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# Laboratory Experiments for Distributed Radar

by Yashas T Shivaram and Timothy J Garner

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# Laboratory Experiments for Distributed Radar

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**14. ABSTRACT**

Distributed, passive radar systems receive signals reflected by radar targets that were transmitted by other systems. The signals received by the passive radars may be processed individually at each receiver node, or the signals from the different nodes may be combined and processed coherently. We implemented both methods in a coaxial-cable testbed. Both methods gave similar results, but coherent processing may give better results at low signal-to-noise ratios.

**15. SUBJECT TERMS**

distributed beamforming, passive radar, matched filter, Electromagnetic Spectrum Sciences

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## 1. Introduction

Distributed, coherent beamforming uses physically separated nodes to act as a phased array antenna.[1] This requires phase, time, and frequency synchronization to better than $10\%$ of the carrier period and position accuracy better than $10\%$ of the carrier wavelength.[2] Distributed, coherent beamforming may be done on transmission, reception, or both. When transmitting, the beamforming weights of the distributed nodes are set such that the signals from each node arrive simultaneously in a desired direction. On reception, the received signals from the nodes may be added together with appropriate beamforming weights to coherently combine signals from a desired direction. Transmit beamforming can use only one set of beamforming weights per transmission. Receive beamforming can be done with any number of sets of beamforming weights for a single reception if sufficient signal processing resources are available.

We emulated a passive radar with a distributed, coherent beamforming receiver through a coaxial-cable testbed. Our goal was to study signal processing of the received signals. We tested how accurately the time difference of arrival between the nodes could be measured. Section 2 describes the transmitted signals in the time and frequency domain and discusses the matched filtering that was used. Section 3 describes the experimental configuration and our results, and Section 4 gives concluding remarks.

## 2. Methods

### 2.1 Transmitted Signals

We used single-frequency (continuous-wave) pulses in our experiments. The pulses have a roughly rectangular envelope multiplied by a carrier sinusoid. The single-frequency pulse has the form

$$x_{\mathrm{CW}}(t) = \Pi\left(\frac{t}{T}\right)\cos\left(2\pi f_c t + \phi\right), \tag{1}$$

where $\Pi(t)$ is a rectangular function with amplitude 1 and width 1 centered at the origin, $f_c$ is the carrier frequency, and $\phi$ is a phase offset. In our experiments, we used $f_c = 2.4$ GHz and $T = 16$ ns, and we did not control $\phi$.

## 2.2 Equipment Configuration

We emulated a passive radar scenario in the laboratory with a coaxial-cable testbed. Figure 1 is a block diagram of the laboratory setup. The scenario had one transmitter, one target, and two receivers. To each receiver, there were two signal paths with different lengths. A shorter cable represented the direct path from transmitter to receiver, and a delay line represented the reflected path from transmitter to radar target to receiver. We used a coaxial-cable delay line on the reflected path to set the time difference of arrival between the direct and reflected paths. We used variable attenuators to control the power levels of both paths. The transmitted waveform was sent through a splitter where one of the outputs was delayed and sent through an attenuator, after which it was combined with the attenuated direct signal coming from the other output of the splitter. The combined signal was split and sent to the receivers for collection. We measured the loss through the cables and splitters using a network analyzer. This setup assumes a stationary target with no clutter.

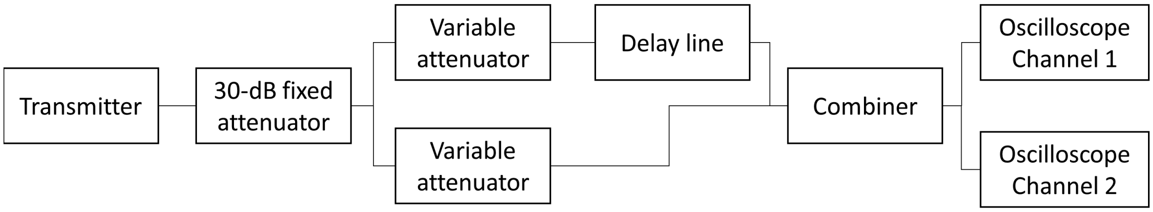

**Fig. 1 Block diagram showing the configuration used in the experiments. The blocks are connected by coaxial cables.**

The delay line added a delay of 187 ns to the reflected path. We set the variable attenuators such that the signal received from the direct path was 34 dB stronger than the signal from the reflected path. We added a low-nose amplifier in front of each oscilloscope channel to increase the signal level to get as much resolution as possible on the delayed-path signals from the oscilloscope's analog-to-digital converters.

