Radar Power Amplifier Circuit and Waveform Optimization for Spectrally Confined, Reconfigurable Radar Systems

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***Abstract*—Increasingly stringent spectral spreading constraints are motivating a paradigm shift in the spectrum engineering of radar systems. Future spectrum requirements will likely dictate narrower spectral masks that will change based on geography. The desire to operate radar systems efficiently with waveforms that will provide desired detection capabilities must mesh with the need to meet spectral mask criteria. To this end, a collaborative research effort between Baylor University and the U.S. Naval Research Laboratory has resulted in the design of reconfigurable circuit and waveform approaches to optimize spectral confinement, power efficiency, and detection capabilities. This paper surveys the joint optimization approach and describes innovations by the authors in circuit and waveform reconfiguration that will be useful in future flexible radar transmitters.**

I. Introduction

Modern radar systems are being confined to tighter spectral allocations, while being forced to perform needed detection functions as well as operate with high power efficiency. The major consumer of power in the radar transmitter is the power amplifier. A commonly used measure of the amplifier's power efficiency is the *power-added efficiency* (PAE):

$$\eta_{ADD} = \frac{P_{out,RF} - P_{in,RF}}{P_{DC}} \tag{1}$$

The PAE is the fraction of the DC supply power that is converted to RF output power; in other words, it is an indicator of how efficiently the amplifier uses the DC supply power.

While efficient operation is desirable, regulations on the spreading of amplifier output power to adjacent channel limit the efficiency that can be reached by the device. The *adjacent-channel power ratio* (ACPR) is the ratio of the total power in a defined adjacent channel to the total power in the channel assigned to the amplifier, and it serves as a useful measure of the out-of-band distortion due to amplifier nonlinearities [1]. Nonlinearities cause intermodulation between in-band frequency components that lead to the spread of frequency content outside the desired transmission band of the amplifier [2-3].

In a wireless communication device, the spectral spreading is usually regulated by a governing body: in the United States, the National Telecommunications and Information Administration (NTIA) regulates all spectrum used for government applications, and the Federal Communications Commission (FCC) regulates all spectrum used for commercial applications. The signal is required to be confined within a spectral mask assigned by the appropriate regulatory agency, as shown in Fig. 1.

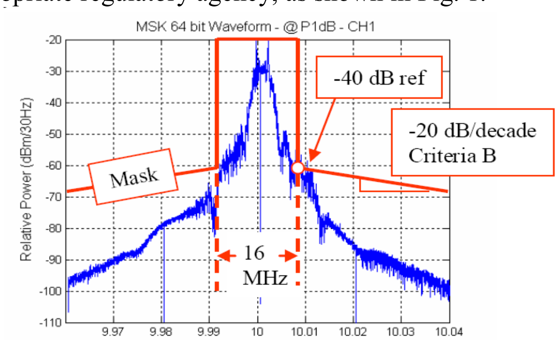

Fig. 1. Spectral mask example, reprinted from [4]

Future radar systems will also face dynamic spectrum allocation in the possible advent of dynamic spectrum access

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as a spectrum-sharing protocol. The radar systems may need to change frequency bands of operation in real-time, and in some cases will have to meet tighter spectrum requirements than others. The possibilities of (1) operating frequency changes and (2) changing spectral masks require an RF transmitter solution that is reconfigurable to allow optimization with respect to detection, efficiency, and minimization of spectral spreading in real time.

To enable future reconfigurable radar systems, the authors have focused their work on (1) load impedance optimization to maximize power-added efficiency while meeting adjacent-channel power requirements, and (2) waveform optimization for detection (ambiguity function) and spectral mask compliance. The following sections present results of the initial work and the prognosis for future developments.

II. LOAD-IMPEDANCE OPTIMIZATION FOR PAE AND ACPR

Steepest-ascent search techniques have been implemented to optimize the PAE and ACPR, similar to the steepest-ascent search presented by the authors for a maximum-power load-pull search in [5]. The search has been tested in the simulations using Advanced Design System from Agilent Technologies with nonlinear transistor models from Modelithics. In addition, bench-top measurement results have also been obtained that verify the search's accuracy. The results indicate that accurate load-impedance tuning optimization can result from a significantly small number of measurements.

