Solid State Amplifiers for Next-Generation Radar Transmitters

Dr. Charles Baylis
2011 International Symposium on Advanced Radar Technologies (ISART 2011)
Boulder, Colorado
July 2011
Outline

• Baylor WMCS Program and Activities
• Review of Single-Stage Amplifier Classes
• Advanced Power Amplifier Architectures
• Real-Time Load-Impedance Optimization
• The Way Forward
  – Joint Waveform and Circuit Optimization
  – Wirtinger Calculus for TIPP Systems
Baylor WMCS Program

- **Wireless and Microwave Circuits and Systems**
- Wireless and Microwave Education and Research in a Caring, Christian Environment
Research

• Faculty
  – Dr. Charles Baylis, Co-Director, microwave power amplifier design, waveform diversity
  – Dr. Randall Jean, Co-Director, microwave sensors and metrology
  – Dr. Yang Li – antenna design
  – Dr. Robert J. Marks II – computational intelligence
  – Dr. Steve Eisenbarth – wireless networks
  – Dr. Mike Thompson - communications

• Graduate and undergraduate student research and teaching assistants
WMCS Teaching Laboratory

- Founded in 2009 with partial sponsorship from Agilent Technologies.
- “Hub” for hands-on teaching activity.
- Provides hands-on component for RF/Microwave Circuits course sequence.
WMCS Advisory Board and Mini-Symposium

• Industry Advisory Board created in 2009 to assist with educational and research mission.

• Annual Mini-Symposium on Wireless and Microwave Circuits and Systems
  – Student/industry forum
  – 5 universities participated in 2011.
Transmitter Amplifier Constraints

• Amplifiers must transmit large amounts of power with high power efficiency.

• Radar spectrum criteria imposed in the Radar Spectrum Evaluation Criteria (RSEC), which are determined by the National Telecommunications and Information Administration (NTIA).

• Spectral mask outlines the required confines of the signal:

Sources of Nonlinearity

• A major source of spectral spreading is third-order intermodulation distortion in the amplifier transistor.
• Assume a third-order nonlinear system approximated by
  \[ v_{out}(t) = a + bv_{in}(t) + cv_{in}^2(t) + dv_{in}^3(t) \]
  • Stimulate with a two-tone input signal:
  \[ v_{in}(t) = A\cos\omega_1 t + B\cos\omega_2 t \]
Math Results

\[ v_{out}(t) = a + b(A \cos \omega_1 t + B \cos \omega_2 t) + c(A \cos \omega_1 t + B \cos \omega_2 t)^2 + d(A \cos \omega_1 t + B \cos \omega_2 t)^3 \]

\[ v_{out}(t) = a + b(A \cos \omega_1 t + B \cos \omega_2 t) + c(A^2 \cos^2 \omega_1 t + B^2 \cos^2 \omega_2 t + 2AB \cos \omega_1 t \cos \omega_2 t)^2 + \]
\[ d(A^2 \cos^2 \omega_1 t + B^2 \cos^2 \omega_2 t)(A \cos \omega_1 t + B \cos \omega_2 t) \]

\[ v_{out}(t) = a + b(A \cos \omega_1 t + B \cos \omega_2 t) + c(A^2 \cos^2 \omega_1 t + B^2 \cos^2 \omega_2 t + 2AB \cos \omega_1 t \cos \omega_2 t)^2 + \]
\[ d(A^3 \cos^3 \omega_1 t + A^2 B \cos^2 \omega_1 t \cos \omega_2 t + AB^2 \cos \omega_1 t \cos^2 \omega_2 t + B^3 \cos^3 \omega_2 t) \]

Third-Order Intermodulation Terms

\[ 2\omega_1 - \omega_2 \quad \omega_1 \quad \omega_2 \quad 2\omega_2 - \omega_1 \]
Intermodulation Results

- For a bandpass signal, each frequency at which the signal is nonzero represents a “tone”.
- In general, all pairs of tones intermodulate:
  - In-band distortion
  - Out-of-band distortion ("spectral spreading")
How to Remove the Sidelobes?

