International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)
Volume 3, Issue 2, February 2014

Collaborating Wireless Sensor Networks of Randomly placed Nodes for Effective Communication and Data Transfer

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***Abstract*— In this thesis, methods for forming a communications link between Wireless Sensor Networks (WSNs) by enabling each WSN to act as a smart antenna are presented. Each WSN is simulated as a set of randomly placed sensor nodes within a planar area. The proposed method involves a searching WSN, a receiving WSN and a link budget for establishing the link. The searching WSN has the task of transmitting a search beam in order to find adjacent WSNs. Like a lighthouse this is done in a rotating beam style search using the sensor nodes as an aperiodic array. Results show that for a random array, we can achieve a specific beamwidth and gain as a function of the number of elements and area. We also demonstrate that for a given required gain level we can spatially thin the array without significant loss of gain or the effects of grating lobes. The receiving WSN uses a spread spectrum based space division multiple access (SDMA) receiver. This receiver is simulated to determine the direction of arrival from the searching WSN and to extract the location information from the searching WSN's signal in additive white Gaussian noise. From the DOA and the location information within the arriving signal, the WSN has sufficient knowledge to respond to the query of the searching WSN and form the communications link.**

***Index Terms*—Antenna array; multiple access; smart antenna; wireless sensor networks; Antenna array.**

I. INTRODUCTION

Recently, attention and interest on the area of wireless sensor networks (WSNs) has rapidly increased due to their wide applications. Typically, the sensor nodes in the WSNs are battery powered for operation. Due to the limited capacity of batteries, the processing and communication capabilities of the sensor nodes are restricted.

A collection of sensors in close proximity to one another may form a Wireless Sensor Network (WSN) by establishing communications with one another through some form of self organization. This group may act collectively to increase sensing or processing power by performing some of the computations onboard the sensor node itself [1].

Many different types of applications for wireless sensor networks exist, in both industry and the military world. Because they are wireless and self-organize, wireless sensor networks have the potential to relay information without a large infrastructure cost or physical impact. Commercial applications of wireless sensor networks include industrial monitoring, building controls, security, traffic management, weather, wildlife tracking, and agricultural field temperature-sensing networks [2]. Still another application consists of sensors that monitor conditions in the London underground tunnels and water systems [3].

In this thesis, we assume the deployed WSNs must communicate their information to the end user without access to a UAV. In the solution proposed here, where the WSNs are deployed to multiple locations nearby to one another, they form a terrestrial Over The Horizon (OTH) network by linking the individual WSNs. In order to form this link, the WSNs must also solve the additional task of locating one another. Each WSN acts collectively to form a smart antenna. A key assumption to this problem is that the distance between WSNs is greater than the individual range of a single sensor node. Thus the sensor nodes in the WSN must act cooperatively in order to have sufficient transmitting gain to reach the next WSN.

This problem combines and draws from several different disciplines in order to propose a solution. Each of these topics will be discussed further in this thesis. In order to form the initial local network, the concepts of localization of the network are required. Once the geometry is known, the sensor nodes of the WSN act collectively to form a distributed smart antenna. A smart antenna generally refers to an array antenna that can adapt its beam pattern using a computer processor [4]. Because the sensor nodes are scattered in a random manner, the concepts of random processes are used to apply them in the smart antenna composition. The concepts of spread spectrum and signal processing come into play in the determination of the direction of arrival for the beams connecting two WSNs.

II. SYSTEM MODEL

A. Sensor Network Model

Consider a set of wireless sensor nodes in Fig.1, dispersed within an arbitrary boundary. The sensor nodes form an ad hoc network by establishing communications with one another. The boundary is defined as the range limit of the communicating sensor nodes within the ad hoc network.

The individual sensor nodes may be randomly positioned within a boundary defining the WSN. The goal of this thesis is to explore methods for forming communication links between adjacent WSNs. By establishing communication links between adjacent WSNs, we can form an extended network made up of what has now become nodes of a larger

