# Experimental Assessment of Tandem-Hopped Radar and Communications (THoRaCs)


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# Motivation

- Increasing spectral congestion is driving research into radar/communication cohabitation strategies
  - Here we consider experimental validation of a co-design approach for a **single multi-function system**
- In [1], a power-efficient, multi-function arrangement denoted as Tandem-Hopped Radar and Communications (THoRaCs) was introduced
  - A two-stage optimization procedure places an undistorted OFDM signal into a **constant amplitude FM noise waveform**
- Here we focus on experimental evaluation of THoRaCs
  - Dual-function radar and communication perspectives are considered in loopback and open-air measurements

[1] B. Ravenscroft, P.M. McCormick, S.D. Blunt, E.S. Perrins, J.G. Metcalf, "A power-efficient formulation of tandem-hopped radar and communications," *IEEE Radar Conf.*, Oklahoma, City, OK, Apr. 2018.

# THoRaCs Structure

- In the THoRaCs formulation, the composite radar + OFDM waveform is directly designed as a **single dual-purpose emission**
  - This composite waveform is *constant amplitude* and *continuous*, **=> thus amenable to high-power transmitters**
  - The two-stage optimization procedure provides *undistorted communication subcarriers*
  - The undistorted OFDM signal is a *component* of a **constant amplitude FM signal**

$$\underbrace{s(t)}_{\text{Composite waveform}} = \underbrace{r(t)}_{\text{OFDM signal}} + \underbrace{e(t)}_{\text{"excess" signal required to enforce right-hand side}} = \exp(j\underbrace{\phi(t)}_{\text{Continuous phase function}})$$

**THoRaCs is NOT constant-envelope OFDM (CE-OFDM) where subcarriers are placed directly in the *exp*(•) term**

# THoRaCs Waveform Optimization

- We wish to generate a pulsed FM radar waveform of duration $T$ and 3-dB bandwidth $B$ that contains $N$ embedded OFDM subcarriers
  - Subcarriers modulated with arbitrary QAM symbols
  - Here there is one symbol / subcarrier / pulse
- As long as $N$ is sufficiently less than $BT$, the two-stage optimization procedure exploits the available degrees of freedom to produce a *true OFDM signal* that **resides within an FM waveform**
- Each waveform is spectrally-shaped to yield low autocorrelation sidelobes
  - A Gaussian shaped power spectrum is employed here
- A total of $M$ unique pulsed waveforms are produced to form a coherent processing interval (CPI)
  - The inherent waveform agility realizes incoherent sidelobes that average out when combined in slow-time

# THoRaCs Optimization – Initialization

- Initialize the $m^{\text{th}}$ pulse, defined on $-T/2 \le t \le T/2$, with a random FM waveform denoted as $s_{0,m}(t)$ via a random instantiation of polyphase-coded FM (PCFM) **[2]**
- Over the same time interval, define the communication signal as

$$r_m(t) = \sum_{n=0}^{N-1} a_{m,n} \left| c_{m,n} \right| \exp\left[ j\left( 2\pi f_{m,n} t + \angle c_{m,n} \right) \right]$$

where, for the $m^{\text{th}}$ pulse,

$f_{m,n}$ is the frequency of the $n^{\text{th}}$ subcarrier,

$c_{m,n}$ is the QAM symbol encoded onto the $n^{\text{th}}$ subcarrier,

$a_{m,n}$ is the amplitude scaling factor that shapes the spectrum at the $n^{\text{th}}$ subcarrier.

**[2] S.D. Blunt, M. Cook, J. Jakabosky, J. de Graaf, E. Perrins, "Polyphase-coded FM (PCFM) radar waveforms, part I: implementation," *IEEE Trans. Aerospace & Electronic Systems*, vol. 50, no. 3, pp. 2218-2229, July 2014.**

# THoRaCs Optimization – Stage One

Desired PSD: $\left|G(f)\right|^2$ Desired comm. signal: $r_m(t)$

Initial segment

$s_{0,m}(t)$

Enforce spectral shape

$$b_{k,m}(t) = \mathbb{F}^{-1}\left\{\left|G(f)\right|\exp\left(j\angle\mathbb{F}\left\{s_{k,m}(t)\right\}\right)\right\}$$

