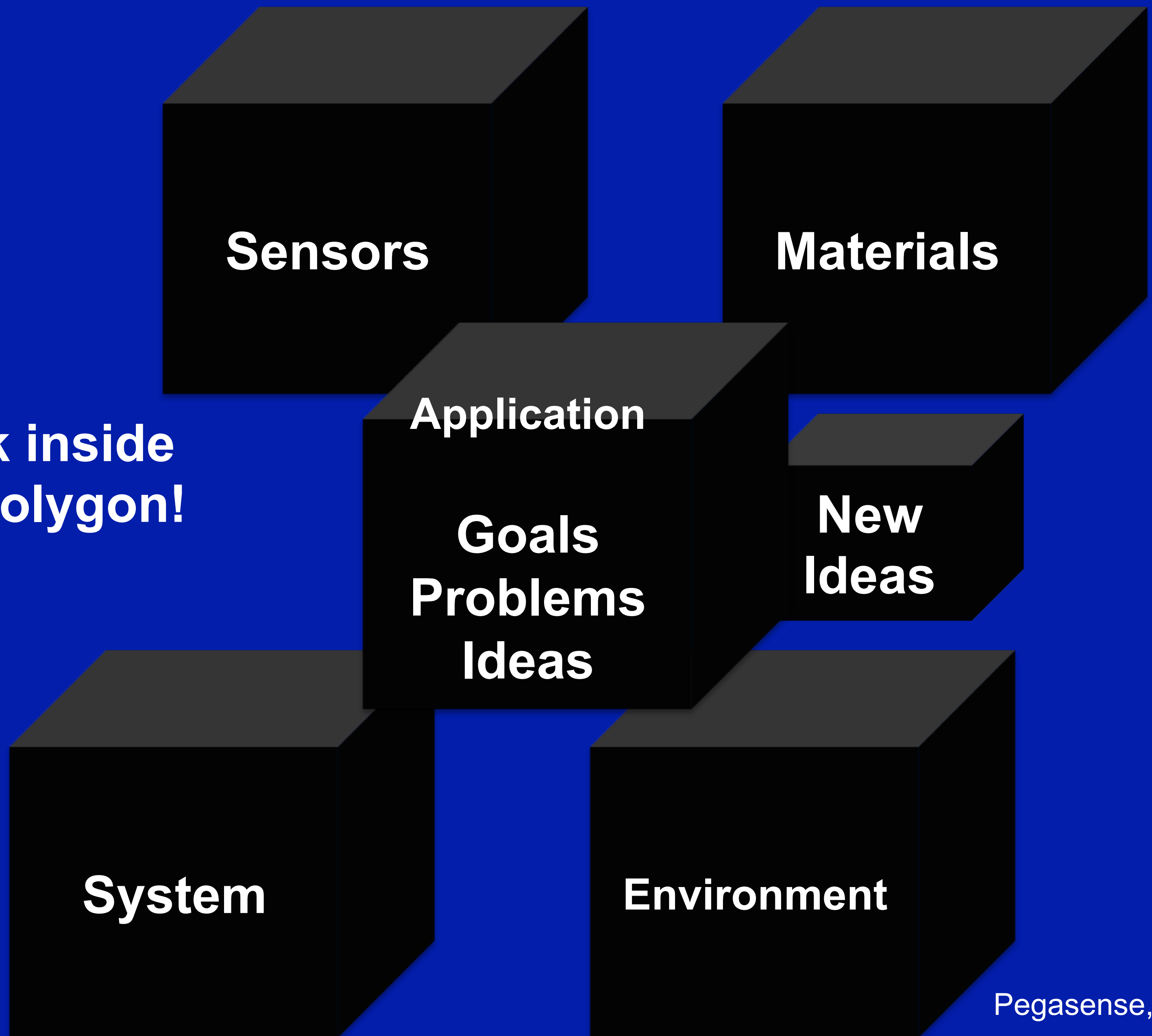
Development of ideas/ technology for 500 years!

Think Inside the Box(es)



Boundaries are Polygonal –refine the choices

Think inside the Polygon!



Confluence of Technology
SAW Wireless Multi-Sensors –Why now?

