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Sub-Millimeter Ranging Accuracy for Distributed Antenna Arrays Using Two-Way Time Transfer

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***Abstract*—Distributed antenna arrays can provide unique capabilities in applications such as distributed communication and sensing. However, in order to coordinate distributed arrays, accurate positioning information of all nodes in the array is required to ensure coherent operations at the target location. Other works have shown that two-way time transfer using spectrally sparse two-tone ranging waveforms provides high accuracy timing synchronization. In addition to time correction, these waveforms may provide inter-node ranging with high accuracy. In this paper the accuracy of ranging via two-way time transfer for a two-node time synchronization system using a two-tone waveform is evaluated. Results are compared to ranging performance using a standard linear frequency modulated waveform (LFM). Experimental results show an accuracy of 0.5 mm using a 40 MHz bandwidth two-tone waveform with a 36 dB signal-to-noise ratio (SNR), supporting a beamforming frequency of up to 40 GHz.**

I. Introduction

Distributed antenna array systems will provide unique capabilities in future wireless applications, ranging from distributed remote sensing arrays to navigation and positioning, by supporting increased signal gains, decentralized processing for increased tolerance to failures, and flexibility through dynamic reallocation of antenna elements [1]. However, synchronizing the signals from elements in a distributed array requires accurate knowledge of the relative spatioelectrical states of the elements. In particular, accurate coordination in time (synchronization) and position are necessary. Two methods are commonly used for synchronization: the one-way time transfer methods, and the two-way time transfer methods. While the former are prevalent in applications such as global navigation satellite systems (GNSS), they suffer from disadvantages when used to estimate propagation delay because they require knowledge of the positions of both the receiving and transmitting nodes [2]. Two-way time transfer methods, on the other hand, can be used to solve for the propagation delay and clock offset inherently assuming a quasi-static channel during the synchronization process. This work investigates the accuracy of internode ranging via a two-way time transfer method [3] using a two-tone waveform, which provides near-optimal delay estimation accuracy. Experimental results are compared to those obtained with a linear frequency modulated (LFM) waveform and one-way time transfer methods, demonstrating ranging accuracy of 0.5 mm.

II. High Accuracy Ranging

The Cramer–Rao lower bound (CRLB) provides a theoretical limit and a way to maximize the accuracy of the time delay waveform which depends mainly on the signal-to-noise ratio (SNR) and the bandwidth of the waveform [4], [5]. The limit of the CRLB is given by

$$\mathrm{var}(\hat{\tau}-\tau) \geq \frac{N_0}{2\zeta_f^2 E_s} \tag{1}$$

where ζ_f^2 is the mean-squared bandwidth, E_s is the signal energy, and N_0 is the noise power spectral density. The ratio

$$\frac{E_s}{N_0} = \tau_p \cdot \mathrm{SNR} \cdot \mathrm{NBW} \tag{2}$$

along with (1) shows the inverse relationship between the variance of the time delay estimation with the SNR, the noise bandwidth NBW of the system, and the pulse duration τ_p. In [5] it was shown that concentrating the power spectral density of a waveform at the edge of the bandwidth (yielding a two-tone waveform), which results in $\zeta^2_{\text{(two-tone)}} = (\pi \cdot \mathrm{BW})^2$, maximizes the mean-squared bandwidth and thus minimizes the variance on the estimated delay of the system. To maximize the SNR of the received two-tone waveform, a discrete-time matched filter is used, given by $s[n] = s_{RX}[n] \circledast s^*_{TX}[-n]$, that peaks at the discrete sample closest to the true time delay of the received signal, which is limited by the timing resolution of the system, in this case 10 μs. Here $s_{RX}[n]$ is the ideal received waveform, and $s^*_{TX}[n]$ is the complex conjugate of the transmitted waveform [4], [6]. The sampling rate of the digitizer serves as a factor limiting the accuracy of the time delay estimation. This is addressed by using a quadratic least-squares fitting to the peak of the matched filter response and the immediately adjacent samples. A closed-form solution is used for finding the delay location of the parabola formed through these points [4]. The propagation delay of the two-way time transfer can be computed as shown in Fig. 1 using the relation [3]

$$\tau_{n0} = \frac{(t_{RX0} - t_{Txn}) + (t_{RXn} - t_{TX0})}{2} \tag{3}$$

where t_{TXn} and t_{RXn} are the times of transmission and reception at node n respectively.

