Crosstalk-Based Calibration for High Accuracy Ranging Using Software-Defined Radios

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***Abstract*—High-accuracy ranging measurements require precise knowledge of systematic delays caused by latencies in the hardware system. In this work, a calibration procedure for estimating such delays using intrinsic crosstalk between the transmit and receive hardware internal to a Software-Defined Radio (SDR) is presented. Since the crosstalk contains a distorted and attenuated version of the transmitted waveform, the signal received on the receiver channel is processed using a matched-filter to increase the processing gain; the delay between transmission is reception of the crosstalk signal provides an estimate of the intrinsic delays in the system. Since the internal latency is generally static after the hardware is initialized, such a calibration may only need to be performed once at system startup. The approach is demonstrated using SDR hardware and shows centimeter-level delay accuracies for waveforms of 7 ms length and 500 kHz bandwidth.**

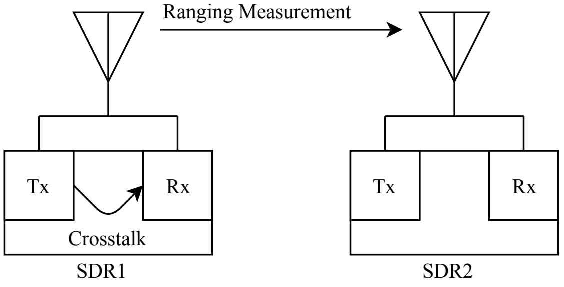

Fig. 1. Block Diagram showing the system layout for crosstalk calibration and ranging measurements.

I. INTRODUCTION

Software-defined radios (SDRs) are increasingly being used in many RF applications in place of discrete hardware due to their flexibility and applicability to radar and communication systems [1]. When used for coherent distributed array applications, the range must be estimated to within a small fraction of a wavelength of the coherent beamforming signal [2]. When being used for high-accuracy ranging applications, precise delay measurements are required, and there are several methods to calibrate ranging hardware to minimize the errors. One potential source of error in a SDR is the internal hardware circuitry and the slight software overhead to store the received data and send back to the computer. There are active and passive ways to calibrate the hardware for internal delays: one method that has been proposed is using a calibration network and multiple calibration tests to calculate the phase errors or time delays due to the hardware [3]; other methods propose using active reflectors to calibrate the system [4]. These solutions work well, but add complexity to the system. The method proposed in this work leverages inherent crosstalk between the transmit (Tx) and receive (Rx) port of a transceiver internal to the ranging system as shown in Fig. 1. A sinusoidal pulse is transmitted from the transmit port and the resulting crosstalk is sampled at the receive port. To assess the ability to accurately determine the range, the transmit port is terminated with an impedance matched load to minimize reflections. A matched filter is then computed using the crosstalk and the transmitted signal, the output of which gives the time delay of the SDR hardware and software. The length of the sinusoidal pulse and the number of pulses used for each test was alternated to determine the best combination of pulse length and number of pulses sent when calibration.

II. THEORY FOR CROSSTALK PULSE DETECTION

Matched filtering is a signal processing concept that is often used to increase the processing gain to better estimate the time delay of the reception of a transmitted signal; the matched filter ideally produces the optimal output Signal-to-Noise Ratio (SNR) [5]. For radar applications, a signal is transmitted, bounces off a target and then received. When using matched filtering for the calibration process, the signal is not bouncing off of a target, but rather it is the time that is takes for the transmitted signal to be picked up via the receiver crosstalk and transferred to the host computer. The matched filter works by correlating the received signal with a time reversed copy of the transmitted signal in the time domain and is given by

$$y_o(t) = \int_{-\infty}^{\infty} y_{in}(\lambda) h(t-\lambda) d\lambda \tag{1}$$

where y_{in} is the received signal and $h(t-\lambda)$ is the filter impulse response. The received signal is given by

$$y_{in} = s(t) + n(t) \tag{2}$$

where $s(t)$ is the transmitted signal and $n(t)$ is additive noise. The noise is assumed to have a flat frequency spectrum. The impulse response $h(t)$ is given by the time-reversed transmitted signal, $s(-t)$, and thus in (1), $h(t-\lambda) = s(-t+\lambda)$.

