

Backtracking Search Optimization for Collaborative Beamforming in Wireless Sensor Networks

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Abstract

Due to energy limitation and constraint in communication capabilities, the undesirable high battery power consumption has become one of the major issues in wireless sensor network (WSN). Therefore, a collaborative beamforming (CB) method was introduced with the aim to improve the radiation beampattern in order to compensate the power consumption. A CB is a technique which can increase the sensor node gain and performance by aiming at the desired objectives through intelligent capabilities. The sensor nodes were located randomly in WSN environment. The nodes were designed to cooperate among each other and act as a collaborative antenna array. The configuration of the collaborative nodes was modeled in circular array formation. The position of array nodes was determined by obtaining the optimum parameters pertaining to the antenna array which implemented by using Backtracking Search Optimization Algorithm (BSA). The parameter considered in the project was the side-lobe level minimization. It was observed that, the suppression of side-lobe level for BSA was better compared to the radiation beampattern obtained for conventional uniform circular array.

Keywords: Collaborative beamforming; Backtracking search optimization algorithm; Wireless sensor networks; Antenna array; Energy-efficient

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1. Introduction

Wireless sensor network (WSN) is a collection of interconnected nodes forming in a sensor network [1]. The sensor nodes are deployed in a dense area with the purpose of acquiring information regarding the object of interest. It is widely used in remote monitoring, health monitoring, environmental monitoring and many more [2]. Each sensor node is able to collaborate in order to monitor, collect data and transmit among each other or to the base station. These sensor nodes are usually dependent on battery power supplies in order to sustain the communication link.

In the vast and progressing technology, WSN has become one of most important key features in the advancement of communication. WSN consists of sensor nodes in bulks that are able to sense their environment and transmit such measurements from the specific parameter to a reserved base station (BS) where the data is processed and stored [3]. Due to the rising technology, the sensor nodes have become smaller and low cost which made it is feasible in term of technicality and economically. WSN has become major interest for researcher in recent years due to the great potential for a wide range of applications [4].

Since the deployment of the sensor nodes can be in a harsh environment where it is inaccessible to human being, the replacement of batteries could be an impossible mission. Likewise, all of the operation involving the sensor nodes whether in sensing, storing data or communication typically are consuming a lot of power [5]. Due to energy limitation and constraint in communication capabilities, the undesirable high battery power consumption has become one of the major issues in WSN.

The intention of this paper is to improve the radiation beampattern performance in order to compensate the power consumption in WSN. Therefore, a Collaborative Beamforming (CB) method is introduced with the aim to achieve the maximum power gain for the antenna array.

CB can be used to create an establishment for the communications between a sensor network and base station. CB is a technique to increase the antenna gain and performance by aiming at the desired objective through intelligent capabilities. It can also reduce the energy consumption in a single node.

In CB, the deployment of random nodes position will affect the performance result of the main lobe and the side lobe level (SLL) of the beampattern. The significant position error of nodes has been studied in [6]. Several works using CB method are based on node selection optimization algorithm (NSOA) [7-9] in order to control the SLL. The proposed algorithm has analyzed the performance of main lobe and SLL in terms of the average number of trials and the achieved SLL suppression. A novel CB method based on hybrid least square speedy particle swarm optimization-based has been utilized to determine the optimum location of sensor node with minimum SLL and controllable size of FNBW [10].

Consequently, the main challenge of this proposed work is to design an efficient algorithm that can determine the optimum location of sensor nodes, for any given random nodes deployment. The sensor design should be simple, reliable and highly energy efficient. The efficient algorithm that consumes less energy for computation and communication is desirable. In this paper, only the selective sensor nodes will cooperate among each other and act as a collaborative antenna array. The configuration of these selection of collaborative nodes will be modeled in circular array formation. Hence, CB algorithm is proposed in order to select the optimum position of circular array nodes by implementing Backtracking Search Optimization Algorithm (BSA). BSA is a simple metaheuristic algorithm that adept in solving numerical optimization problems. BSA has much simpler structure that capable in solving multimodal problems and its boundary control mechanism is very effective in achieving population diversity, which ensures efficient searches [11].

