A Precise RF Time Transfer Method for Coherent Distributed System Applications

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***Abstract* — A method for creating an absolute common time reference between distributed RF systems was demonstrated using software-defined radios by exchanging RF time-alignment waveforms. A timestamp-free protocol was implemented to reduce the non-deterministic sources of latency typical of digital timestamp exchange methods. The protocol is synthesized on the field-programmable gate array of National Instruments Universal Software Radio Peripheral transceivers. Measurements indicate time alignment can be achieved with a standard deviation of less than 100 ps. A demonstration using the protocol to align L-band transmissions from distributed nodes is presented.**

***Index Terms* — Time alignment, timestamp-free, software-defined radio, coherent distributed systems.**

I. INTRODUCTION

The coordination of distributed RF systems has been gaining interest in the telecommunications and RF system communities [1]. Generating a coherent signal from multiple distributed nodes has the potential to increase link range, data rates, and efficiency for power-constrained wireless transmitters. This requires synchronization at multiple time scales. The RF carrier of each node must be locked to a common frequency and phase [2-4]. In addition, nodes must have a common absolute time reference to ensure symbols or pulses from the distributed transmitters overlap at the target.

In order to produce overlapped symbols or pulses, the transmissions from distributed nodes must be aligned to a fraction of the information bandwidth. The time alignment requirements can be quite challenging if the bandwidth of the coherent RF waveform is large (e.g. 100 MHz bandwidth requires nanosecond rms timing errors). These requirements prohibit the use of many common time-transfer systems such as global positioning system (GPS). To overcome this challenge, a timestamp-free system is implemented for better precision and for use in environments without GPS availability.

In most time alignment protocols (e.g. the Network Time Protocol (NTP)), nodes exchange digital time stamps at the Media Access Control (MAC) layer. Improvements can be achieved by moving the time alignment functionality to the physical layer (PHY), thereby reducing the sources of non-deterministic delays [5]. The timestamp-free method is a PHY approach which embeds the time alignment information in the scheduling of the message exchanges between nodes [6]. This work discusses the implementation of such a time alignment protocol using software-defined radios (SDRs) and a two-node demonstration of an L-band coherent transmission.

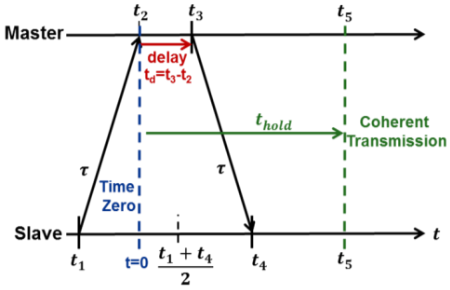

Fig. 1. Timestamp-free synchronization protocol.

II. SOFTWARE-DEFINED RADIO TIME ALIGNMENT PROTOTYPE DESIGN

Similar to the concept implemented at audio frequencies in [6], Fig. 1 shows a diagram of the timestamp-free protocol, which leverages the reciprocity of the wireless channel to remove the propagation delay (τ) between the nodes and establish a common time reference. The time alignment procedure starts when the slave node transmits a linear frequency modulated signal (LFM) to the master node at time t_1. Upon reception at time t_2, the master node detects the signal through peak detection of a matched filter output. After a short delay, t_d, the master node transmits an identical LFM at t_3, and is received at the slave node at t_4.

If t_d is zero, the slave node can determine t_2 from $(t_4+t_1)/2$ due to the reciprocity of the channel. In reality, t_d is not zero since some additional processing time is used to shut down the receiver while transmitting, and there are slight delay differences between the transmit and receive hardware. However, the portion of t_d which is deterministic can be compensated for through a calibration measurement, t_{cal}. Thus, the slave node can determine $t_2 = (t_1+t_4)/2-t_{cal}$ and t_2 is used as a common time zero reference (t=0). After a predetermined hold time, t_{hold}, the nodes simultaneously transmit a coherent RF waveform at t_5.