Repeat $K$ times

Fourier transforms

Project onto orthogonal complement of subcarriers & then insert OFDM signal

$$\tilde{b}_{k,m}(t) = P_{\perp r_m}\left\{b_{k,m}(t)\right\} + r_m(t)$$

Extract continuous phase to enforce constant amplitude & enforce pulse shape

$$s_{k+1,m}(t) = \begin{cases} \exp\left(j\angle\tilde{b}_{k,m}(t)\right) & \left|t\right| \le T/2 \\ 0 & \left|t\right| > T/2 \end{cases}$$

**Stage one:**

optimized $m$th pulse

$s_{K,m}(t)$

# THoRaCs Optimization – Stage Two

**Same as Stage One, just with the spectral shaping removed**

Initialize with final stage one waveform

$$\tilde{s}_{\ell=0,m}(t) = s_{K,m}(t)$$

$$d_{\ell,m}(t) = P_{\perp r_m}\left\{\tilde{s}_{\ell,m}(t)\right\} + r_m(t)$$

Repeat $L$ times

$$\tilde{s}_{\ell+1,m}(t) = \begin{cases} \exp\left(j\angle d_{\ell,m}(t)\right) & |t| \le T/2 \\ 0 & |t| > T/2 \end{cases}$$

Permits modest deviation from desired spectrum while enforcing desired comm. signal structure

Final optimized $m$th waveform

$$\tilde{s}_{L,m}(t)$$

# Options for OFDM Parameterization

- In the formulation of $r_m(t)$, three design parameters are examined:
  1) Size of the OFDM symbol constellation
  2) Number of OFDM subcarriers $N$ relative to waveform $BT$
  3) Placement of subcarriers within the radar spectrum

**All $N$ subcarriers forced to reside within 3-dB bandwidth**

| Symbol constellation | Subcarrier percentage | Subcarrier placement |
|---|---|---|
| 4-QAM | 25% $BT$ | "Contiguous Fixed" |
| 16-QAM | | "Contiguous Hopped" |
| 64-QAM | 75% $BT$ | "Non-Contiguous Hopped" |

"Contiguous Fixed": Subcarriers grouped together, static from pulse-to-pulse

"Contiguous Hopped": Subcarriers grouped together, location moves from pulse-to-pulse

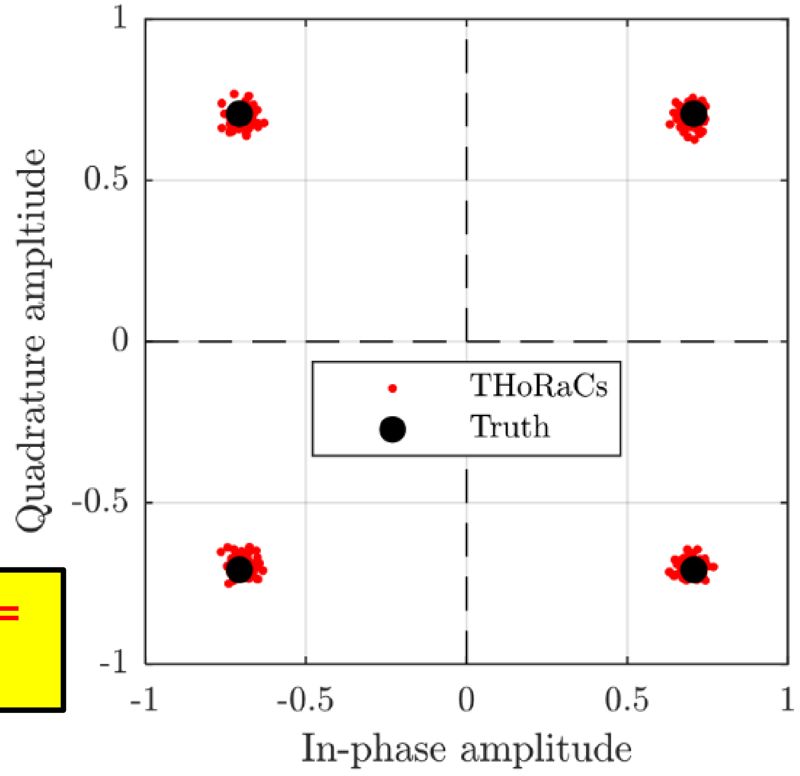
"Non-Contiguous Hopped": Subcarriers move independently from pulse-to-pulse