The proposed Backtracking Search Optimization-based Collaborative Beamforming (BSA-based CB) algorithm is expected to improve the transmission gain and radiation beampattern performance. Hence, the power consumption in the WSN can be reduced significantly. The proposed algorithm is also simple, reliable and highly energy efficient. Up to date, a CB approach to determine optimum sensor nodes location to participate in WSN by employing BSA algorithm has not been reported or published so far by other authors.

2. Proposed Collaborative Beamforming Method

This paper is basically to develop a system where an efficient CB algorithm is implemented in order to determine the optimum location of the sensor nodes in circular array formation. CB technique will improve the performance of radiation beampattern by increasing the antenna gain and minimize SLL with aiming at the desired objective through intelligent capabilities.

The sensor nodes are located randomly in WSN environment. The configuration of the collaborative nodes will be modeled in circular array formation as illustrated in Figure 1. It is shown that only the selected sensor nodes will transmit synchronously towards any desired angle or direction.

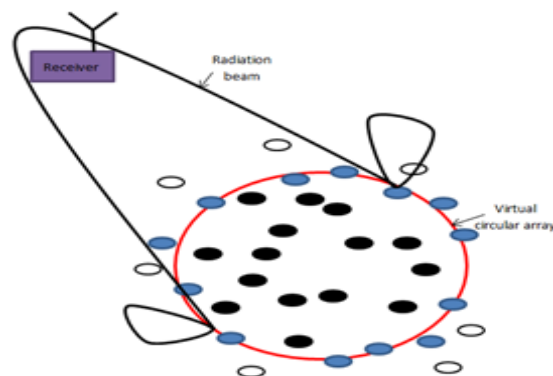


Figure 1. CB in circular array formation

In a network, the stationary sensor nodes will be randomly placed at the position S network= $(s_1, s_2, \dots, s_{\text{network}})$. Each of the sensor node denoted in the Cartesian coordinate (x_k, y_k) where k represent the total number of nodes. The angle $\phi = [-\pi, \pi]$ represents the azimuth direction and $\theta = [0, \pi]$ represents the elevation direction.

2.1. Circular Array Factor Modelling

Circular arrays can provide a 2D angular scan, both horizontal ϕ and vertical θ scans. Circular arrays are basically 1D linear arrays but in a circular form that allow array to be scan horizontally for 360° with no distortions near the end-fire directions. The distortions in the array pattern of a circular array due to mutual coupling effect are same for each element and this makes it easier to deal with the mutual coupling effect.

The collaborative array of the antenna is equipped with a single omnidirectional antenna element for each sensor node. Hence, all of the sensor nodes are located on a 3-dimensional plane which represented by plane x , y and z . By assuming plane $z=0$, the plane will be parallel to the earth's surface. Therefore, the array factor (AF) of circular array is given as follows [12]:

$$AF(\theta, \phi) = I_n \sum_{n=1}^N e^{j[kr_n \sin \theta \cos(\phi - \phi_n) + \alpha_n]} \quad (1)$$

Where:

$$\alpha_n = -kr_n \sin \theta_0 \cos(\phi_0 - \phi_n), \quad (2)$$

$$r_n = \sqrt{(x_n)^2 + (y_n)^2} \quad (3)$$

$$\phi_n = \tan^{-1} \frac{y_n}{x_n}, \quad (4)$$

Here : ϕ_n : $2\pi \times \frac{n-1}{N}$ Angular position of the n th element on the x - y plane,

k : Wave-number, where $k=r=N.d$ and d denotes angular spacing between elements,

r : Radius of the circle defined by the circular array,

ϕ_0 : Direction of maximum radiation,

ϕ : Angle of incidence of the plane wave,

α_n : Phase excitation of the n th element.