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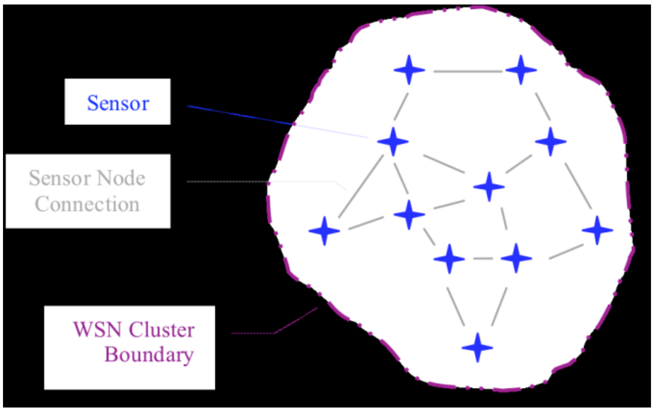

Fig.1.Wireless Sensor Network

Over The Horizon (OTH) network. The general case is shown in Fig.2. Once the OTH network is connected, the individual WSNs become part of a larger network that can relay sensed data to an end user.

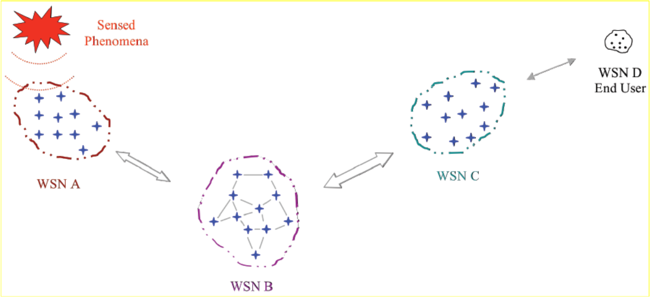

Fig.2. Generalized Over The Horizon Network of WSN
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III. COMMUNICATIONS LINK: LINK BUDGET

A. Link Budget Equation

The link budget allows us to perform a tradeoff analysis when we are given control over components of the link [3].

$$\mathbf{M_{dB} = P_t + G_t + G_r - (E_b/N_o)_{Re} - R_b - kT_s - L_s - L_o} \qquad (1)$$

where M_{dB} is the link margin (dB), P_t is the transmitter power (dBW), G_t is the gain of the transmitting array (dBi), Gr is the receiving array gain (dBi), E_b/N_0 is the energy per bit to noise power spectral density ratio (dBW/Hz), R_b is the bit rate of the communications between WSNs (dB-bit/sec), k is Boltzman's constant ($1.38 * 10^{-23}$ J/K), T_s is the effective system temperature (K°). The path loss, Ls (dB) is the loss of a signal over the distance from point A to point B, and Lo includes "other losses" such as transmitter inefficiencies, line loss, polarization mismatch, etc. [7]. The link margin is the difference between what we need to establish the link and what we have available from the combined components of the communications link. We assume that each transmitter can vary its power output in discrete steps, but that all elements transmit at equal levels. The gain of the transmitting and receiving arrays refer to the gain of the random planar array of judiciously selected elements.

B. Link Budget Gain Calculation

We wish to know what level of gain is required for the transmit and receive antenna arrays forming the communications link. We can solve the link equation to determine, with margin M, what gain the two WSN arrays must produce.

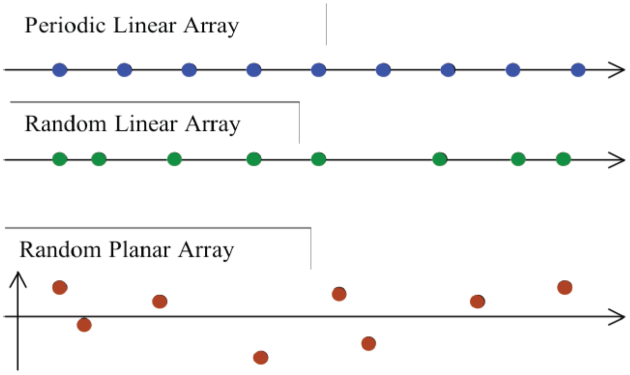
$$M_{dB} = P_t + G_t + G_r - Pr - Ls \qquad (2)$$

where M_{dB} represents the difference between the actual received power and the minimum usable power, given by the receive sensitivity. Also note that the total power transmitted by the array of N_t transmitting elements is N_tP_t.

IV. THE SEARCH FOR OTHER WIRELESS SENSOR NETWORKS

A. Beam Forming with planar arrays of randomly placed Sensor Nodes

A random array is an array antenna whose elements are no longer defined by a fixed geometric spacing but rather the element locations are now random variables. A one-dimensional periodic linear array has a fixed inter-element spacing, while the element spacing in a random linear array is a random variable. The elements are randomly placed along both the x and y-axes in a random planar array, i.e., the interelement spacing is random along both axes.