# Simulated Assessment: Subcarrier Capacity

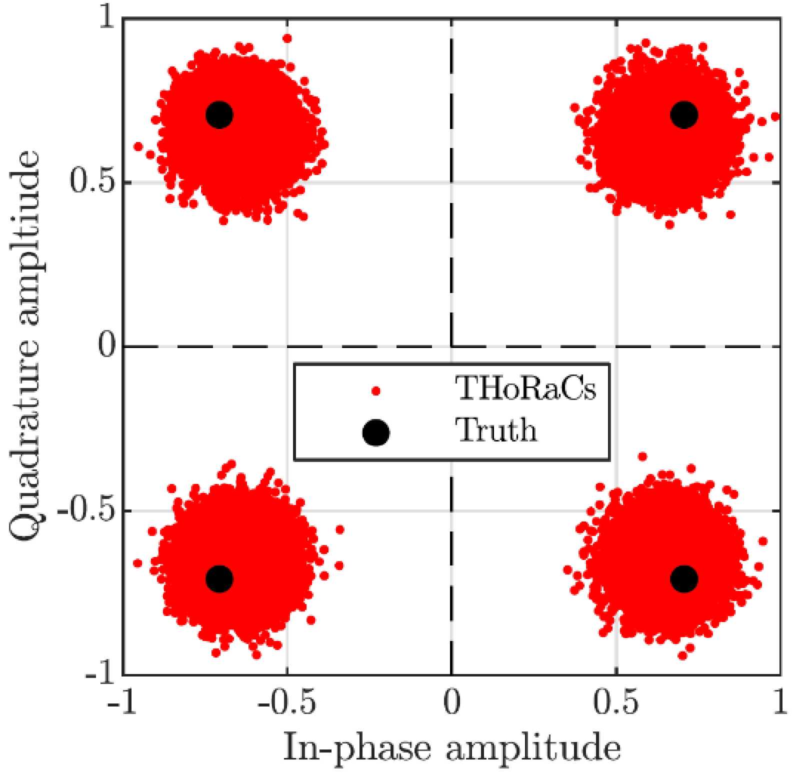
- A *noise-free* simulation of the **optimized** THoRaCs waveforms is conducted to assess **distortion** caused to the embedded OFDM signal via *optimization only*
  - A set of $M = 10^3$ THoRaCs waveforms with $BT = 200$ are optimized and the OFDM subcarriers are demodulated with knowledge of the constellation and subcarrier placement
- Two instantiations of embedded OFDM parameters are considered
  - 4-QAM constellation with $\boldsymbol{N = 50}$ **(25% of** $\boldsymbol{BT = 200}$**)** & $\boldsymbol{N = 150}$ **(75% of** $\boldsymbol{BT = 200}$**)** subcarriers per pulse, embedded via the "Contiguous Fixed" placement strategy
  - Highlights impact of OFDM distortion caused by the optimization procedure
- The "spread" of the demodulated symbols around their respective constellation points is assessed via the root-mean-square (RMS) error vector magnitude (EVM), expressed as a *percentage* of the average symbol energy