In this equation, I_n and α_n represent the amplitude and phase excitation for the n th element of the sensor nodes, respectively. N represent number of nodes and d is the distance between two sensor nodes. ϕ is the azimuth angle measured from the positive x -axis, and θ is the elevation angle measured from the positive z -axis. Moreover, θ_0 and ϕ_0 are the direction of the main beam or the position of the base station or sink node. The normalized power gain, G , in decibel is stated as follow:

$$G(\theta, \phi)_{db} = 10 \log_{10} \left[\frac{|AF(\theta, \phi)|^2}{\max |AF(\theta, \phi)|^2} \right] \quad (5)$$

3. Backtracking Search Optimization Algorithm (BSA)

BSA is an evolutionary algorithm (EA) for solving real-valued numerical optimization problems based in iterative process. EAs are widely used to solve non-linear, non-differentiable and complex numerical optimization problems. BSA can be used to optimize array pattern to suppress side lobes while maintaining the gain of main beam [13-15].

BSA has a simple structure that is effective, fast and capable of solving multimodal problems. BSA is an approach of mathematical solving that allows it to easily accustom to numerical optimization problems. BSA's boundary control mechanism is very effective in achieving population diversity, which ensures efficient searches. BSA has applied new strategies for crossover and mutation operations in generating a trial population and it has quite powerful local and global search abilities.

Figure 2 depicts the flow of the BSA system. Firstly, it will generate the initial population. Population P represents by real value which indicate the coordinate of the cluster head. Then,

the historical population, oldP is also generated following the same method as initial population, P.

