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SMART ANTENNAS FOR SPATIAL RAKE UWB SYSTEMS

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ABSTRACT

This paper introduces the concept of an electrically small two element antenna array that can provide unambiguous angle of arrival information for broadband or ultra-wideband (UWB) signals. Applications include interference mitigation, location awareness, and in a "spatial rake" receiver system.

1. INTRODUCTION

One dilemma facing designers of broadband and ultra-wideband (UWB) systems is the trade-off between antenna size and gain. Higher antenna gain means a more robust link that can send more data further and faster. But a high gain antenna is large and bulky. Furthermore, the field of view of a high gain antenna is relatively narrow, making a single high gain antenna inappropriate for use in an ad-hoc network. Multiple high gain antennas might provide a sufficient field of view coverage, but the size of the overall array is likely to be prohibitively large.

The present paper introduces a potential solution to this problem: an electrically small, "smart" UWB antenna system combining small size with direction finding (DF) or angle of arrival (AoA) capability [1]. This paper will begin by reviewing a standard direction finding technique known as amplitude comparison DF. Then this paper will introduce a novel variation of this technique well suited for broadband and UWB use. Finally, this paper will describe how broadband amplitude comparison can be used in a variety of applications. These applications include interference mitigation, localized positioning capability, and spatial rake signal processing. The aim of this paper is to demonstrate that antenna directionality can be obtained in an electrically small form factor and provide a host of benefits for designers of broadband and UWB systems.

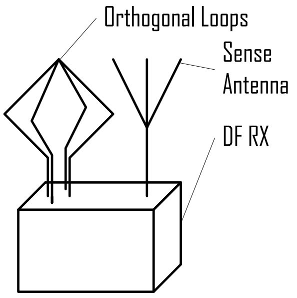
2. AMPLITUDE COMPARISON DF

Amplitude comparison is a technique for radio direction finding (DF). It involves a pair of vertically oriented loops with orthogonal axes, and a vertical whip or "sense" antenna. Excellent discussions are available in the literature [2-4]. Figure 1a depicts a typical DF receiver (RX).

Each of the two vertical loops has the typical dipole "doughnut" antenna pattern with nulls lying in the horizontal or azimuthal plane. Figure 1b shows these antenna patterns. Mathematically, the pattern function $P(\theta,\phi)$ is given by:

$$P(\theta,\phi)=\begin{cases}\sin^2\phi & Loop\#1\\ \cos^2\phi & Loop\#2\end{cases} \tag{1}$$

A vertical loop will be maximally sensitive to signals in the plane of the loop, and minimally sensitive to signals incident along the axis of the loop. A sense antenna has a uniform omni-directional pattern.



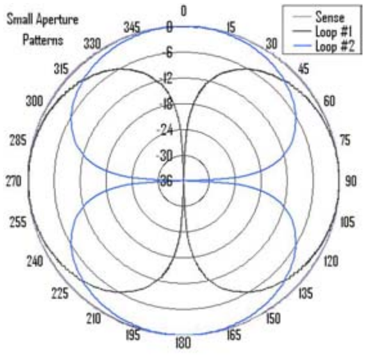


Figure 1a (left): *Prior art direction finding receiver with orthogonal loops and sense antenna.*
Figure 1b (right): *Loop patterns and sense antenna pattern in horizontal plane. Radial scale is in dB.*

The two loop antenna signals may be summed to create a virtual loop antenna oriented in any direction in the plane. A goniometer or other variable summing amplifier may be used. Figure 2 shows the effective virtual loop pattern. The virtual loop pattern may be oriented to either maximize or minimize the received signal. Alternatively, the angle of arrival (ϕ) of an incident signal may be found from the amplitude of the first loop signal (A_1) and the amplitude of the second loop signal (A_2):

$$\phi = \tan^{-1}\frac{A_1}{A_2}. \qquad (2)$$

This virtual pattern has two nulls and two maxima in the horizontal plane. Thus, it is subject to a "front-back" ambiguity: there is no way to unambiguously identify whether a signal arrives from the front or the back. Similarly, the solution obtained from Equation 2 is also subject to an ambiguity. Because the amplitudes are by definition positive, Equation 2 will only yield solutions in a 180° range.

The sense antenna resolves this ambiguity. The two lobes of the virtual loop pattern exhibit a 180° phase difference. A "cardioid" or heart-shaped pattern follows from summing the virtual loop response with the response of the sense antenna. Because the addition is constructive for one lobe and destructive for the other, the resulting combined sense and loop pattern has a single sharp null. This null may be aligned with an incoming signal in order to unambiguously identify the signal's angle of arrival. Figure 2 also shows the cardiod pattern formed by summing the omni-directional sense antenna pattern with the virtual loop pattern. Alternatively, the sense antenna yields a phase reference that provides a sign for the amplitudes in Equation 2 and makes Equation 2 applicable for a full 360° range.

