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Intermodulation Radar with Dynamic Fundamental Tone Cancellation for Linearity Improvement

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Abstract—**Intermodulation radar takes advantage of device nonlinear behavior for enhanced target detection. By selectively down-converting intermodulation tones at the radar receiver, it can distinguish nonlinear targets from linear background. One challenge of designing intermodulation radars is the linearity of the transceiver. The linearity of the receiver is critical for effectively suppressing the potentially stronger fundamental tones received by the receiver. In this paper, an intermodulation radar receiver with dynamic fundamental tone cancellation is proposed to relax the linearity requirement for the receiver. The impact of the phase and amplitude mismatch between the cancellation tones and the received tones is studied to understand specifications and performance limits of the proposed architecture.**

Keywords — Clutter rejection, intermodulation radar, linearity, sensitivity, tone cancellation, third-order interception.

I. INTRODUCTION

Radar systems are widely used for target sensing and tracking. One difficulty for conventional radar is how to effectively distinguish the target from clutters, as it is costly for the radio frequency front-ends to have a high angular resolution and be able to always follow the target. There are a lot of research works on special hardware and algorithms to help with clutter rejection [1]-[3]. Recently, nonlinear radar has drawn attention for its capability of clutter rejection [4]-[6]. It takes the advantage of nonlinear targets' harmonic or intermodulation responses. Instead of detecting the same frequency as the transmitted signal, nonlinear radar detects harmonic [4][5] or intermodulation [6] of the transmitted signal(s). Since most of the clutters in nature is linear, only the nonlinear targets can generate sufficient harmonic and intermodulation response. Hence, the nonlinear targets can be distinguished from the linear background. Compared with harmonic radar, intermodulation radar has the advantage of transmitting and receiving signals in the same frequency band, which potentially simplifies the radio frequency (RF) front-end of the radar receiver and eases the radio band licensing requirements.

Ideally, if the transceiver is perfectly linear, the intermodulation radar would have infinite rejection to the linear clutter based on coherent down-conversion of the intermodulation tones. However, the linearity of the transceiver significantly limits the ability of clutter rejection. In a highly cluttered environment, the clutter-produced fundamental power received by the receiver could be much stronger than the target-reflected intermodulation tones. Therefore, the receiver's nonlinearity causes undesired intermodulation frequency components, which could mask the target-generated intermodulation signals. To address this issue, a fundamental tone cancellation method is proposed in this paper to relax the linearity requirement of the intermodulation radar.

The paper is divided into four sections. Section II introduces the fundamental tone cancellation architecture for intermodulation radar. Section III presents the simulation and experiment results to show the effectiveness of the proposed architecture. Section IV draws a conclusion and discusses future works.

II. THEORY OF LINEARITY ENHANCEMENT FOR INTERMODULATION RADAR

A. Intermodulation Radar Architecture

In Fig. 1, two sinusoidal probing signals with frequencies f_1 and f_2 are combined and sent out through the transmitter (TX) antenna. When the transmitted signals reach a nonlinear target, intermodulation tones at $2f_1 - f_2$ and $2f_2 - f_1$ are generated and reflected back. Assuming most of passive clutters illustrate predominantly linear behavior, they mainly reflect the fundamental tones. The receiver antenna picks up both the intermodulation tones ($2f_1 - f_2$ and $2f_2 - f_1$) from the nonlinear target and the fundamental tones (f_1 and f_2) from clutters. The received signals are amplified and down-converted by the mixer. Note that the local oscillator (LO) signal of the mixer is running at $2f_1 - f_2$. Therefore, its output signal around DC only corresponds to the nonlinear target's intermodulation response at $2f_1 - f_2$, which can be extracted by a low-pass filter (LPF). If everything is ideal, the only information extracted at the receiver baseband is from the nonlinear target of interest.