## 2.3 Signal Processing

We recorded and saved a copy of the transmitted signal directly from the transmitter and recorded the signals received through the coaxial-cable network. We used the transmitted signal as a matched filter template.[3] The matched filter was implemented using the correlation function from the Numpy library in a Python script.[4]

We truncated the received signals to remove the direct signal path and then ran the truncated signals through the matched filter. The location of the peak amplitude of the output of the matched filter gives an estimate of the arrival time of the pulse from the delayed path.

Two methods were used to estimate the arrival time difference of the delayed pulses between the two oscilloscope channels. In the first method, called the separate correlation method, we estimated the arrival times on each channel separately and compared them. In the second method, the summed correlation method, we emulated a receive beamformer by time shifting one of the received signals and adding it to the signal from the other channel. We did this for a range of time shifts. For each time shift, we put the combined signal through the matched filter and computed the maximum magnitude of the output. For both methods, the arrival time difference would correspond to a direction of arrival in an over-the-air scenario.

## 3. Results

Figure 2 shows the transmitted signal. We excluded the ramp-up portion and most of the ring-down portion of the transmitted signal and used only the portion where the pulse envelope was relatively constant for the correlation calculations. This left a pulse with a duration of about 16 ns.

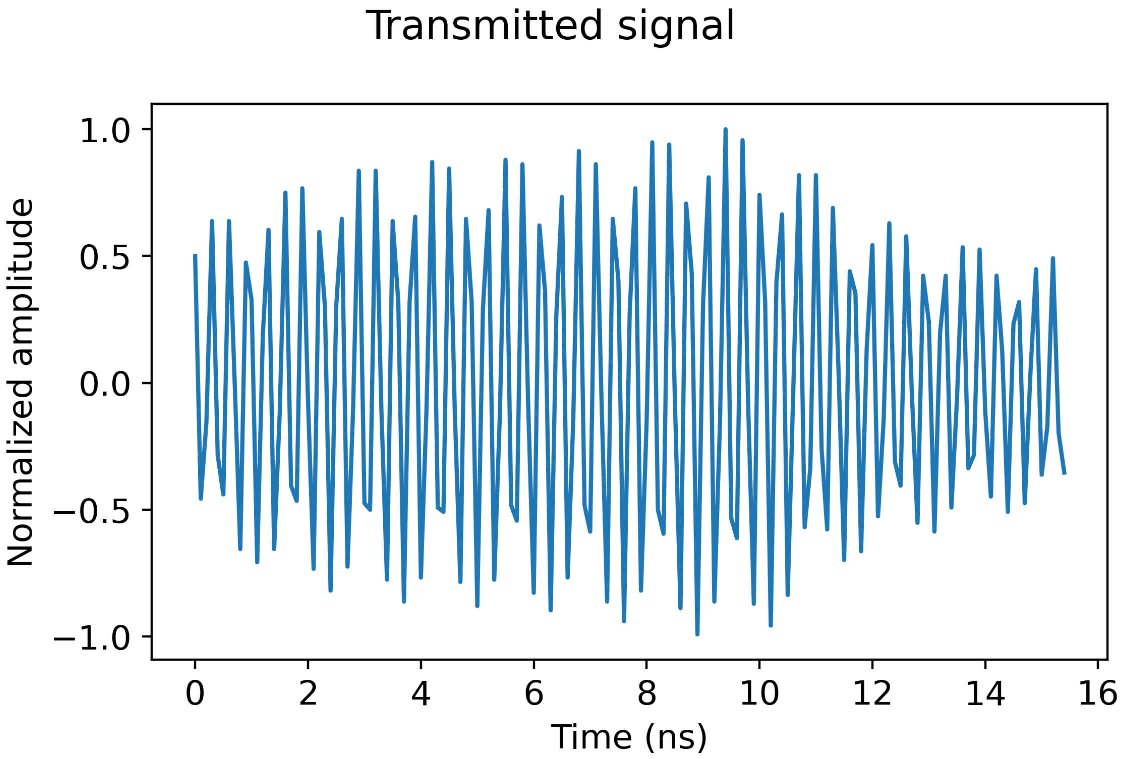

**Fig. 2 Normalized transmitted signal**

Figure 3 shows the received signals from both channels. These signals include the ramp-up and down portions of the pulse, but they are truncated to exclude the direct pulse and to include only the pulse that traveled through the delay line.

