System Equalization for Specific Emitter Identification

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System Equalization for SEI

- **Goal:** To achieve interoperable *Specific Emitter Identification* (SEI)
  - Between channels within a collection system
  - Between collection systems within a platform
  - Between multiple platforms of various types
- Interoperable SEI allows for exchange of data between collection assets with high confidence
System Equalization for SEI: Objectives

- Quantify effects of passband anomalies in both magnitude and phase inherent in a collection system on SEI features

- Determine system specifications and necessary amount of frequency response “flatness” based on allowable SEI match criteria

- Develop and test algorithms to characterize and compensate for distortions in a given collection system

- Implement procedures using digital hardware for real-time system equalization adaptive to tuning scenario, the channel selection, and temperature

- Integrate calibration procedures with existing collection system(s)
Problem Description

• For a given emitter
  – Magnitude and group delay distortion introduced in one collection system and/or system channel is different from that of another
  – Distortion exaggerated for wideband and frequency agile signals due to off-tuning

• Resulting SEI features are colored from anomalies in passband

• Past equalization attempts dealt only with magnitude anomalies in passband

• Often limited to only a fraction of system operating bandwidth
Analysis Approach

• Determine analytically distortion in SEI features resulting from differential magnitude and group delay in intercepted signal’s amplitude versus time spectrum
  
  – Assumed Narrowband FM waveform
  
  – SEI features generated using N-pt DFT coefficients of demodulated frequency versus time waveform

  – Distortion in SEI features quantified using Normalized Euclidean Distance (NED) match metric

  • Metric compares like coefficients between distorted test, undistorted reference signals

  • Determined allowable levels of sideband magnitude and group delay distortion from collection system on extracted FM features using match score criteria of 0.1
Spectral Characteristics of FM Waveform

- Narrowband FM signal (baseband amplitude spectrum of carrier with 1st sideband pair) shown having a frequency modulation rate $f_{\text{MOD}}$, maximum frequency deviation $f_{\text{DEV}}$, and Modulation Index $\beta = \frac{f_{\text{DEV}}}{f_{\text{MOD}}}$ for $\beta < 0.1$

- Carrier magnitude equal to 1, sideband magnitude equal to $\beta/2$

- Carrier phase and frequency modulated by sideband resultant parallel to frequency (x) axis
  - Maximum frequency deviation equal to
    $$f_{\text{DEV}}(\text{max}) = 2 \cdot \text{sideband magnitude} = \beta \ (\beta < 0.1)$$

- Differential magnitude and group delay between sidebands will alter FM vs. time waveform from which SEI features are extracted
Using Demodulated FM Waveform to Generate SEI Feature Set

- Intercepted pulse demodulated to yield amplitude (AM), frequency (FM)
- Sample window determined from pulse width, pulse rise time
- Samples of FM (in red) used to generate SEI Feature coefficients

- SEI Features are complex coefficients returned from N-pt DFT of FM versus time waveform, calculated as

\[ X(k) = \sum_{n=0}^{N-1} x(n)e^{-\frac{2\pi kn}{N}} \quad k = 0,1,2\ldots, N-1 \]

- SEI features \( a_k + jb_k \) can be expressed as vectors, having a magnitude and phase given as

\[ \sqrt{a_k^2 + b_k^2} = \text{magnitude of complex vector } k \]

\[ \theta_k = \tan^{-1}\left(\frac{b_k}{a_k}\right) = \text{phase of complex vector } k \]

- Differences in magnitude and phase between like SEI feature coefficients a function of differential magnitude, group delay between sideband pairs
SEI Feature Distortion and NED Metric

- SEI feature coefficients are compared to a reference using the Normalized Euclidean Distance (NED) match metric, given as

\[
NED = \frac{\sqrt{(a_{ref} - a_{test})^2 + (b_{ref} - b_{test})^2}}{\sqrt{a_{ref}^2 + b_{ref}^2} + \sqrt{a_{test}^2 + b_{test}^2}}
\]

- Score less than 0.2 is considered a “match”; target score of 0.1 used to establish system requirements

- NED score can be written as a function of phase shift, amplitude difference between test and reference coefficient vectors

- Both phase shift, amplitude difference between coefficient vectors a function of differential magnitude, group delay between sidebands
Sideband Magnitude Distortion

• Ideally, the magnitude response $K$ is constant across frequency, preserving the magnitude relationships between carrier and sideband components

$$K = K_{LSB} = K_{CARRIER} = K_{USB} = \frac{\text{output spectral component magnitude}}{\text{input spectral component magnitude}}$$

• Using the magnitude response at the carrier frequency as reference, the differential magnitude response in lower and upper sideband components $\Delta K_{LSB}$, $\Delta K_{USB}$ are defined as

$$\Delta K_{LSB} = \frac{K_{LSB}}{K_{CARRIER}}, \quad \Delta K_{USB} = \frac{K_{USB}}{K_{CARRIER}}$$

• Differential Magnitude distortion $\Delta K_{LSB}$, $\Delta K_{USB}$ in sideband components will result in distortion in the frequency deviation of the frequency versus time waveform