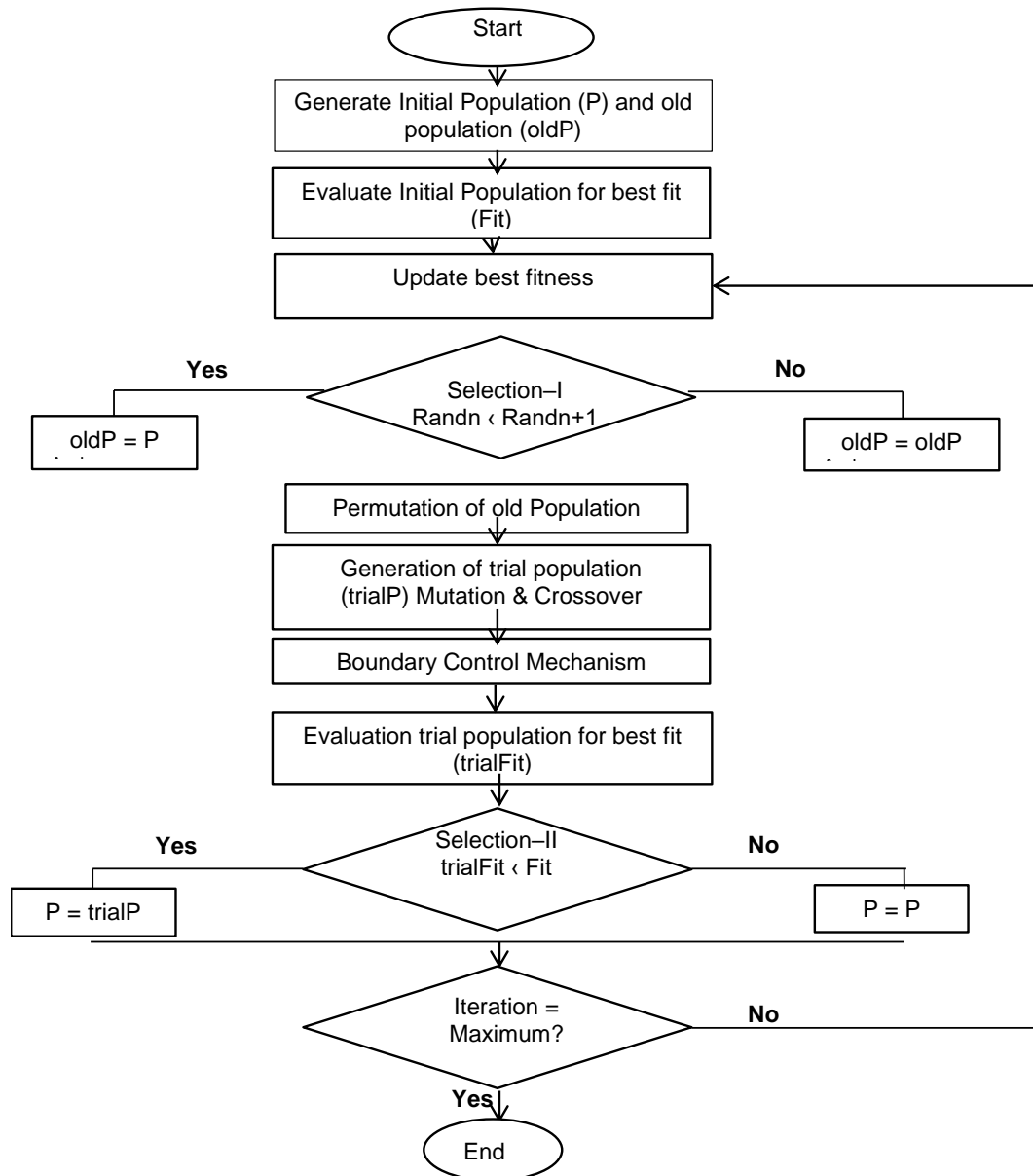


Figure 2. General structure of BSA

After initialization, both of the population will go through first selection to find the best fitness among each other. In BSA, This historical population can be restructured at the starting of iteration by using the 'if-then' rule as follows:

$$\text{if } a < b \text{ then oldP} := P|_{a,b} \sim U(0,1) \quad (6)$$

Where, $:=$ is the update operation and $U(0,1)$ is a random number between 0 and 1. Since, BSA has advantage in keeping a memory where it sets a population belonging to a randomly selected previous generation as oldP and remembers this oldP until it is changed. Subsequently, the individuals in oldP sequence is randomly altered using shuffling function as:

$$\text{oldP} := \text{permuting}(\text{oldP}) \quad (7)$$

The initial form of trial population Mutant is created using the following function:

$$\text{Mutant} = P + F \cdot (\text{oldP} - P) \quad (8)$$

Where, F is a generation strategy that is used to control the amplitude of the search-direction matrix ($\text{oldP} - P$). BSA is taking partial advantage of its experiences from previous generation to generate a trial population. The crossover process produces the final form of the trial population, TrialP. In Selection II stage, P will be replaced to corresponding TrialP if they have better fitness values. The best individual of P , known as Pfit is set as global minimizer if its fitness value is better than global minimum. The iteration will take loop until it reaches the maximum.

4. Results and Analysis

The performance of the proposed BSA-based CB algorithm is illustrated in term of radiation beampattern. The computed optimization results in radiation beampattern are analyzed for different cases of number of nodes involved. The validation performances are demonstrated between BSA and corresponding results obtained from conventional uniform circular array (CFA). The parameter set up for the array factor is shown in Table 1 as follows:

Table 1. List of Parameter used in CB

Parameter	Symbol	Value
Direction of main beam	θ_0	0°
Frequency	f	150 MHz
Iteration	It	200

Case 1: A 10-node circular array is considered with first null beam width (FNBW) of 42° . The computed radiation beampattern is shown in Figure 3. It is clearly observed that the suppression of SLL for BSA is better than the radiation beampattern obtained for CFA. The minor lobes have been minimized with the highest peak of SLL to be approximately -6.3 dB. Compare to CFA, the highest peak is -3.63 dB. In Figure 4, the iteration for radiation beampattern of 10-node BSA is presented. It is observed that out of 200^{th} iteration, it takes 71^{th} iteration to achieve convergence time of fitness function.