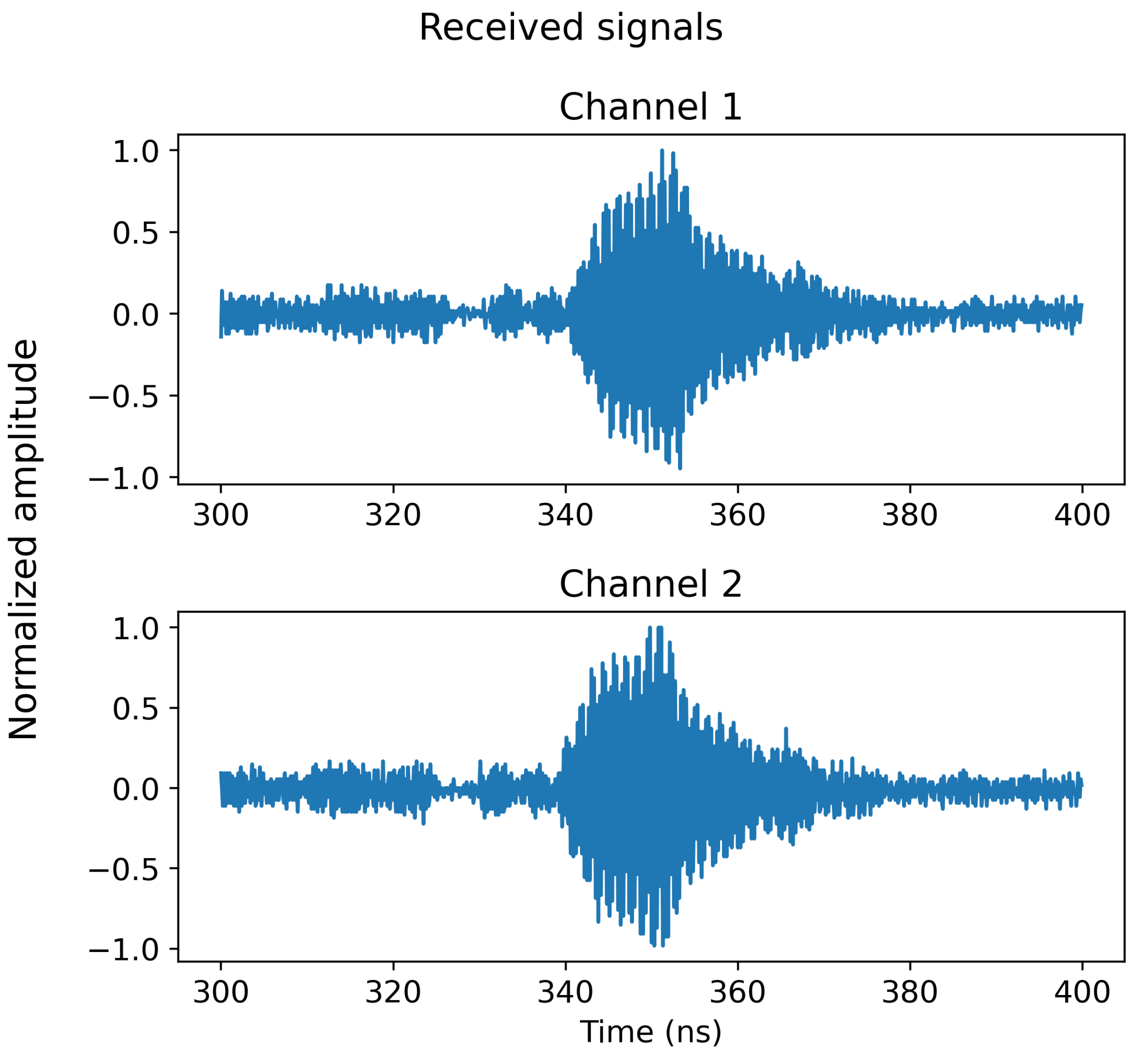

**Fig. 3 Normalized received signals for both oscilloscope channels**

Figure 4 shows the results of postprocessing using the separate-correlation method. The correlations of the transmitted signal with both receive channels are plotted. The correlation with both channels has a similar shape. The peak magnitude of the correlation occurs about 1.7 ns later in Channel 1 than Channel 2 because of the difference in cable lengths.