B. Linearity Requirement for Intermodualtion Radar Receiver

In reality, the nonlinearity of the LNA and the mixer leads to $2f_1 - f_2$ signals when they receive clutter reflections at f_1 and f_2. If the receiver-generated $2f_1 - f_2$ signal is comparable to, or stronger than the target-generated $2f_1 - f_2$ signal, the radar will make a false detection. As a result, the sensitivity of the receiver is degraded. Unfortunately, the nonlinearity of cascaded devices are enhanced by the preceding devices' gain. The overall system IIP3 of cascading devices can be calculated as:

$$\frac{1}{IIP3_{total}} = \frac{1}{IIP3_1} + \frac{G_1}{IIP3_2} + \frac{G_1 G_2}{IIP3_3}. \quad (1)$$

In [6], two stages of diplexers were used to eliminate the fundamental tones before they reach the devices in the receiver

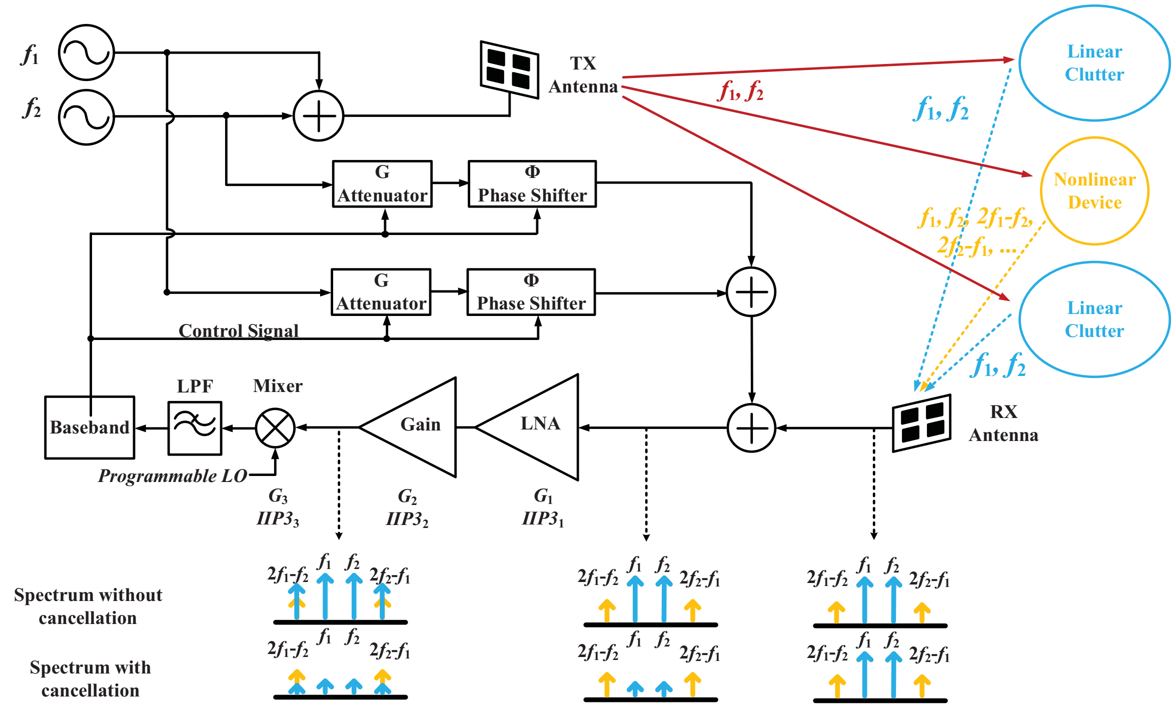

Fig. 1. Architecture of the proposed fundamental tone cancellation.

chain. They are usually hard to design and expensive. Instead of using the expensive diplexer, the fundamental cancellation technique is proposed in this paper.

