AN IMPROVED METHOD FOR RADIO FREQUENCY DIRECTION FINDING USING WIRELESS SENSOR NETWORKS

Mickey S. Batson, John C. McEachen, and Murali Tummala
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, California, USA

ABSTRACT

We present the design of a remotely deployable distributed wireless antenna system formed from wireless sensor network nodes. Specifically, the focus is on enhancing the detection range of a distributed wireless antenna system. The primary objective is to create a methodology to steer the beam in the desired direction to enhance radio frequency (RF) direction finding and follow-on signal reception. The distributed wireless antenna system uses a combination of time difference of arrival (TDOA) and adaptive beamforming to localize the target and enhance the reception in the target direction. The TDOA lines-of-bearing are calculated using a combination of the Cross-Ambiguity Function to calculate the actual time difference and the Newton-Raphson technique to focus the beamforming efforts. A Least Mean Squares (LMS) adaptive beamforming algorithm is then used to localize the target for further prosecution. Simulations indicate considerable improvement can be achieved using this combined method.

I. INTRODUCTION

We present an improved method for identifying the direction of an RF emission using a wireless sensor network. The network consists of an interconnected set of wireless sensor motes that monitor and collect data pertaining to RF signals of interest. The collected data has to be transmitted to another location for processing and interpretation. A typical network node consists of one or more sensors, a transceiver with an omni-directional antenna, an onboard processor and a battery.

An example deployment of interest would be a large number of sensor nodes dropped from an aircraft, Unmanned Aerial Vehicle (UAV) or Unmanned Underwater Vehicle (UUV) to densely cover an area of interest. Left unattended, these nodes can then gather data, collaborate among themselves to form a wireless ad-hoc network, and transmit the collected data back to end-users located far from the scene of danger.

A methodology has been developed using a combination of both TDOA and beamforming in order to enhance collection in a specified direction. It is envisioned that the individual sensor nodes will have a low-cost omnidirectional antenna, but this methodology will take advantage of the number of nodes and have the sensors working together as a coherent antenna array. [1]

Research in [2] first proposed an architecture for using wireless sensor networks to sense the RF environment for the purpose of target direction finding. Specifically, they proposed a distributed architecture consisting of a randomly distributed collection of wireless sensor motes in communication with central node, or central controller, which performed follow-on processing of individual node signal strengths to computer the array factor. The work in [2] demonstrated that a random selection of a subset of all nodes by the central controller could substantially mitigate the effect of sidelobes, or grating lobes, while narrowing the beamwidth considerably.

This paper draws from the work in [2] and wireless antenna foundations of [3] to develop a methodology for identifying and converging on a signal of interest. Specifically, we explore the use of Time difference of arrival (TDOA) to rapidly converge on a quadrant of interest then use a traditional beamforming approach to perform fine tuning.

A. Time-difference of Arrival (TDOA)

TDOA takes advantage of the fact that a transmitted signal will arrive at the different elements at different time instants, as shown in Fig. 1. In the distributed wireless antenna array each sensor forms a two-node collector pair with the central controller. The basic principle of the two-element linear array will then be extended to encompass the entire antenna grid. The sensors within our grid will take advantage of the fact that our grid is densely populated and that the sensors are spread over a wide area. [4]

Defining TDOA in terms of the emitter and antenna element positions is accomplished using the vectors $\underline{r}_1$ and $\underline{r}_2$ from Fig. 1 where $\underline{r}_1$ is the distance from the central controller to the emitter and $\underline{r}_2$ is the distance from an individual antenna element to the emitter. [4]

Equation (1), illustrates the difference in the length of the two vectors $\underline{r}_1=[x_e - d/2 \ y_e]^T$ and $\underline{r}_2=[x_e + d/2 \ y_e]^T$, divided by the speed of light c, yields the TDOA:

$$TDOA = \frac{|\underline{r}_2| - |\underline{r}_1|}{c} = \frac{1}{c}\left(\sqrt{\left(x_e + \frac{d}{2}\right)^2 + y_e^2} - \sqrt{\left(x_e - \frac{d}{2}\right)^2 + y_e^2} \right), \quad (1)$$