Mature Essential Components

SAW Sensor

RF Receiver Technology

Post-processing

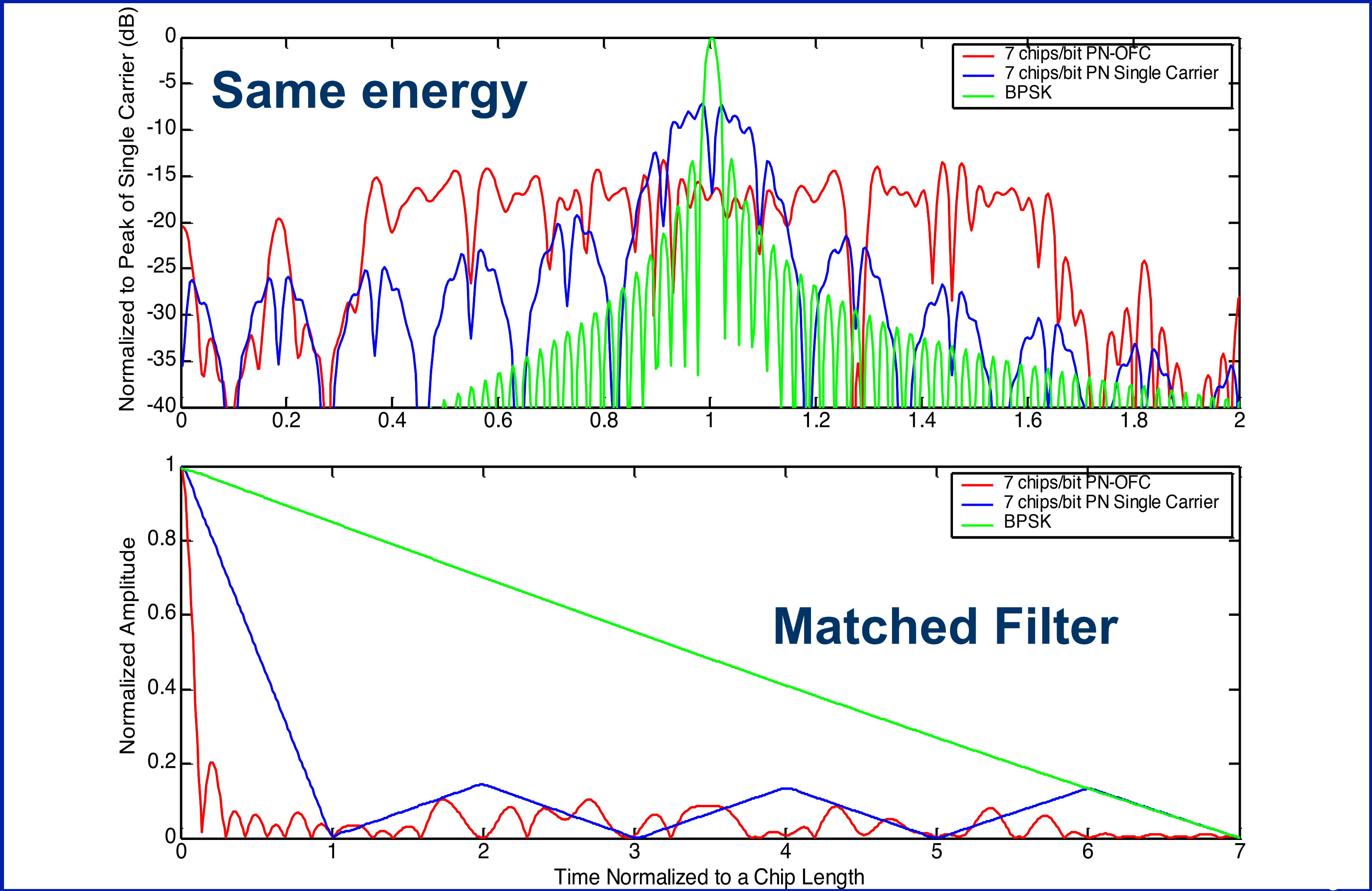
It's all about S/N Ratio for any sensor system

- Regardless of the signal format:
  - $P_{Rx} < P_{Tx}$ signal
  - $BW_{Rx} < BW_{Tx}$ signal
  - $f0_{Tx} = f0_{Rx}$

Interrogation signal_{max}:

- Large Tx peak voltage; long duration; P_{max}
  - Pulse optimized for dynamic range, power, interference
- Synchronous, coherent integration of multiple Tx sweeps – larger signal but latency
- Signal processing gain (PG) $PG \sim T * BW$
- Frequency dispersion increases PG

PG Comparison
1-Bit, 7-chip PN, 7-chip OFC



PG-Coding Summary

- Signal time length, T_{sensor}, yields more power or energy
- Signal bandwidth, BW_{sensor} yields better sensitivity and selectivity
- T_{sensor}*BW_{sensor} = PG, enhancement of both
- OFC provides T_{sensor}*Bw_{sensor} code diversity

SAW Sensor System Case for 4 GHz Avionics' Band

- Multi-sensor system
- State-of-the-Art Challenge for SAW sensors
- Orthogonal Frequency Coding (OFC) for SAW Sensors
- TxRx
  - Custom RF front-end
  - Software Defined Radio (SDR)
- Post-processing built on previous efforts and further optimized

Avionics Band SAW Sensor Specifications

- f_0=4.3 GHz, BW = 200 MHz
- %BW = 4.65% – narrow band
- Does not meet UWB definition (>500 MHz)
- If UWB is available/possible signal format, technology development on TxRx would be required.

Multi-Sensor System Approach

- Multiple mini-cell sites
- 5-10 sensors per cell site
- Mini-cell sites are networked
- Expected sensor range ~5m (15 ft)
- OFC encoding for multiple SAW sensor RFID and parameter extraction within a single cell site

SAW Sensor Challenge

- Fabrication Approach:
  - YZ Lithium Niobate
  - 1st f_0=4.3GHz, lambda~.8um
    - Line width~ 0.2um is challenging in commercial fab
  - Harmonic SAW device design
    - 3rd harmonic – 1.43 GHz, lambda~2.4um
      - Line width~ 0.6um is well within commercial fab
    - 5th harmonic -860 MHz, lambda~4 um
      - Line width ~1 um is even better for commercial fab
  - UCF has been successfully fabricating harmonic transducers and reflectors with approximately same performance as for fundamental designs with similar parameters

