Outline

• Background

• Passive Intermodulation Distortion (2 parts)
  – Part 1, PIM effects, Electro-Thermal PIM
    • Test Equipment, Microwave Circuits / Antennas
  – Part 2, PIM effects
    • Non Electro-Thermal PIM, Filter PIM

• Behavioral Modeling
  – Behavioral model
  – Measurement Equipment

• Simulation and Modeling of Large Systems
  – Part 1, New circuit concepts
  – Part 2, fREEDA
PIM Measurement System (Analog Canceller)
Problem

• Need to measure small signals in the presence of large signals.
  – E.g. GPS receiver, radar, distortion measurement
Cancellation Theory

- Sum with equal amplitude/anti-phase signal of original signal
Cancellation Theory

• Amplitude Measurements Only
• Non Newton-Based Iteration

Cancellation Errors

• Phase error:
  – Mostly result of errors in $\beta$ and $\alpha$ in $\theta_S$ equation
  – Dependent on phase separation of signals
  – Can be minimized in iteration

• Amplitude error:
  – Results from path non-linearities
  – Dependent on phase, frequency, time
  – More sensitive than phase errors due to sole reliance on amplitude measurement
  – Minimized through path amplitude calibration
Amplitude Calibration

- **Standard (baseline):** Generate calibration matrix: Ampl. vs. Freq.
  - Occurs pre-test
  - Does not capture time-dependent or phase-dependent effects
  - Only needs to be done once (ideally)
  - Speed depends on density of matrix
  - Inherent interpolation error

- **In-line:** Perform calibration on-the-fly
  - Occurs during cancellation
  - Minimizes time-dependency
  - Very fast: single measurement
  - No interpolation error
Analog Cancellation

- Initial cancellation is statistical
  - Cancellation converges to 70-90 dB

<table>
<thead>
<tr>
<th>Target $C_T$ (dB)</th>
<th>Iterations</th>
<th>Meas. analog cancellation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Av.</td>
<td>Max</td>
</tr>
<tr>
<td>0</td>
<td>1.00</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>1.01</td>
<td>2</td>
</tr>
<tr>
<td>40</td>
<td>1.31</td>
<td>2</td>
</tr>
<tr>
<td>50</td>
<td>1.72</td>
<td>3</td>
</tr>
<tr>
<td>60</td>
<td>2.01</td>
<td>4</td>
</tr>
<tr>
<td>70</td>
<td>2.63</td>
<td>11</td>
</tr>
<tr>
<td>--</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Forced 2 Iter.
High Dynamic Range Measurement

- Cancellation Dynamic Range ($\text{DR}_C$):
  - Ratio of the highest-power signal that can be cancelled to the minimum detectable signal (MDS) after cancellation
  - Not simple combination of $C_A$ and $\text{DR}_R$
High Dynamic Range Measurement

• **Limits on Dynamic Range:**
  - RF signal source spurious leakage
    • Suppressed inherently through cancellation
  - Coupling of external RF emissions
    • Suppressed through RF shielding/isolation
  - AC power supply leakage
    • Eliminate by using DC power (i.e. batteries)
  - System thermal noise

• **Ultimate limit on cancellation: quantization error**
  - Quantization in DAC leads to finite resolution for VM output step
    • Can be improved with attenuation at a cost to dynamic range
  - Quantization in receiver leads to finite resolution for measurement
    • Calibration accuracy cannot exceed measurement accuracy
Two-Tone IMD Measurement

- Two-tone IMD measurement system built using separate cancellers for each channel
- Can be used for transmission or reflection
Intermodulation Dynamic Range, $\text{DR}_{\text{IM}}$

- The change in reference makes $\text{DR}_{\text{IM}}$ theoretically independent of DUT characteristics and system configuration.
Two-Tone IMD Measurement

• Key to high dynamic range: linearity
  – Isolators reduce undesired mixing of channels through reverse path
  – Minimize external spurious content
    • External RF coupling, AC supply leakage
  – Low-PIM components:
    • Silver-plated
    • Physically large
    • Distributed implementations

• Bandwidth Limitations:
  – Isolators (typically half-octave):
    • Narrowest bandwidth in system, but only limits frequency range of a single channel
  – Shared channel components
    • Wider bandwidth than isolators but must include entire frequency range from lower IM product to upper IM product
  – Bandwidth limitations only affect maximum tone separation; system emphasis is on very small tone separation (to 1 Hz)
Measured Results (DR_{IM3})

