Spectral and Spatial Artifact Suppression for RF Devices
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I. Summary

☐ write this after body is done
What we did, whats left to do, how we intend to approach the remaining work

☐ ok to take from proposal verbatim for the intro? For now, Section II. Intro is lifted nearly verbatim from Proposal

II. Introduction

Enabling shared spectrum access between radar and communications (SSPARC) systems is an important objective that will mitigate spectrum congestion. Solutions to solve this objective will require dynamic allocation of time/frequency/space slots among all spectral users. Regardless of the allocation approach, precise signal containment in both spectral and spatial dimensions is required. After all, without the ability to limit a signal to a desired spatial/spectral window, allocation optimization becomes irrelevant. ☐ Define SSAS here?

A. SSPARC ? *delete this subheading? should be SSAS not SSPARC?*

This work contains several innovations that can be decomposed into two categories: i) techniques to reduce the errantly transmitted energy due to nonlinear distortions in SSPARC radios and radars, and ii) techniques that operate on the receiver side to mitigate nonlinearly distorted signals. All of the proposed innovations aim to increase concurrent operating capability of radar and communication systems. The proposed innovations can be applied to either codesign or coexistence SSPARC systems. Furthermore all of these innovations can be agnostically paired to other SSPARC mechanisms that are developed by other_________ ☐ insert term for SSPARC participants ... was “bidders.” And introduce SSAS before next heading because abbrevs is not working in headings

B. SSAS Problem Discussion (Pull material from proposal; outline all three thrusts) ? *delete this sub-heading?*

1) Thrust 1. Algorithms to mitigate spectral artifacts for multiplexed signals: It is well-known that signals with high dynamic range tend to be distorted by system nonlinearities. It is possible to have low amounts of distortion even for signals with high dynamic range, but this comes at the expense of low power efficiency. That is, reducing dynamic range can improve the operating point of a system in the distortion-power-efficiency trade-off space. Ideally, signals are designed to either be constant modulus (CM) or have a low peak-to-average power ratio (PAR).

Shaping radar signals to be CM is relatively easy since radar signals do not carry information and are not multiplexed with other signals. However, when other signals are multiplexed or when information is encoded in the signaling, the problem is much more complicated. Under the SSPARC paradigm, nodes may transmit multiplexed signal aggregation that contain both communications signals and radar signals. While multiplexing both deterministic signaling (radar) and information-bearing signaling (communications) through the same radio frequency (RF) transmit chain will necessarily increase the signal PAR on average and thus increase nonlinear distortions, signal multiplexing also provides additional degrees of freedom for optimizing the joint signal. Our innovation is to leverage our past experience in minimizing nonlinear distortion for communications signals to solve this new problem of minimizing the distortion for radio/radar multiplexed signals. Our solution will be applicable for both the codesign and the coexistence paradigms. It is well-known that signals with high dynamic range tend to be distorted by system nonlinearities. It is possible to have low amounts of distortion even for signals with high dynamic range, but this comes at the expense of low power efficiency. That is, reducing dynamic range can improve the operating point of a system in the distortion-power-efficiency trade-off space. Ideally, signals are designed to either be constant modulus (CM) or have a low peak-to-average power ratio (PAR). Shaping radar signals to be CM is relatively easy since radar signals do not carry information and are not multiplexed with other signals. However, when other signals are multiplexed or when information is encoded in the signaling, the problem is much more complicated. Under the SSPARC paradigm, nodes may transmit multiplexed signal aggregation that contain both communications signals and radar signals. While multiplexing both deterministic signaling (radar) and information-bearing signaling (communications) through the same radio frequency (RF) transmit chain will necessarily increase the signal PAR on average and thus increase nonlinear distortions, signal multiplexing also provides additional degrees of freedom for optimizing the joint signal. Our innovation is to leverage our past experience in minimizing nonlinear distortion for communications signals to solve this new problem of minimizing the distortion for radio/radar multiplexed signals. Our solution will be applicable for both the codesign and the coexistence paradigms.