**4-QAM** constellation and "**Contiguous Fixed**" subcarrier placement

**RMS EMV = 0.45%**




***N* = 50 subcarriers/pulse**




***N* = 150 subcarriers/pulse**

**RMS EMV = 10.9%**

**Increasing *N* degrades demodulation accuracy for fixed *BT***

# Experimental Assessment: Hardware Implementation

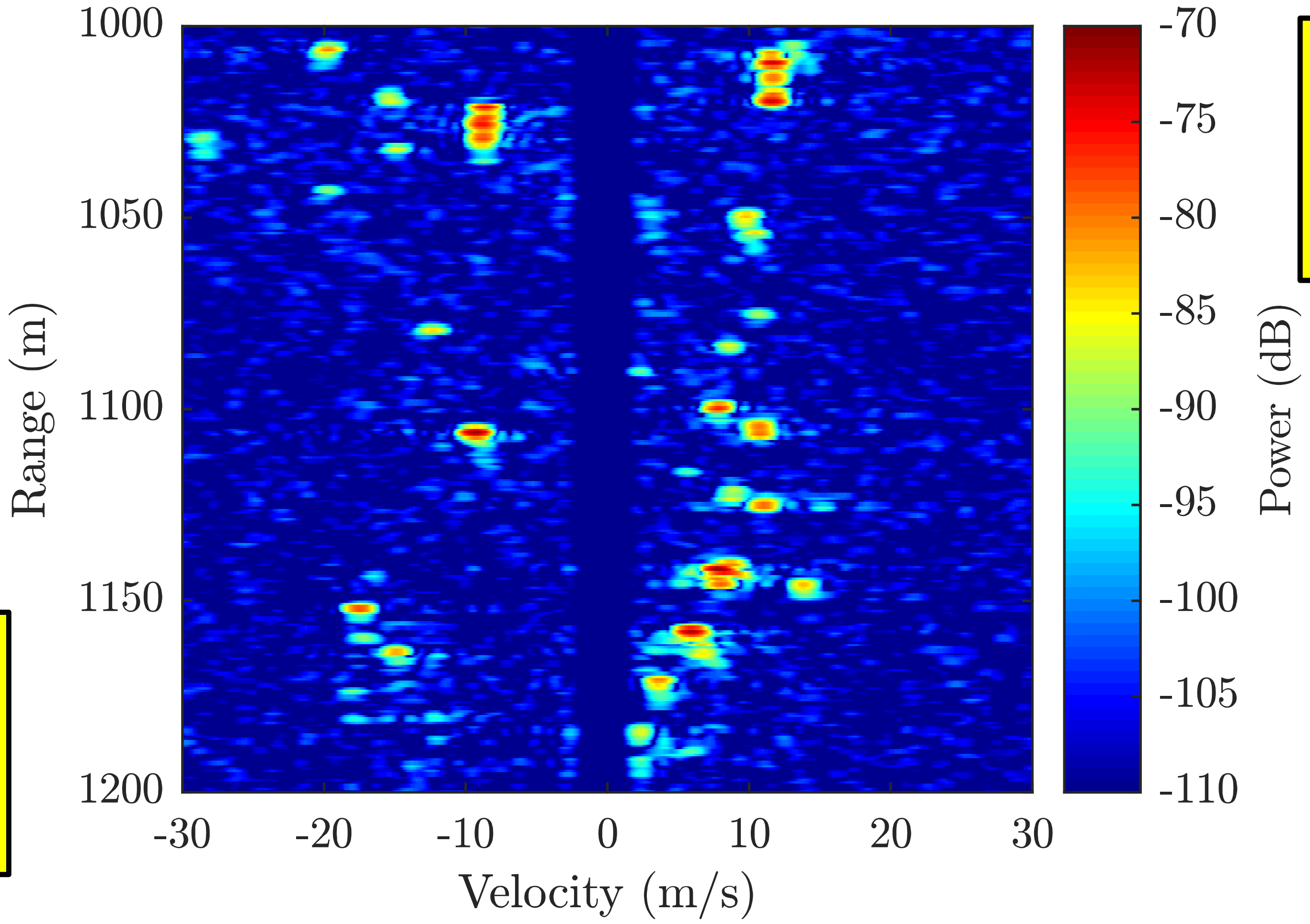
- For all *experimental* evaluations conducted, a set of $M = 10^3$ THoRaCs waveforms were optimized having $BT = 200$ ($B = 66.7$ MHz and $T = 3$ μs)
  - The collective CPI has aggregate $BT = 2 \times 10^5$ that yields ~53 dB of *coherent integration gain* at the radar receiver
- Each waveform is **physically implemented** on a Tektronix arbitrary waveform generator (AWG) for transmission
  - Digitally up-sampled to 10 GS/s at a center frequency of 3.55 GHz and PRF of 25 kHz
- Each received signal is captured by a Rohde & Schwarz real-time spectrum analyzer (RSA)
  - I/Q sampled at a rate of 200 MHz