where x_e and y_e are the respective x-y coordinates of the emitter and d is the distance between the two-node collector pair.
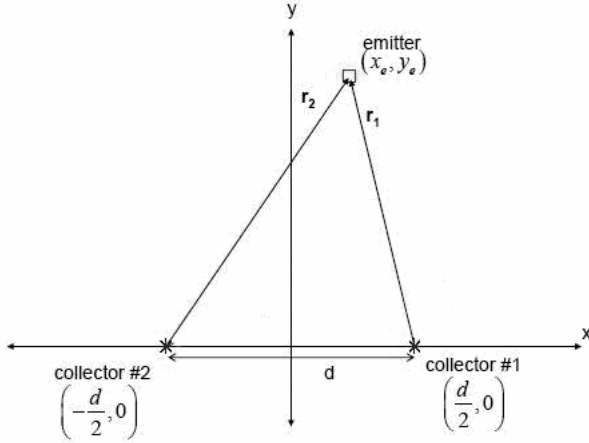
Figure 1. TDOA Geometry for a collector pair. [4]

Multiple TDOA measurements can be used to estimate emitter position in a manner analogous to a navigator performing triangulation. However, since the nodes do not have good angular spread relative to the target only a line-of-bearing is discernable. [4]

B. Adaptive Beamforming

The wireless antenna sensor nodes are deployed randomly over an area of interest, resulting in a random positioning of the sensor nodes. Subsequently, these sensor nodes form clusters and their locations are determined using location discovery techniques. These locations are then reported back to the central controller.

The sensor nodes will make up an array antenna that performs adaptive control of the pattern in order to maximize the array pattern in the direction of the target. The pattern of the array is controlled by dynamically varying the phase and amplitude of the received signal from each element. [1]

Since the sensor grid will require the ability to steer the main lobe an adaptive algorithm will be implemented. The LMS algorithm recursively computes and updates the complex weights. [1] The LMS algorithm requires knowledge of the desired signal, which will be assumed.

The error between the observed and desired signal is used to calculate the weights required to adaptively form the beam in the desired direction. The error is defined to be:

$$e(t) = \alpha(t) - b(t) \qquad (2)$$

where $\alpha(t)$ is the reference signal and $b(t)$ is the output of the beamformer.
The complex weights are adjusted and applied to the signal received by the array elements in an iterative manner. For each data sample, the complex weights are chosen to minimize the mean-square error between the beamformer output $b(t)$ and the reference signal $\alpha(t)$ given by [1,3,6]

$$E\left[e^2(t)\right] = E\left[(\alpha(t) - b(t))^2\right] \qquad (3)$$

where $E[\bullet]$ is the expectation operator. The minimum mean-square error (MMSE) is obtained by setting the gradient vector of Equation (3) with respect to $\underline{w}$ to zero.

The value of the weight vector at time $(t+1)$ is updated as follows:

$$\underline{w}(t+1) = \underline{w}(t) + \frac{1}{2}\mu\left[-\underline{\nabla}_{\underline{w}} E\left[e^2(t)\right]\right], \qquad (4)$$

where μ is the convergence factor. After obtaining the gradient vector $\underline{\nabla}_{\underline{w}} E\left[e^2(t)\right]$ the weight vector is updated by substituting into Equation (4).
Simplifying, we have:

$$\underline{w}(t+1) = \underline{w}(t) + \mu \underline{g}(t) e^*(t), \qquad (5)$$

where $*$ represents complex conjugation and the instantaneous estimates given by *[α(t)g(t)]* and *[g(t)g^H(t)]* have been used instead of *E[α(t)g(t)]* and *E[g(t)g^H(t)]*, respectively. The term *E[g(t)g^H(t)]* is commonly known as the array correlation matrix R_{gg} and denotes the correlation between the signals received by the various array elements. [1, 3, 6]

II. ANALYSIS OF TDOA METHODS AND BEAMSCANNING METHODS

A. TDOA Analysis

When the complex envelopes of an emitter signal are collected by the two sensors then TDOAs were determined directly by calculating the cross-ambiguity function (CAF). A frequency difference of (FDOA) can also be determined from calculating the CAF, which could be very useful if prosecuting a mobile target. [4, 5] However, our target is assumed stationary or slow moving. The complex envelopes of the two signals will be denoted by $s_1(t-\tau)$ and $s_2(t),$ where t is the time of the first sample, and τ is the time delay between the two. The CAF is defined as

$$CAF(f,\tau) = \int_0^T s_1(t-\tau) s_2^*(t) e^{-j2\pi ft} dt \qquad (6)$$

where f is frequency, T is the integration time, and $*$ denotes the complex conjugate. Since the function peaks when $\tau = TDOA$ and $f = FDOA$, it is often used as a means to determine these two quantities simultaneously. [4, 5] The solution is determined by locating the peak of the CAF, $|CAF(f,\tau)|$. [4, 5] It is worth noting that when the sensors or the emitter are not in motion that the cross-ambiguity function is simply the autocorrelation function. In Fig. 2, the TDOA of the sensor located the farthest from the central controller is depicted. The frequency difference of arrival is zero which is expected.