III. EXPERIMENTAL SETUP

The experiment used an Ettus X310 SDR with two UBX 160 daughterboards each containing a transmit channel and

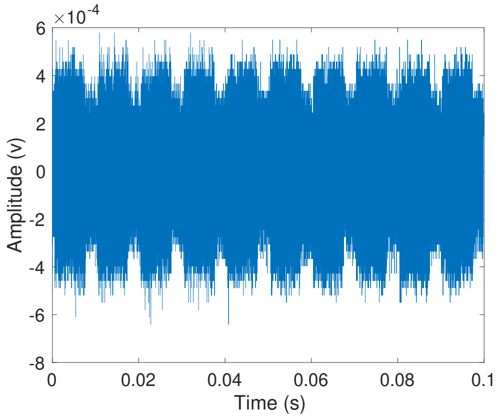

Fig. 2. Several pulses from the received crosstalk.

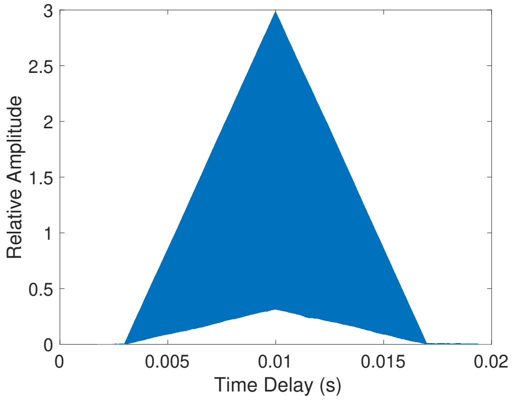

Fig. 3. Matched filter output from crosstalk and transmitted signal.

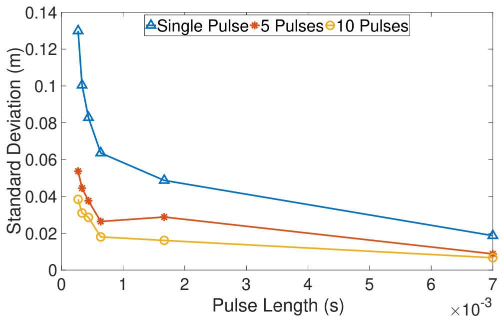

Fig. 4. Standard deviation for different duty cycles and pulse groupings.

a receive channel. The crosstalk is present on both daughterboards and the same analysis can be done on the receiving ports from both daughterboards when transmitting from the same transmitter. The transmit port was terminated with a 50-Ω load to minimize reflections and the receive port was left open. The calibration waveform was a 500 kHz pulsed sine wave transmitted with a carrier frequency of 2 GHz with an output power of 20 dBm. The sampling rate on the receiver was 10 MSps. Due to software limitations, the maximum waveform length tested was 7 ms. The different lengths of tone pulses used were as follows:

$$Pulse\ Length = \frac{7}{5n+1} ms \tag{3}$$

where $n = 0, 1, 2, 3, 4, 5$. For each pulse length, 1000 measurements were conducted.

When a signal was sent from the transmit port, the resulting crosstalk was received and down converted back to baseband as shown in Fig. 2. It can be seen that the received signal is near in amplitude to the noise floor. The received baseband crosstalk was then cross-correlated with the transmitted baseband waveform through the matched filter. The resulting matched filter output is shown in Fig. 3. The x-axis of Fig. 3 represents the time delay and the y-axis represents the resulting amplitude from the matched filter; the delay through the system thus corresponds to the peak of the matched filter output. Clearly, after matched filtering the crosstalk signal is strong enough for rough delay estimation, however a more accurate time delay was acquired by interpolating with the max peak and several points around the peak and then choosing a new max peak from the interpolation. The first fifty and last fifty time delays of a pulse length were discarded because the matched filter gave time delays 1.2 times or greater compared to the rest of the data.

IV. DELAY MEASUREMENT RESULTS

The standard deviation of the crosstalk delay was computed for six different pulse lengths and three different pulse train lengths. The results in Fig. 4 demonstrate that a higher accuracy is achieved with longer pulse lengths or an increase in the number of pulses used for testing. For open loop distributed arrays, the goal is to have an internode range accuracy less than $\frac{\lambda}{15}$ for 90% coherent gain [2]. Given the measured delay accuracies, a single 7 ms pulse enables coherent operation at frequencies up to 1.06 GHz. If five 7 ms pulses are used for calibration then the highest operational frequency increases to 2.27 GHz. If ten 7 ms pulses are used, then the highest frequency is 2.98 GHz. Thus, systematic delays may be estimated to good accuracy using only the intrinsic crosstalk inherent in the transceiver system.

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