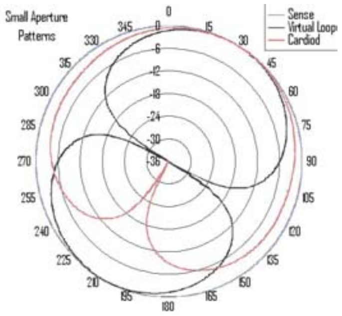


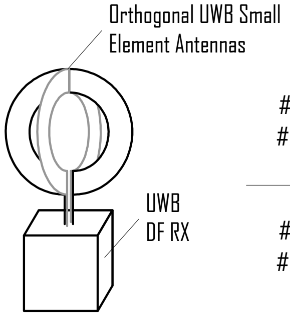
Figure2: *Virtual loop, sense, and cardiod patterns. Radial scale in dB.*

3. BROADBAND TWO ELEMENT DF

Using two orthogonal broadband or UWB planar loop antennas, the angle of arrival of an incoming signal may be obtained by the amplitude comparison method already described. Figure 3a presents such a receiver. As noted above, the traditional narrow band amplitude comparison DF method suffers from a front-back ambiguity and cannot resolve whether a signal was incident in the forward or reverse direction. Unlike the narrow band case, a broadband or UWB DF receiver does not require a sense antenna to resolve the ambiguity.

In a broadband or UWB system, waveform polarity may be used to resolve the front-back ambiguity. The 180° phase difference in a narrow band DF receiver manifests itself as a waveform inversion in the broadband limit. Thus, on opposite sides of the loop, the antenna will receive an inverted signal. By detecting whether signals from particular antennas are upright or inverted, the quadrant from which the signal arrived may be unambiguously identified.

Start with the "first" quadrant (x, y positive). Suppose received signals from both antennas are upright. In the "second" quadrant (x negative, y positive), the signal from the first antenna is now inverted while the signal from the second antenna is still upright. In the "third" quadrant (x, y both negative), both signals are inverted. In the "fourth" quadrant (x positive, y negative), the signal from the first antenna is upright while the signal from the second antenna is inverted. See Figure 3b.



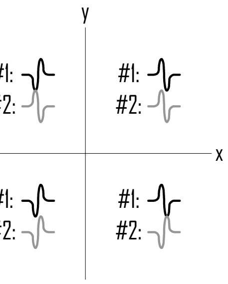


Figure 3a (left): *A UWB small aperture direction finding receiver.*

Figure 3b (right): *Example pattern of waveform inversions used to identify quadrant of arrival.*

A particular asymmetric coding sequence may be used to identify an absolute reference point for a binary phase shift keyed (or BPSK) modulated sequence. For instance, suppose an upright waveform is denoted by a "1" and an inverted waveform is denoted by a "0". Then a training sequence such as 11011 might be sent as a header of a packet. If 00100 is received instead, the receiver knows that the packet is inverted. Thus, a receiver can identify exactly and unambiguously which signals are upright and which are inverted.

This broadband or UWB direction finding technique offers a variety of significant advantages. First, by relying on waveform inversion, a sense antenna can be avoided in many circumstances of interest. Thus, direction finding is possible with only a two channel receiver instead of a three channel receiver. Even if a third "sense" channel is required in some cases, the inversion detection technique described in this paper yields a more robust form of angle of arrival measurement. Second, the technique of this paper can use electrically small elements with dipole like patterns. Thus, a direction finding array may be made exceptionally small, limited only by the signal to noise ratio obtainable from small antenna elements. Finally, signals from two small elements may be summed to create a virtual pattern that may be aligned to either enhance or null out particular signals. The following section looks at these and additional applications in greater detail.

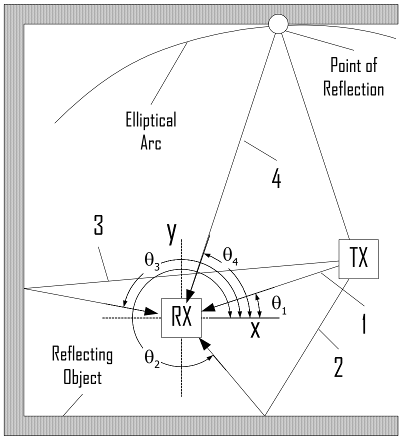
4. APPLICATIONS

The broadband or UWB direction finding technique introduced in this paper has utility in a wide variety of applications. One key application is use in a "spatial rake receiver." Other applications include radar probing of an environment, positioning or tracking systems, and interference mitigation.

