Networking Improvements using Electronically Steerable Directional Antennas

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Abstract - Radio Frequency links can benefit greatly by using an electronically steerable directional antenna approach versus tradition antennas such as omni-directional or standard directional antennas. The trade-offs involving cost, complexity, and communication advantages need to be fully explored. Current low cost, high volume manufacturing techniques make it possible to design small antenna elements to make up compact antenna arrays. In this paper, we will discuss the results of laboratory and field tests of custom-built electronically steerable directional antennas.

Keywords: phased array, steerable antenna, directional networking

1 Introduction

Current technology limits Radio Frequency (RF) links to low-gain omni-directional antennas or higher-gain standard directional antennas that only operate when the radios are within a limited beamwidth of each other. Standard directional antennas only radiate in a small area but have higher gain, so they have little usefulness in an environment where radios are mobile because they can quickly leave the radiating pattern of the standard directional antenna. The goal of this paper is to show the enhanced capability gained by using electronically steerable directional antennas over traditional antennas that are commonly used in communication systems. Electronically steerable directional antennas’ benefits include reduced interference, higher gain, increased transmission range, and more stable links due to increased signal strength. Increased spatial reuse and longer transmission ranges translate into an increased network capacity with more simultaneous transmissions and fewer hops. Because of phase shifting and electronic nulling, these antennas also improve communications in congested or contested environment.

2 Related work

A low-power, small-size smart antenna, called an electronically steerable parasitic array radiator (ESPAR), has been designed in [1]. They achieve beamforming by tuning the load reactances at parasitic elements surrounding the active central element, and they propose a fast beamforming algorithm based on simultaneous perturbation stochastic approximations with a maximum cross-correlation coefficient criterion. An ESPAR is presented in [2] that guarantees that the antenna pattern is properly controlled by adjusting the bias voltages and the value of the loaded reactances. And, they show how to optimize the values of bias voltage vectors, which give the desired omni or sector patterns. The ESPAR system draws low power and is appropriate for battery-powered devices that have low-range requirements (i.e. laptops), but its usefulness for long-range communications is limited. A dual-frequency circularly polarized electronically steerable microstrip patch antenna array suitable for land-mobile communications is presented in [3], where full azimithal coverage is possible by electronically switching between the four elements. The microstrip patch antenna is low cost and easily manufactured but has a narrow frequency band which limits the type of communication devices that can use it. PHASER, a prototype for low-power directional communications in wireless sensor networks, is presented in [4] that includes three components: a low-power radio, an RF signal processing chip, and two off-the-shelf antennas. They achieve the directionality and obtain the desired patterns for constructive and destructive interference by splitting the output signal from the low-power radio chip and controlling the phase of each signal as it is transmitted to each antenna. In our research, we will be shifting the phase of the antenna signal to achieve the necessary beamforming and gain. We have taken low cost, easily produced antennas and combined them with a low-cost phase shifter to show the communication gains in an outdoor environment.

3 Antenna design

There is a trade-off between the range and the tracking/acquisition speed when deciding on the antenna design. A standard directional antenna such as a Yagi antenna offers a narrow beamwidth and high gain. In order to offer 360 degrees of coverage, a Yagi antenna has to be mechanically steered because of the small beamwidth. A mechanically steered antenna will require a motor-driven gimbal to steer the antenna in the direction needed with the required accuracy, all in a timely fashion. An electronically steered antenna array will be able to point to a position almost instantaneously, without the need for a complex motor-driven mounting structure.
3.1 RF Sector antenna design

The first design tested for this paper uses three antenna arrays that feed a multi-channel networking radio. The antenna arrays are mounted in a radome consisting of a plywood and Lexan enclosure to protect them from the weather. The Lexan sheet was formed into a bubble (one for each antenna array). The antenna array was secured in the plywood box and covered with the bubbles, as seen in Figure 1. The completed antenna assembly was raised and mounted on a platform seven feet above the ground.

![Figure 1. Array Antenna in Radome](image)

Each individual antenna element has a pattern similar to Figure 2. This pattern was one of a series of patterns taken in an anechoic chamber at various frequencies. This pattern shows that this antenna will have a gain of 6.7 dBi towards the front of the antenna (which is over 18 dB greater than in the opposite direction). This is what gives the antenna its directionality.

![Figure 2. Pattern of RF Sector Antenna Array Element](image)

This panel is one of seven panels that make up one antenna array. Each antenna array consists of seven directional antennas elements set in an arrangement to cover six horizontal sectors and one vertical sector to cover above. The electronically steerable antennas arrays used antennas elements designed for use in the 698 - 960 MHz range and 1710 – 2700 MHz (with an average gain of 7.5 dBi). The individual beamwidth will allow the antenna array to provide 360 degree coverage with six sectors. The RF signals from the seven antenna elements feed into the RF-switch in Figure 3, which will pass the signal-of-interest back to the radio on one channel and block RF signals from the other antennas. The RF switch is controlled by our custom-developed software.

![Figure 3. RF Switch](image)

3.2 Phase-shifting antenna design

Our second design includes a phase-shifting steerable antenna array with 16 custom-built antenna elements installed end-to-end in a cylindrical pattern in order to provide 360 degrees of coverage at any given time without physical movement. A phase-shifting steerable antenna is a multiple-antenna system in which the radiation pattern can be reinforced in a particular direction and suppressed in undesired directions by changing the phase of the waveform.