# Experimental Radar Assessment: Open-Air

- **Experimental assessment** of the radar operation of optimized THoRaCs waveforms was conducted in an MTI mode
  - Vehicular traffic captured from the roof of a building on the University of Kansas campus
- Captured reflections of the CPI are pulse-compressed with loopback-measured versions of the waveforms
  - Accounts for hardware distortion effects
- Range-Doppler response is formed via standard FFT Doppler processing
  - Zero-Doppler projection clutter notch (stationary platform)
  - Taylor window applied across Doppler

# Experimental Radar Assessment: Open-Air

**4-QAM** constellation and "**Contiguous Fixed**" subcarrier placement with $N = 50$ (25% of $BT$) subcarriers




**Low range sidelobes due to incoherent combining in slow-time**

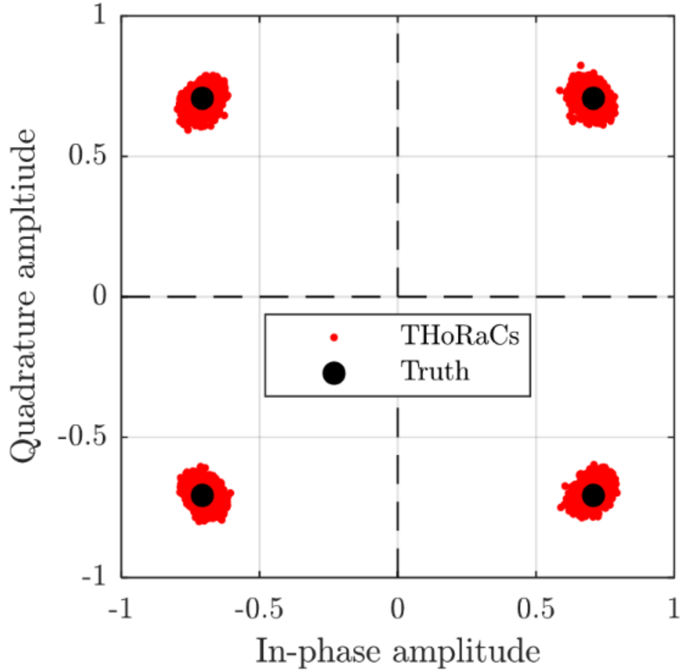
**Results agree with previous radar assessment of FM noise waveforms**

# Experimental Comm. Assessment: Loopback

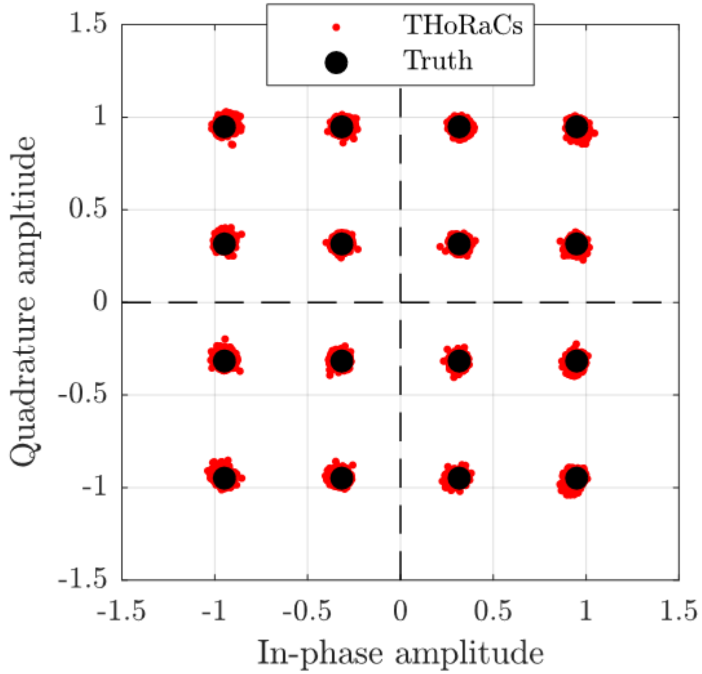
- To assess communication performance, loopback captures are first performed to establish a baseline
  - Transmitter (AWG) is connected directly to receiver (RSA) and both are referenced from the same clock to avoid synchronization issues (not realistic)
  - Hard-wired channel does not possess multi-path and removes need for equalization
  - Lack of synchronization and channel equalization **are addressed** in open-air measurements
- Optimized THoRaCs waveforms with three instantiations of embedded OFDM parameters are considered
  - 4-QAM, 16-QAM and 64-QAM constellations with $N$ **= 50 (25% of** $BT$ **= 200)** subcarriers per pulse, embedded via "Contiguous Fixed" placement strategy
  - Corresponds to data rates of 2.5, 5.0 and 7.5 Mbps, respectively, at PRF = 25 kHz
- The RMS EVM again used to assess the **accuracy** of symbol demodulation