Once the TDOAs were determined the Newton-Raphson technique was used to determine a line-of-bearing. The Newton-Raphson algorithm is based on estimation theory and uses an over-determined set of linear equations of the form

$$\underline{m} = f(\underline{z}, t), \qquad (7)$$

where $\underline{m}$ is a *k*-vector representing the TDOA measurements and $\underline{z}$ is the location of the emitter.
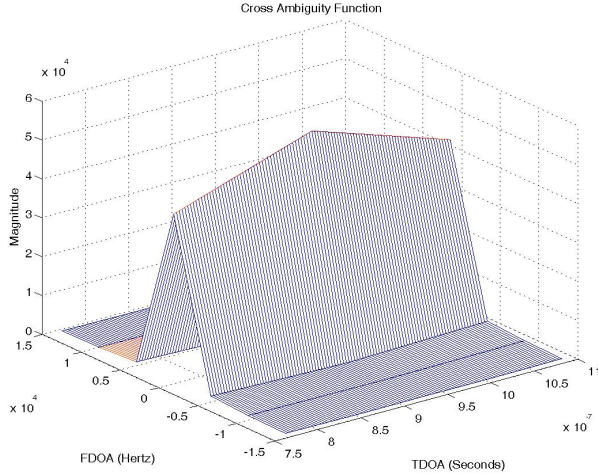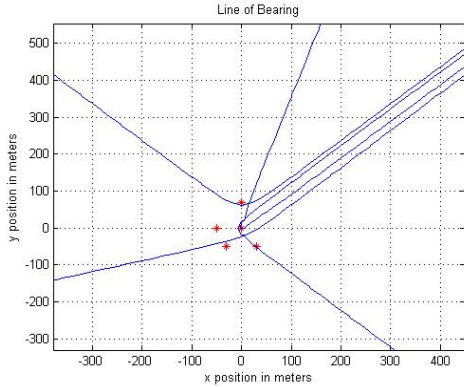

Figure 2. Max distance 3D.

Figure 3. 4 Sensors. 15 TDOA Estimates per Two-node Collector pair.

The time difference of arrival was calculated using the cross-ambiguity function discussed earlier. This would be the *k* TDOA observations referred to as the $\underline{m}$ vector. The $\underline{m}_i$ vector is the TDOA measurements for the current estimated position as shown in Equation (8).

$$\delta\underline{m} = \underline{m} - \underline{m}_i \tag{8}$$

By iterating through this process the current solution is used as the next estimated emitter location until the solution falls below some predetermined small threshold. A least squares estimation is applied to yield an emitter position estimate.

In Fig. 3, the target emitter was located at 45° from the central controller in the first quadrant. Three frequencies 157 MHz, 800 MHz and 2.4 GHz were simulated and all produced similar results. Only the 157 MHz frequency is illustrated in this paper. Several simulations were conducted with the figure shown being representative of the results. Since the wireless antenna grid is not moving and the emitter is at the same relative bearing to all the two-node collector pairs a geolocation was unobtainable. However, as seen in Fig. 3 a nice line-of-bearing to the target can be calculated.

A method for computing TDOAs and then subsequent lines-of-bearing has been presented. As was

shown the CAF and Newton-Raphson methods were able to determine a line-of-bearing to the target. Now an illustration of beamscanning will be presented.

B. Beamscanning

Method Two described in [2] is used for our sensor grid. The central controller selects the number of array elements needed to form the desired beam. The central controller in effect creates an array, which is merely a subset of the total array. For example, consider a sensor grid that contains *K* elements randomly spread over a total area, A_1. The central controller will select, Λ nodes within an area, A_2, where $A_2 \leq A_1$ and $\Lambda \leq K$. The central controller will create a *P* node subset from the Λ nodes where $P<<\Lambda$. This subset will form the basis for the array factor. The following is an analysis of the LMS adaptive beamforming algorithm.

$$\Psi(\theta,\phi) = e^{\left(j\frac{2\pi}{\lambda}*(x\sin(\theta)*\cos(\phi)+y\sin(\theta)\sin(\phi))\right)} \tag{9}$$

where λ is the wavelength of the signal in meters. *x* and *y* are the location of the individual antenna elements in meters. θ is the elevation angle and ϕ is the azimuth angle.