The array factor for a random linear array is similar to the array factor for a periodic array except that now the element spacing term in the exponential is a random variable. For the purposes of performance comparison, the periodic array is termed the *design array* and its array factor is the *design array factor AF* (θ). The phase contribution from each element in a random linear array is no longer a deterministic term, i.e., nd_x , but rather from the actual x coordinate of the *nth* element, xn, and thus the phase is also a random variable. The array factor for linear random array becomes:

$$AF(\theta) = \sum_{n=0}^{N-1} A_n e^{jkx_n \sin\theta} \qquad (3)$$

Because the element location is now a random variable the array factor is also a random variable. It is customary to represent the array factor of a random array in terms of the ensemble average, referred to as the *average array factor*, given by:

$$\overline{AF(\theta)} = E\left[AF(\theta)\right] \qquad (4)$$

We extend further the random linear array to the random planar array on N elements. Thus, for N total elements, the array factor becomes:

$$AF(\theta,\phi) = \sum_{n=0}^{N-1} A_n e^{jk[(x_n \sin\theta\cos\phi+\beta_x)+(y_n \sin\theta\sin\phi+\beta_y)]} \qquad (5)$$

Substituting

$$\beta_x = -kx_n \sin\theta_o \cos\phi_o \text{ and } \beta_y = -ky_n \sin\theta_o \sin\phi_o \quad (6)$$

gives the array factor for the *N* element random planar array:

$$AF(\theta,\phi) = \sum_{n=0}^{N-1} A_n e^{jk[(x_n \sin\theta\cos\phi - x_n \sin\theta_o \cos\phi_o) + (y_n \sin\theta \sin\phi - y_n \sin\theta_o \sin\phi_o)]} \quad (7)$$

where $(\theta, \varnothing_o)$ determine the beam pointing angles. This equation is used to determine the array factor in all subsequent calculations involving random planar arrays.

B. *Matlab Simulation Results – Random Planar*

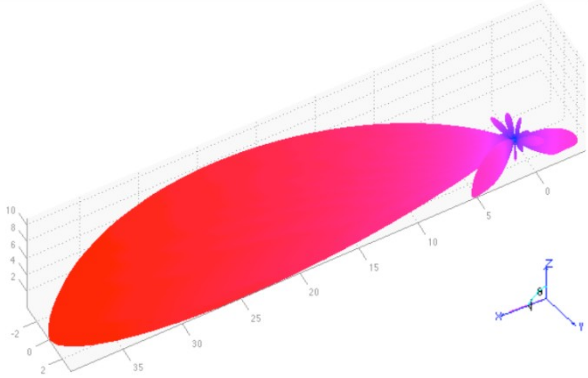


Fig.3 Three Dimensional Gain Pattern of 25 Element 3λ * 3λ Random Planar Array Steered to θ = 90° and φ = 0°.

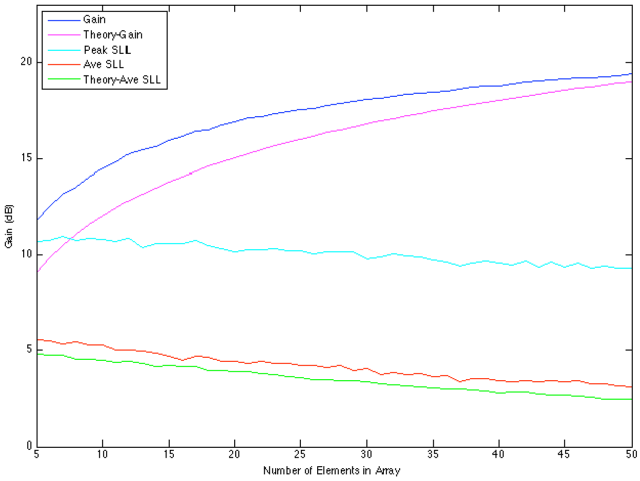


Fig.4 Maximum Gain, Average Side Lobe Level, and Peak Side Lobe Level as a function of the Number of Elements in a Random Planar Array of Size 5λ * 5λ