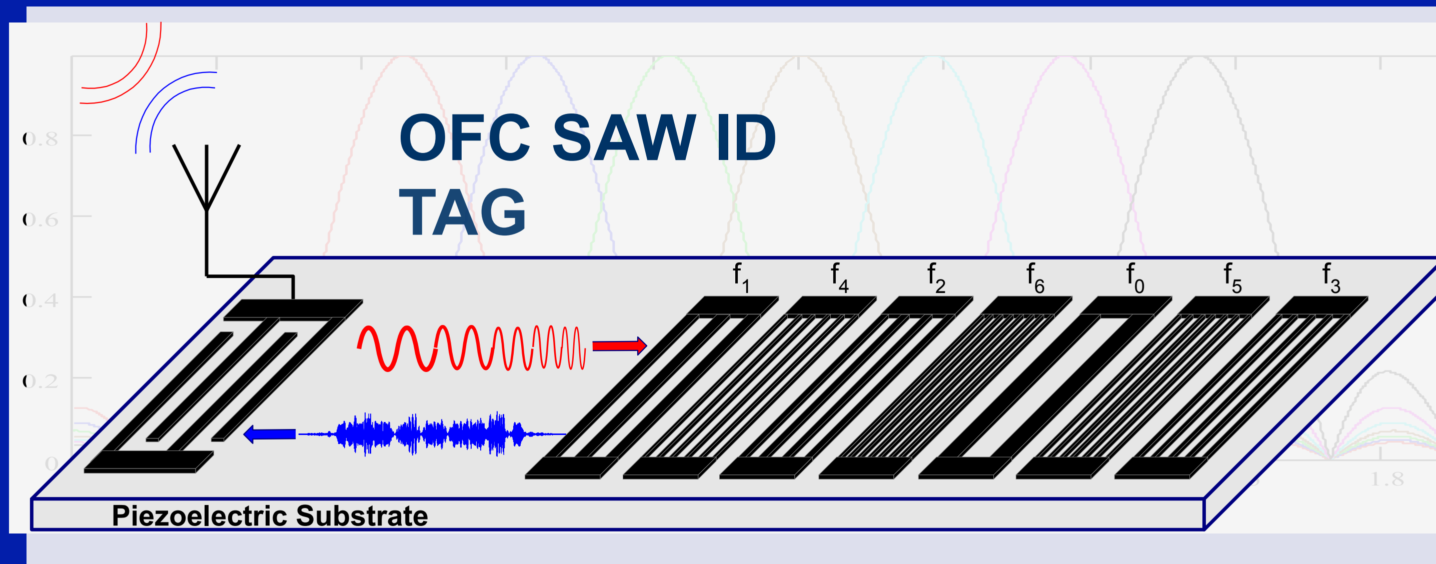
Orthogonal Frequency Coding Concept

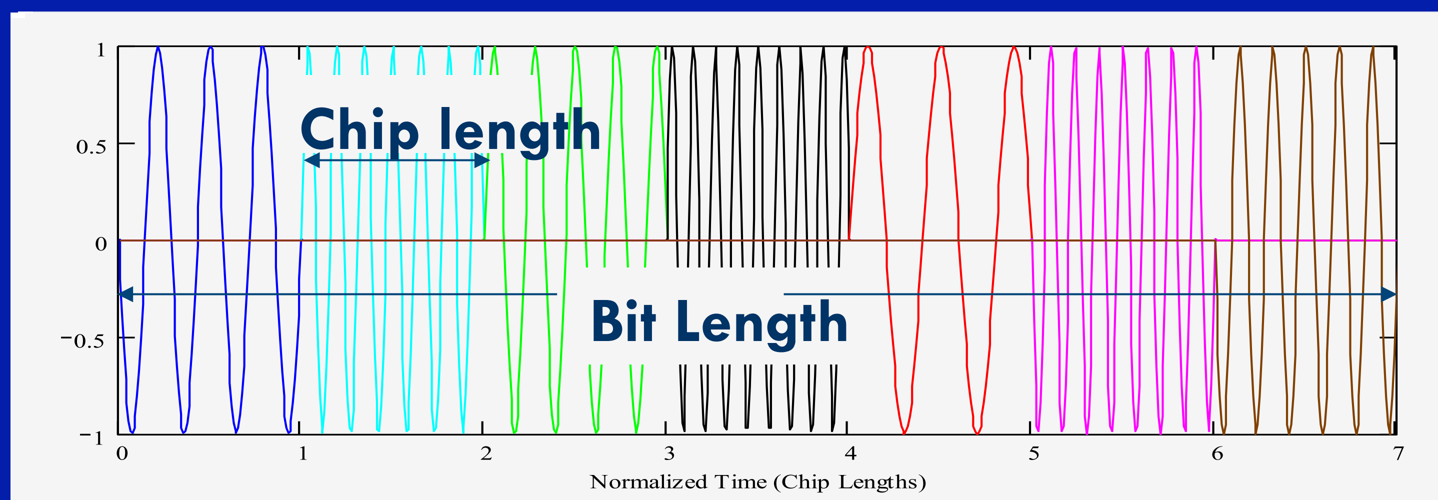
Processing gain is approximately the time bandwidth product