The central controller then calculates the array weights $\underline{w}$ by summing each element over all possible values of θ and φ.

$$\Psi(\theta,\phi) = \sum_{m=1}^{M}\sum_{n=1}^{N} w^*_{mn} e^{j\frac{2\pi}{\lambda}\left(x_{mn}\sin(\theta)\cos(\phi)+y_{mn}\sin(\theta)\sin(\phi)\right)} \tag{10}$$

where $P=MxN$ is the total number of nodes in the subset and w_{mn} is the complex weight

$$w^*_{mn} = W_{mn} e^{j\frac{2\pi}{\lambda}\left(x_{mn}\sin(\theta_0)\cos(\phi_0)+y_{mn}\sin(\theta_0)\sin(\phi_0)\right)} \tag{11}$$

applied to the $(m,n)^{th}$ element. The maximum value of $\Psi(\theta,\phi)$ occurs at $(\theta,\phi)=(\theta_0,\phi_0)$, and the main lobe points towards (θ_0,ϕ_0).

Each data sample of the signals collected from the chosen nodes iteratively updates the corresponding array weights. The magnitude and angle of $\Psi(\theta_0,\phi_0)$ are stored. This completes an iteration of the adaptive beamforming solution.

Now the central controller takes another 500 data samples from each node within a new subset of *P* nodes. Then the process described earlier is repeated and the final result is added to the previously stored result. This process is shown in Equation (12).

$$\Psi_{Total}(\theta,\phi) = \sum_{i=1}^{L}\Psi_i(\theta,\phi) \tag{12}$$

where *L* equals the total number of subsets created. Substituting Equation (10) into the above equation results in the following:

$$\Psi_{Total}(\theta,\phi) = \sum_{i=1}^{L}\left[\sum_{m_i=1}^{M}\sum_{n_i=1}^{N} w^*_{m_i n_i} e^{j\frac{2\pi}{\lambda}\left(x_{m_i n_i}\sin(\theta)\cos(\phi)+y_{m_i n_i}\sin(\theta)\sin(\phi)\right)}\right]$$

$$\tag{13}$$

where $P=MxN$ is the total number of nodes in each subset.

This magnitude is then plotted in dB against all possible values of azimuth and elevation. This process is repeated until a desired solution has been found.

Method Two in reference [2] was shown to have an energy cost per sensor of δ joules/transmission. Reference [2] demonstrated that this energy cost per sensor did not increase even though the total number of transmissions within the network may increase.

III. BEAMWIDTH CONTROL

With the desire to enhance RF collection in a specified direction it is important to understand how to control the beamwidth of the beam. When in localization mode a wider beam would be preferred. After the signal has been localized it would be preferable to narrow the beam in order to enhance collection. As can be seen in Fig. 4-5, the main beam beamwidth has continued to get narrower as the central controller chose nodes that are further away from its own location. In affect, the central controller is reducing the node density of the antenna array.

Unfortunately, there are limits to how wide the initial search beam may become. As the number of array elements are increased, unless the overall size of the array is increased, an upper limit on the beamwidth is reached. This can be seen through analysis of both planar array beamwidth and the random array discussed in the previous section.

The beamwidth for a planar array is determined by using Equations (24) and (25). In order to determine the respective beamwidth the array is separated into x and y linear arrays. These equations for the respective scan angles for both elevation and azimuth are shown in Equation (26) [1].

$$\Theta_{elevation} = \sqrt{\left(\frac{1}{\cos^2(\theta_a)\left[\theta_{x_a}^{-2}\cos^2(\phi_0)+\theta_{y_a}^{-2}\sin^2(\phi_0)\right]}\right)}, \quad (14)$$

$$\Theta_{azimuth} = \sqrt{\left(\frac{1}{\left[\theta_{x_a}^{-2}\sin^2(\phi_0)+\theta_{y_a}^{-2}\cos^2(\phi_0)\right]}\right)}, \quad (15)$$

where ϕ_0 is the desired azimuth scan angle and θ_a is the desired elevation angle. It can be seen how the beamwidth in the azimuth and elevation directions impacts the gain of the beam. [1]

$$\theta_{x_a} = \cos^{-1}\left[\cos\theta_a - 0.443\left(\frac{\lambda}{(L+d)}\right)\right],$$

$$\theta_{y_a} = \cos^{-1}\left[\cos\theta_a + 0.443\left(\frac{\lambda}{(L+d)}\right)\right] \quad (16)$$

where $d = L/N$, L is the length of the uniform linear array and N is the number of nodes along the length of the uniform linear array. Now shown below for the azimuth [1].

