Optimization of Distributed and Collaborative Beamforming in Wireless Sensor Networks

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Abstract—Collaborate beamforming in wireless sensor networks (WSNs) is a concept of using beamforming technology to establish link in the networks. It can effectively increase the transmission distance and improve the energy efficiency of the networks. Due to random deployment of the sensor nodes in the networks, proper assignment for the sensor nodes in wireless sensor networks is vital to achieve better array pattern synthesis. In this paper, a node selection method based on uniform space linear array synthesis is presented. A virtual line was constructed in the network topology as a reference guide to optimize the selection of nodes to mimic the uniform space linear array. The node selection for collaborative beamforming is further optimized using genetic algorithm. Using the method, simulation results show an improvement of radiation beam pattern.

Keywords-component; wireless sensor networks; collaborate beamforming; genetic algorithm.

I. INTRODUCTION

Wireless sensor networks (WSNs) vast numbers of interconnected sensor nodes with sensing, processing and communication capability. Each sensor is able to collaborate to collect data and transmit among sensor nodes or to the base station (BS). The transmitted data will be further process in the BS. Typically, the deployment area of the sensor node have characteristic of unsupported facilities such as energy source. Therefore, sensor node is often batteries-powered for operation. Due to limited battery-life, the processing and communication abilities of the sensor node are restricted.

Many studies have been devoted in cluster based hierarchical routing protocol to increase energy conservation during the wireless communication [1]. Such techniques show significant improvement in prolonging the lifetime of the WSNs. Beam-formation scheme was introduced in WSNs as an alternative solution to increase energy conservation [2], [3]. The sensor nodes cooperate among themselves by sharing data transmission to the destination receiver. The sensor nodes organize themselves into a virtual antenna array to perform a narrow beamforming toward the desired destination. Hence, the data can be transmitted over a long distance, which unreachable using a single node transmission.

Several related efforts on distributed beamforming in WSNs have been report by researchers [4], [5], [6] to investigate the performance of beamforming based on random theory array. Due to the random deployment of sensor node in WSNs, it will generate phase errors which could significantly degrade the beamforming performance. Sensor nodes array which are uniformly spaced has been utilized to overcome the issued cause by random topology of the WSNs [7], [8]. Particle Swarm Optimization (PSO) algorithm is used to optimize the selected nodes, implementing beamforming based on linear array sensor nodes [9], [10].

Due to the random topology condition in WSNs, the synthesis of the sensor node antenna based on linear array sensor nodes is a nonlinear optimization problem. Therefore, artificial intelligence optimization method such as genetic algorithms (GA), which is widely applied in various applications, shows great potential in solving this nonlinear optimization problem solutions [11], [12], [13], [14].

This paper is organized as follows: In section II, the system model of the WSNs and array synthesis are presented. In section III, nodes selection of linear array sensor nodes is presented. A novel optimization solution based on linear array sensor nodes using genetic algorithm is presented in section IV and section V contains the simulation results and discussion. Lastly, the conclusion will be made in section VI.

II. SYSTEM MODEL AND ARRAY SYNTHESIS

A. Sensor Network Model

The notation model of the sensor nodes and the destination is shown in Fig. 1.
The sensor nodes assume random distribution across the x-y plane. Each sensor node indicates based on Cartesian coordinate (x_i, y_i) where i represents the node number. The destination of the receiver is indicated in spherical coordinate, (r, θ, φ).

In the WSNs modeling, the following assumptions are made:

- Each node has only a isotropic omnidirectional antenna.
- Each node is capable of cooperating with its surrounding nodes within the transmission distance.
- There is no multipath fading or shadowing effect in the WSNs.
- The location of each node is identified.
- The location of the transmitting destination point is assumed to be in far-field.
- All nodes and destination point are stationary.