• The resulting effective frequency deviation $f_{DEV}'$ in terms of sideband attenuation $K_{LSB}$, $K_{USB}$, and the original deviation $f_{DEV}$ is calculated as

$$f_{DEV}' = \frac{(\Delta K_{LSB} + \Delta K_{USB})f_{DEV}}{2}$$
Effect of Sideband Magnitude Distortion on SEI Feature Coefficient

- The resulting NED score in terms of differential sideband magnitude response $\Delta K_{LSB}, \Delta K_{USB}$ can be shown to equal

$$NED(\Delta K_{LSB}, \Delta K_{USB}) = \frac{|(\Delta K_{LSB} + \Delta K_{USB}) - 2|}{2 + (\Delta K_{LSB} + \Delta K_{USB})}$$

- The SEI feature vector is not rotated, as the resultant of the sideband pair remains parallel to the horizontal frequency axis

- Expressed in dB, the differential magnitude response $\Delta K_{LSB}, \Delta K_{USB}$ is analogous to the passband magnitude ripple of a system
Impact of magnitude distortion in sidebands greatest when $\Delta K_{\text{LSB}} = \Delta K_{\text{USB}}$

NED error for this case calculated as

$$NED(K) = \frac{|K - 1|}{1 + K}, \quad K = \Delta K_{\text{LSB}} = \Delta K_{\text{USB}}$$
Group Delay and Sideband Phase Distortion

- The corresponding phase shift $\Delta \phi$ in a sideband can be calculated using the delay difference $\Delta \tau$ with respect to the carrier:

$$\Delta \phi(f) = \int \Delta \tau(f) = \int m \Delta f = -m \frac{\Delta f^2}{2} \cdot 2\pi \quad \text{(in rad)}$$

$$\Delta \phi(f) = -m \Delta f^2 \cdot 180 \quad \text{(in deg)}$$

- The phase distortion $\Delta \phi$ is determined by integrating the delay:

- The phase distortion in terms of the differential delay is $\Delta \phi(f) = -\Delta \tau \Delta f \cdot 180$ (in deg)

- Sideband phase distortion with respect to the carrier can be written as

$$\Delta \phi_{\text{LSB}} = -f_{\text{MOD}} \Delta \tau_{\text{LSB}} \cdot 180, \quad \Delta \phi_{\text{USB}} = f_{\text{MOD}} \Delta \tau_{\text{USB}} \cdot 180 \quad \text{(in deg)}$$
Effect of Sideband Phase Distortion on SEI Feature Coefficient

- Phase distortion of $\Delta \phi_{\text{LSB}}$, $\Delta \phi_{\text{USB}}$ induced on sideband pair will result in both magnitude and phase distortion of corresponding SEI feature coefficient.

- Magnitude of SEI feature coefficient reduced by

  $$\cos \left( \frac{\Delta \phi_{\text{LSB}} - \Delta \phi_{\text{USB}}}{2} \right)$$

- Phase of SEI feature coefficient shifted by

  $$\frac{\Delta \phi_{\text{LSB}} + \Delta \phi_{\text{USB}}}{2}$$
• Impact of phase distortion greatest when $\Delta \phi_{LSB} = -\Delta \phi_{USB}$

• NED error for this case calculated as

$$NED(\Delta \phi) = \sqrt{\frac{1}{2} [1 - \cos(\Delta \phi)]}, \quad \Delta \phi = |\Delta \phi_{LSB}| = |\Delta \phi_{USB}|$$
Analysis Verification Using Filtered FM Signals

**Case 1:** \( \Delta \phi_{\text{LSB}} = -\Delta \phi_{\text{USB}} \)

**Case 2:** \( \Delta \phi_{\text{LSB}} = \Delta \phi_{\text{USB}} \)

**Case 3:** \( 0 < \Delta \phi_{\text{USB}} < 360^\circ \) 
\((\Delta \phi_{\text{LSB}} = 0)\)

\[ NED(\Delta \phi) = \sqrt{\frac{1}{2} [1 - \cos(\Delta \phi)]} \]

\[ NED(\Delta \phi) = \begin{cases} 
\frac{1 - \cos(\Delta \phi)}{1 + \cos(\Delta \phi)} & 0 \leq \Delta \phi \leq 90 \\
\frac{1}{1 - \sin(\Delta \phi)} & 90 \leq \Delta \phi \leq 270 \\
\frac{1}{1 + \sin(\Delta \phi)} & 270 \leq \Delta \phi \leq 360 
\end{cases} \]

\[ NED(\Delta \phi) = \begin{cases} 
\tan\left(\frac{\Delta \phi}{4}\right) & 0 \leq \Delta \phi \leq 180 \\
\tan\left(\frac{\pi - \Delta \phi}{4}\right) & 180 \leq \Delta \phi \leq 360 
\end{cases} \]

