Effects of Spectral Interference on High-Accuracy Ranging in Coherent Distributed Arrays

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***Abstract*—The effects of noise-like interference on spectrally-sparse, high-accuracy microwave ranging for coherent distributed antenna arrays are analyzed in this work. Coherent operation between separate nodes in distributed arrays is dependent on the level of accuracy in estimating the internode distances. Internode ranging accuracy is mainly affected by the waveform characteristics along with the signal-to-noise ratio (SNR), or the signal-to-interference-plus-noise ratio (SINR) in the case of added interference. In this work it is shown that the optimal bandwidth of the ranging waveform (a spectrally-sparse, two-tone signal) is dependent on the spectral shape of the interference.**

I. Introduction

Distributed wireless systems have lately seen increased interest due to their abilities to achieve high performance in communication and remote sensing operations in comparison to single-platform systems. With proper coordination between the different nodes of the distributed system, it is possible to achieve high gain and efficiency while maintaining flexibility and low cost. Distributed systems achieving coherence in an open-loop architecture, where no feedback from the destination is used, is the most flexible and convenient architecture [1]. Although the open-loop architecture has increased advantages, enabling phase-coherent beamforming between nodes is not a trivial task and relies on high accuracy range estimation between the array nodes.

It has been shown that two-tone waveforms have improved range estimation performance over other type of waveforms [2]. Furthermore, the performance of time delay estimates is easily tunable by modifying the separation of the frequencies in the two-tone waveform. It is well-known that the minimum achievable ranging accuracy is dependent on the spectral characteristics of the waveform as well as the SNR. This work presents an analysis of the effects of non-uniform spectral interference on high-accuracy ranging, setting up a method for mitigation of interference. The effects of interference are analyzed using a software-defined radio (SDR).

II. High-Accuracy Ranging

The accuracy of a range estimate is determined by both SNR and mean-square bandwidth or effective bandwidth β^2 of the waveform, given by

$$\beta^2 = \frac{1}{E} \int_{-\infty}^{\infty} (2\pi f)^2 \left|S(f)\right|^2 df \tag{1}$$

where $S(f)$ is the spectral intensity of a signal $s(t)$ for a frequency f and E is the signal energy. The mean-squared bandwidth is specific to the characteristics of the transmitted waveform, and can be maximized in a given bandwidth to values greater than that achieved with a standard linear-frequency modulated (LFM) waveforms. The time delay estimation performance is governed by the Cramer-Rao lower bound (CRLB) at moderate to high SNR, and the lowest possible variance for the time delay estimate is given by

$$\sigma_t^2 = \frac{1}{\beta^2 \cdot \frac{2E}{N_0}} \tag{2}$$

where N_0 is the noise power per unit bandwidth.

A two-tone signal with ideal characteristics is expressed as

$$s(t) = e^{j2\pi(f_0-\delta f)t} + e^{j2\pi(f_0+\delta f)t} \tag{3}$$

where f_0 is the center frequency of the signal, and δf is one-half of the separation of the two tones. Calculating the mean-square bandwidth of the above signal and inserting it into (3) yields the variance of the range estimates,

$$\sigma_{t_{f_0}}^2 = \frac{1}{\left[\left(2\pi\delta f\right)^2 + \left(2\pi f_0\right)^2\right] \cdot \frac{2E}{N_0}} \tag{4}$$

In (4), the center frequency of the signal and the one-half of the separation of the two tones is replaced by $f_0 = \frac{f_{max}+f_{min}}{2}$, and $\delta f = \frac{f_{max}-f_{min}}{2}$ where $f_{min} = f_0 - \delta f$, and $f_{max} = f_0 + \delta f$. Also, the signal energy can be expressed as $E = \frac{A_S^2 \tau}{R}$, where A_S is the root-mean-square (RMS) amplitude of the received signal pulse, τ is the pulse width duration, and R is the resistance. Similarly, the noise power per unit bandwidth becomes $N_0 = \frac{A_N^2}{RB}$, where A_N is the RMS amplitude of the noise, and B is the available bandwidth, yielding

$$\sigma_{t_{f_0}}^2 = \frac{A_N^2}{\left[2\pi^2\left(f_{max}^2 + f_{min}^2\right)\right] \cdot \left[2A_S^2 \tau B\right]} \tag{5}$$

In the case of interference, Eq. (5) needs to be modified to represent the new lower bound. In this paper the interference is considered as an uncorrelated received signal (for example a router transmitting on an overlapping bandwidth) and in this case is modeled as a Gaussian noise. Thus this signal can be considered as an additive noise [3] and A_N needs to be modified to take into account the added interference signal and it is represented by $A_{NI} = A_N + A_I$, where A_I represents the magnitude of the interfering signals.