• Filtering?
  – Radar systems often operate in megawatt range.
  – It is difficult to use microstrip cavity filter capabilities over 1 kW.
  – Not cost-effective or practical

• Linearization
  – Remove the sidelobes by making the amplifier more linear.
  – We need to maintain efficiency at the same time.
Linearity vs. Efficiency

- Efficiency increases with output power.
  - GaAs MESFET power amplifier example shown below.
- Linearity decreases with increasing output power for amplitude modulated signals.
Efficiency Measures

• Drain Efficiency:

\[ \eta = \frac{P_{out,RF}}{P_{DC}} \]

• Power-Added Efficiency:

\[ \eta_{ADD} = \frac{P_{out,RF} - P_{in,RF}}{P_{DC}} \]

• Overall Efficiency:

\[ \eta_{OVERALL} = \frac{P_{out,RF}}{P_{DC} + P_{in,RF}} \]
Linearity Measures

• **Adjacent Channel Power Ratio (ACPR)**
  
  – Ratio of the power in a specified band outside the signal to the RMS power in the signal*
  
  – Examines how nonlinearity affects adjacent channels.

• **Error Vector Magnitude**
  
  – Vector distance between desired and measured signal vector normalized by the signal amplitude

• **Carrier-to-Intermodulation (C/I) Ratio**
  
  – Measured in a two-tone intermodulation test.
  
  – Raab: C/I should be at least 30 dB for a linear PA.*

• **Noise Power Ratio**
  
  – Measures in-band distortion.

Amplifier Classes

• Class A:
  – Max Drain Efficiency: 50%
  – Best Intrinsic Linearity

• Class B:
  – Max Drain Efficiency: 78.5%
  – Reduction of Linearity

• Class C:
  – Bias below threshold.
  – Higher efficiency but less linearity than B.

• Class E, F: Higher efficiency switching modes.
Linearity and Efficiency Configurations

• Acknowledgment: Article in *IEEE Transactions on Microwave Theory and Techniques* and 4-part series of articles in *High Frequency Electronics* by Raab et al. provide an excellent survey of different topologies and their advantages.

• Much information from these articles is used in this section.
Predistortion

- “Uncompress” the compression by a component with an oppositely shaped compression characteristic.

- Challenging for systems with memory
- Requires adaptive lookup table → memory requirements can be large.
Feedforward

- The linear input signal is used as a reference to subtract unwanted spectral components from the output signal.

- Linear error amplifier requires additional DC power.
- Combiners also contribute to efficiency decrease.
- Drift is possible; may require a control system.

Envelope Tracking

• The supply voltage is adjusted based on envelope amplitude.
• The efficiency is improved, but buck/boost converters require additional DC.
• Works well for high peak-to-average-power ratio (PAPR):


Envelope Elimination and Restoration (Kahn Technique)

• The amplitude modulation is removed from the signal and re-inserted after the PA.
• Allows the amplitude to run at optimum efficiency without amplitude distortion.
• Must align amplitude and phase modulation (need low AM-to-PM conversion).

Doherty

- Carrier Amplifier: Class B
- Peaking Amplifier: Class C
- Peaking amplifier turns on when the signal becomes large.
- Linearity is at Class B level from this design.
LINC (Linear Amplification with Nonlinear Components)

- The amplitude modulation $M(t)$ is “hidden” in the phase and returned to the amplitude after the summer:

  $$v_1(t) = \cos(\omega t + \cos^{-1}(M(t)))$$

  $$v_2(t) = \cos(\omega t - \cos^{-1}(M(t)))$$

  $$v_{out}(t) = G \cos(\omega t + \cos^{-1}(M(t))) + G \cos(\omega t - \cos^{-1}(M(t)))$$

  $$v_{out}(t) = 2G \cos \omega t \cos(\cos^{-1}(M(t))) = 2GM(t) \cos \omega t$$

- But how can a summer be implemented?
Implementation Options

• 180-Degree Coupler
• Chireix Outphasing Combiner*
• Linearity and efficiency vary by modulation scheme for each design.
• 180-degree coupler is more robust for linearity.

180-Degree Coupler

- It is matched and reciprocal.
- Power can be lost to the fourth-port termination, depending on the modulation scheme.

Chireix Combiner

- Combiner ports are not isolated, so the impedances seen by each amplifier stage can change dynamically.