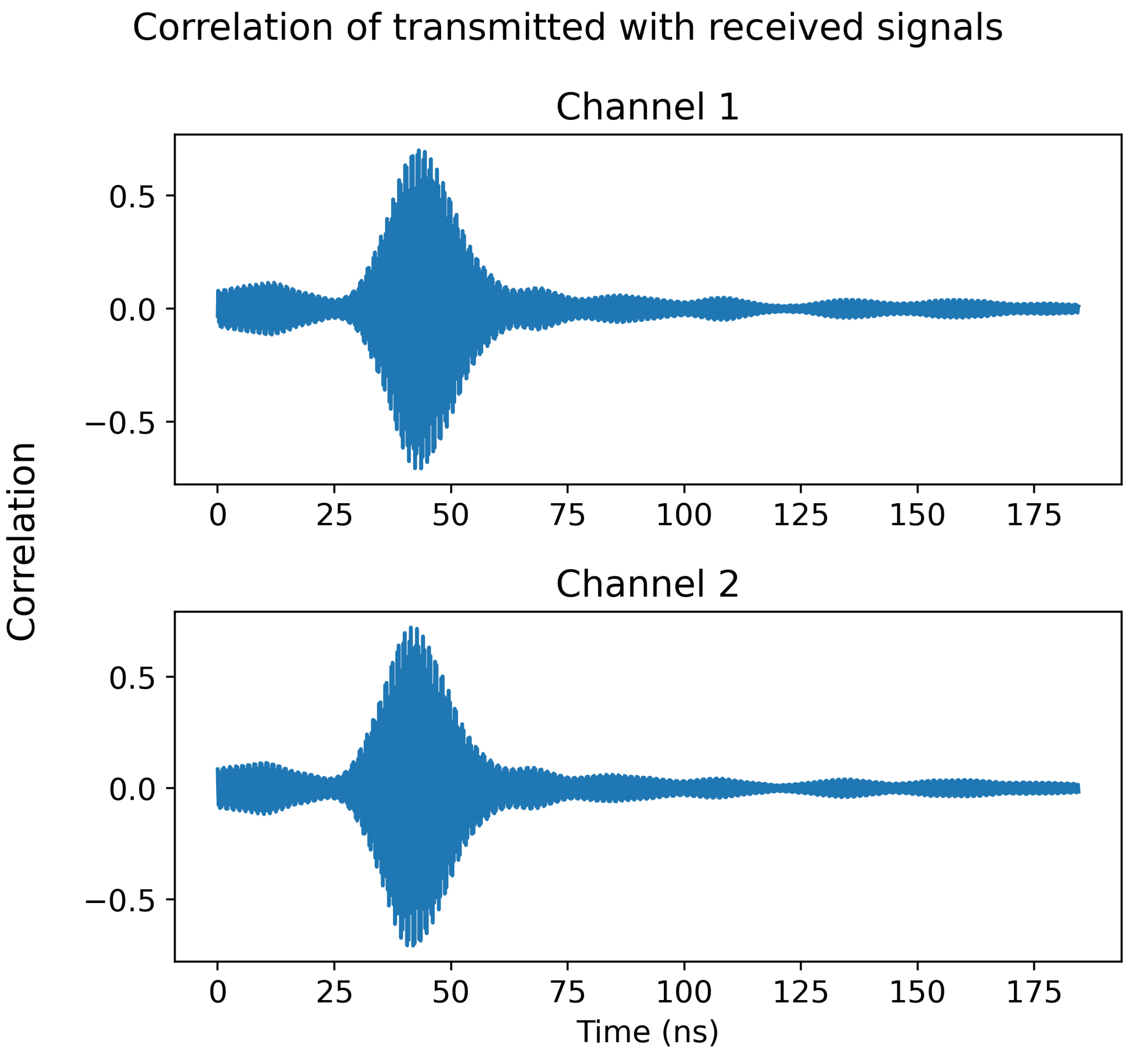

**Fig. 4 Correlation of transmitted signal with received signals for both oscilloscope channels. The time axis is the time shift between the transmitted signal and the received signal and is normalized to start at zero.**

Figure 5 shows the peak magnitude of the correlation of the transmitted signal with the sum of the received signals versus the time shift of Channel 1's received signal. The maximum absolute value of the correlation occurs when the time shift is 1.7 ns, which matches the result found when the two channels were correlated with the transmitted signal individually.