C. *Fundamental Tone Cancellation Architecture*

If two sinusoidal signals have the same amplitude but opposite phase (i.e., 180 degree out of phase), the summation of those two signals will lead to cancellation. Based on this idea the cancellation can be achieved by a search algorithm that establishes cancellation tones to minimize the undesired output. Instead of directly measuring the receiver input at the RF frequency, monitoring the down-converted baseband output at a much lower frequency can significantly reduce the cost.

The proposed architecture is shown in Fig. 1. To perform cancellation, LO is first set to f_1+Δf. The fundamental tone f_1 is down-converted to Δf and sent to the baseband. Then, the baseband uses Fast-Fourier Transform (FFT) to measure the amplitude and phase of the signal at Δf. The baseband processor can estimate the attenuation and phase shift needed for the cancellation to work. The output of the phase shifter is then summed with the received signal and achieves cancellation. However, since the received signal can have arbitrary power and phase, plus the hardware loss and phase shift also changes in different environment, a gradient descent algorithm can be applied to find the optimal point for the best cancellation. After the f_1 cancellation is done, the same procedure will be repeated for f_2. After both fundamentals are cancelled, the LO will be set to $2f_1 - f_2$ for normal operation. The cancellation is done sequentially in this proposal. Real-time tuning for the cancellation parameters can also be done in background by splitting the signal after the gain stage of the RX into parallel paths with higher hardware cost.

Since the received signal can have arbitrary amplitude and phase, to achieve perfect cancellation, the attenuator and phase shifter need to have infinite resolution and cover the entire range. In practical system, the attenuator and phase shifter have finite resolution. As a result, there will be residue fundamental tones at the output of the power combiner. To understand the impact of the mismatch in the amplitude and phase, assume RX Antenna received a single tone:

$$V_0(t) = A_0 cos(\omega t + \varphi_0). \tag{2}$$

The cancellation tone is

$$V_1(t) = A_1 cos(\omega t + \varphi_1). \tag{3}$$

Applying trigonometry

$$V_{out}(t) = V_0(t) + V_1(t) = A_{out} cos(\omega t + \varphi_{out}), \tag{4}$$

$$A_{out} = \sqrt{A_0^2 + A_1^2 + 2A_0A_1 cos(\varphi_0 - \varphi_1)}.$$

The amplitude A_{out} indicates the amplitude of the residue fundamental tone. For two fundamental tones cancellation, each tone's residue can be calculated by (4).

III. Simulation and Experiement Results

To evaluate the impact of the amplitude and phase mismatch between cancellation tone and received tone, MATLAB is used to calculate and plot A_{out} versus different amplitude and phase errors using (4). Fig. 2 shows the result. Each curve in the plot has a fixed phase error. The x-axis is the amplitude error. The y-axis is the attenuation of the fundamental tone in dB after cancellation. With zero phase error and zero gain error, infinite attenuation can be achieved. However, for practical components, -0.5 dB gain error and 1-degree phase error correspond to 24.66 dB cancellation.

To simulate the effectiveness of the fundamental tone cancellation for intermodulation radar, the following parameters are assumed for the overall RX to calculate the intermodulation distortion with and without cancellation: IIP3 is 0 dBm and gain

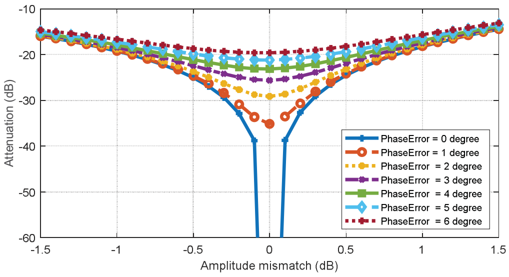

Fig. 2. Cancellation effect with amplitude and phase mismatch.