In a recent conference paper, the authors demonstrated the ability to perform load-pull comparisons for an amplifier under chirp waveform excitation [6]. Fig. 2 shows the assessment of the ACPR spectral spreading using a spectrum analyzer through measurement in adjacent-channel power mode. Fig. 3 shows the results of a load-pull measurement of a packaged amplifier under chirp excitation. The load-pull contours displayed are for output power (PAE could also easily have been used) and ACPR.

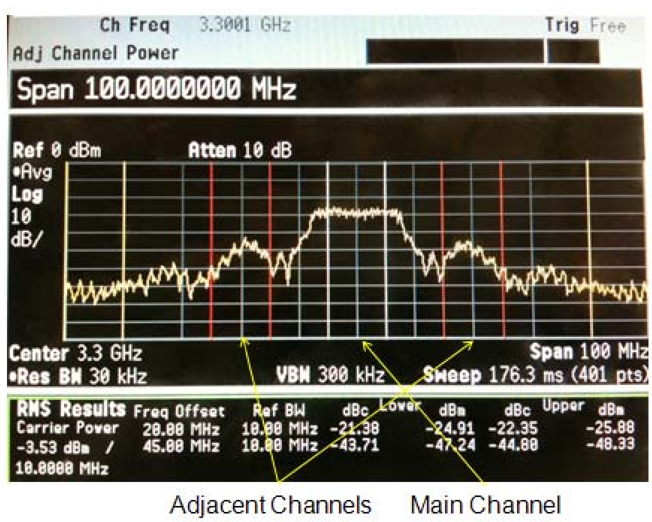


Fig. 2. Spectrum analyzer measurement in ACPR mode, reprinted from [6]

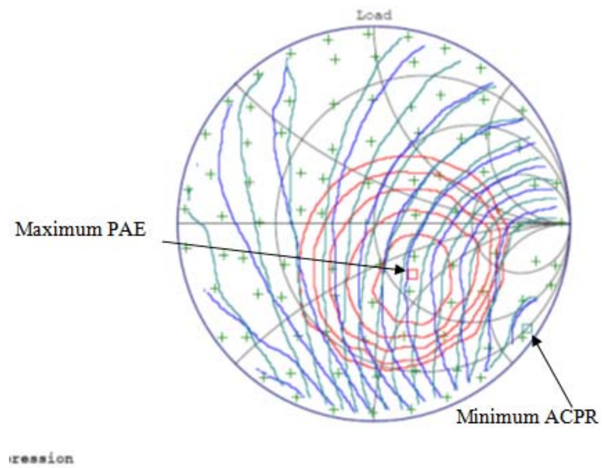


Fig. 3. Output Power and ACPR load-pull results for chirp waveform excitation, reprinted from [6].

The authors are completing design of an algorithm to perform the load-impedance optimization with a smaller number of measurements through a computationally intelligent search using real-time measurements on the laboratory bench. The results will be included in a future publication.

III. WAVEFORM OPTIMIZATION BASED ON AMBIGUITY FUNCTION AND SPECTRAL COMPLIANCE

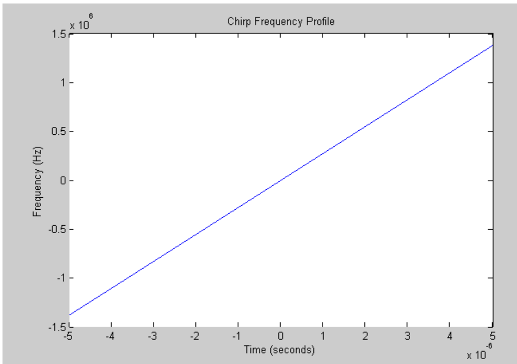
The ambiguity function is a measurement of a radar's detection capabilities based on the correlation properties of the chirp waveform in the time and frequency domains. The ambiguity of detection based on a waveform $s(t)$ is given as a function of the error in time τ' and the error in Doppler frequency u':

$$\chi(\tau', u') = \int_{t=-\infty}^{\infty} s(t')s^*(t'-\tau')e^{-j2\pi u't'}dt' \qquad (1)$$

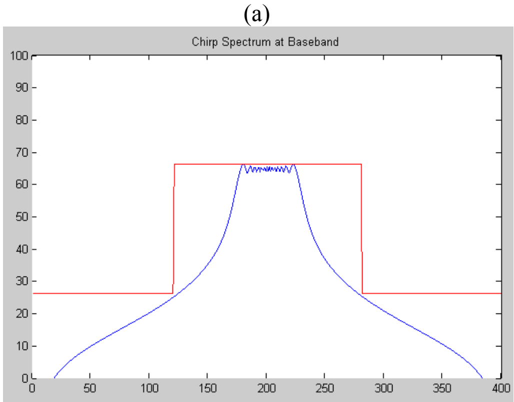
The ambiguity function represents the output of the radar correlator when a waveform that has an erroneous time shift and/or Doppler shift is detected.

