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Node Collaboration for Distributed Beamforming in Wireless Sensor Networks

Chen How Wong, Zhan Wei Siew, Hou Pin Yoong, Aroland Kiring, Kenneth Tze Kin Teo
Modelling, Simulation & Computing Laboratory, Material & Mineral Research Unit
School of Engineering and Information Technology
Universiti Malaysia Sabah
Kota Kinabalu, Malaysia
msclab@ums.edu.my, ktkteo@ieee.org

Abstract—**Collaborative beamforming (CB) is introduced in wireless sensor networks (WSNs) to improve the transmission power and the energy efficiency of the networks. Using a subset number of nodes from a network of sensors, they collectively transmit a common message with different proper weights to an intended location. Different geometrical location of the subset of nodes will produce different transmission gains. Due to erratic deployment of the sensor nodes in the networks, the 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 circular array is presented. Simulation and performance analysis are carried out to demonstrate the beam pattern performance of uniform circular in performing collaborative beamforming.**

Index Terms— **Collaborative beamforming; circular array; array signal processing; wireless sensor networks.**

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.

In WSNs, one of the important constraints is energy source. To improve the energy conservation during the communication duration, network protocol such as LEACH is introduced in WSNs [1], [2]. The protocol has been further improved using fuzzy [3] and Adaptive Particle Swarm Optimization algorithm [4] which has shown notable improvement in extending the lifetime of the sensor nodes. Alternative solutions such as collaborative beamforming (CB) is introduced to increase the energy conservation in [5]-[7]. A cluster of sensor nodes in collaborating among themselves to transmit a shared transmission message to an intended destination. The cluster acts as a virtual antenna array, producing high directivity, beamformed signal to the intended destination. Consequently, it does not only significantly improve the transmission range but can also be energy efficient because the required transmission energy is spread over the nodes.

Several efforts have been studied for CB in WSNs context. The fundamental analysis of the CB for uniform nodes distributions is derived by [8], where the beam pattern performance is investigated based on random array theory developed by [9]. The analysis for Gaussian nodes distribution was further studied by [10]. Due to the random placement of the sensor nodes, phase errors occur which could degrade the resultant beam pattern. To overcome the problem, a uniform linear array has been proposed to select participating nodes to perform a suitable beam pattern by [11], [12]. The solution based on uniform linear array can be further optimized using Particle Swarm Optimization or genetic algorithm [13], [14]. Both solutions show a reduction in sidelobe level (SSL). Inspired by [11], this literature investigates a node selection scheme based on uniform circular array (UCA). Circular line least square fitting technique is used to obtain the optimal participle nodes.

The details of this paper are organized as follow. Section II presented the model of the WSNs and the uniform circular array factor. In section III, the node selection method based on UCA sensor nodes is described. The performance analysis metric is explained in section IV. The simulation results and discussions are presented in section V. Finally, section VI concludes the paper.

II. SYSTEM MODEL

A. Sensor Network Model

Consider a cluster of sensor nodes in the WSNs are randomly distributed over the x-y plane and as shown in Fig. 1.

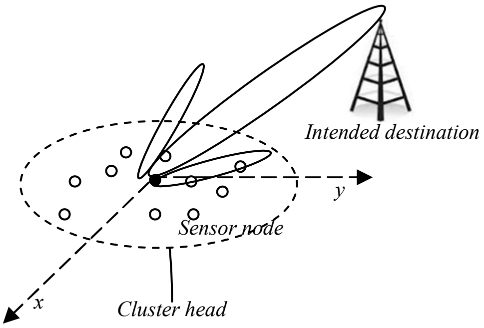

Fig. 1. Cluster of sensor nodes collaborative beamforming to intended destination.

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The following assumptions are made in the WSNs networks:

- The locations of nodes are randomly distributed in the networks following a uniform distribution.
- Each of the node location is identified.
- Intended destination and sensor nodes are stationary in the networks.
- Each node has a single isotropic antenna.
- Data sharing is permitted among nodes in a cluster networks.
- The intended destination point is located in far-field.
- No multipath fading or shadowing effect in the WSNs.

B. Uniform Circular Array Factor

UCA has been found in many applications such as smart antenna, and sonar system. One of the advantages for UCA is the reliable capacity in directional communication systems.

Consider N number of sensor nodes located in a circle with radius R on the x-y plane with uniformly spacing d as shown in Fig. 2. Let O denote the intended destination which is expressed by the spherical coordinate (r_o, θ_o, ϕ_o). The $\theta\in[0, \pi]$ represents elevation angle and $\phi\in[-\pi, \pi]$ is the azimuth angle of the signal. The location of each nodes is represented by polar coordinate (r_i,,ϕ_i) , where i represent the nodes number.