### B. Linear Array Synthesis Model

Linear array is one of the most commonly used array structure in many applications such as antenna and sonar, due to its simplicity and beam shaping properly. The geometric arrangement of an N×1 element linear array with uniform spacing along the x-axis direction is shown in Fig. 2. Assuming that a signal p(t) coming at the angle of θ_n the distance of each element with origin point as the reference node is d_n. The time arrival of the signal for each element is t_n. The time arrival can be represented by (1)

$$ t_n = \frac{d_n \cos(\theta_n)}{c} $$

where c is the speed of light. The element weight for each element can obtained using (2)

$$ w_n = I_n e^{j\omega t_n} $$

where ω is the frequency in radian. It is assumed that the amplitude I_n is unity. The array factor of an N×1 element array is given by (3):

$$ AF(\theta) = \sum_{n=1}^{N} w_n e^{j k d_n (\cos(\theta) - \cos(\theta_s))} $$

where k, θ, and θ_s are the wave number k=2π/λ, θ is the azimuth angle, and θ_s is the scan angle. The normalized gain of the beam pattern can be computed using (4)

$$ G(\theta, \phi) dB = \frac{|AF(\theta)|^2}{\max |AF(\theta)|^2} $$

III. NODE SELECTION FOR LINEAR ARRAY SENSOR NODES

Node selection for linear array sensor nodes is a method used to select a set of sensor nodes array which collaborate among themselves to perform beamforming mimicking the performance of an ideal uniform linear array.

The Node cluster head needs to choose to communicate with its neighboring nodes in order to perform beamforming. Within the communication range of the cluster head, it will act as the center node of the linear array sensor nodes.

Rather that searching through the entire nodes in the cluster within the transmission range of cluster head, the algorithm will chooses a set of sensor nodes in a uniform spacing linear way. To avoid any grating lobe effect, the optimize inter-nodes spacing must be λ/2, where λ is the wavelength of the transmitter frequency. The constraint in (5) must be fulfilling in order to construct a set of virtually nodes locations.

$$ \sqrt{(V(x_{n+1}) - V(x_n)) + (V(y_{n+1}) - V(y_n)) = \lambda / 2} $$

where n = 1, 2, 3…N. N is the total number of elements required to perform beamforming and V(x_n, y_n) is the coordinate of the virtual element.

A reference virtual line can be constructed within the active cluster using (6)

$$ y = m(x - P_x) + P_y $$

$$ m = \tan^{-1}(\beta) $$

where β is the rotational angle of the slope, m is the gradient of the slope, Px and Py are the node locations of the cluster head along x-axis and y-axis respectively.

The algorithm is then search for the closest node C(x_n, y_n) compared with virtual node V(x_n, y_n). The closest node will be only be selected if it fulfills the constraint (8)

$$ S(x_n, y_n) = \min \left| V(x_n, y_n) - C(x_n, y_n) \right| $$

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A new set of solution can be found by changing the rotation angle using (7). The new set of solution is then analyzed and compared to the previous solution until an optimum set of solution is found.

IV. OPTIMIZATION SOLUTION USING GENETIC ALGORITHM

A. Genetic Algorithm

GA is a global search algorithm based on natural selection and natural genetic mechanism. The optimization problem can be modelled accordingly based on its biological environment. Each chromosome in a population represents a possible solution in the optimization problem. The GA creates a biological environment which the chromosomes to evolve to the best. After endless round of evolution, the weak chromosomes are discarded, leaving only the fit and strong chromosomes [15] in the population. The flowchart of the GA is shown in Fig. 3.

B. Encoding Technique

The encoding technique encoded the information of a solution into a single chromosome. The GA creates a chromosome which contains an array of sensor node location (gene), as shown in Fig 4.

\[ G(x_1, y_1) \quad G(x_2, y_2) \quad G(x_3, y_3) \quad G(x_4, y_4) \quad \ldots \quad G(x_n, y_n) \]

Figure 4. Chromosome structure.

\( G(x_n, y_n) \) is the possible candidate node location which is the neighbor to the virtual node.

