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SPOTFORMING WITH AN ARRAY OF ULTRA-WIDEBAND RADIO TRANSMITTERS

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Abstract– Ultra-wideband (UWB) array signal processing has the distinct advantage in that it is possible to illuminate or focus on "*spots*" at distant points in space, as opposed to just illuminating or steering at *certain directions* for narrowband array processing. The term "*spotforming*" is used to emphasize the property that point-focusing techniques with UWB waveforms can be viewed as a *generalization* of the well-known narrowband beamforming techniques. Because methods in spotforming can lead to powerful applications for UWB systems, in this paper we derive, simulate and experimentally verify UWB spot size as a function of frequency, bandwidth and array aperture.

1. INTRODUCTION

The uses of arrays and beamforming techniques have been discussed for UWB waveforms since the early days of research in this field [1-5]. In this paper we discuss the use of a distributed set of transmitters for UWB radio communications [6-8]. A set of distributed radios can be used to communicate to a distant specific point in space. For example, distributed transmitters can be used to communicate with a particular *spot* in a room from the outside of a building. Spot forming would therefore be very useful in covert communication applications where the problem is to talk to a specific "good guy" in the midst of "bad guys." Hence, UWB radios have ultra-low LPI/LPD properties while allowing robust communication links.

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Another application might be a squad communicating with their agent inside a building. Distributed *readers* can also be used in a sentry archway interrogating long-distance RFID tags of valuable assets within vehicles passing through a gate. Such links with multiple antenna elements or radios improves covertness and connectivity.

The design of a distributed radio is based on certain assumptions on the characteristics of ultra-wideband (UWB) pulse, pulse propagation, and noise. We assume propagating pulses are localized in time and space. For a distributed set of UWB pulse transmitters that results in correlated pulses at a particular point in space at the receiver, and assuming independent noise, one can expect improved signal-to-noise, as the number of antenna elements is increased. This property of UWB pulses allows one to design "spots" as opposed to "beams" in narrow band systems. Beamforming techniques impose constraints on the directions of propagation; there is no constraint with respect to a localized spatial point. Our aim in this paper is to obtain an understanding of the spot size for UWB arrays. We attempt to determine the spot size as a function of frequency, bandwidth, and array aperture.

2. TECHNICAL APPROACH

We have derived analytical models, performed simulations and experiments for UWB distributed radios. The results are based on certain assumptions such as free space propagation and use of a linear array with uniform element spacing. All elements of the distributed antenna transmit the same waveform, a Mexican hat pulse, or a raised cosine UWB pulse, as shown below.

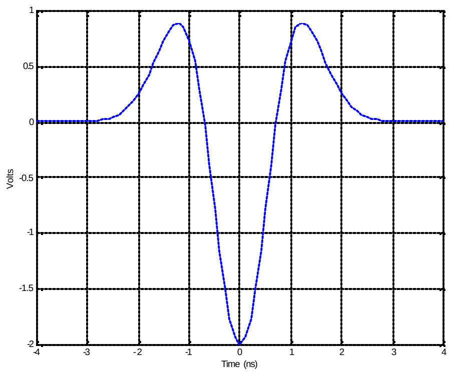

Figure 1-a: An example of a Mexican hat pulse, where the bandwidth adjusted by change of time scale.

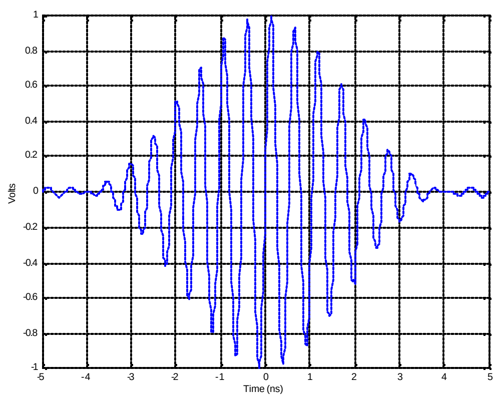

Figure 1-b: An example of a raised-cosine pulse that can also be used for the analysis presented in this paper.