Load Pull: Found maximum PAE at 68.6% with a source impedance of (6.65 – j6.45)

Source Pull: Found maximum PAE at 61.5% with a source impedance of (4.2 – j8.95)

Modelithics Transistor Model
Circuit Design with Parasitic/T-Line Models

Source Matching Network

Load Matching Network

Parasitic component and transistor models donated by Modelithics
Load-Pull Efficiency Comparison

- Both Designs: Maximum Efficiency near 50 ohms
- Test with CW (M(t) = 1)
- Maximum PAE for Chireix design = 50%
- Maximum PAE for 180-degree coupler design = 51%
GaAs PHEMT Amplifier for Different $M(t)$ Levels

• 180-degree coupler is perfect parabola $\rightarrow$ Excellent linearity

• Chireix demonstrates linearity flaws.
Joint Optimization: The Way Forward

- State-of-the-art approaches to improving spectral conformity have traditionally included separate examination of
  - Circuit design
  - Waveform design
- The technology and theory now exist to *simultaneously* optimize both!
- Knowing the circuit nonlinearities speeds the optimization  → Wirtinger Calculus for TIPP Systems.
TIPP Systems

- Assume a time invariant periodicity preservation (TIPP) system.

LTI: All currents and voltages oscillate at the same frequency.

TIPP: All currents and voltages are periodic with the same period (harmonic levels can change).
TIPP Systems

• Assume a TIPP Operator $Z$:

$$v(t) = Z \{i(t)\}$$

• There is a corresponding operator on the vectors of Fourier coefficients:

$$\hat{v} = Z \hat{i}$$

• For a particular “operating point” large signal, $Z$ is a matrix.
Affine Approximation

• Consider a nonlinear function $f(x)$:

$$f(x_0 + \Delta x) \approx f(x_0) + \frac{df(x_0)}{dx} \Delta x$$

• Affine approximation around the operating point of a nonlinear function
Wirtinger Calculus for TIPP Systems

\[ v(t) + \Delta v(t) \approx Z\{i(t)\} + \frac{\partial v(t)}{\partial i(t)} \Delta i(t) + \frac{\partial v(t)}{\partial i^*(t)} \Delta i^*(t) \]

- In terms of the Fourier series coefficient vectors:

\[ \bar{v} + \Delta \bar{v} \approx [Z]\bar{i} + [J_{\bar{v}}(\bar{i})]\Delta \bar{i} + [J_{*\bar{v}}(\bar{i})]\Delta i^* \]

- The TIPP parameters give an affine approximation around a nonlinear operating point.
Agilent X-Parameters \(^1\star\)

Each X parameter is a function of \(|A_{11}|\).

\[
B_{ef} = X_{ef}^{(F)}\left(|A_{11}|\right)P^f + \sum_{g,h} X_{ef,gh}^{(S)}\left(|A_{11}|\right)P^{f-h}a_{gh} + \sum_{g,h} X_{ef,gh}^{(T)}\left(|A_{11}|\right)P^{f+h}a_{gh}^*
\]

\(P = e^{j\angle A_{11}}\) provides phase correction for harmonic conversion.

**C. Baylis et al., “Going Nonlinear,” IEEE Microwave Magazine, April 2011.

\(^1\star\)X-parameters is a registered trademark of Agilent Technologies.
Fast Load-Impedance Optimization Algorithm*

- Traditional:
  - 400 Γ states
  - Maximum Power = 22.76 dBm
- Steepest Ascent:
  - 17 Γ states
  - Maximum Power = 22.72 dBm
- Accurate results for small number of simulations

Conclusions

- Spectral spreading from radar systems must be mitigated, but not at the cost of system efficiency.
- Several useful design approaches exist for linearity and efficiency improvement.
- An apparent solution is in joint waveform and circuit optimization with the Wirtinger calculus.
- An approach and test platform for real-time load-pull and waveform optimization is under development at Baylor University.
Acknowledgments

• Dr. Robert J. Marks II, Baylor University
• Baylor Research Assistants: Loria Wang, Josh Martin, Matthew Moldovan, Hunter Miller, Robert Scott
• This work has been supported in part by a Young Investigator Grant and two Undergraduate Research and Scholarly Achievement Grants from the Baylor University Vice Provost for Research.
• Agilent Technologies, for cost-free loan of the Advanced Design System software.
• Maury Microwave for donation of ATS Software DLL Libraries.
• Modelithics, Inc., for donation of model libraries.
• Raytheon (sponsorship) and Maury Microwave for Load-Pull Algorithm Support (in-kind support)
• Larry Cohen, Jean de Graaf, and Dr. Eric Mokole, U.S. Naval Research Laboratory, for collaboration.
References


• J. de Graaf, Personal Interaction.

• S. Cripps, RF Power Amplifiers for Wireless Communications, Artech House, 1999.


References, cont.

• Application Note AN-005: “2.5-2.7 GHz 20 W Doherty Amplifier for WiMAX Applications Using the NPT25100,” January 2008.
References, cont.

References, cont.

References, cont.