The array factor of the N sensor node is given by (1).

$$AF(\theta,\phi)=\sum_{i=1}^{N} I_i e^{(jkR(\cos(\theta-\phi_i)+\beta_i)} \tag{1}$$

where

$$kR=\sum_{i=1}^{N} d_i \tag{2}$$

$$\phi_i = 2\pi(i+1)/N \tag{3}$$

$$\beta_i = -kR\cos(\theta_o-\phi_i) \tag{4}$$

I_i represents the excitation of the ith element of the array which is assumed unity, d_i is internodes distance from element i to i+1. $k=2\pi/\lambda$,is the wave number, and λ represent the wavelength of the transmission frequency.
The normalized beam pattern for can be expressed using (5).

$$G(\theta,\phi)_{dB}=\frac{|AF(\theta,\phi)|^2}{\max|AF(\theta,\phi)|^2} \tag{5}$$

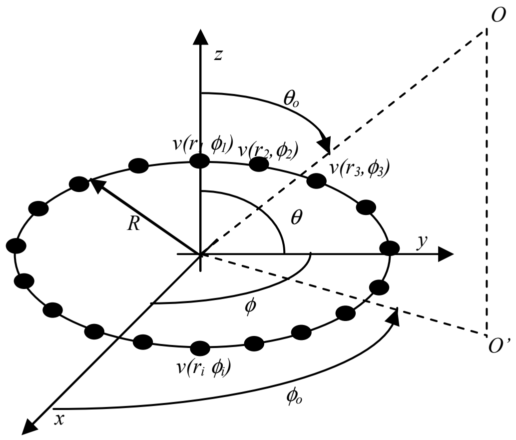

Fig. 2. Uniform circular array.

III. NODE SELECTION BASED ON UNIFORM CIRCULAR ARRAY

The objective of the node selection scheme based on UCA is to approximate the beam pattern performance of the sensor array node as close as possible to the UCA. The subset of the participle sensor nodes will share transmission data among themselves within the active cluster to perform CB.

Inside the cluster of the WSNs, a node which acts as cluster head must be selected to communicate with its surrounding nodes to perform CB. The location of the cluster head will be the center of the UCA.

The desired total number of sensor nodes, N, must be defined first before the virtual array is structured. Virtual array node location of UCA is then constructed based on the requirement total number of sensor nodes and the circle radius R. To avoid grating lobe effect, the internodes spacing of the UCA must follow the constraint defined in (6).

$$\lambda/2 \le \frac{2\pi R(i+1)}{N} \tag{6}$$

The virtual array nodes location $V(x_i,y_i)$ will be the reference of the scheme to select the collaborative nodes. The algorithm will choose the closest node $C(x_i,y_i)$ by comparing it with the virtual array nodes location. In this case, the constraint (7) must be fulfilled by the node in order to be selected to perform CB.

$$C(r_i,\phi_i)=\min|V(r_i,\phi_i)-S(r_i,\phi_i)| \tag{7}$$

where $V(x_i,y_i)$-$S(x_i,y_i)$ is the distance between the virtual node and the neighbor node within the active cluster. The flowchart of the Node Selection based on UCA is shown in Fig. 3.

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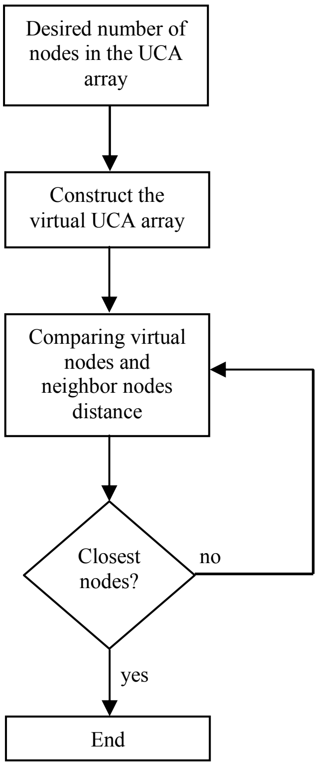

Fig. 3. Node selection based on uniform circular array.

IV. PERFORMANCE ANALYSIS METRIC

The effectiveness of the node selection based on UCA must be analyzed in order to measure the performance of the approach. The comparison between the sensor nodes array based on UCA must be compared with the original virtual UCA.