- Narrowband FM signals generated at various FM rates (sidebands move apart) and passed through given delay response (\( \beta = 0.1 \))
- NED error between filtered, unfiltered signal computed
  - Used FM FFT coefficient corresponding to rate (bin with most energy, excluding bin 0)
- Known slope of delay in test filter (\( m = 8.4375 \text{ nsec/MHz} \)) used to determine sideband phase shift
  \[ \Delta \phi_{\text{Sideband}} = f_{\text{Sideband}} \Delta \tau_{\text{Sideband}} \cdot 180 \text{ (in deg)} \]
Analysis Results Using Filtered FM Signals

- Measured results (on left) agree with predicted results (on right)
  - Case 1 (in black): NED = 0.1 when $\Delta \phi = 11.48$ degrees
    - This case analogous to shifts in Half Voltage Point
  - Case 2 (in blue): NED = 0.1 when $\Delta \phi = 35.1$ degrees
  - Case 3 (in red): NED = 0.1 when $\Delta \phi = 22.84$ degrees
- Case 1 used to determine system group delay specification requirements
\[ NED(K) = \frac{|K - 1|}{1 + K}, \quad K = \Delta K_{LSB} = \Delta K_{USB} \]
Magnitude Specification for NED < 0.1

- Recommended magnitude “flatness” determined from worse case scenario
  - Equal magnitude distortion in both sidebands with respect to carrier
  - For NED error < 0.1, allowable distortion in sidebands $K$ can be found as

$$
\frac{9}{11} < K < \frac{11}{9} \quad (\pm 0.872 \text{ dB})
$$

$$
K = \frac{\text{distorted sideband magnitude}}{\text{undistorted sideband magnitude}}
$$

$$
|H(\omega)| \text{ dB} \quad \text{or} \quad 0.872 \text{ dB}
$$

$$
+ 0.872 \text{ dB} \quad \text{or} \quad - 0.872 \text{ dB}
$$

Distortion Scenarios
\[ \Delta \tau = \frac{\cos^{-1}(1 - 2NED^2)}{\pi f_{MOD}} \]
Recommended group delay “flatness” determined from worse case scenario

- Equal differential delay between sidebands, phase shifted in opposite direction

For NED error < 0.1, allowable differential group delay $\Delta \tau$ is a function of the FM rate $f_{\text{MOD}}$, and can be found as

$$\Delta \tau = \frac{1}{5\pi f_{\text{MOD}}} \quad (\Delta \tau \text{ in usec, } f_{\text{MOD}} \text{ in MHz})$$
Characterization Approach

- Linear frequency modulated signal swept across device passband
  - Collection made of both input and output signal
  - Transformed into frequency domain using MATLAB™

- Magnitude, phase, and group delay responses from collected data:

\[
|H(\omega)| = \frac{|Y(\omega)|}{|X(\omega)|}, \quad \varphi(\omega) = \angle Y(\omega) - \angle X(\omega), \quad \tau(\omega) = \frac{\Delta \varphi(\omega)}{\Delta \omega}
\]
Characterization Example

- Relative time maintained between injected and collected signal to determine absolute delay of signal
Characterization Results

- IF magnitude response across RF operating range (on right), group delay on left
- Statistical analysis performed to determine required number of filter designs to compensate entire system
Compensation Filters Designed From Characterization Results

44-tap FIR w/ linear phase

32-tap FIR w/ unity magnitude

(± 0.04 dB max in care region)

- Digital filters designed for implementation on baseband I and Q samples
  - Complex coefficients for non-symmetric group delay compensation
- Alternative: equalize prior to down-conversion to enable real tap weights in filter design
• Example of test waveform (5 MHz Rate, ±1 MHz Deviation) tuned across IF filter model

- Less spreading of FM features due to magnitude, group delay differences in spectral components
- Improved accuracy of features
  - NED Error in 5 MHz bin reduced to less than 0.125 across band
  - Coefficient Magnitudes vary from ~0.85 - 1.05 MHz vs. theoretical value of 1
  - Phase of coefficients vary ~± 17 deg. from theoretical value of 90 deg.
- Allows for high confidence matching independent of receiver tuning
Resulting SEI Features Utilizing Magnitude Compensation Only

- Magnitude compensation provides marginal improvement in NED
- Not sufficient across entire band
Resulting FM Features Utilizing Baseband Phase Compensation Only

5 MHz FM FFT Coefficients

Mean NED Error vs. Off-Tuning, s1w2, 5 MHz Bin

FM Coefficients vs. Off-Tuning Frequency

NED vs. Off-Tuning
AM Transient Reduction

- AM envelope of test pulse shown (600 nsec PW, 1/20 of IF filter BW) tuned off-center
  - Ideal envelope (in red)
  - Unequalized (in black) exhibits distortion due to differential magnitude, group delay
  - Equalized (in blue) restored to ideal

- Reduced overshoot, transient noise improves TOA accuracy, SEI measurement
Summary

• System magnitude, group delay specifications determined for SEI based on distortion in pulse FM

• Algorithms for end-to-end characterization developed and employed

• Compensation filter design methodology developed for design of complex FIR filters to handle asymmetric system response

• Implement procedures using digital hardware for real-time system equalization adaptive to tuning scenario, the channel selection, and temperature

• Integrate calibration procedures with existing collection system(s)