PG for a 7 frequency 7 chip OFC is 49 ~17dB

$$\tau_b = j \cdot \tau_c$$

where $j =$ # of chips

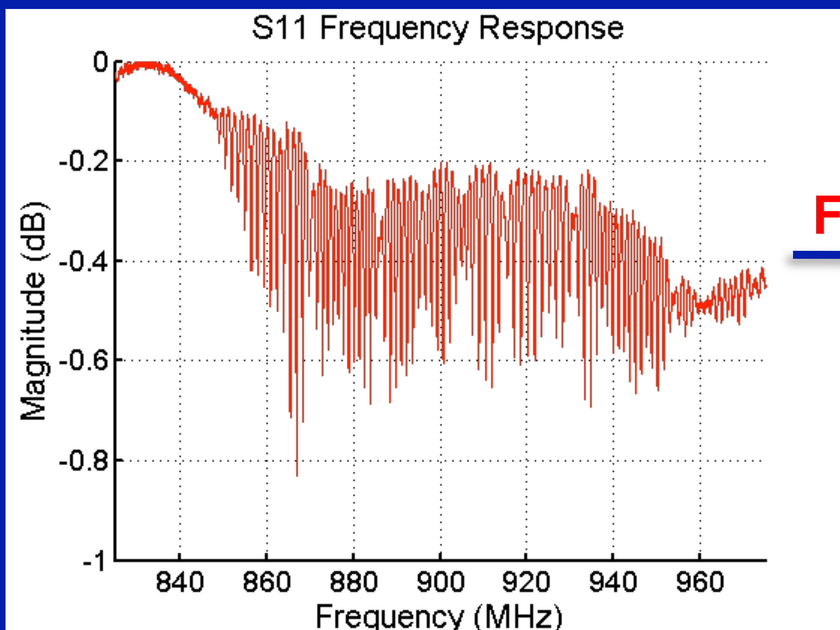




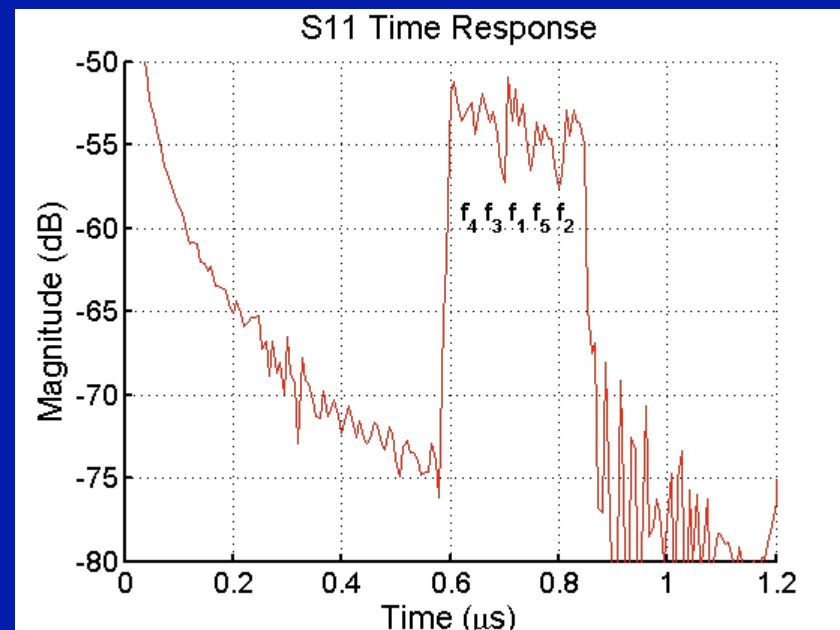
Example SAW OFC Sensor

Light Micrograph

f4 f3 f1 f5 f2

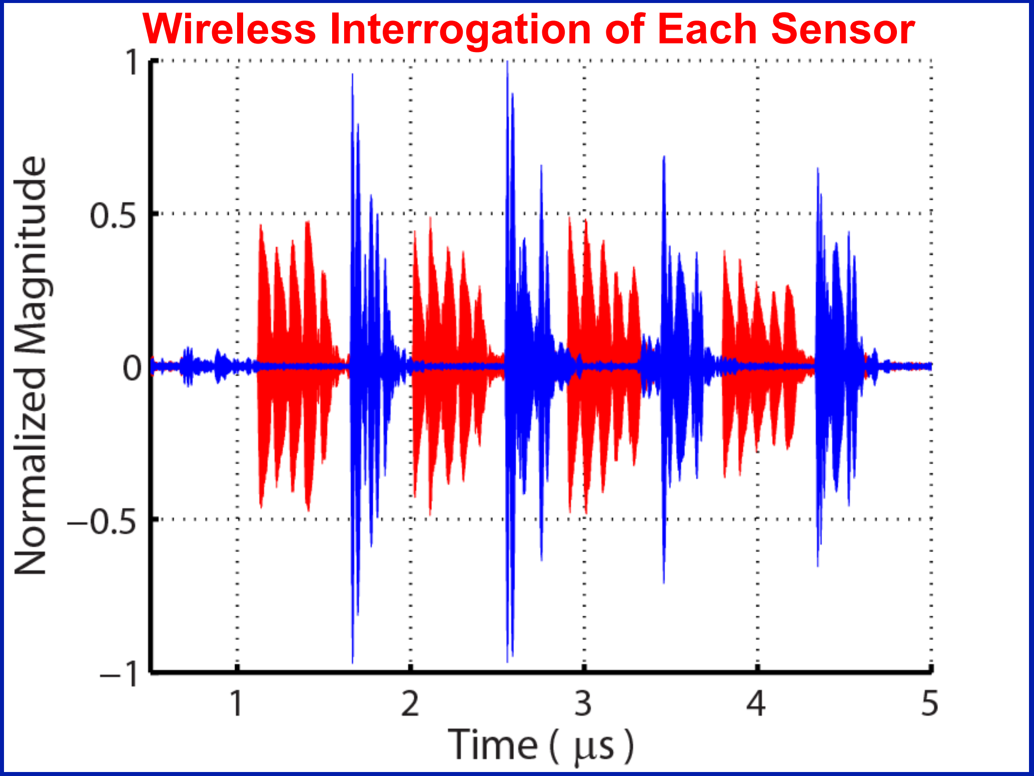


FFT



8 Multi-Sensor System Layout

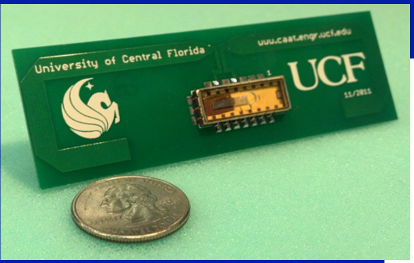
- 8 devices were designed to fit within a 5μs window.
- Each device was wirelessly interrogated (individually) with a VNA for calibration