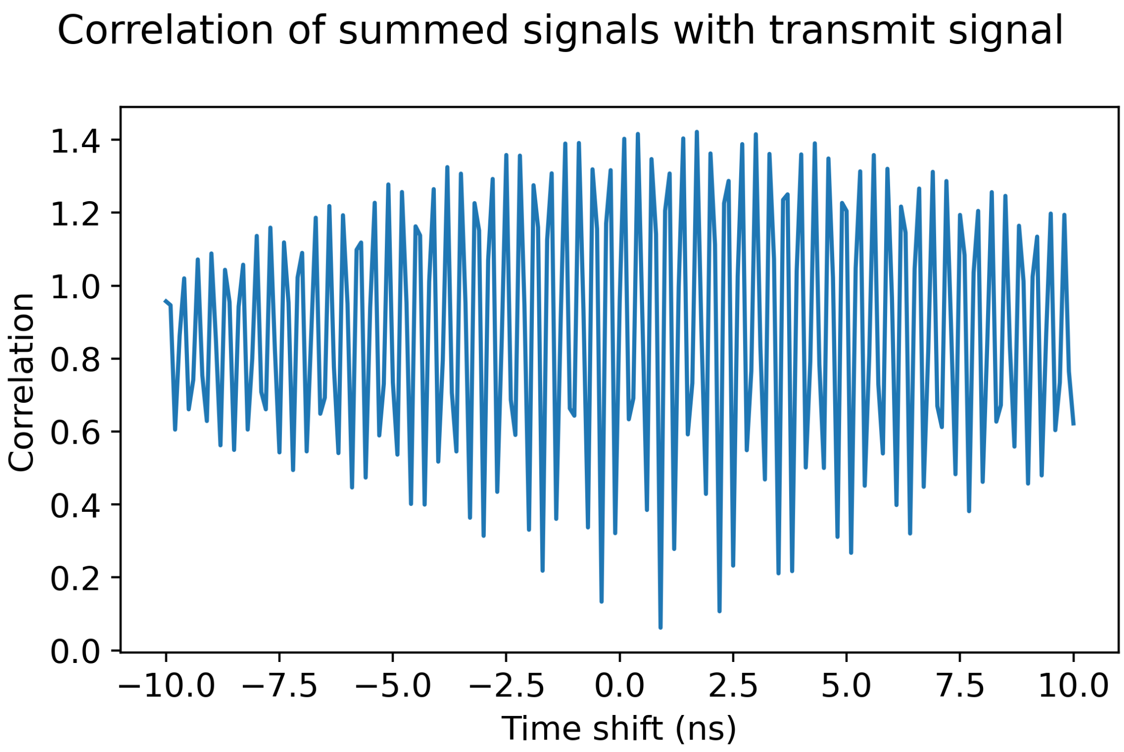

**Fig. 5 Maximum correlation magnitude of transmitted signal with summed received signals vs. time shift between received signals. Channel 2's received signal was fixed, and Channel 1's received signal was shifted relative to Channel 2.**

## 4. Conclusion

The separate correlation method will be easier to implement than the summed correlation method. When the individual received signals are correlated separately, the correlation operation may be done locally at each node, and only the estimated arrival times at each node need to be shared. To implement the summed-correlation method, the received signals would need to be sent to a single location for processing, which would increase the network resource requirements. The computational cost of summing the signals before correlating would also grow rapidly as the number of nodes increases.

The summed correlation method will give a signal-to-noise ratio improvement if the noise at a given receiver is not correlated with the noise at the other receivers. Further work is needed to determine if the benefit is worth the increase in complexity and computational cost.

For both methods, it may be possible to obtain more accurate results if sub-sample interpolation is used, particularly with high signal-to-noise ratios. However, in this work we used only whole-sample time shifts.

The work covered in this report emulated distributed radar receivers operating in ideal channel conditions. A system receiving signals over the air would encounter impairments including multipath propagation, clutter, and external interference. Further work is necessary to evaluate performance in realistic environments. However, the data gathered for this work are helpful for initial development, becuase many potential sources of error were excluded.

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## List of Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| $f_c$ | carrier frequency |
| GHz | gigahertz |
| ns | nanoseconds |
| $T$ | pulse duration |
| $t$ | time |
| $\Pi(t)$ | pulse envelope |
| $\phi$ | carrier phase |

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