$$\phi_{x_0} = \cos^{-1}\left[\cos\phi_0 - 0.443\left(\frac{\lambda}{(L+d)}\right)\right],$$

$$\phi_{y_0} = \cos^{-1}\left[\cos\phi_0 + 0.443\left(\frac{\lambda}{(L+d)}\right)\right] \quad (17)$$

where $d = L/N$, L is the length of the uniform linear array and N is the number of nodes along the length of the uniform linear array. Examining equations (16) and (17) it can be seen that as the number of elements increases for a specific area, i.e. the node density increases, the beamwidth reaches an upper-bound for a given wavelength [1].

Figure 4 illustrates for both the uniform linear array and the randomly dispersed array that when the number of sensors is increased, but the size of the array is held constant, i.e., the node density increases, the beamwidth increases resulting in a loss of gain, up to a limit.

Consequently, a central controller may find the direction of a target emitter by scanning with a large beamwidth, but the number of scans required to do this will have some lower bound due to the limit on the size of the beamwidth. Thus if we can find a way to reduce the initial scan area, we can improve the minimum time to find the direction to a target.
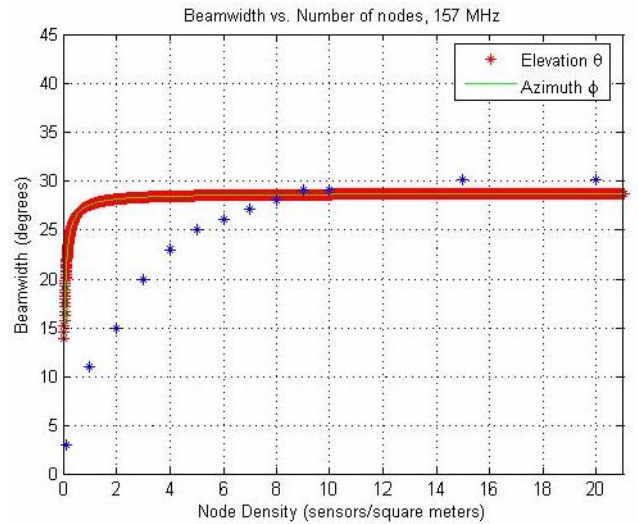

Figure 4. Beamwidth versus Node Density where the blue asterisks represented values from the randomly dispersed array of equation (13) and red values represent calculated values from equations (16) and (17).

Reference [2] demonstrated how the central controller can control the beamwidth of the mainbeam through the node selection process.

As can be seen from Fig. 5 - 6, the frequency of the SOI and the size of the distribution area of the subset

around the central controller, have the greatest effect on beamwidth. The subset creation will be used to transition the beam from a signal localization mode to either a passive or active signal prosecution mode.

What is significant about the results from reference [2] is that no additional transmission burden has been placed on the individual sensor nodes, therefore giving a capability to control the beamwidth without increasing the overall energy consumption of the array.

IV. DIRECTION FINDING METHODOLOGY

The proposed methodology for enhancing collection in a distributed wireless antenna system is described as follows. A two-tiered hierarchical clustering sensor network architecture is assumed. A primary node (i.e. UAV, UUV, etc.) is tasked with maintaining frequency, phase and data synchronization among the remaining nodes (or secondary nodes) within the cluster. The network is comprised of K sensors spread over and area, A_1.
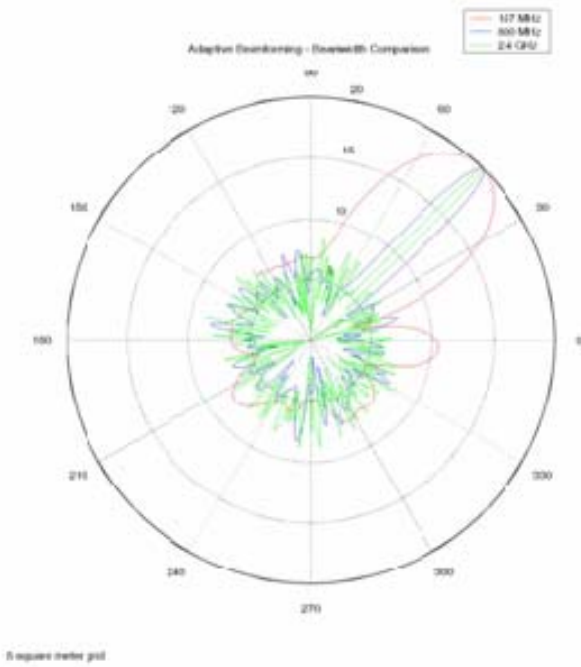