C. Fitness Function

Fitness function is required to examine of each chromosome from population. The chromosome with better fitness function will produce better result. The objective of the optimization is to reduce the sidelobe level (SSL) of the beamforming. The fitness function is described in (9).

\[ \text{Fitness} = \min \sum_{R} \sum_{j} \left| AF(\theta) \right|^2 \]  

(9)

where \( R \) is the region SSL need to be minimized, \( j \) and \( k \) is the angle within the region.

D. Selection and Crossover Process

The roulette wheel selection method is used during the selection process. A pair of chromosomes is randomly selected as parents, and a pair of offspring is created by recombining the chromosomes of the parents. This process is known as the crossover process. A crossover probability \( P_c \) is set as the crossover operation rate. \( N \) point crossover are selected as the crossover strategy where \( N \) is the number of nodes needed to collaborate in order to perform beamforming. The crossover process is illustrated in Fig. 5.

E. Mutation Process

Mutation is intended to prevent the solutions from falling into a local optimum of the optimization problem. This is achieved by adding small deviating changes into the particular gene. During this process, the mutation operator is given a chance to randomly change the genetic information via crossover operator with mutation probability \( P_m \). A new evolution process will be run by involving the mutated chromosomes. The deviating changes by the mutation process are usually very small. At the end of the evolution process, the solution can be tweak based on the nearest point.
V. Simulation Result and Discussion

A WSNs model is simulated based on the parameters in Table I. The parameters used in GA are summarized in Table 2. Two different cases were studied by using different destination direction with the same number of collaborate nodes.

For the first case, 9 nodes are required to form a uniform linear array of sensor nodes. The desired beam angle is set at -30°. The random deployment of the WSNs topology is shown in Fig. 6. The cluster within the transmission range of cluster head and the virtual line is shown in Fig. 7. Linear array method selects a set of sensor nodes array in Fig. 8. In contrast, GA linear array method selects a set of sensor nodes array in Fig. 9. The beamforming analysis result is shown in Fig. 10. The result shows that the GA linear array sensor nodes had a smaller SSL on average compared to the linear array sensor nodes. The most significant suppression of the SSL is most prominent in the region of 30° to 90°. At 60°, there is an approximate decrease of 5.12 dB form -10.15 dB, compared to the linear array sensor nodes.

For the second case of simulation, similarly, 9 of nodes is set to form a uniform linear sensor nodes array. The desired beam angle is set at 50°. The same topology and same set of nodes selected by linear array had been use for the case study. GA linear array method selects a set of sensor nodes array in Fig. 11. The beamforming analysis result is shown in Fig. 12. Similarly, the GA linear array sensor nodes shows a smaller SSL on average compared to the linear array sensor nodes in the simulation result. At -60°, the most significant suppression of SSL most noticeable in the region between -30° and 10°. There is an approximate decrease of 5.02 dB from -8.01 dB, compare to the linear array sensor nodes.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of sensor</td>
<td>200</td>
</tr>
<tr>
<td>Sensor deploy area (m²)</td>
<td>100</td>
</tr>
<tr>
<td>Number of selected nodes</td>
<td>9</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>300</td>
</tr>
<tr>
<td>Desination node angle</td>
<td>-30</td>
</tr>
</tbody>
</table>
The beamforming performance of the selected sensor nodes using genetic algorithm had shown improvement in term of reducing SSL. The result also shows that implementation of genetic algorithm in selected sensor nodes can maintain the main beam’s beamwidth as compared with linear array sensor nodes using (8).

VI. CONCLUSION

Optimizing method for linear array sensor nodes using GA has been introduced. The result shows that by using genetic algorithm, the selection of node to perform linear array sensor nodes is able to reduce the SSL of the beamforming. For future study, different geometric arrangements of sensor array could be used as a reference model in order to select sensor nodes to perform beamforming collaboration.
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