# Experimental Comm. Assessment: Loopback

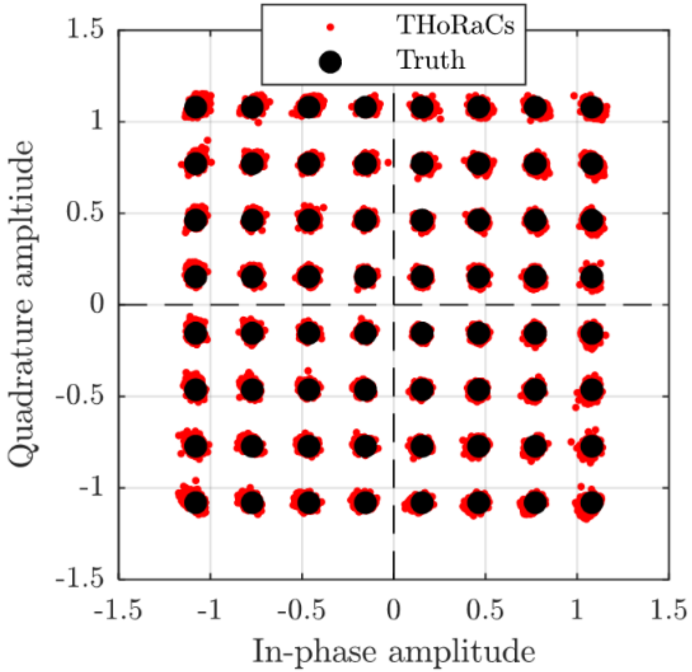
**4, 16 and 64-QAM** constellations with "**Contiguous Fixed**" subcarrier placement and ***N* = 50 (25% of *BT*)** subcarriers




