High Accuracy Wireless Time Synchronization for Distributed Antenna Arrays

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***Abstract*—A method for high accuracy time synchronization of nodes in a distributed antenna array that achieves time alignment accuracy of less than 10 ps is demonstrated. This technique utilizes a two-step process, first performing coarse time synchronization using a conventional pulse-per-second-based time alignment to distribute a global timestamp on device startup, then performing a refinement process using a pulsed dual-tone waveform that is matched filtered and interpolated for fine delay estimation. This process is demonstrated experimentally using software-defined radio nodes separated by 1.2 m using a carrier of 5.8 GHz and a dual-tone waveform with 50 MHz bandwidth.**

I. INTRODUCTION

Distributed wireless sensing and communication networks have been gaining interest due to their robustness to failures stemming from a decentralized architecture, lower implementation cost than single-platform systems due to requiring smaller, lower-cost nodes, and capability to increase signal gain and throughput, among other benefits [1]–[3]. Coordinating distributed wireless systems is, however, significantly challenging. Presently, these networks most often operate in a non-coherent manner, collecting measurements independently and individually communicating the measurements to a central location for processing. More recent trends have been shifting towards distributed antenna array concepts where each node coordinates with the others to operate in a phase-coherent manner enabling technologies such as distributed multiple-input multiple-output (MIMO) and distributed phased arrays. This allows for increased gain compared to single-platform systems, and also enables distributed arrays to adapt to changing requirements. However, to accomplish this, each node must align its time, frequency, and phase with the other nodes in the network to ensure that the signals combine coherently at the destination [4]. Of these, time alignment is critical to ensure that the waveforms arrive synchronously at the destination. In this paper we present a new method for achieving distributed time synchronization of nodes in a distributed antenna array that is based on the transfer of a two-tone waveform. We demonstrate experimental time synchronization accuracies below 10 ps using commercial software-defined radios (SDRs).

II. TIME TRANSFER SYSTEM

For frequency-locked, or *syntonized*, systems, a local time model for each of the nodes in the array is given by $T_n(t) = t + \Delta_{0n}$ where t is the global "true" time at N_0 and Δ_{0n} is the bias between nodes N_0 and N_n which is assumed to be quasi-static during the synchronization period.

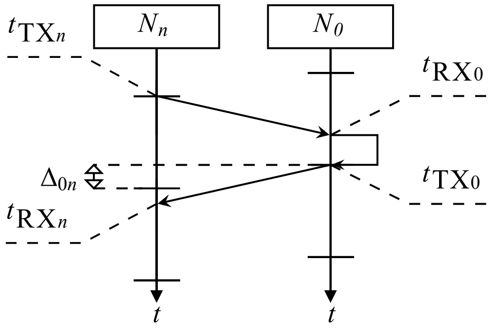

Fig. 1. Two-way time transfer protocol digram. Node N_n initiates the time transfer sequence by transmitting a ranging waveform at t_{TXn}, node N_0 receives and transmits another waveform at t_{RX0} and t_{TX0} respectively, timestamping its receive and transmit times, for node N_n to use to determine its time offset relative to node N_0. Horizontal lines represent local clock ticks at each node.

To perform system time alignment it is necessary to estimate and compensate for the bias Δ_{0n}. This can be accomplished directly under the assumption that the channel is symmetrical during the synchronization exchange period by performing a two-way time transfer exchange as shown in Fig. 1. During this process, a node N_n in the array initiates a synchronization exchange with the primary node N_0 by transmitting a high accuracy ranging waveform [5]; N_0 will receive the waveform and estimate its local time of arrival, then transmit its own ranging waveform along with the receive and transmit times, t_{RX0} and t_{TX0}. Based on these timestamps, node N_n can estimate its local clock bias relative to N_0 as

$$\Delta_{0n} = \frac{t_{\mathrm{RX0}} - t_{\mathrm{TX0}} - t_{\mathrm{RX}n} + t_{\mathrm{TX}n}}{2}. \tag{1}$$

To ensure high-accuracy, the transmission times are scheduled to within one clock tick on the node and the receive pulse time delays are estimated using a two-step matched filter and interpolation process. Upon receive, a waveform is first digitally matched filtered against its ideal zero-delay reference waveform to provide a coarse delay estimate to within one clock tick. Next, quadratic least squares (QLS) fitting is used on the peak of the matched filter and its two adjacent points to estimate the true time delay to sub-clock tick precision [6].