The estimation accuracy is then given by the standard deviation, which is thus

$$\sigma_{t_{f_0}} = \frac{A_{NI}}{2\pi A_S \sqrt{\left(f_{max}^2 + f_{min}^2\right)\tau B}} \tag{6}$$

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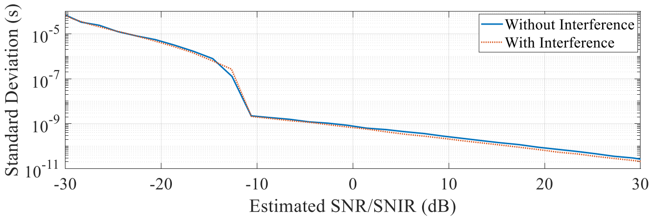

Fig. 1. Measured ranging accuracy with different SNR/SINR values.

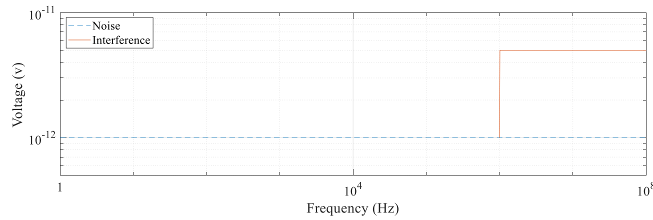

Fig. 2. Example noise and interference amplitude spectral densities.

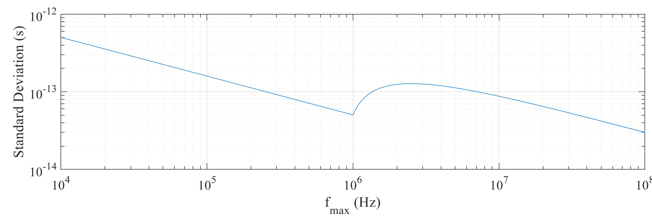

Fig. 3. CRLB versus tone separation for the noise profile in Fig. 2, showing a region ($1 \times 10^6 - 5 \times 10^7$ Hz) where the ranging performance degrades. The specific regions depend on the spectral noise shape.

Since this work focuses on modifying the frequencies of the two tones waveform to obtain the desired accuracy, A_S, τ, and B are kept constant. For different observations of A_{NI}, the frequencies f_{max} and f_{min} can be redesigned to satisfy the accuracy requirements using (6).

Experimental evaluation showing the similarities in behavior between the interference and the additive noise is shown in Fig. 1. The ranging accuracy is compared for two cases: first A_I is set to zero and A_S is modified to change the SNR values; in the second case A_S is kept constant and A_I is modified to change the SINR values. This experiment was done using Ettus USRP X310 software-defined radio (SDR). The transmitting and receiving daughterboards (UBX 160) were connected using a 2 m cable with 30 dB attenuator, allowing a controlled evaluation of the SNR/SINR estimates. The carrier frequency was set to 2 GHz, and a two-tone waveform of 1.2 ms pulse width was used with $f_{max} = 1$ MHz and $f_{min} = 100$ KHz. It can be seen that when the interference is uniformly added across the signal bandwidth the estimation accuracy is unchanged. In the following, the effects of non-uniform spectral interference is analyzed.

III. Impact of Non-Uniform Interference

To monitor interference accurately without disturbing the operation of the ranging radar, it is possible to sense the interfering signals in the duration where no reflected pulses are detected. This way, estimating A_{NI} will not affect or delay the ranging process. Estimation of the pulse delay is accomplished using a matched filter, where the received pulse is correlated with the linear filter $h[n]$, giving

$$S_{out}[m] = \sum_{m=-\infty}^{\infty} h[n-m] S_{Rx}[m] \tag{7}$$

where $h[n] = S^*_{Tx}[-n]$ is the linear filter that maximizes the SNR of the received signal, S_{Tx} is the transmitted signal, and S_{Rx} is the received signal.

The pulse location is then determined by the peak of the matched filter output, and, knowing the pulse length, the portion of the signal containing only noise and interference is selected. A_{NI} can then be calculated by obtaining the RMS amplitude of the no-signal region. An example of the effects of non-uniform spectral noise on the estimation accuracy in the presence is shown in Figs. 2 and 3. The CRLB was calculated for a waveform with $\tau = 1\ ms$, $A_S = 0.1$ V $f_{min} = 1$ KHz, and by varying f_{max}. The bandwidth of the two-tone signal is between 0 and f_{max}, and the remainder of the noise contributions were filtered out. The noise and interference amplitude spectral densities are shown in Fig. 2, and the lower bound is shown in Fig. 3. Clearly, the effects of non-uniform interference create regions in the CRLB where simply increasing the tone separation yields a degradation in the ranging performance. Thus, in cases where the interference is constant over all the allocated bandwidth it is convenient to operate in the entire bandwidth. But in the case where the interference could be only affecting a portion of the bandwidth, it is important to analyze spectral power density of the interference, since it may be costly to operate at very wide tone separations. This can be done by dividing the available bandwidth into n bins and A_{NI} is calculated separately for every bin. In many cases a higher accuracy (lower standard deviation) can be achieved by operating with a smaller bandwidth that has low noise levels rather than consuming the whole available bandwidth while suffering from high noise power. In the case where n_1 number of bins are found to have low A_{NI} compared to a higher noise/interference power in the other $n_2 = n - n_1$ bins, it is possible to apply a bandpass that filters out the frequencies of the n_2 bins and then operate only in the n_1 selected bins.

References

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