

Internode Ranging Using a Stepped-Frequency Coherent Pulse Train for Mitigation of Multipath Effects in Distributed Phased Arrays

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Distributed antenna arrays have attracted significant interest in recent years because of their proposed efficacy in areas such as satellite and 6G infrastructure, remote sensing, and cooperative vehicle-to-vehicle communications. By coordinating the operation of multiple nodes, such arrays offer increased flexibility, scalability, and signal gains over traditional single-platform systems. However, precise knowledge of the electrical states of the nodes and effective techniques for coordination are each required in order to achieve reliable coherent operations such as beamforming, where transmitted signals must arrive at a desired receiver location aligned closely in time, frequency, and phase. In open-loop systems, where the array must operate reliably without external feedback, alignment of the electrical states of wirelessly-distributed nodes poses a significant challenge.

In order to enable phase-coherent beamforming to an arbitrary destination, one of the principal challenges to overcome is that of array element localization; synchronization and syntonization (frequency-alignment) of the platforms are also significant fundamental obstacles, but reliable operation is dependent on the ability to compensate for differential path length between nodes and the receiver direction. Wireless sensor network localization is a topic of significant interest in literature, but has rarely been considered at the precision necessary for distributed array operations, where location precision on the order of a small fraction of the beamforming wavelength is required. Previously, we have employed the two-tone waveform along with a two-way time transfer technique for high-accuracy internode range estimation (A. Schlegel et. al, "A Microwave Sensor With Submillimeter Range Accuracy Using Spectrally Sparse Signals," in IEEE Microwave and Wireless Components Letters, vol. 30, no.1, pp. 120-123); however, this waveform is vulnerable to multipath ambiguities because it produces high time sidelobes in the matched filter output, thus it is of interest to develop a more robust ranging waveform. In another previous work, we experimentally demonstrated a practical technique by which we can convert pairwise distances for a set of multiple nodes into an estimate of the relative array locations [M. J. Dula et. al, "Decentralized Localization Of Distributed Phased Array Elements Using High-Accuracy Ranging and Multidimensional Scaling," in 2024 IEEE Wireless and Microwave Technology Conference (WAMICON), 2024, pp. 1-4]. This technique is strongly dependent on the accuracy of the internode ranging measurement, underscoring the need for precise and resilient range estimation.

In this work, we implement a two-tone stepped-frequency waveform which is designed to preserve the optimal ranging precision of the two-tone waveform while using a coherent pulse train to synthesize a large bandwidth for resolving multipath ambiguities. The waveform is evaluated through modeling and simulation as well as an experimental implementation in software-defined radios. Nodes are placed in an indoor, multipath-rich environment where they transmit pairwise with one another to estimate internode ranges before computing a relative location geometry. We characterize the performance of the ranging waveform by calculating the average error vector magnitude between estimated and true node locations in a cluttered multipath environment.