**RMS EMV = 4.0%**




**RMS EMV = 3.0%**

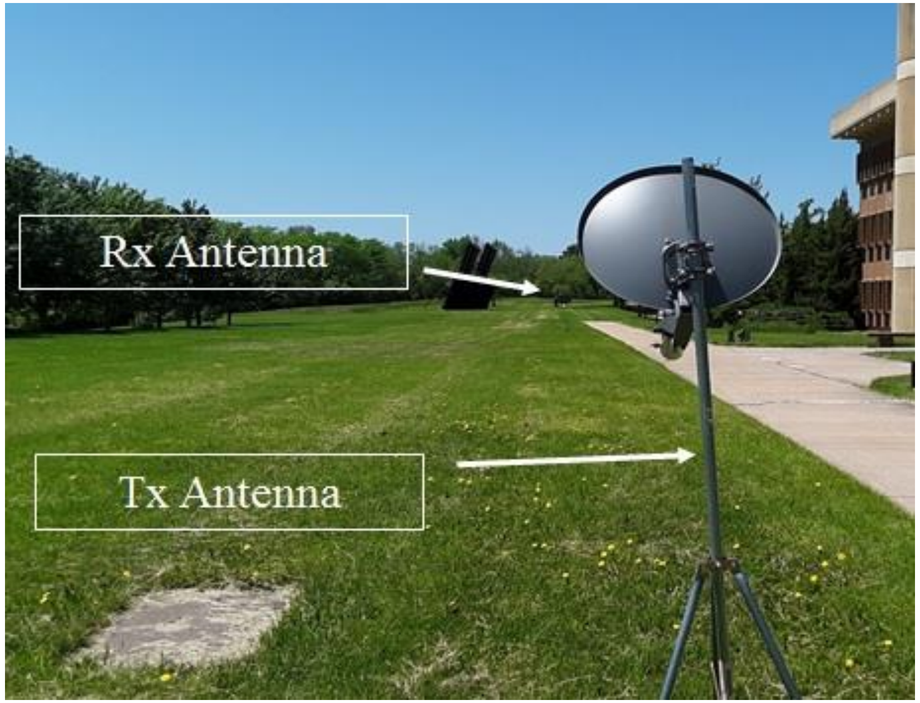



**RMS EMV = 3.2%**

**Excellent agreement with true symbols – no demodulation errors**

# Experimental Comm. Assessment: Open-Air

- The **open-air communication** capability of THoRaCs waveforms was <u>**experimentally assessed**</u> in a line-of-sight (LOS) configuration
  - Transmit and receive antennas placed directly facing each other separated by ~ 50 meters
  - Direct LOS is present with some multipath due to surrounding buildings/trees and ground bounce
- The same three waveform sets evaluated for loopback communication were evaluated in open-air
  - Transmit antenna is fed by AWG and RSA obtains signal captured by receive antenna
  - <u>No common reference clock</u>



# Experimental Comm. Assessment: Open-Air

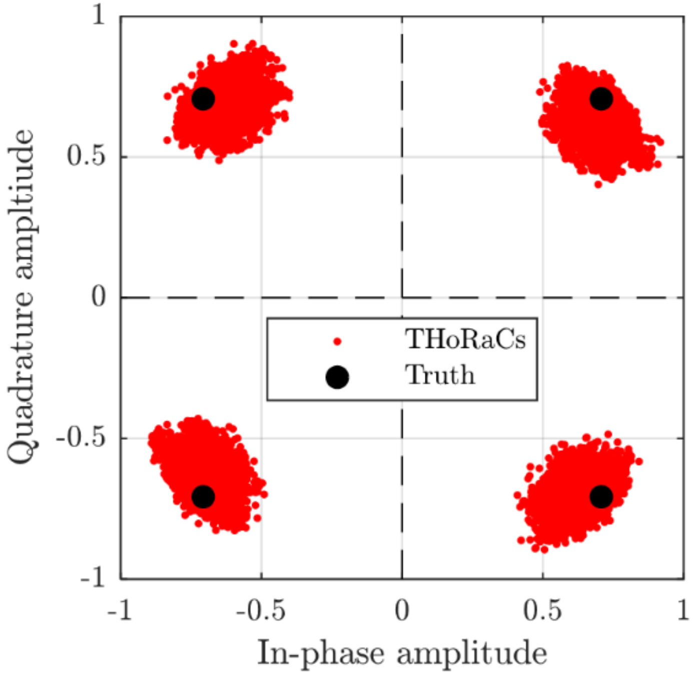
- Open-air communication operation requires the receiver to perform synchronization and channel estimation/equalization
  - Accomplished via a-priori knowledge of pilot symbols
- Embedded OFDM signal does **not** contain a cyclic prefix
  - Standard OFDM frequency domain equalization is expected to realize degradation due to mismatch effects
- Equalization is instead performed by estimating the inverse channel response with a Wiener Filter (WF) and forming an inverse filter using a zero-forcing (ZF) equalizer
  - Inverse filter is applied to captured waveform to compensate for channel distortion
- Communication performance is assessed through demodulated RMS EVM and symbol error rate (SER)

# Open-Air Comm. Equalization/Synchronization

- For each set of 1000 waveforms, every $50^{th}$ pulse serves as a *pilot* waveform for channel equalization
- Receiver must perform synchronization due to lack of a common clock
  - Pulse-to-pulse frequency offset (small) can be estimated as a constant phase drift between pulses (with some estimation error inherent)
- The $1^{st}$ and $2^{nd}$ pulses of each 1000 pulse set are used as pilots to estimate the phase offset
  - Frequency offset compensation applied to all other pulses in a progressive manner
- Progressive frequency offset compensation is restarted at every $50^{th}$ pulse when channel re-estimation occurs
  - Reduces error-induced phase shift