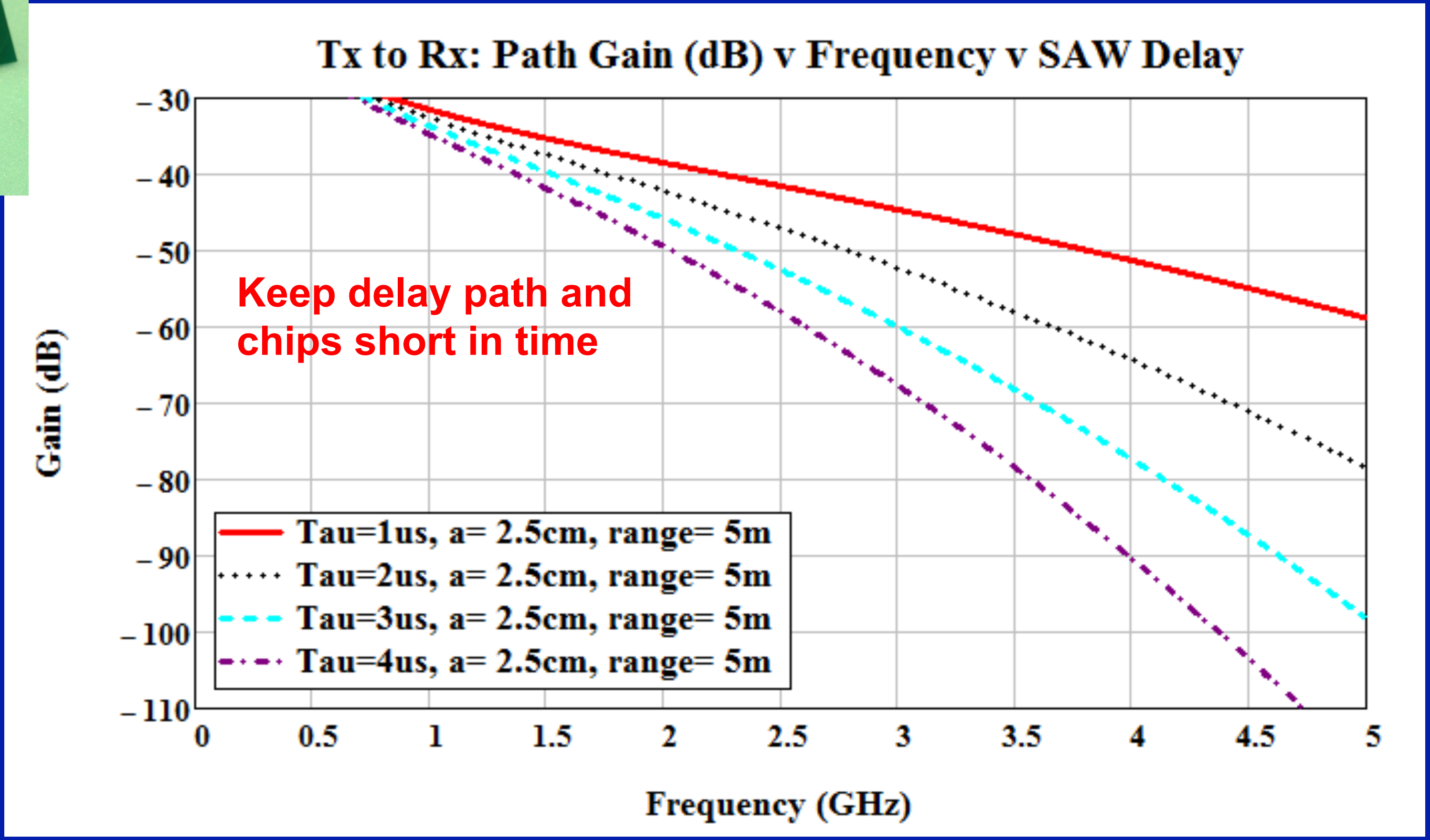


Measured Sensor's Impulse Response

SAW Sensor Acoustic Path Gain/Loss versus Frequency versus SAW Delay

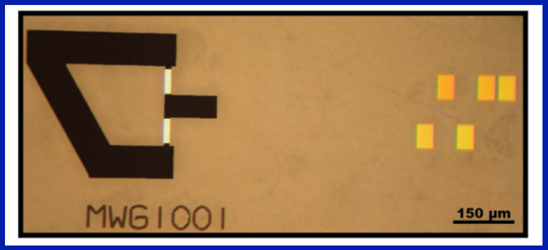
Assumes $VSWR_{max}$<2:1

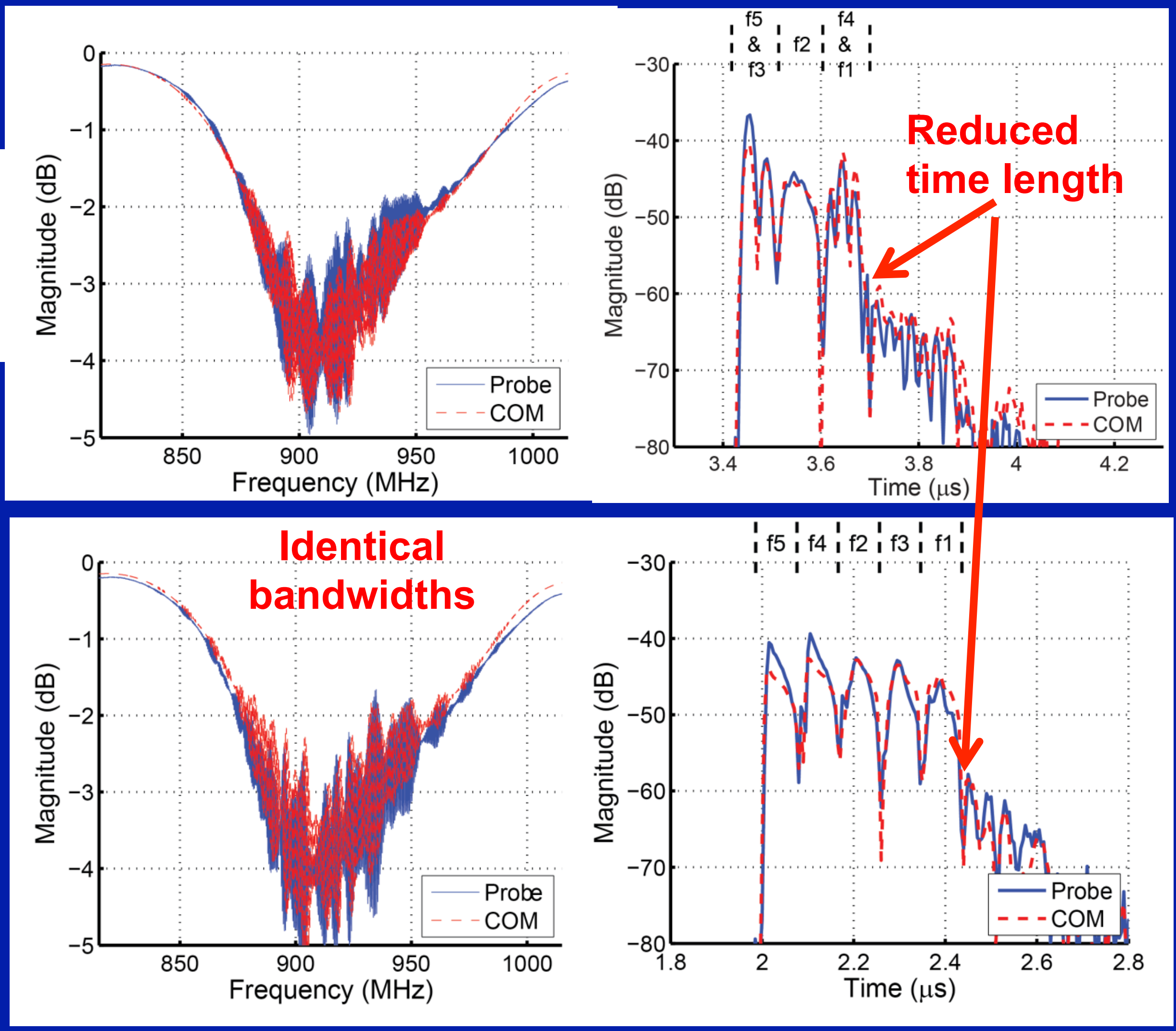




Comparison of Serial vs Mixed-OFC Sensors

Sensor die micrographs

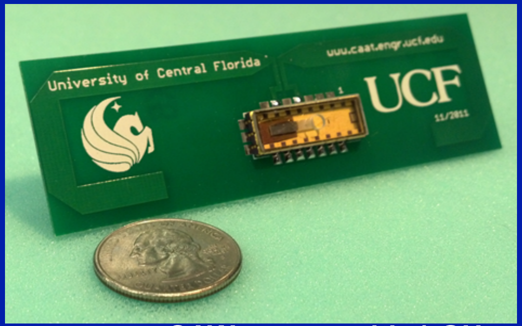




SAW Design Approach

- Harmonic SAW designs
- Reflective OFC delay lines
- Assume 6 OFC chips – 46,000 code set
  - Actual useful code set is significantly smaller
- BW_{chip}=33.3 MHz, T_{chip}=30 nsec
- T_{OFC}=180 nsec, N_{refl}~129
  - Short delays for better chip/sensor uniformity