To examine the performance of the approach, similar metric by [11] is used here. This metric is introduced to calculate the total errors in distance between the selected nodes and the original virtual UCA as shown in Fig. 4.

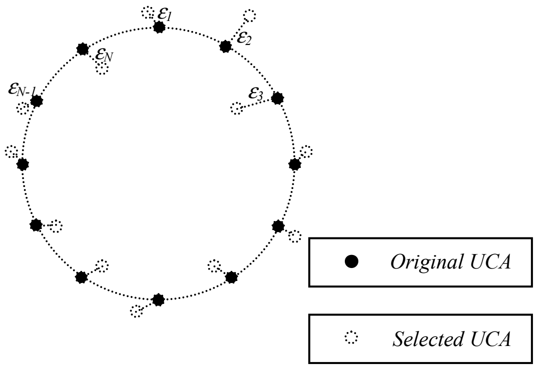

Fig. 4. Total errors distance between original and selected UCA.

The total error Euclidean distance (EED) for N element UCA is express by (8).

$$\varepsilon_{total} = \sum_{i=1}^{N} \varepsilon_{\mathrm{i}} \tag{8}$$

V. SIMULATION AND DISCUSSION

Several cases of WSNs model are simulated to study the behavior and performance of the node selection method. The simulation parameters are summarized in Table 1.

For each of the simulation, the density of the network is ranged from 100 to 1200 number of nodes. 1000 trials of Monte Carlo simulation were performed to find the average beam pattern. The mean of the total EED error calculated using the performance metric is described in section IV.

To study the effect of nodes number of the node selection method, simulation result of case 1 and case 2 has been compared in terms of EED as shown in Fig. 5. When the density of the WSNs is low as 100 and the nodes in the selection method increase, the total EED of case 2 increase approximate 2.5 times larger compare to case 1. As the density increase, the EED continues to decrease. The EED remains steady after the density of nodes is 600 for case 1 and 800 nodes for case 2. A higher EED means the selection nodes does not mimic the virtual UCA. The average beam pattern case 1 and case 2 with density 100 nodes is show in Fig. 6. The result in Fig.6 shows that the selection method can perform better beam pattern compare to the virtual UCA in low density network. Increasing the number of selection nodes can slightly improve the directivity. The average beam pattern case 1 and case 2 with 800 nodes is shown in Fig. 7.

Simulations of case 2 and 3 are to investigate the effect of active cluster size for the node selection method. The result of EED is shown in Fig. 8. Larger active cluster in case 3 have slightly higher EED as compare to the smaller active cluster in case 2. High EED of the case 3 review the method does not mimic virtual UCA. The average beam pattern for case 2 and 3 with it virtual UCA is shown in Fig. 9. The beam pattern for case 3 has the narrowest main beam follow by beam pattern of case 2 and the virtual UCA. It reviews that the virtual UCA does not has the optimum beam pattern performance and increase of cluster size can achieve better beam pattern.

TABLE I. LIST OF SIMULATION PARAMETER TO MODEL THE WSNS

	Case 1	***Case 2***	***Case 3***	***Case 4***	***Case 5***	***Case 6***
Sensor deploment area (m^2)	100	100	100	100	100	100
Total nodes number	10	20	20	20	20	20
Cluster radius, *m*	2	2	4	4	4	2
Frequency (M*Hz*)	300	300	300	300	300	600
Virtual UCA radius, *m*	1	1	1	3	4	1

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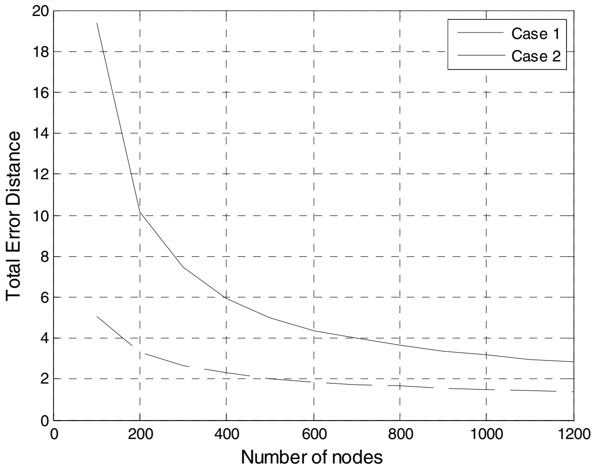

Fig. 5. Total EED for case 1 and 2.