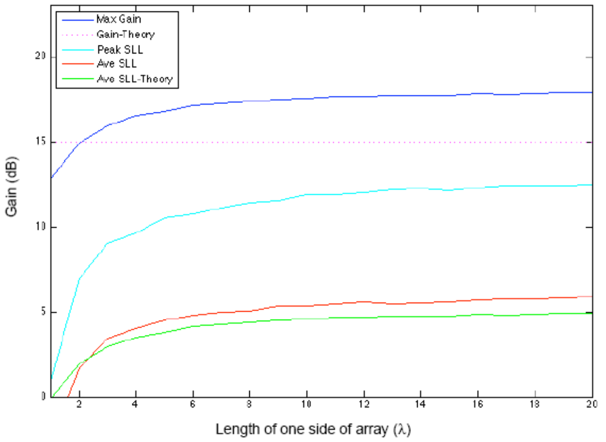


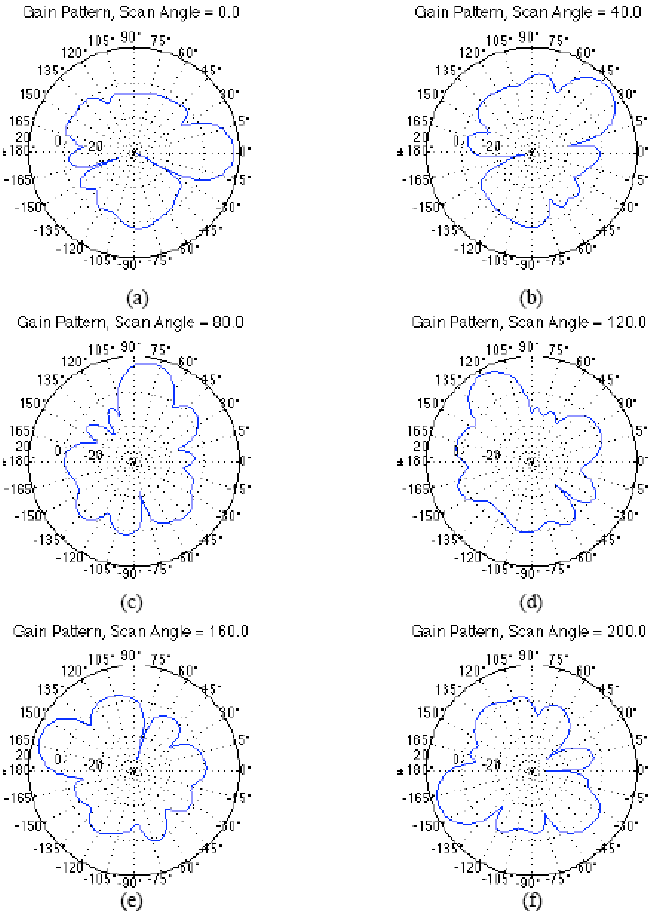
Fig.5 Maximum Gain, Average and Peak Side Lobe Levels as a Function of Random Planar Array Size for Fixed Number of Elements = 20

V. SEARCH METHOD

In order for one WSN to find another, a method must be employed to systematically search the horizon. In this thesis we have chosen to employ a "lighthouse" approach in that we form a narrow beam and transmit in a given direction, then steer the beam across the horizon in search of an adjacent WSN.

A. *Simulation Results of Beam Steering*

We have chosen a half power beamwidth of approximately 20 degrees and set the array size at 2.5λ * 2.5λ composed of random planar array of 40 elements to obtain a gain of 16 dB as a convenient number. To steer the beam, we change the phase of each element in accordance with the last equation .



(a) (b) (c) (d) (e) (f)

Fig.6 H-plane Patterns for a Random Planar Array of 40 Dipoles as Beam is Scanned From 0 to 200° in 40° Steps

B. *Direction of Arrival*

When the receiving WSN detects a signal from the searching WSN, it needs to know the relative geometries of the two WSNS in order to form its array and then send a reply. The location information of the sending WSN is contained within the message signal transmitted, but the direction of arrival (DOA) must be calculated.

Among many methods available, A new method based upon spread spectrum techniques for space division multiple access (SDMA) applications that does not involve iterative matrix solutions, reference beams or specific array geometry has been selected. Because this method does not possess the computational intensity of the above methods, is suitable for random arrays and has the capability for blind DOA determination.

