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# Collaborative Beamforming Optimization using Imperialist Competitive Algorithm

***Abstract**. This study focuses on optimizing the spacing between element of virtual non-linear antenna array (LAA) using Imperialist Competitive Algorithm (ICA) to form collaborative beamforming (CB) in wireless sensor network (WSN). The spacing between element is optimized to produce a beampattern with minimize sidelobe level (SLL) and narrow First Null Beamwidth (FNBW). The results are compared with Backtracking Search Algorithm (BSA) and conventional LAA (ULA) to study the superiority of ICA in optimizing beampattern. The results show that ICA able to reduce maximum SLL until 25.9% and 23% as compared to ULA and BSA respectively.*

***Streszczenie.** Niniejsze badanie koncentruje się na optymalizacji odstępów między elementami wirtualnej nieliniowej macierzy antenowej (LAA) przy użyciu imperialistycznego algorytmu konkurencyjnego (ICA) w celu utworzenia wspólnego kształtowania wiązki (CB) w bezprzewodowej sieci czujników (WSN). Odstęp między elementami jest zoptymalizowany w celu uzyskania wzoru wiązki z minimalnym poziomem płatków bocznych (SLL) i wąską pierwszą zerową szerokością wiązki (FNBW). Wyniki są porównywane z algorytmem Backtracking Search Algorithm (BSA) i konwencjonalnym LAA (ULA) w celu zbadania wyższości ICA w optymalizacji wzorca wiązki. Wyniki pokazują, że ICA jest w stanie zredukować maksymalny SLL do 25,9% i 23% w porównaniu odpowiednio do ULA i BSA. (**Wspólna optymalizacja kształtowania wiązki przy użyciu imperialistycznego algorytmu konkurencyjnego**)*

**Keywords:** collaborative beamforming, metaheuristic algorithm, WSN.
**Słowa kluczowe:** wspólne formowanie wiązki, algorytm metaheurystyczny, WSN.

## Introduction

Wireless sensor network (WSN) consisting of a large numbers of sensor nodes that are randomly distributed in a wide monitoring area that have been widely used for data collection in various application [1]–[3]. WSN nodes are equipped with data processing and wireless transmission capabilities [2]. Given the restriction on node size, economic cost, calculation ability and infeasibility, the sensing range and communication range of a single node are limited [3]. Therefore, the multi-hop communication has to be used to communicate with the base station (BS) that is located far away from monitoring area for final processing [2]–[4]. However, this results in the increased communication delay, reduce communication reliability and leads to high routing overhead which are unacceptable for scenarios that require real time performance [3], [5]. Collaborative beamforming (CB) is an effective technique for improving the energy efficiency and communication performance of WSNs [3]. In CB, sensor nodes can form a virtual antenna array (VAA) to perform high directivity and high gain beam to achieve direct communication with the BS without multi-hop [3], [6]. However, the randomly distributed nodes of VAA causes higher side lobe level (SLL) of the beam patterns, which also increases the interference and reduces the amplitude concentration of the main lobe [4]. Thus, it is important to suppress the maximum SLL of VAA in CB.

Nonetheless, the optimization of beampattern is a non-linear problem which cannot be solved by conventional methods [7], [8]. With the rapid development of computer technology, there are a lot of metaheuristic algorithms that have been applied to the beampattern optimization such as Particle Swarm Optimization (PSO) [9], Genetic Algorithm (GA) [10], Backtracking Search Algorithm (BSA) [11], Chicken Swarm Optimization (CSO) [12], Firefly Algorithm (FA) [13] and Cuckoo Search Algorithm (CSA) [14]. These highly flexible algorithms have few restrictions on the optimization objectives, which make them suitable to solve the complicated and non-linear optimization problems [15]–[18]. Hence, the algorithms have gain interests among researchers in optimizing designing antenna array to reduce maximum SLL.