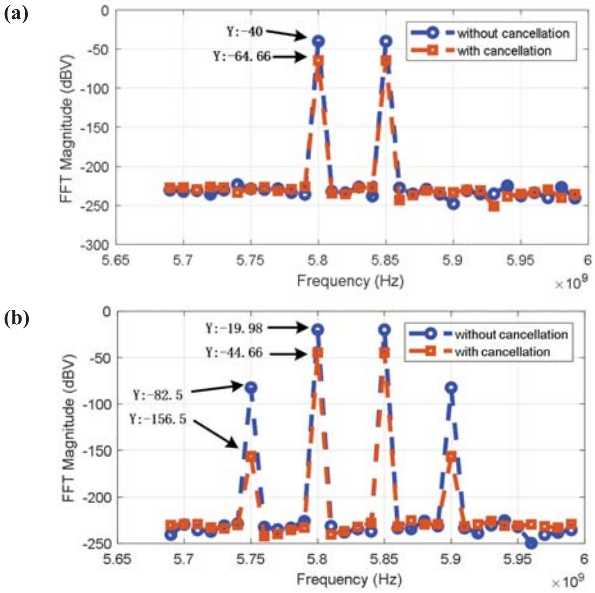

Fig. 3. (a) Spectrum at receiver input with and without cancellation. (b) Spectrum at receiver output with and without cancellation.

is 20 dB; antenna receives two -30 dBm fundamental tones at 5.8 GHz and 5.85 GHz; the cancellation tone has -0.5 dB gain error and 1-degree phase error. The simulation results are plotted in Fig. 3. The first plot (a) shows the spectrum of the fundamental signals received by the RX antenna. It verifies that the proposed fundamental tone cancellation achieves 24.66 dB attenuation with practical design parameter and the result matches the calculation. The second plot (b) shows the spectrum of the signals at the output of the receiver. Without the proposed cancellation, the 3rd order intermodulation tone is -82.5 dBV. With the proposed cancellation, the 3rd order intermodulation tone is -156.5 dBV. The attenuation is 74 dB, which means that the sensitivity for the target detection is improved by 74 dB.

A simplified setup shown in Fig. 4 is used to verify the analysis and simulation results. A signal generator generates 5.8 GHz signal and splits into two paths by a power splitter. A programmable phase shifter is inserted in one path and then a power combiner is used to sum the two paths. The phase shifter has -1.2 dB insertion loss. The output power level is recorded with different phase shift values. Fig. 5 shows the measurement results in comparison with simulation results. The *x*-axis is the phase error, and the *y*-axis is the attenuation of the fundamental tone in dB. The error in the measurement may come from the phase shifter inaccuracy. As can be seen, the fundamental tone can be attenuated by 18 dB, which means that the 3rd order intermodulation tone can be reduced by 54 dB.

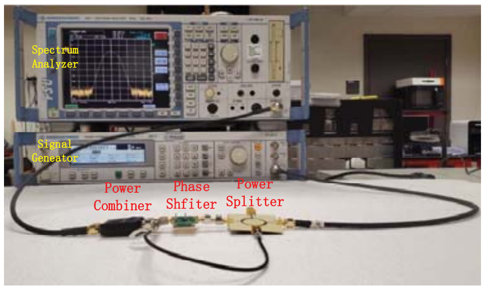

Fig. 4. Experiment setup.

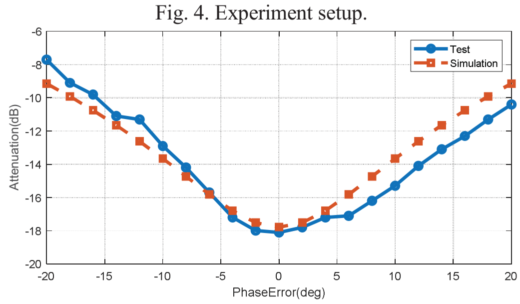

Fig. 5. Measurement vs. simulation results.

IV. Conclution

In this paper, a fundamental tone cancellation technique was proposed to enhance the linearity of intermodulation radar. Experiment and simulation results showed that the proposed technique can effectively improve the sensitivity of intermodulation radar. Future work will be focused on designing and testing an intermodulation radar with the proposed scheme.

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