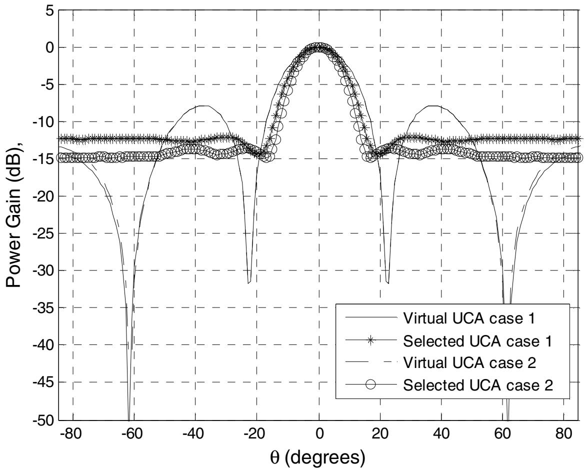

Fig. 6. Average beam pattern for case 1 and 2 with density of 100 nodes.

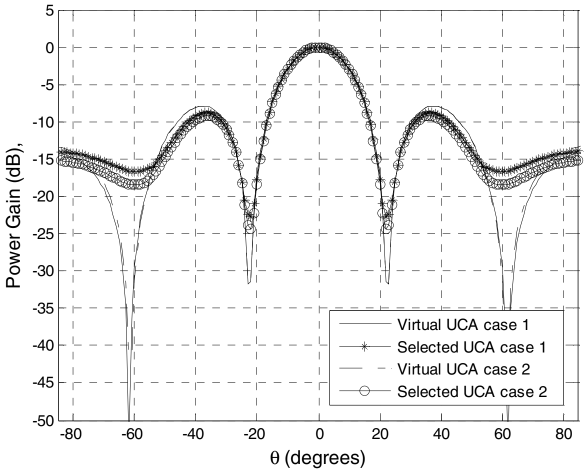

Fig. 7. Average beam pattern for case 1 and 2 with density of 800 nodes.

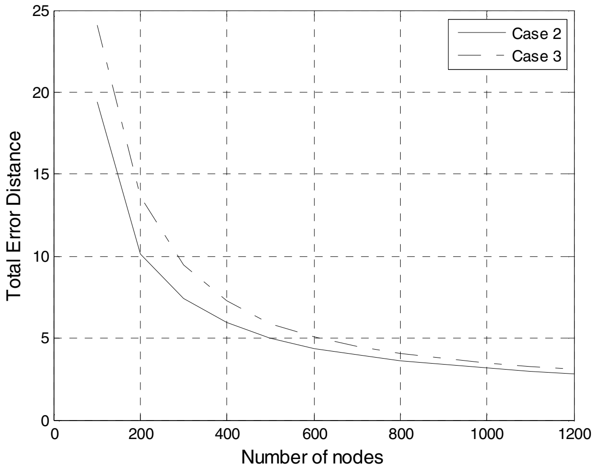

Fig. 8. Total EED for case 2 and 3.

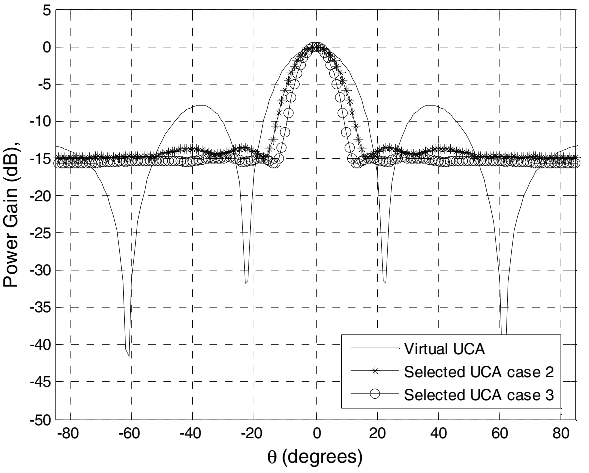

Fig. 9. Average beam pattern for case 2 and 3.

Simulation of Case 4 and 5 is to study the effect of virtual UCA's size. The result of EED for both cases is same and shown in Fig. 10. It reviews that increasing the virtual array size does not influence the performance for same cluster size. The average beam pattern with density of 100 nodes is shown in Fig. 11. Increasing the virtual UCA size does not only improve the beam pattern performance but also improve the method's performance in mimicking the virtual UCA.

Case 2 and 6 is simulated and compared to study the effect of transmission frequency of the method. The result of EED is shown in Fig. 11. The average beam pattern is shown in Fig. 12. The EED result is same for both cases. It review that the selection method is independent to the transmission frequency. However, as the transmission frequency increase, the directivity of the beam pattern will increase as well. This follows the conventional theory of electromagnetic and array signal processing.