III. EXPERIMENTAL CONFIGURATION AND RESULTS

A schematic for the experimental setup is shown in Fig. 2. The measurement system consisted of two Ettus Research

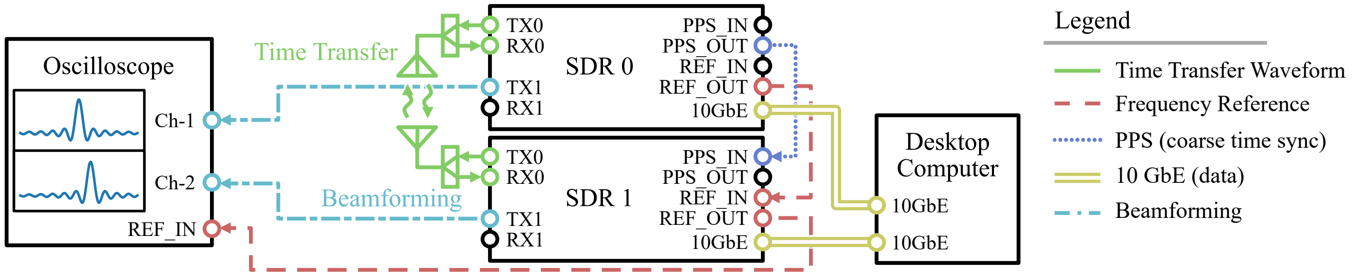

Fig. 2. Experimental measurement system schematic.

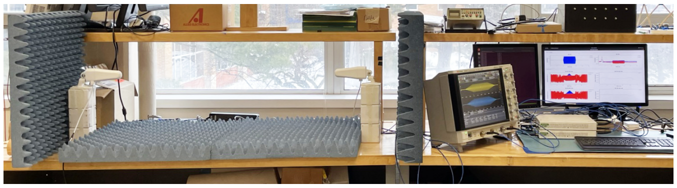

Fig. 3. Wireless time transfer experimental setup. Ettus Research X310 SDR, control PC, and oscilloscope for measuring beamforming (right); Yagi-Uda antennas for wireless time transfer (left).

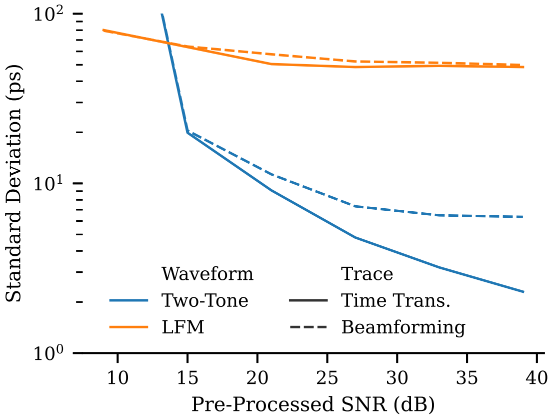

Fig. 4. Time transfer and beamforming alignment standard deviation vs. time transfer waveform type and SNR. All waveforms used $50\,\mathrm{MHz}$ bandwidth. SNR control accuracy was $\pm 1\,\mathrm{dB}$.

X310 SDRs, each with two UBX-160 daughterboards enabling two transmit and two receive channels on each SDR. The first transmit/receive channel on each SDR was used for wireless time synchronization; the synchronization was operated in a time-domain duplexing mode so that only one antenna could be used on each platform for both transmit and receive without transmit to receive leakage concerns. The transmit antennas were $5.9\,\mathrm{GHz}$ Laird 13.2-dBi Yagi-Uda antennas separated by $1.2\,\mathrm{m}$, pictured in Fig. 3. Due to a limited receive buffer, the devices need to be coarsely time-aligned at device startup to ensure that the receive node will be receiving samples within the same window that the transmit node is transmitting; this was accomplished using a pulse-per-second (PPS) signal connected from the primary to secondary node. On startup, the devices both reset their local clocks to zero on the rising edge of the PPS trigger—in practice this was found to be sufficient to align to within tens of cycles of the 200 MHz local clocks.

To determine the overall time synchronization performance for information transfer using wireless time transfer between platforms, the second daughterboard on each SDR was connected to a Keysight DSO5804A $20\,\mathrm{GSa/s}$ oscilloscope. Each daughterboard transmitted a modulated time-aligned two-tone pulse of $1\,\mu\mathrm{s}$ duration, with a carrier of $1.2\,\mathrm{GHz}$ and tone separation of $50\,\mathrm{MHz}$. The signal-to-noise ratio (SNR) of the time-transfer waveform was varied and the time delay between each beamforming channel at the oscilloscope was characterized. For each SNR level, 500 waveforms were collected then digitally demodulated, correlated, and interpolated to find the peak using QLS. The results for two-tone and linear frequency modulated waveforms are shown in Fig. 4. The SNR was computed by taking the ratio of average peak power from the centermost 100 samples of the signal to the average peak power of 100 samples of noise $\sim 10\,\mu\mathrm{s}$ after the time transfer burst. The SNR for each of the experiments was controlled to within $\pm 1\,\mathrm{dB}$. A small, static bias was present which varied from run-to-run was manually calibrated out; after calibration all inter-channel biases were below $10\,\mathrm{ps}$. From these measurements it is shown that a beamforming accuracy of below $10\,\mathrm{ps}$ is possible using wireless time transfer and a two-tone waveform for delay estimation.

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