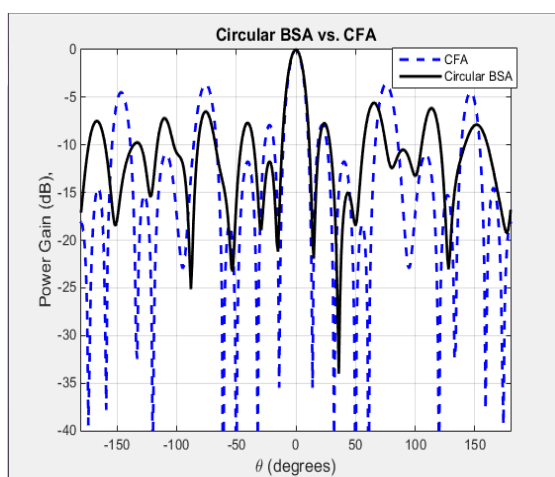


Figure 3. Radiation Beampattern of 10-node BSA against CFA

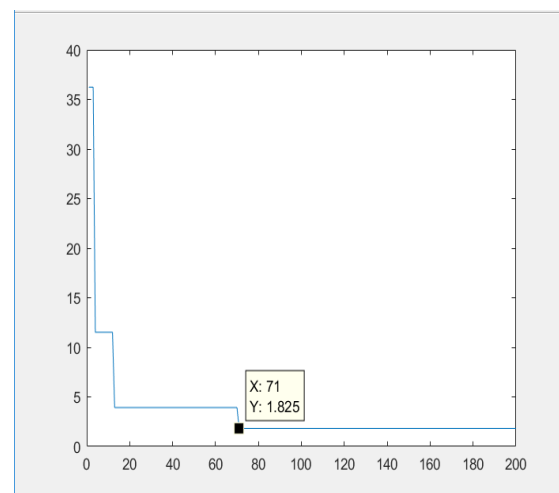


Figure 4. Iteration for Fitness Function of 10-node BSA

Case 2: A 12-node circular array is considered with FNBW of 32° . The computed radiation beampattern is shown in Figure 5. The FNBW is slightly narrower compared to the radiation beampattern of 10-node circular array. CFA exhibits relatively high SLL at -65° and 65° with -3.85 dB of power gain. Compared to CFA, the highest SLL for BSA is at -6.06 dB which indicate a higher minimization level of SLL. In Figure 6, the iteration for radiation beampattern of 12-node BSA is presented. It is observed that out of 200th iteration, it takes 43rd iteration to achieved convergence time of fitness function.