The method involves chipping the phase of the received signals at each array element with individual spreading sequences. In computer memory identically chipped *virtual signals* are generated from a virtual receiver array for *I* expected directions of arrival. The received signals are then summed and a quadrature correlation is performed between the received signal and each of the *I expected* DOA virtual signals. Correlation values (*Ri*) exceeding a threshold are identified as signals received from an expected DOAi. From the phase of the correlation *Ri*, the message signal information may be extracted. Interfering signals are not well correlated and thus minimized [14].

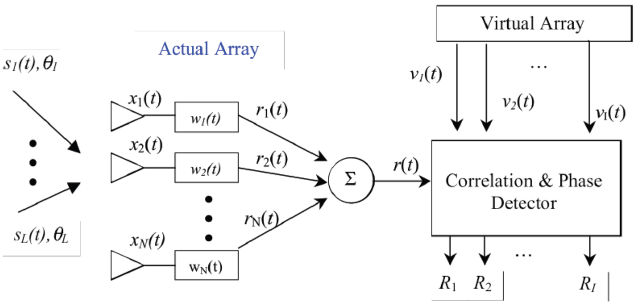


Fig.7 Direction of Arrival determination using SDMA receiver

VI. CONCLUSIONS

A. Summary of Research

In this thesis we explored methods for forming an Over The Horizon (OTH) communications link of Wireless Sensor Networks (WSNs) by enabling each WSN to act as a smart antenna array. Methods for establishing the OTH communications link via beam forming and direct sequence spread spectrum Space Division Multiple Access (SDMA) were presented and modeled using MATLAB. Methods for forming a search beam for a transmitting WSN and determining the direction of arrival of the received beam for a receiving WSN were presented.

B. Significant Results

We investigated the random planar array performance in terms of the half power beam width, the gain of an array of *N* elements and side lobe performance. The objective was to apply these results to wireless sensor networks to first form a search beam to locate adjacent WSNs, then form a narrow high gain beam to form a communications link. The particular WSNs are assumed to be fixed in location, but the inter-element spacing follows a uniform random distribution within a defined boundary. We demonstrated that we could select a wide beam for the search pattern and simultaneously select the gain. To achieve a given beamwidth, we can choose a physical size, likely a sub-section of the WSN under consideration. Within this physical area, we have control over the gain by choosing the number of elements employed in the array. Alternately, for a given required gain level we can thin the array (or reduce density) without significant loss of gain or the effects of grating lobes. It does not matter which particular sensor nodes within the WSN are used as long as, on average, they are randomly distributed within the physical area chosen. This is important if the objective is to distribute the burden of transmitting, and thus energy consumption among the nodes within the WSN.

C. Topics for Further Research

In the process of carrying out this work many issues for further research came to light. In this work, we demonstrated a SDMA method to determine the DOA of a signal in two dimensions assuming vertical polarization. Indeed, the SDMA method shows promise for much greater capabilities. In this thesis, the virtual signals were only used to determine the DOA across the horizon but could be extended to include the hemisphere. In this work, the spreading was applied only to the receiving WSN to determine the DOA and extract the message. Alternately, the searching WSN could spread its transmitted search signal in the manner described in Chapter IV on SDMA for the receiving array leading to further processing gain. For the SDMA receiver, we assumed that only the direct signal reached the receiver. For a terrestrial communications link, there would certainly be a multipath signal fading [11]. Future work may investigate the receiver's capability to reject multipath signals and increase the communication link range or bit rate. In this work, we assumed that the location of each sensor and that the location error could be estimated. Additionally, future work may address methods for combining the signals received at each of these individual sensor node locations.

The path loss model in this work used a wireless LAN model based on antenna heights of 1 m or above. A better path loss model would give a more accurate estimate of the margin required to form the communications link between two adjacent WSNs. Future work may seek to develop path loss models for ground level transmitter-receiver pairs based on empirical data using actual sensor motes under a variety of operating conditions. Applications for linking together WSNs are only limited by the imagination. The WSNs need not be random or fixed in place on the ground. For example, one WSN may be a periodic array placed on the side of a building and the other could be an array placed on the top or side of a truck. As the truck passes a station, the fixed station would search for the truck's array, establish a communications link and pass information wirelessly to the fixed node. Since the link is established autonomously, the truck doesn't need to stop, or indeed perform any action. A future effort may examine such applications that have potential military value.

ACKNOWLEDGEMENT

I would like to acknowledge the intellectual support and help from the guide professors of the Institute. I would specially like to thank Prof. Ravi Mohan for his motivating support.

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