![Figure 4. Phase-shifting Steerable Antenna Element](image)

Each of the sixteen elements in the phased-shifting steerable antenna are custom-built, tested, and calibrated. One element is shown in Figure 4. A custom-built circuit will control the phase shift of the antennas. An element of the circuit and antenna was built and tested in an anechoic chamber at various frequencies and various voltages.
4 Control software

Software was written in C++ for a Linux platform and runs on a Raspberry Pi 3B+ to control both electronically steerable antennas designs. The Raspberry Pi 3B+ is connected to the RF-switch via General Purpose Input Output (GPIO) pins in order to select which element of the electronically steerable antenna is transmitting or how to shift the phase. The Raspberry Pi 3B+ is also connected to the radio via a 100 Mbps Ethernet, so it can analyze radio data to help determine which element or phase shift of the antenna array to make active. When deciding which element or phase shift of the antenna array should be active the software first looks to see where the radio-of-interest is located. It will enter into a search pattern to look for signals-of-interest. Once a signal is present on an element, the software will check the signal strength from each of the other elements and select the element with the highest signal or adjust the phase. This will ensure we are getting the highest quality signal and not just any signal. The process happens very rapidly with the antenna switching as quickly as 227 nanoseconds. The ability to scan quickly allows the antenna to have the added feature of tracking. If the signal-of-interest moves, the antenna will detect a stronger signal on a different element and will switch which element is active or change phase. The antenna elements are configured in a particular pattern that gives 360 degrees of coverage.

5 Results

5.1 RF Sector antenna design

In the RF sector antenna design, we tested for link quality improvement. The outdoor environment selected to demonstrate this work was the Air Force Research Laboratory test site at Stockbridge, NY. The Stockbridge Test Site is situated on 300 acres in a RF quiet environment that is conducive to testing a variety of RF and optical communications technologies [5]. The topology shown in Figure 6 is comprised of one node equipped with the RF sector directional antenna (node 1) and five nodes each equipped with an omni-directional antenna (nodes 2-6) each elevated ten feet off the ground. The frequency chosen was 924 MHz with a maximum data rate of 1.2 Mbps. User Datagram Protocol (UDP) traffic was passed from node 1 to node 2, then from node 1 to node 3 and so on until each node was tested. The throughput was set at 450 Kbps, multiple tests measurements were gathered, and the results were averaged. The maximum distance between radios was approximately 300 meters. By using the electronically steerable directional antenna, the throughput on average increased by 25.7% over the omni-directional antenna.

In another series of tests, node 6 was set up as a data source and node 1 was the data destination. Attenuation was introduced into the RF path until the link using the omni-directional antennas was broken (i.e., the signal strength was too low to transfer data). For our application an error rate of 60% or higher was deemed unusable. The test was then re-run using the electronically steerable directional antenna at node 1. The average link quality improvement was 3 dB. The chart in Figure 5 shows that the error rate when using the omni-directional antenna stopped transferring useful data when 16 dB attenuation was introduced to the RF transmit chain. When using the electronically steerable directional antenna and running the same set of tests, it is shown that the useful data continued until 19 dB attenuation was introduced to the RF chain.

Figure 5. Error Rate of Omni-directional antenna vs. Directional antenna

To overcome this 3dB difference, the radio with an omni-directional antenna would need to transmit using twice as much power to achieve the same signal strength at the receiver. Less transmit power will allow an energy savings and reduce interference to other users.

5.2 Phase-shifting antenna design

For the phase-shifting antenna design, our goal was to achieve at least 180 degrees of phase shifting. Our design provides a phase shift capable of over 250 degrees depending on which voltage is supplied. The data was gathered by testing two phase-shifting antenna elements in an anechoic chamber. Figure 6 shows tests run at 2300 MHz, with input
voltages of 0 through 15 volts direct current and a phase shift of up to 250 degrees occurring at 15 volts. The phase shift is in reference to a second phase-shifting antenna element with a non-zero phase. In this case, the reference antenna element is -160 degrees out-of-phase. The voltage is stepped through in 1 volt increments with the results plotted in Figure 7. Each color represents one voltage level and the comparative phase shift of the signal, with respect to the phase of the reference signal.

![Figure 7. Phase Shift due to input voltage](image)

Figure 7. Phase Shift due to input voltage

Figure 8 shows the antenna pattern of one phase-shifting antenna element. This antenna element shows the gain of 1 dB in the forward-looking direction. The beam looking to either side of this antenna element will show a drop of -20 dB, which allows beamforming and nulling when configured in an array.

![Figure 8. Patch Antenna Beam Pattern](image)

Figure 8. Patch Antenna Beam Pattern

By matching the phase of each individual antenna element, the gain of the antenna array will be increased in one direction, by allowing the individual antenna beams to constructively combine. When the phase of the antenna element beams are out-of-phase with each other, the beams will destructively combine, leading to less gain. Less gain will allow the antenna array to null out a section of the coverage area to avoid undesired interference.

6 Conclusion

It has been shown that by using electronically steerable directional antennas the amount of data that can be handled by RF links can be increased with less self-interference. Trade-offs can be made, depending on the communication needs as to what kind of antenna system is used. In typical omni-directional communications, energy intended for a particular destination ends up causing unnecessary interference to other radios, which require the other radios to increase their transmit power to overcome the interference. By incorporating directional communications and having radios concentrate transmitted energy only in the intended directions, there are benefits like higher gain, longer transmission ranges, lower latency, improved link connectivity, and reduced interference from undesired directions. The signal to interference and noise ratio (SINR) can be increased by enabling the receiver to selectively receive signals only from a certain desired direction, thereby avoiding interference from undesired directions. Electronically steerable directional antennas are especially advantageous for military networks because of the added security feature of nulling out undesired interference and being selective of what direction to transmit concentrated energy.

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7 References