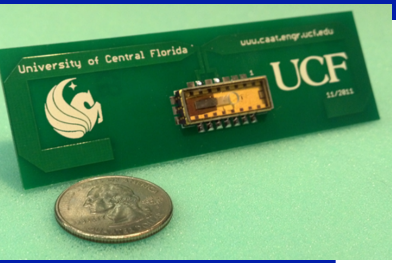
Antenna

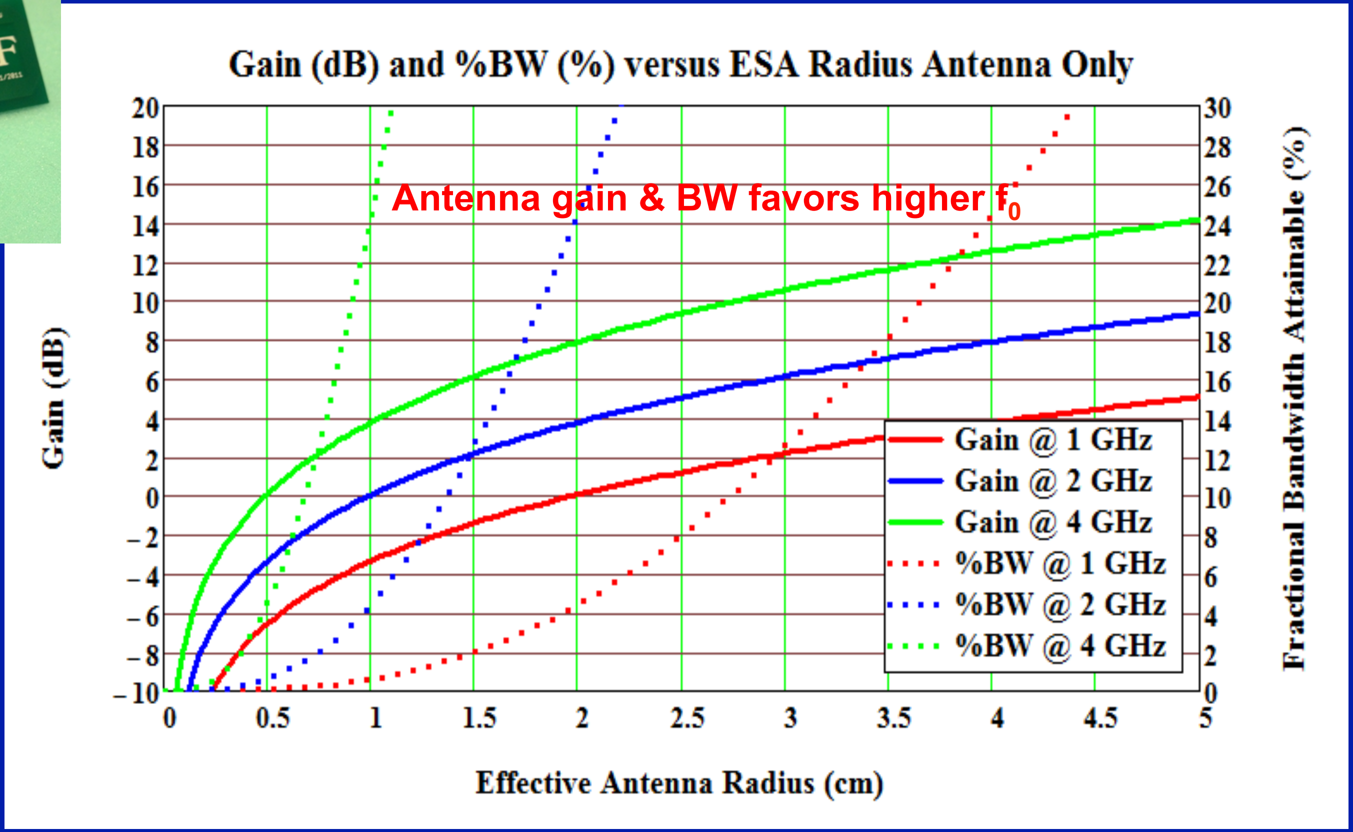


SAW sensor with 1 GHz PCB folded dipole antenna

- EM wavelength=7cm @ 4.3 GHz
- %BW=4.65 – narrow band
- Using electrically small antenna (ESA) approximation G_{ant}~10dB, for 2.5 cm
- Antenna on SAW device: G_{SAW}~20dB
- TxRx antenna larger with 30dB gain for Tx and Rx, respectively.
- Total system antenna gains: ~ 80dB

Approximate Antenna Gain and Bandwidth for Electrically Small Antennas (ESA)

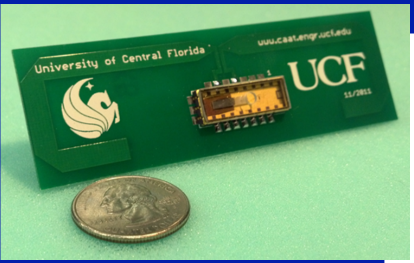




Assumes $VSWR_{max}$<2:1

Using Wheeler's derivation approximations

Tx to Rx: Free Space Path* Antenna *SAW Propagation Gain versus Frequency



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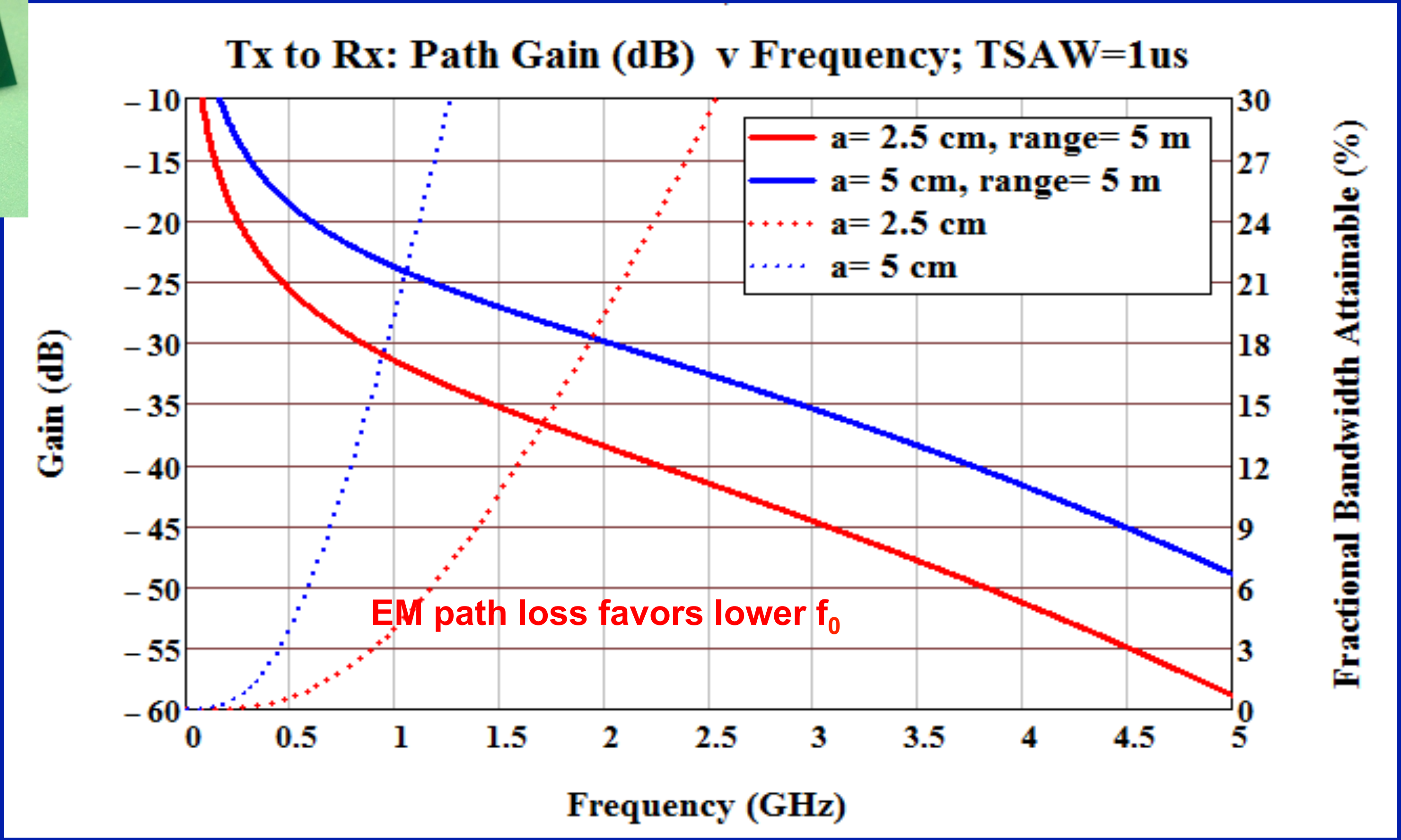