III. Experimental Configuration

The block diagram of the experimental two-way time-transfer circuit is shown in Fig. 2. The system used wireless time transfer with a cabled frequency reference between two software-defined radio (SDR) nodes (Ettus Research X310 SDRs with UBX-160 daughterboards). Both two-tone waveforms and the more common LFM waveform were used to

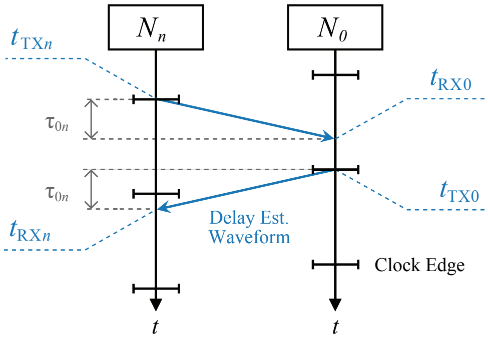

Fig. 1. Timing diagram for two-way time transfer distributed array. Here node N_n initiates time transfer with the primary node, N_0 and the delay estimation waveform is transmitted between the nodes with timestamps saved at each transmission and reception [3].

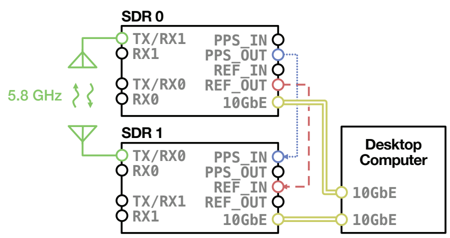

Fig. 2. Schematic diagram of the two-way time-transfer system. Nodes 0 and 1 are represented by two software-defined radios SDR 0 and SDR 1, respectively, both controlled by a single PC running GNU Radio software.

determine relative accuracy. The two SDRs were connected to two L-Com 8-dBi 2.3–6.5 GHz log-periodic antennas through 6-ft coaxial cables and two Analog Devices HMC427A control transfer switches. The antennas were placed 90 cm apart. The SDRs were controlled through GNU Radio software. A two-tone waveform with pulse duration of 10 μs and 5.8 GHz carrier frequency was exchanged between the two nodes 0 and 1. The experiment consisted of two sub-experiments: measurements of the two-way propagation delay were taken while (1) varying the SNR from 6–36 dB in 3-dB increments at 40 MHz bandwidth, and (2) varying the bandwidth of the two-tone waveform (i.e., the tone separation) and LFM waveform from 5–50 MHz in 5 MHz increments while holding the SNR fixed at 30 ± 1 dB.

IV. Experimental Results

The standard deviation plus bias of the spatial separation between nodes was calculated from one set of measured one-way time delays between two selected nodes. The inter-node distance d_{01} between nodes 0 and 1 was computed from the relation $d_{01} = ct_f$ where t_f is the time-of-flight with bias. As described above, either the tone bandwidth or SNR may be used to improve the accuracy. Two experiments were thus conducted: one varying the SNR with a fixed bandwidth of 40 MHz; and one varying the bandwidth with a fixed SNR of 30 ± 1 dB. The standard deviation was computed for each data point over one minute of data with a measurement interval of 500 ms. The results versus SNR are shown in

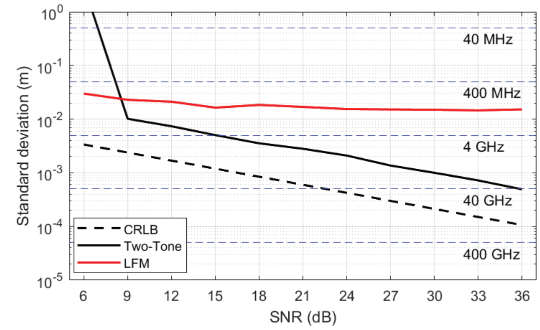

Fig. 3. Accuracy of time ranging for wireless time transfer measured at SNR 6–36 dB with ± 1 dB tolerance with a bandwidth of 40 MHz. The accuracy is the standard deviation of the inter-node distance computed in meters, and the CRLB is the theoretical lower bound using (1) and (2). The horizontal lines represent the beamforming frequency.

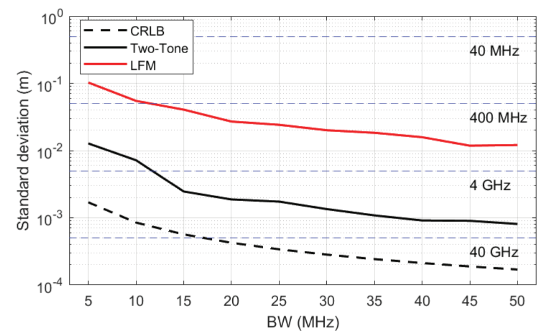

Fig. 4. Accuracy of time ranging for the system as a function of the waveform bandwidth. The standard deviation of the distance was calculated in meters over a bandwidth range of 5–50 MHz in 5 MHz increments at 30 ± 1 dB SNR. The horizontal lines represent the beamforming frequency.

Fig. 3. The standard deviation decreased as the SNR increased, reaching a minimum of 0.5 mm at 36 dB for the two-tone waveform. Fig. 4 shows the results versus bandwidth, showing a similarly decreasing accuracy as the bandwidth increases, and a significant improvement when using the two-tone waveform compared to the LFM. Also shown on each figure are the boundaries at which the performance supports a given distributed beamforming frequency. It can be seen that the two-tone approach supports distributed beamforming at frequencies extending up to 40 GHz.

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