In the experiments performed, the focal point was set in the near field of array but in the far field of individual elements. The array gain was computed at the focus and its surroundings, and the gain of the array was represented by its energy gain with $1/R^2$ path loss factored out. The "spot size" was computed at 3 dB drop from the peak at the focus.

Consider a linear array (see Figure 2 below) of aperture length $2b$. Let the vertical distance from the antenna center to the focal point be represented by v, while vl and vu represent the lower and upper boundaries, respectively, for the 3 dB beam width. With this geometry we can explicitly solve for vu and vl, and implicitly for w, as shown in the following equations:

$$vu = \begin{cases} (b^2 - c1^2)/2c1, & for\ ts1 \geq \Delta \\ \infty, & otherwise \end{cases} \tag{1}$$

$$vl = \begin{cases} (b^2 - c^2)/2c, & for\ ts \geq \Delta \\ 0, & otherwise \end{cases} \tag{2}$$

$$-\sqrt{v^2 + w^2} + \sqrt{v^2 + (b+w)^2} = \Delta + \sqrt{b^2 + v^2} - v \tag{3}$$

where,

$$\Delta = 0.13/BW\ (GHz) \quad [meters]$$
$$c = \Delta - v + \sqrt{v^2 + b^2}$$
$$ts = b + v - \sqrt{v^2 + b^2}$$
$$c1 = c - 2\Delta$$
$$ts1 = \sqrt{v^2 + b^2} - v$$

The above equations apply to Mexican hat type UWB pulses. Similar, equations can also be developed for raised cosine pulses.

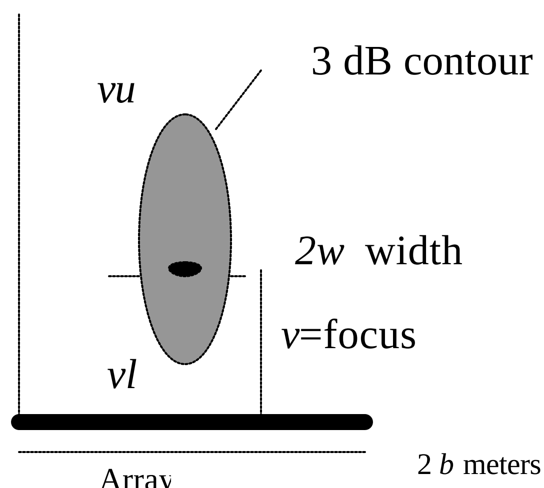

Figure 2. Array focuses on the spot at the dark center spot. The 3 dB beam width is shown by the ellipse. The parameters vl and vu are the lower and upper edges of the 3 dB boundary, and $2w$ is the horizontal width.

By using a pulse of a certain frequency, bandwidth, and space-time shape, the 3 dB spot width is specified by *vl* and *vu* the lower and upper cutoff points, respectively; *2 w* is the spot width. The focusing array is *2b* wide and has been assumed to have uniformly spaced elements.

Figure 3 below summarizes the bore side spot width results as a function of range for a linear array of 11 elements with an aperture of 40 m.

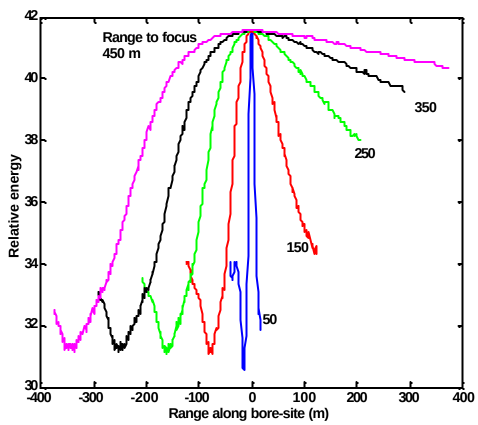

Figure 3: Spot size along range at different ranges, for uniform linear array with a 0.4 GHz Mexican hat pulse at different center frequencies.

To verify these analytical results we also performed laboratory experiments using a set of 5 radios: 4 transmitters and 1 receiver. The received waveforms were aligned at the focal point. With delay lines of 17.5 psec. in resolution, the waveforms were aligned using simple alignment algorithms. After alignment, the energy of the total received waveform was measured and compared to analytical equation discussed earlier. Note that range square factor distorts the gain in spot focusing and increases the gain from shorter ranges. The results shown averaged out the noise over 500 copies of the received signals. The experiments were repeated two times over two days to show repeatability.