Figure 5. Array Pattern. 157 MHz (outer pattern-red), 800 MHz (middle pattern-blue) & 2400 MHz (inner pattern-green). Nodes within a 25 sq. m. grid of the beamcontroller.
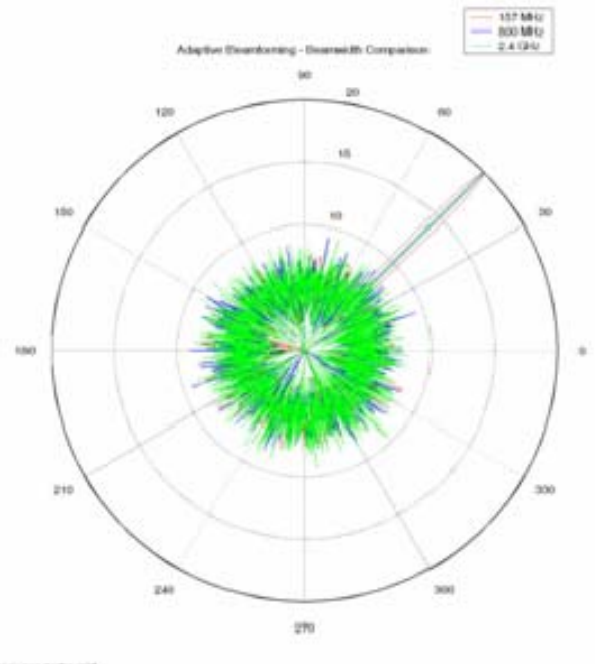

Figure 6. Array Pattern. 157 MHz (outer-red), 800 MHz (middle-blue) & 2400 MHz (inner pattern-green). Nodes within a 2500 sq. m. grid of the beamcontroller.

-- Step 1. The central controller acts as a reference antenna by gaining initial intercept and frequency-of-interest (FOI) determination.

-- Step 2. The central controller will then determine the TDOA collected from the Y sensors furthest from its location. Each sensor forms a two-node collector pair with the central controller. The central controller will utilize the cross-ambiguity function presented earlier to calculate the TDOAs between each of these Y sensors and the central controller.

-- Step 3. The central controller will then use the modified Newton-Raphson technique to localize the signal-of-interest to two specific lines-of-bearing.

-- Step 4. The central controller will then begin the beamforming process. From the area, A_1, the central controller will create a random P_i node subset from the Λ nodes contained within a given area, A_2. Following the algorithm stated above the central controller will create L subsets to create the appropriate beam for a given (θ_0, ϕ_0).

-- Step 5. Based on the results of this localization the beamcontroller can randomly choose sensors that are dispersed within a larger area to further narrow the beam into the target direction in order to maximize reception.

V. TDOA COST ANALYSIS

For the TDOA computation of steps 2 and 3 above, the total transmissions are defined as

$$T_{TDOA} = \Omega\Upsilon, \tag{18}$$

where Ω is the total number of two-node collectors and Υ is the total number of received data samples sent back

to the central controller per two-node collector pair. These received data samples are then used by the Central Controller to determine the line of bearing.

If the cost per transmission is δ joules/transmission, χ_1 joules is the energy expended when the receiver is on, but waiting to transmit and assumes the worst case. χ_2 joules is the energy required to fully energize a transmitter that has been in a sleep mode and also assumes the worst case. The total energy cost to calculate a line of bearing is then defined as

$$\begin{aligned}\Gamma_{TDOA} &= \delta T_{TDOA} + (\Omega-1)\Upsilon\chi_1 + \Omega\chi_2 \\ &= \delta\Omega\Upsilon + (\Omega-1)\Upsilon(0.1\delta) + \Omega(0.5\delta)\end{aligned}, \quad (19)$$

where Γ_{TDOA} is in units of joules. The first term in Equation (19) is the energy expend the data. The second term in Equation (19), is the total energy expended waiting to transmit. This term assumes that a node awaits for all other nodes to transmit before it can transmit. χ_1 is defined in terms of a fraction of the energy expended to transmit the data. The third term is the energy expended to bring all of the participating nodes out of a sleep mode, which assumes that all participating nodes were in a sleep mode. χ_2 is also defined as a fraction of the energy to transmit the data. The energy cost per sensor is

$$\Xi_{TDOA} = \delta\Upsilon + \Upsilon(0.1\delta) - \frac{\Upsilon(0.1\delta)}{\Omega} + (0.5\delta), (20)$$

where Ξ_{TDOA} is measured in units of joules/sensor.