The ambiguity function for a given waveform can be easily plotted in MATLAB; in addition, its spectrum can be plotted with a spectral mask. Fig. 4(a) shows the spectrum of a given linear chirp waveform with a defined spectral mask. Fig. 4(b) shows the ambiguity function of the waveform. It is well-known that the piecewise linear chirp has an ambiguity function that has a tilt angle defined by the relationship of bandwidth to time width [7]. Chirps with larger bandwidth possess less ambiguity in time and more ambiguity in frequency, while chirps with larger time width possess more ambiguity and time and less ambiguity in frequency.

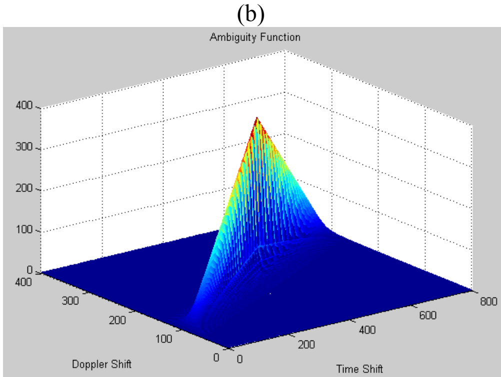
A waveform optimization routine has been constructed to optimize the waveform based on its ambiguity function and spectral properties. Fig. 5 shows the best waveform, as chosen by the optimization; it maximizes the desired ambiguity function qualities while providing spectral mask compliance.



(a)



(b)



(c)

Fig. 4. (a) Frequency versus time characteristic, (b) spectrum, and (c) ambiguity function for a piecewise linear up-chirp

IV. Joint Circuit and Waveform Optimization

The next step on the way forward to real-time reconfigurable future radar transmitters is the real-time optimization of both the circuit and waveform in a computationally intelligent process. Using the load-pull test-bench, Matlab can play waveforms through the signal generator using their I-Q definitions. When simultaneously using the signal generator with the load tuners, the load impedance and chirp waveform can be optimized simultaneously. The goals of this simultaneous optimization are the following:

(1) Optimize the detection capability by optimizing the ambiguity function of the amplifier's *output* waveform.

(2) Optimize the power efficiency through the load impedance and waveform.

(3) Require the optimum solution to meet spectral mask requirements.

Optimization goal (1) requires measurement of the waveform leaving the amplifier, not Matlab knowledge of the waveform created by the signal generator at the amplifier input. In a way, this goal encourages predistortion of the amplifier to get the desired ambiguity function at its output. Optimization goal (2), in addition to the obvious load-pull for optimum PAE, will minimize effective types of windowing at meeting spectral requirements, such as *sinc* windowing in the time domain (which creates a rectangularly shaped spectrum) because this approach causes the amplifier to operate at a back-off level from the optimum efficiency input power and creates a signal with higher peak-to-average-power ratio. Optimization goal (3) will require the result to fulfill spectral requirements, a goal that has been emphasized in both of the individual optimization exercises of the work to date.

IV. Conclusions

This paper presents a new framework for future radar systems that involves the joint, real-time optimization of the radar transmitter power amplifier matching circuitry and waveform. The desired objectives are to meet detection goals, optimize the transmitter's power efficiency, and abide within the spectral constraints. These goals must be accomplished in future radar systems, which will likely need to be frequency agile and to adapt to changing spectral masks. This paper has provided a survey of the results of collaborative research in establishing such an optimization approach by researchers at Baylor University and the U.S. Naval Research Laboratory toward this end, and also describes the way forward in joint waveform and circuit optimization. The continuation of this research will provide the RF enabling technology for radar systems that are flexible in frequency and in detection capabilities of both range and Doppler.

Acknowledgments

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