In these experiments, an array of four elements was used to focus the 2 GHz wideband signal at points away from the array with an aperture of 30 inches. The total received signal energy was measured at different point along range. The figure compares the simulation with the experiment, showing a close correlation between two.

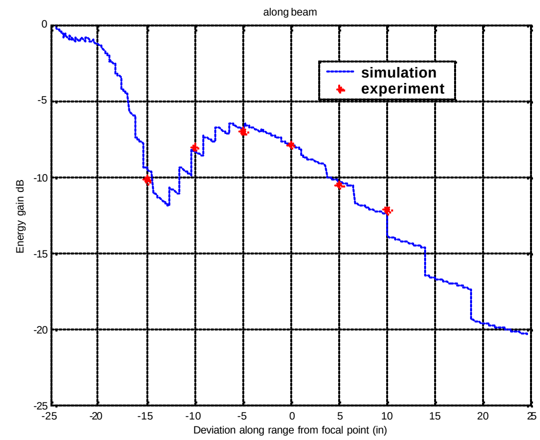

Figure 4: Experimental validation of simulation model of total received energy vs. range.
The antenna four elements, spaced 10 in apart, transmit 2 GHz signal focused 29 in away. Closed form equations were also developed for the spot size.

Fig. 5 compares the derived equations with the simulation results showing a close correlation between the two for the spot lengths.

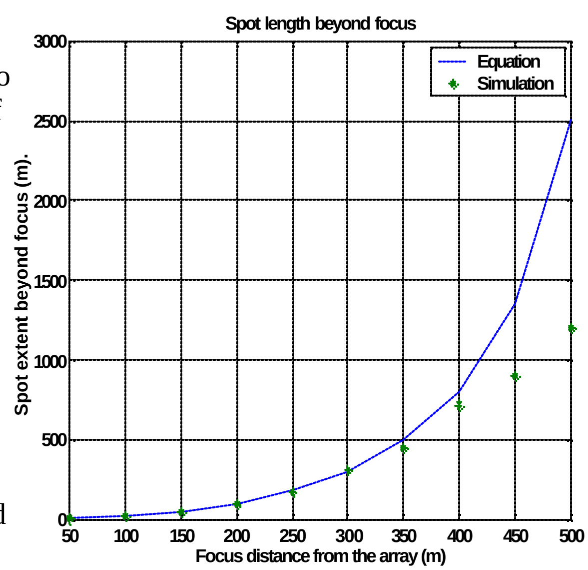

Figure 5: Comparison of simulation with the closed form solution of upper end of the 3dB contour of the focal point in spot forming.

3. CONCLUSIONS AND FUTURE WORK

The main results of this work are that spot forming is possible in the near field of an UWB array antenna. The spot size is a decreasing function of the bandwidth and the aperture, as expected. New architectures for the array will be needed to reduce the spot size even further. Some of the main challenges in the design of the distributed radio are the timing, pulse shaping, spectral design, and antenna design. We are in the process of designing a set of UWB transmitters timed on a linear array and to spot focus to a distance of about 100 m in range. The objective is to illuminate a spot of dimensions 3 ft x 3 ft. The integration of the signal from the different elements could assume different forms, In the RF domain this can be achieved with signals from different elements properly delayed and amplified before summing. Alternatively, passive reflectors can be used to represent the different element, with signal from them converging on feed horn. Yet a third alternative is to convert the signal to base band, and integrate the resulting signal.

Another area of investigation would be to design a 2-D distributed set of transmitters (for example, a circular array surrounding a building). The challenge here would to synchronize and time the transmitting radio. Use transmitter location information, and using coding techniques the synchronization [9, 10] and timing problems can be solved.

Our analysis dealt with uniform spaced arrays. One advantage of spot forming is that the array can be increased in total aperture using non-uniform spacing of elements, to reduce the spot size. This subject is outside the scope of this paper and will be presented in a future paper. A dual problem to be investigated is the link noise characterization. The spatial and temporal correlation of the noise comes into play in this problem.

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