Assumes 1 usec delay, SAW@1 GHz ~1 dB/usec loss

TxRx Considerations

- TxRx –SDR with RF front-end board
  - Build on GHz knowledge base –follow wireless technology for cellular, etc.
  - Software Defined Radio (SDR)
  - f_0 within many current commercial product lines
  - RF frontend board development
  - Noise-like signal interrogation
  - ADC
    - BW will require high speed ADC or multiple ADCs.

Interrogation Signal Format

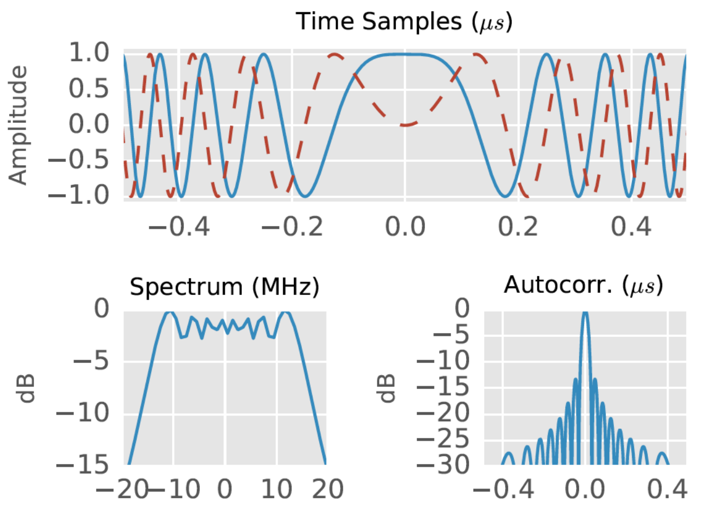

Fig. 2. A rectangular gated linear FM chirp with a time length of $1\mu s$ and a bandwidth of 32 MHz with real part (——) and imaginary part (- - -). The side-lobe levels are high in the auto-correlation response, but the spectrum is relatively flat.

Chirp

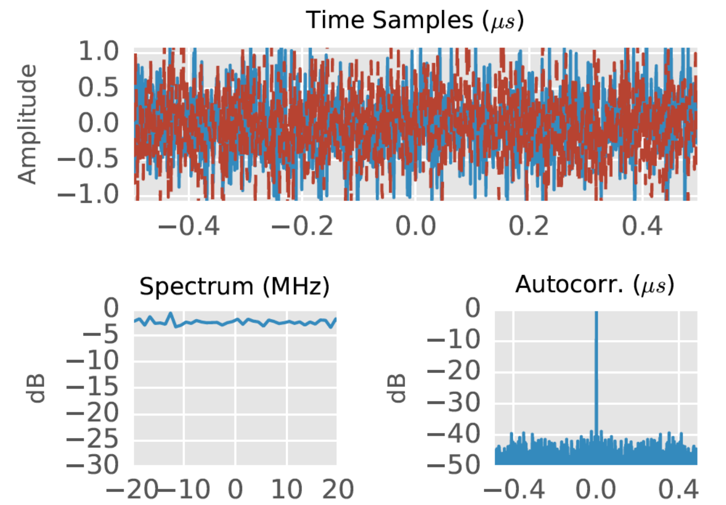

Fig. 4. A randomly generated interrogation signal with a time length of $1\mu s$ and with real part (——) and imaginary part (- - -). Averaging of multiple interrogation yields a flat spectrum. The autocorrelation has no sidelobes, reducing ambiguity in the time response.

White Noise

- **Tx determines BW or UWB, not the sensor**
- **Large coding space**
- **PG=Time*Bandwidth**

- **Low time sidelobes**
- **Large coding space**
- **Cross-correlation of Tx~0**

J. R. Humphries *et al.*, "Noise Radar Approach for Interrogating SAW Sensors Using Software Defined Radio," in *IEEE Sensors Journal*, vol. 17, no. 20, pp. 6760-6769, Oct.15, 15 2017. doi: 10.1109/JSEN.2017.2746519

Comments and Discussion @ 4 GHz Band

- Path, antenna, SAW_{prop} loss @ 5m: ~ 52dB
- SAW mismatch and reflector loss: ~ 20 dB
- PG: 15.5 dB
- SAW sensor loss variation: ~15-20 dB
- SAW fabrication achievable with harmonic operation
- Path forward based on 1 GHz SAW systems.

Looks feasible!

OFC Sensors to Date

- SAW device platform and transceiver system
  - Temperature
  - Gases
  - Cryogenic temperature sensing
  - Cryogenic liquid level
  - Room temperature, reversible H_2 gas
  - Closure
  - Strain
  - Magnetic-field

Thank You!

ACKNOWLEDGMENTS

- CAAT collaborations at the University of Central Florida (UCF), Orlando.
- UCF graduate student efforts, past and continuing, on SAW sensor technology systems.