2) Thrust 2. Algorithms to mitigate spatial artifacts for spatially shaped signals: In multi-antenna systems signals are sent to each antenna element and then weighted and/or phased to achieve a desired aggregate beam pattern. When there is unmitigated nonlinear distortion in the RF chain, due to the power amplifier, for instance, the beam pattern of the transmission will also be distorted. We propose two innovations for correcting this problem:

i) Optimizing beamforming weights with nonlinear Tx chains: We will optimize the transmitting beam pattern by taking the nonlinear distortion into account when determining the beam weights.
ii) Minimizing beam error through signal modification: A more holistic approach is to jointly optimize signal distortion and the antenna weights. This will provide better performance, but may not be possible in certain systems where the signal processing for the transmit signaling is separated from the beam-weight optimization signal processing. When joint optimization is possible, the PAR of the transmitting signal is jointly optimized with the beam weights. Under this paradigm, we can also optimize the signal to minimize spectral splatter, thereby performing the spectral and spatial optimizations in a coupled way through a single globally optimization procedure.

3) Thrust 3. Receiver-side mitigation of spectral artifact noise: The nonlinear distortion caused by RF chains exhibits specific qualities defined by the nonlinear distortion function. For example, the distortion from clipping nonlinearities tends to have a non-Gaussian and non-white distribution. Our innovation is to use this information at the receive side of radars/radios to improve the system performance. For instance, communications signals are drawn from a finite signal constellation. With knowledge of the constellation, as well as partial information about the nonlinearities, we can use decision-directed techniques to subtract distorted communications inference [interference? so it's a radar signal of interest? see question list - are we doing this?] from a signal of interest. [the following is more closely related to what we've done – beef it up? keep previous section?] The low-entropy signals typically used as radar sounding pulses are also amenable to being subtracted from desired signals. This can be more complicated or impossible if the radar signal saturates the receiver front end. However, often, high-power radars will be given a large guard band so that users are separated by large spectral distances. In this situation, the interference to neighboring users is purely nonlinear distortion of the radar signal. We are proposing to use decision-directed techniques coupled with noise whitening techniques to mitigate this kind of adjacent channel interference.

III. SSAS Project Status

IV. PAR Reduction for Signal Aggregation (Thrust 1)

A. Detailed problem statement

When multiple signals are multiplexed, the aggregate signal will have a high probability of having a high PAR. This is a result of the Central Limit Theorem in that the sum distribution of the multiplexed signal approaches complex Gaussian. Having a high PAR means that the signal power is inefficient and prone to non-linear distortion from power amplifier. However, a multiplexed signals have more degrees of freedom for lowering the PAR.

For any linear modulated signal, the signal can be generalized as set of linear equations $\tilde{\mathbf{x}} = \mathbf{A}\mathbf{x}$, where $\mathbf{A}$ is the linear modulation such as $\mathbf{A} = \mathbf{I}$ for single carrier, $\mathbf{A} = \mathbf{H}$ for Hadamard spreading (CDMA), $\mathbf{A} = \mathbf{Q}^H$ for OFDM, and etc. Than multiplexed signals can be aggregated linearly as

$$\begin{aligned}\tilde{\mathbf{x}} &= \mathbf{A}_1\mathbf{x}_1 + \mathbf{A}_2\mathbf{x}_2 + \mathbf{A}_3\mathbf{x}_3 + \cdots \\ &= \sum_{p=1}^{P} \mathbf{A}_p\mathbf{x}_p\end{aligned} \tag{1}$$

where A is the linear modulation such as $A = I$ for single carrier, $A = H$ for Hadamard spreading (CDMA), $A = Q^H$ for OFDM, and ect. From (1) we have three degree of freedom to optimize the aggregated signal in reducing the PAR.

$$\tilde{\mathbf{x}} = \sum_{p=1}^{P} \alpha_p \mathbf{A}_p \left(\mathbf{x}_p^{(k)} + \epsilon_p^{(k)}\right) \tag{2}$$

where $\alpha_p \in \mathcal{A}_p$ is a set of combination value, $k \in \mathcal{K}$ is a set of alternate signal, and $\epsilon_p^{(k)} \in \mathcal{E}_p$ is a set of perturbed error values. Each of these terms can be manipulated to optimize the PAR.