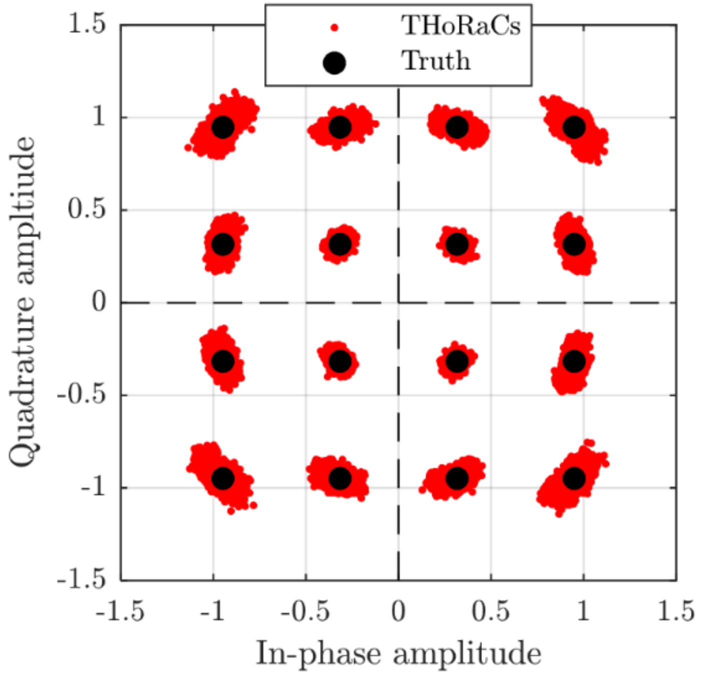
# Experimental Comm. Assessment: Open-Air

**4, 16 and 64-QAM** constellations with "**Contiguous Fixed**" subcarrier placement and ***N* = 50 (25% of *BT*)** subcarriers



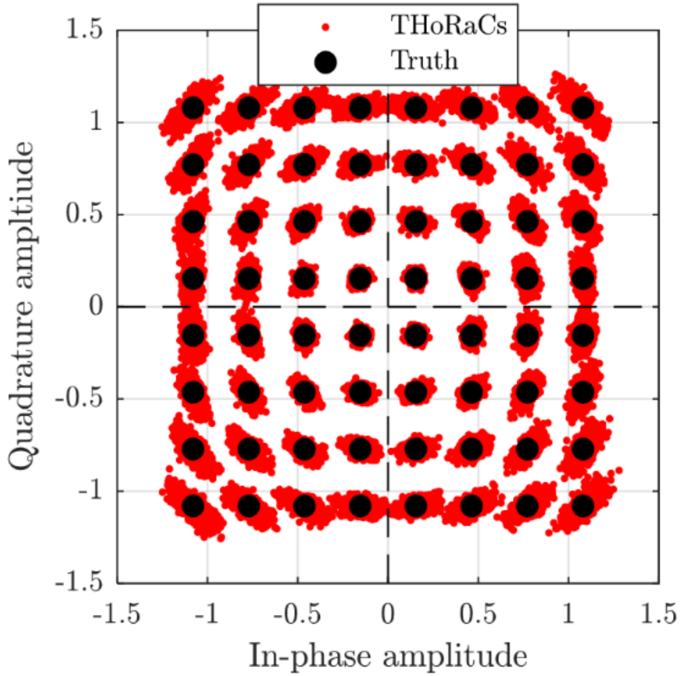

**RMS EMV = 10.2%**

**SER = 0**




**RMS EMV = 5.6%**

**SER = 0**




**RMS EMV = 5.2%**

**SER = 1.8 × $10^{-3}$**

**Increased (and phase-oriented) spreading compared to loopback baseline**

# Conclusions

- **Experimental assessment** of THoRaCs in radar and communication modes demonstrates viability as a dual-function waveform
- Channel estimation, equalization, and synchronization was crude and unsophisticated
  - Communication performance stands to benefit from more sophisticated estimation/equalization/synchronization methods along with error correction coding
- Nonlinear distortion and memory effects of a high-power transmitter could further impact communication performance … though not as much as standard OFDM