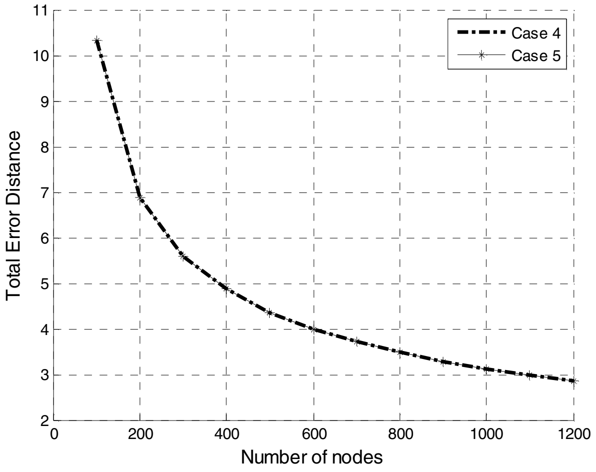

Fig. 10. Total EED for case 4 and 5.

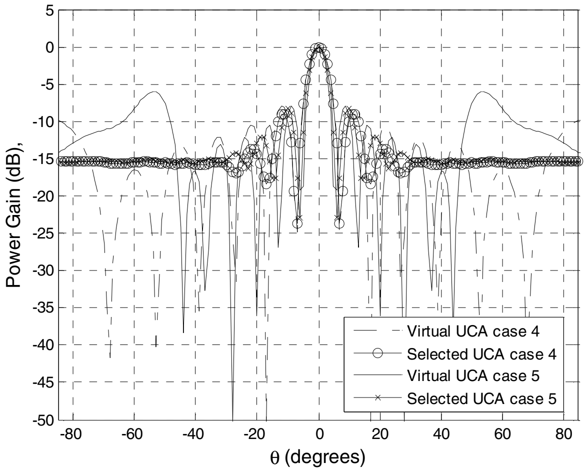

Fig. 11. Average beam pattern for case 4 and 5 with density of 100 nodes.

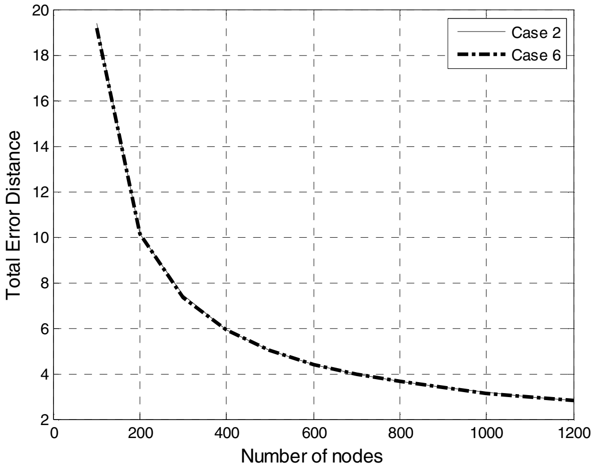

Fig. 12. Total EED for case 2 and 6.

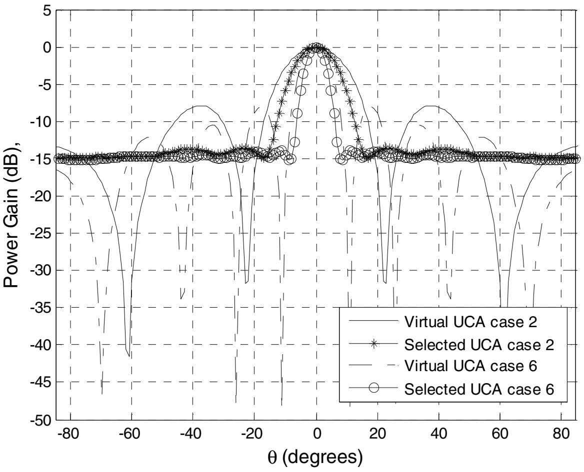

Fig. 13. Average beam pattern for case 2 and 6.

VI. CONCLUSION

The performance of the node selection based on UCA has been investigated and analyzed. Using the node selection method, the radius of the virtual array needs to be set as same as the cluster size in order to optimize the beam pattern. The selected nodes can mimic the beam pattern of the UCA if the density of the WSNs is high enough. In low density WSNs, the selection method can outperform the virtual UCA beam pattern with similar directivity and low SSL. For future study, different geometric arrangements of sensor array could be used as reference models to improve the performance of CB.

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