PAR generally is defined by

$$PAR(\mathbf{x}) = \frac{\|x\|_\infty^2}{\|x\|_2^2/N_x} \tag{3}$$

where $\|\cdot\|_l$ denotes the l-norm of the vector. Combining (2) and (3) you get

$$PAR(\tilde{\mathbf{x}}) = \frac{\| \sum_{p=1}^{P} \alpha_p \mathbf{A}_p \left(\mathbf{x}_p^{(k)} + \epsilon_p^{(k)}\right) \|_\infty^2}{\| \sum_{p=1}^{P} \alpha_p \mathbf{A}_p \left(\mathbf{x}_p^{(k)} + \epsilon_p^{(k)}\right) \|_2^2/N_x} \tag{4}$$

A general PAR reduction problem for any aggregated linear modulation signal can be written as

$$\begin{aligned} \text{Minimize} \quad & \left\| \sum_{p=1}^{P} \alpha_p A_p \left(x_p^{(k)} + \epsilon_p^{(k)} \right) \right\|_\infty \\ \text{Subject to} \quad & k \in \mathcal{K} \\ & \alpha_p \in \mathcal{A}_p \\ & \epsilon_p^{(k)} \in \mathcal{E}_p \end{aligned} \tag{5}$$

There are number of approaches in dealing with this PAR problem. Many of the proposed methods such as clipping, coding, tone reservation (TR), tone injection (TI), active constellation extension (ACE), and multiple signal representation techniques achieve PAR reduction in the expanses of other signal characteristics like bit error rate (BER), data rate lost, computational complexity, and so on. In [1] an overview of many of these techniques have been conducted.

B. Radar Spreading

SSPARC requires the mitigation of radar interference on the communication signal. One approach of this is to orthogonalize the communication and the radar signal. Spectral spreading the communication signal $\mathbf{x} \in \mathbb{C}^{N_x}$ with the radar signal $\mathbf{r} \in \mathbb{C}^{N_r}$ is one way to approximate this orthogonalization. The spread transmitted signal will be

$$\mathbf{y} = \mathbf{F}_r \mathbf{x} \tag{6}$$

where $\mathbf{x}$ is the communication constellation symbols, $\mathbf{F}_r$ is the circulant matrix of the radar signal. To maintain the proper size of the signal, $N_x \geq N_r$, and $\mathbf{F}_r$ is a circular convolution with zero padding of$N_x - N_r$ to be $N_x \times N_x$ matrix.

The receiver will receive the signal

$$\mathbf{z} = \mathbf{F}_h \mathbf{F}_r \mathbf{x} + \beta[\mathbf{r}, 0, 0, \ldots, 0, 0]^T + \mathbf{n} \tag{7}$$

where $\mathbf{F}_h$ is the channel effect, The radar signal $\mathbf{r}$ is zero padded to match the size of the communication signal.

Radar signals are generally composed of pulse compression waveform in order to decouple the range resolution and signal energy. This pulse compression waveform of the radar signal allows for the following proprieties:

$$\mathbf{F}_r^H \mathbf{r} \approx [1, 0, 0, \ldots, 0, 0]^T \approx \mathbf{0} \tag{8}$$

$$\mathbf{F}_r^H \mathbf{F}_r \approx \mathbf{I} \tag{9}$$

H denotes the Hermitian conjugate of matrix and T denote the Transpose of the matrix. The Hermitian conjugate of a circulant matrix is equal to the matched filter convolution matrix. (8)

The de-spreading of the signal is done by

$$\hat{\mathbf{x}} = \mathbf{F}^H \mathbf{z} \tag{10}$$

using the radar proprieties from (8) and (9) you get

$$= \mathbf{F}_h \mathbf{x} + \boldsymbol{\beta}[h, 0, 0, \ldots, 0, 0]^T + \mathbf{F}^H \mathbf{n} \tag{11}$$

This shows that radar signal $\boldsymbol{\beta}$ has compressed, mitigating the interference to just few samples. However there is a problem with this mitigation. The PAR of the signal is very high.

The high PAR causes nonlinear distortion when the signals come close to or exceeds the saturation level of the power amplifier. To resolve this problem, several options were considered and analyzed.

1) Analytical/Simulation Results:

2) Lab results:

3) Outlook and remaining work:

C. Thrust 2: Spatial Shaping with Nonlinear Components

1) Detailed problem statement:

2) Analytical/Simulation Results:

3) Lab results:

4) Outlook and remaining work:

V. Administration

A. Meetings/Discussions (Leidos/SAZE)

B. Presentations

C. Conferences

1. 60th Annual Meeting of the MSS Tri-Service Radar Symposium, Springfield, VA, July 21 – 25, 2014, "Receiver cancellation of radar in radio" by K. L. Tokuda, J. H. Kim, R. J. Baxley, J. S. Kenney, and L. S. Cohen
2.

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