The proposed timestamp-free time alignment protocol uses two National Instruments (NI) 2943R Universal Software Radio Peripherals (USRPs) transceivers with a sample rate of 120 MS/s. Each NI 2943R has two RX and two TX ports. The TX1 and RX1 ports of the SDR were

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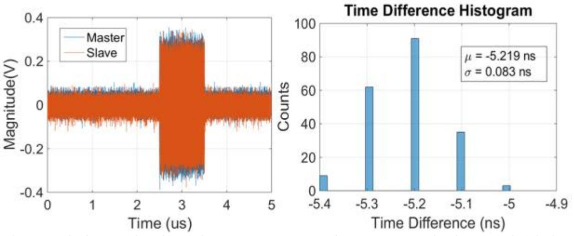

Fig. 2. (left) A single coherent RF waveform transmission and (right) the statistics from 200 recorded pulses.

used for exchanging timing waveforms, while TX2 is dedicated to transmitting the coherent RF waveform. A counter was used to trigger the coherent RF waveform transmission 40 µs after t=0 (see Fig. 1). In this implementation, the coherent RF waveform is a 1 µs, 40 MHz pulsed LFM at 1.44 GHz. An initial calibration adjustment is made to compensate for t_d and any deterministic delays. To compensate for t_d more accurately than the sample rate, the field-programmable gate array (FPGA) stores a lookup table of 10 copies of the coherent RF waveform with different sub-sample time delay offsets. All functionality is synthesized on the FPGA of the SDR to achieve highly deterministic timing.

IV. TIME ALIGNMENT MEASUREMENTS

A wired test setup was used to characterize the determinism of the time alignment protocol. In this setup, the time-alignment channels are coaxial cable, and the RF waveforms of each USPR are independently sampled with an oscilloscope. A common frequency reference was shared to isolate the performance of the time alignment system, but will be replaced by a wireless frequency transfer system in future tests [7]. Fig. 2 shows the coherent pulsed LFM transmitted by the master and slave nodes in the wired setup. A set of 200 coherent LFM pulses were collected to characterize the relative timing of the transmission (t_5 in Fig. 1). The master and slave coherent LFM signals were matched-filtered in post processing to determine the time difference between the two pulses. The histogram in Fig. 2 shows the time difference between the master and slave transmission has a mean of 5.2 ns, which can be removed through t_{cal} and a standard deviation of less than 100 ps. The standard deviation of the time difference, caused by non-deterministic errors (noise, thermal variation, etc.) is the limiting factor in achieving coherence.

The time transfer system was tested in an outdoor environment with wireless timing signal exchanges, as shown in Fig. 3. The two USRPs were placed 5 m apart and transmitted to a receiver 85 m away. Fig. 4 shows the ability to use the time-transfer system, after calibrating for positional differences, to align the waveform transmissions to achieve a coherent waveform at the receiver. By intentionally offsetting the node transmissions, the energy of each transmitter can be measured by the oscilloscope and the ideal energy of a coherent transmission can be calculated. Coherent pulses were generated with >90% of the ideal coherent energy.

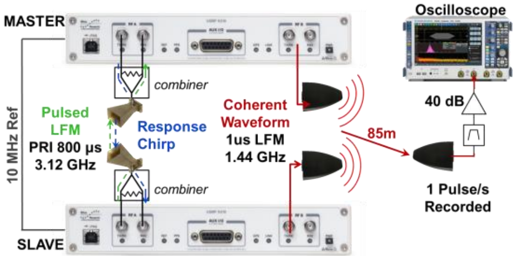

Fig. 3. Wireless test setup and captured outdoor data using the timestamp-free time alignment procedure.

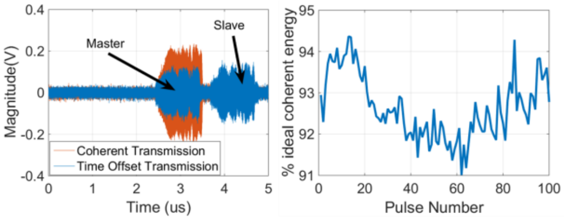

Fig. 4 (left) Received waveforms when the node transmissions are intentionally offset and when they are time aligned and (right) percent of the ideal coherent energy achieved when using time alignment for coherent transmission.

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