- 460 MHz with an input power of 26 dBm.
Measured Results ($DR_{IM3}$)

- Spurious tone at 1 MHz only shows up in upper IM3 in transmission
  - Source currently unknown
Measured Results (PIM)

- Pasternack PE6154, PE6152
  - Standard 2W terminations, similar form-factor
Measured Results (PIM)

- Pasternack PE6097 (5W), PE6035 (10W)
  - High power, terminations with large “finned” aluminum heatsinks
Summary PIM Measurement

• Analog Canceller
  – Minimum $\text{DR}_{\text{IM3}}$:
    • Transmission: 94 dBc at 1 Hz ($C_T = 60$ dB)
    • Reflection: 111 dBc at 1 Hz ($C_T = 50$ dB)
  – Minimum $\text{DR}_{\text{IM3}}$ between 100 Hz – 30 kHz:
    • Transmission: 113 dBc ($C_T = 60$ dB)
    • Reflection: 130 dBc ($C_T = 50$ dB)
  – Limited improvement with additional cancellation except at $\Delta f < 10$ Hz
    • At these tone separations, the MDS is the phase noise off the carrier signals: extra cancellation directly reduces the MDS, improving $\text{DR}_{\text{IM3}}$
  – Spurious tones reduce performance at 10 MHz, and 100 MHz
    • Sources currently unknown
References


Time-Frequency Effect
Filter PIM
Thesis:
Can we use variation in group delay to develop an optimum waveform to create large nonlinear effects.
Switched Tone Response of a Filter

\[ f_1, f_2, 2f_1 - f_2, 2f_2 - f_1 \]

Antenna \[ f_1, f_2 \]

Bandpass Filter \[ 2f_1 - f_2, 2f_2 - f_1 \]

Low Noise Amp

Analog-to-Digital Converter

\[ 2V_0 \]

\[ \frac{1}{50} \]
Time-Frequency Response of a Filter
Modeling

\[ V_0 \]

\[ -V_R + \]

\[ R \]

\[ L_1 \]

\[ C_1 \]

\[ L_3 \]

\[ C_3 \]

\[ L_5 \]

\[ C_5 \]

\[ R \]

\[ -V_1 + \]

\[ R_N \]

\[ C_{N1} \]

\[ L_{N2} \]

\[ C_{N3} \]

\[ L_{N4} \]

\[ C_{N5} \]

\[ R_N \]
Memory Effect

Pulse ADS Sim: 7th-Order Lowpass Prototype at Center Frequency

- Voltage (mV)
- Time (microseconds)

Multiple Transmissions
Linear PIM

Figure 1

- t_{start} = 9.6925e-007 s,  t_{end} = 9.9937e-007 s,  FFT blocks = 128

- t_{start} = 1.1517e-006 s,  t_{end} = 1.1626e-006 s,  FFT blocks = 128
Stepped Two-tone Signals

Frequency separation stepped logarithmically from 1 kHz to 1 MHz
What are the effects of these transients on wireless communications?

- sharp filtering can degrade received signal-to-noise ratio

Nearest work: Chohan/Fidler (1973) -- impact on FSK & PSK, no metric
How do we measure parameters of coupled resonator circuits?

- The Q factor of the outer resonators in a chain may be determined with time-domain analysis.

\[
\tau = \frac{t}{\ln(V_0^2) - \ln(V_R^2(t))}
\]

Table 2: Measured Q-Value Estimation, 900 MHz Chebyshev Design

<table>
<thead>
<tr>
<th>Filter Order</th>
<th>BW</th>
<th>Passband Ripple (dB)</th>
<th>2-Port Q Value</th>
<th>1-Port Q Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4%</td>
<td>0.01</td>
<td>23.3</td>
<td>24.6</td>
</tr>
<tr>
<td></td>
<td>5%</td>
<td>0.01</td>
<td>18.4</td>
<td>20.1</td>
</tr>
</tbody>
</table>

Nearest prior work: Pereda (1992) -- Prony analysis, dielectric resonators, not a ‘coupled’ structure.
2-port $S$-parameters can be extracted from short-pulse time-domain responses

Nearest prior work: **Courtney (1999)** – permittivity measurements, nanosecond impulses

Time- & frequency-domain views, short pulses
465-MHz 1% Chebyshev filters
**Time-Frequency Effects: Nonlinear Metrology**

- Can we exploit filter properties for **nonlinear** measurements?