The TDOA determination process would take a total of t_{TDOA} seconds.

$$t_{TDOA} = \Omega\varsigma\Upsilon + \Omega\varepsilon + \Omega\Upsilon t_1 + \Omega t_2, \quad (21)$$

where Ω is the number of nodes, ς is the cost per TDOA estimate to perform the CAF, Υ is the number of TDOA estimates per two-node collector pair and ε is the time required to calculate the line of bearing using the NRT. The time a node takes to transmit is t_1. This term assumes a TDMA type medium access, in which a node has a time slot and awaits for all other nodes to transmit before it can transmit. The time required to awake the nodes is t_2 and assumes the worse case, that all nodes selected are in a sleep mode.

Now the total time required to do combination TDOA and beamforming can be defined as follows:

$$t_{TDOA/\Psi} = t_{TDOA} + t_{BF}, \quad (22)$$

where t_{TDOA} is the time to required to localize the target and t_{BF} is the time required to form one beam. After substituting Equation (21) into Equation (22) and combining like terms the total time required can be rewritten as

$$t_{TDOA/\Psi} = \Omega\varsigma\Upsilon + \Omega\varepsilon + \Omega t_1 + \Omega t_2 + t_\Psi + \Lambda t_1 + \Lambda t_2. \quad (23)$$

Equation (23) assumes the worst case that all the nodes need to be brought out of a sleep mode. In addition, it assumes that the nodes used in the TDOA calculations are not used in the beamforming calculations.

The total energy to enhance collection using a combination of TDOA and beamforming is defined as

$$\Gamma_{TDOA/\Psi} = \Gamma_{TDOA} + \Gamma_{BF}, \quad (24)$$

where again Γ_{TDOA} is defined in Equation (19) as the energy required for TDOA and Γ_{BF} is drawn from [2] as the energy required to form one beam using the multiple random selections method. After substitution, Equation (24) can be rewritten as follows:

$$\Gamma_{TDOA/\Psi} = \Omega\delta\Upsilon + (\Omega-1)\Upsilon\chi_1 + \Omega\chi_2 + \delta\sum_{i=1}^{L_2}P_i + (\Lambda-1)\chi_1 + \Lambda\chi_2$$

$$\Gamma_{TDOA/\Psi} = \Omega\delta\Upsilon + (\Omega-1)\Upsilon(0.1\delta) + \Omega(0.5\delta) + \delta\sum_{i=1}^{L_2}P_i + (\Lambda-1)(0.1\delta) + \Lambda(0.5\delta)$$

$$(25)$$

VI. COST COMPARISON

The energy cost using the combination of TDOA and beamforming will always be less than the beamscanning only method as long as the following criteria is met:

$$\Gamma_{TDOA/\Psi} \leq \Gamma_{bs}$$

$$\Omega\delta\Upsilon + (\Omega-1)\Upsilon(0.1\delta) + \Omega(0.5\delta) + \delta\left(\sum_{i=1}^{L_2}P_i\right) + (\Lambda-1)(0.1\delta) + \Lambda(0.5\delta)$$

$$\leq \eta\delta\left(\sum_{i=1}^{L_2}P_i\right) + \eta(\Lambda-1)(0.1\delta) + \Lambda(0.5\delta)$$

$$\Omega\Upsilon + \Omega\Upsilon(0.1\delta) - \Upsilon(0.1\delta) + \Omega(0.5\delta) \leq (\eta-1)\sum_{i=1}^{L_2}P_i + (\Lambda-1)(\eta-1)(0.1\delta)$$

$$T_{TDOA} + \Omega\Upsilon(0.1\delta) - \Upsilon(0.1\delta) + \Omega(0.5\delta) \leq (\eta-1)T_\Psi + (\Lambda-1)(\eta-1)(0.1\delta)$$

$$(26)$$

Upon close inspection of Equation (26), it can clearly be seen that the our proposed method will always use less energy than [2] as long as the number of transmissions to perform the TDOA plus the additional factor associated with the energy spent waiting to transmit and the energy required to bring a sensor out of a sleep cycle is less than the number of transmissions required to conduct the 360° beamscan minus the target beam. The target beam will be formed in both cases.