4.1. SPATIAL RAKE RECEIVER

A rake receiver (or more specifically, a "temporal rake receiver") collects and coherently adds energy arriving at different times so as to optimize a received signal. The direction finding technique described in the present paper may be used to identify and characterize a variety of multi-path components incident on a receiver. This enables a "spatial rake receiver:" one that collects, rejects, and otherwise combines multi-path components so as to optimize a received signal.

For example, consider the propagation environment shown in Figure 4a below. A transmitter (TX) communicates with a receiver (RX) via four paths: a direct path (#1) and three indirect paths (#2-4) that bounce off a reflecting object. The received signals are shown in Figure 4b. These signals are composed of four wavelets, one for each path. These wavelets may be inverted by a combination of the propagation environment and the antenna responses. An omni-directional or sense antenna receives Signal #0. A loop in the x-plane receives Signal #1 and a loop in the y-plane receives Signal #2.



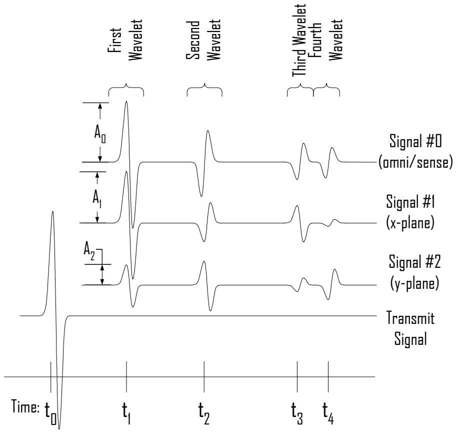


Figure 4a (left): *A propagation environment with four signal propagation paths.*

Figure 4b (right): *Time domain signals as transmitted and as received by a sense antenna (Signal #0), and two orthogonal small element antennas (Signals #1 and #2).*

Signal #0 exhibits the inversions due to the propagation path, allowing them to be distinguished from the inversions due to the function of the angle of arrival antenna system. Combining amplitude comparison (to determine the angle) and inversion analysis (to resolve the front-back ambiguity) the angle of arrival of each multi-path component may be determined. Then, these individual wavelets arriving from different directions may be summed to yield an optimized signal. This process may be called a "spatial rake."

4.2. LOCATION AWARENESS

Another application is in a UWB positioning or locating system. The methods of this paper allow a transponder type UWB positioning system to determine both range and bearing using a significantly smaller aperture than a traditional time difference of arrival (TDOA) AoA system would require. Whereas a traditional TDOA AoA system might require two antennas to be separated by feet, the present invention allows an aperture no larger than a single antenna to make an AoA measurement.

Knowing the time of flight of a direct signal allows calculation of the range between a transmitter and a receiver. If a receiver also measures an angle of arrival, then both range and bearing follow. Unlike traditional UWB location systems that rely on multi-lateration from a collection of ranges, the system envisioned in this paper enables a localized location awareness that allows an individual receiver to locate a transmitter without requiring a complicated network of receivers to collect, share, and analyze range data. Alternatively, adding bearing information into a multi-lateration calculation makes such a calculation more robust and accurate.

Further, knowing the time of arrival of a single bounce multi-path signal establishes the location of a reflector on an ellipse whose foci are located at the transmitter and the receiver. If the receiver can determine the angle of arrival, then the exact point of reflection is known. This enables a bi-static radar probe of the environment surrounding the transmitter and receiver so that one may compile a radar map of the surroundings or identify intruders or other changes in the environment.

4.3. INTERFERENCE MITIGATION

The concepts of this paper may also be applied toward the problem of interference rejection. The signals of the two orthogonal antennas may be combined so as to null out an undesired interfering signal: in effect rotating a virtual antenna so as to align a null of a virtual antenna with the direction from which an undesired signal is incident. In addition, the two orthogonal elements could be used to null out a transmitted signal in a particular direction.

5. CONCLUSIONS

In short, directionality in a UWB or broadband system does not necessarily require electrically large antennas or arrays. The present paper describes how a small two element array can use waveform inversion to obtain unambiguous angle of arrival information for broadband or UWB signals. Even in a multi-path environment, waveform inversion and a sense antenna signal can yield valuable information about the angle of arrival. This multi-path information enables a "spatial rake receiver," one that coherently adds signals arriving from different directions. In addition, angle of arrival information is useful for location awareness in positioning as well as radar systems. Also, the directivity of a two element array is useful for interference mitigation in both reception and transmission.

6. DEDICATION

This paper is dedicated to the memory of the author's feline friend, Poynting, who died January 2, 2004.

7. REFERENCES

[1] H. Schantz, "Improved System and Method for Ascertaining Angle of Arrival of an Electromagnetic Signal," U.S. Patent Pending.

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