  - IP3 of an amplifier can be measured using a filter & switched-tone source
  - A device’s passband can be extracted from 1 port

**Simulated fast-switching filter response**

7th-order 465-MHz Chebyshev design
(a) input, 1 tone, (b) output, 1 tone, (c) output, 2 tones

**Nearest prior work:** Walker (2005) – steady-state two-tone testing

**Passband extraction for bandpass filter**

7th-order 900-MHz Chebyshev design

![Passband extraction](image)
How can we improve linearity by applying time-frequency techniques?

- The IMD associated with amplitude modulation can be reduced by trading signal bandwidth for smaller Peak-to-Amplitude Ratio.

IET, 09/09

Distortion reduction for $N = 20$

non-multiplexed (red) vs. multiplexed (blue)

Ophir 5162 amplifier

Wideband & narrowband spectra for $N = 10$
generated by Agilent N6030A + QM3337A modulator
Summary: Time-Frequency Effects

Narrowband transients last longer than expected.

(a) identified resonant cascade as a source of long tails
(b) developed a differential-equation simplification
(c) showed frequency-dependence of the tails causes pulse overlap
(d) evaluated ISI and IMD for frequency-hopping scenarios

Used filter transients to develop new measurement techniques:

(a) $Q$-factor of a single resonator
(b) bandwidth, without $S$-parameters
(c) broadband $S$-parameters from a single time-domain trace
(d) device passband from a single input port

Time-multiplexing & filtering — LITMUS:
reduces IMD associated with amplitude modulation
Summary

- High dynamic range measurement system
- Time-Frequency effects produce apparent PIM
Review of Time-Frequency Effects
Time-Frequency Effects: Tucker/Eaglesfield (1946)

- commonly-used 6-element bandpass filter
- oscilloscopes can capture filtered pulse envelopes
- differential operators (precursor to Laplace Transforms) can be used to solve for analytical forms for pulse responses

Time-Frequency Effects: Hatton (1951) & McCoy (1954)

- amplitude transients & frequency transients for a single resonator

- while comparing frequency-modulation to amplitude-modulation...

- overshoots in amplitude & frequency are possible for input frequency transitions within a filter’s passband

Lowpass vs. bandpass transient responses

\[ u_b(t) \approx u_l(t_N) \cos(\omega_0 t + \theta) \]

- transient response at midband is a time-scaled version of the lowpass turn-on response
Time-Frequency Effects: Chohan/Fidler (1973)

- frequency transients, steps of phase/frequency at filter input
  - while investigating filtering effects on FSK- and PSK-type signals…
  - generalized earlier narrowband Laplace methods for any order & any Q value

• resonators: transmission line & microstrip

- attributed nonlinearities to
  (a) crystalline structure
  (b) charge carrier density
  (c) Abrikosov vortices

- resistance is a function of current

\[ R_1(x,t) = R_1 \left[ 1 + \frac{I^2(x,t)}{I_0^2} \right] \]

“Nonlinearity of superconducting transmission line and microstrip resonator”

Time-Frequency Effects: Pereda (1992)

- estimation of quality factor from resonant decay

\[ S(n\Delta t) = \sum_{i=1}^{p} A_i \exp\left((\alpha_i + j2\pi f_i)n\Delta t\right) \]

\textbf{Prony analysis} for \( n = 0, \ldots, N - 1, \) \hspace{1cm} (1)

- while investigating resonance in dielectric resonators…

- reduced time to compute resonant frequencies and quality factor using FDTD and Prony analysis

“Computation of resonant frequencies and quality factors of open dielectric resonators by a combination of finite-difference time-domain and prony’s methods,”

Time-Frequency Effects: Dunsmore (1999)

- Time-domain coupled-resonator filter tuning
  - showed how to tune individual resonators using time-domain return loss

“Tuning band pass filters in the time domain,”
Time-Frequency Effects: Courtney (1999)

- Frequency measurements from time-domain traces

- found a way to measure $T$ and $\Gamma$ by time-domain-reflectometry with nanosecond impulses

Nonlinear distortion reduction by time-multiplexing

- found a way to reduce IMD by transmitting subcarrier frequencies in different time slots.