Additionally, the combination of TDOA and beamforming will always be faster as long as the following criteria is met:

$$t_{TDOA/\Psi} \leq t_{bs}$$

$$\Omega\varsigma\Upsilon + \Omega\varepsilon + \Omega\Upsilon t_1 + \Omega t_2 + t_\Psi + \Lambda t_1 + \Lambda t_2 \leq \eta t_\Psi + \eta\Lambda t_1 + \Lambda t_2$$

$$\Omega\varsigma\Upsilon + \Omega\varepsilon + \Omega\Upsilon t_1 + \Omega t_2 \leq (\eta-1)t_\Psi + \Lambda(\eta-1)t_1$$

$$t_{TDOA} + \Omega\Upsilon t_1 + \Omega t_2 \leq (\eta-1)t_\Psi + \Lambda(\eta-1)t_1$$

$$(27)$$

Equation (27) shows that this new method will be faster than [2] as long as the time required to form the beams, less the target beam, plus the amount of time spent

waiting to transmit and the time required to bring a sensor out of a sleep mode is greater than the time to determine the target line-of-bearing. In practice, the combination of TDOA and beamforming will always be faster than beamscanning only.

Focusing on the 45° beams from Figure 5, it can be observed that a 360° scan could be conducted at 15° increments with sufficient overlap to not leave gaps in coverage. This can be accomplished with $\eta = 24$ beams. Using the beamwidth from Figure 5 and the method in [2] it would require 6850 time units (a time unit being related to processor cycles) to scan 360∘.

The energy and time cost are dependent on the number of beams that need to be formed for beamscanning only. As stated earlier, the number of beams required would be based on the solid angle of the beam and the desired overlap of the beams. Table 1 depicts the energy cost and times for various η. The tic-toc command in MATLAB® was used to determine that $t_\psi = 25$ time units were required to create a beam, ε was determined to be equal to 0.1 time units and ς was determined to be 2 time units per CAF estimate for each two-node collector pair. These times would vary based on hardware and software implementation. Additionally, it is expected that these times would be much lower in a real world implementation. From [2], the energy to form one beam is 399.9δ joules. From Equation (19), the total energy to do TDOA is 45δ joules, where $\Omega = 4$ sensors.

# of beams, η	Γ_{bs}, (joules)	$\Gamma_{TDOA/\Psi}$, (joules)	t_{bs},	$t_{TDOA/\Psi}$,
10	2874δ	445δ	3000	612
24	6722.6δ	445δ	6850	612
30	83872δ	445δ	8500	612

Table 1. Energy and Time Cost comparison between beamforming method of [2] vs. the combined TDOA beamforming method of this paper.

It can be seen from the results shown in Table 1 that the combination of TDOA and beamforming in most practical cases will always be faster and more energy efficient than the beamscanning only method.

VII. SUMMARY

In summary, a methodology for enhancing direction finding and reception in a distributed wireless antenna system has been presented. This methodology demonstrated how to focus energy in a specified direction using a combination of TDOA and adaptive beamforming techniques. It was shown that the combination of TDOA and adaptive beamforming provides a rapid localization of the target. In addition the energy burden can be distributed throughout the entire network creating a significant energy savings. This process is not only more accurate, but is also less computational burdensome to the central controller.

REFERENCES

[1] Balanis, C. A., *Antenna Theory Analysis and Design*, 2nd edition, Wiley, New York, 1997.
[2] Batson, M. S., McEachen, J., Tummala, M., *Enhanced Collection Methodology for Distributed Wireless Antenna Systems*, IEEE Conference on Systems of Systems, San Antonio, Texas, April 2007.
[3] Litva, J. and Lo, T., *Digital Beamforming in Wireless Communications*, Artech House, Norwood, MA, 1996.
[4] Loomis, H. H. , "Geolocation of Electromagnetic Emitters," NPS-EC-00-003, Naval Postgraduate School, Monterey, CA, Revised October 2003.
[5] Steinberg, Bernard, *Principles of Aperture and Array System Design*, John Wiley & Sons, Inc., 1976.
[6] Harry L. Van Trees, *Optimum Array Processing, Part IV of Detection, Estimation, and Modulation Theory*, John Wiley & Sons, New York, 2002.