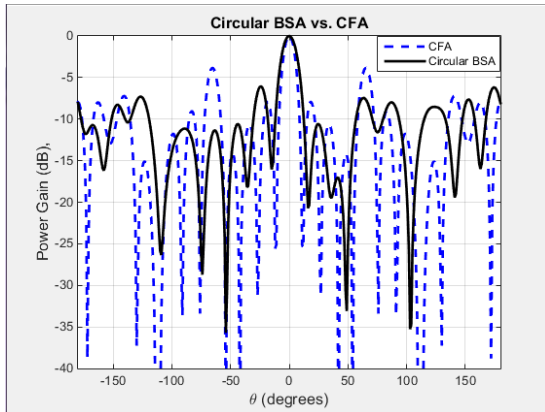


Figure 5. Radiation Beampattern of 12-node BSA against CFA

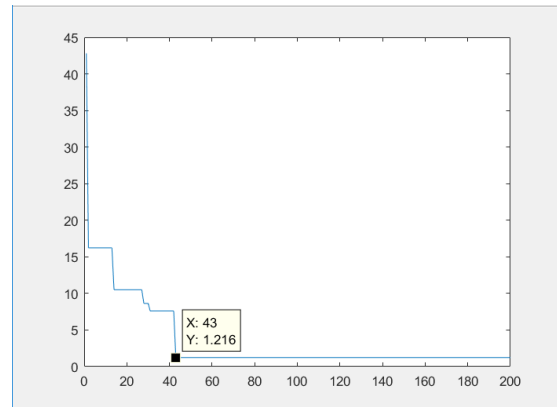


Figure 6. Iteration for Fitness Function of 12-node BSA

Case 3: A 16-node circular array is considered with FNBW of 41° . The computed radiation beampattern is shown in Figure 7. It is clearly observed that the suppression of SLL for BSA is better than the radiation beampattern obtained for CFA. The minor lobes have been minimized with the highest peak of SLL to be approximately -7.27 dB. Compare to CFA, the highest peak is -4.01 dB. In Figure 8, the iteration for radiation beampattern of 16-node BSA is presented. It is observed that out of 200th iteration, it takes 53rd iteration to achieved convergence time of fitness function.

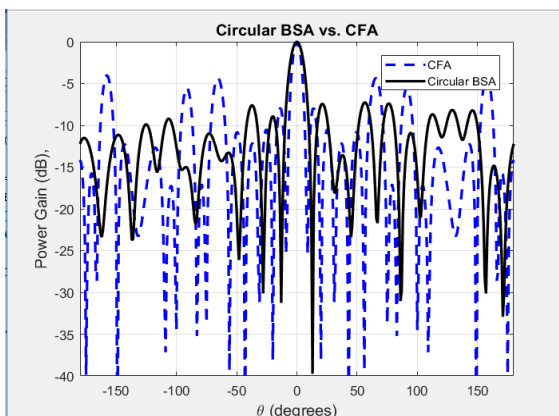


Figure 7. Radiation Beampattern of 16-node BSA against CFA

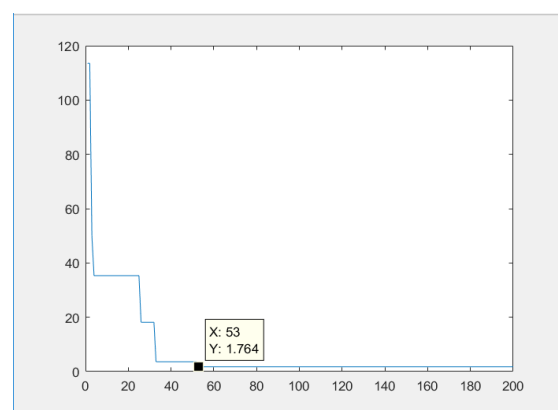


Figure 8. Iteration for Fitness Function of 16-node BSA

The performance of the radiation beampattern is observed. Based on the observation, the proposed algorithm is able to improve the radiation beampattern performance by designing sensors that are simple, reliable and highly energy efficient. The efficient algorithm is able to

determine the optimal circular array nodes, thereby producing the maximum power gain for the antenna array. Hence, the power consumption in the WSN can be reduced significantly with the SLL minimization.

From the finding, we can conclude that the proposed BSA-based CB algorithm can improve the performance of the radiation beampattern. It is observed that BSA is able to suppress the SLL as compared to CFA. The maximum power gain achieved indicates the successful minimization of SLL. As the number of nodes increasing, the FNBW is narrowing.

5. Conclusion

The problem of array beamforming is the presence of error beampattern caused by random sensor position errors. Thus, this paper has successfully ensured the minimization of side lobe level which manage to improve the performance of the radiation beampattern. The radiation beampattern expression of the proposed algorithm is obtained, and it is further proved. Different number of nodes have been successfully analyzed and proven. This efficient algorithm is able to determine the optimal circular array nodes, thereby producing the maximum power gain for the antenna array. Hence, the power consumption in the WSN can be reduced significantly.

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