WSNs can be divided into two types of sensor nodes which are static WSN [2]–[5], [19]–[29] and mobile WSN (MWSN) [30]–[35]. The suppression of maximum SLL of CB can be done through optimizing node selection and node position for static and mobile WSN respectively. Node position involves carefully choosing the optimal site for each antenna and positioning it, whereas node selection works on the basis that the position of the antenna elements in an array are selected [36]. Optimizing node selection and position in the better positions to form VAA can reduce the maximum SLL [4], [35]. Previous studies have introduced several techniques to optimize node position of MWSN using metaheuristic algorithms. An Improved Non-Dominated Sorting GA (INSGA-II) [30] Distributed Parallel CSA (DPCSA) [1], Improved CSA (IPCS) [31] and Improved Multi-objective Dragonfly Algorithm (IMODACH) [32] are introduced to optimize the position of MWSN to form a random array of CB.

Those methods successfully reduce SLL, motion energy consumption and transmission rate of MWSN. Node selection methods in the form of LAA to perform CB have been proposed by [19] to reduce maximum SLL by calculating optimal number of array node from 1000 random sensor nodes to form LAA using CSA. Aside from LAA form, there are also some researches that use Circular Array Antenna (CAA) form as a guide array in node selection optimized by PSO [25] and BSA [26] to reduce maximum SLL. In VAA, an array node influences not only the electromagnetic (EM) field generated by its own amplitude but also by other nodes [5]. In addition, the shapes of the antenna array also affect the maximum SLL, where the maximum SLL generated by a regularly-shaped antenna array is lower than that of a random array with the same number of elements [4].

Moreover, it has been proven in the no free lunch (NFL) theorem that an ultimate metaheuristic method that works for all optimization problem does not exist [37]. Thus, we proposed an Imperialist Competitive Algorithm (ICA) to solve the beampattern optimization of CB. ICA is a recently developed metaheuristic algorithm introduced by [38]. The algorithm was inspired by socio-political behaviours which is more intelligent than biological behaviour [39]. ICA has been applied in many engineering fields for image processing, data clustering, designing PID controller and scheduling which confirm its competitiveness over other evolutionary algorithms in term of convergence rate [39]. However, ICA has not yet been applied in optimizing the beampattern of antenna array which gives the opportunity in this paper to prove that the algorithm able to solve the optimization problem in designing VAA. A group of array nodes based on LAA due to its simplicity and regular-shaped is chosen to form VAA of CB by including constraint to avoid the mutual coupling and grating lobe.

In this paper, ICA is applied to optimize the element spacing of a non-linear LAA due to the assumption of randomly distributed VAA that can be the reference array for node selection or node positioning in CB. The optimization of element spacing of non-linear LAA is proposed to fulfil the multi-objectives optimization (MOO) which are to reduce the maximum SLL and FNBW as well as reduce power gain at null placement.

**Array Factor of LAA**

The array factor of LAA is referred by [20] and [40]:

(1) $$AF(\theta,\phi) = \Sigma\, e^{j\zeta_n} e^{j\alpha_n}$$

Both the current signal phase, $\zeta$ and the synchronizing phase weight, $\alpha$ can be determined by:

(2) $$\zeta_n = K(x_n \sin\theta \cos\phi + y_n \sin\theta \sin\phi + z_n \sin\theta)$$

(3) $$\alpha_n = -K(x_n \sin\theta_0 \cos\phi_0 + y_n \sin\theta_0 \sin\phi_0 + z_n \sin\theta_0)$$

where $K$, $\theta$, $\phi$, $x_n$ and $y_n$ are the wave number $K = 2\pi/\lambda$ with $\lambda$ is the wavelength, elevation angle, azimuth angle, $x$-coordinate and $y$-coordinate $(x_n, y_n)$ of the $n^{th}$ element respectively. $\theta_0$ and $\phi_0$ are the maximum radiation angles.

**Problem Formulation of Fitness Function**

In this paper, the distance between element is optimized to fulfil three objective functions in MOO which are to reduce the maximum SLL, and FNBW with null steering capability. These MOO functions have been proposed in [20]. The objective function SLL minimization, $of_{SLL}$ is represented in:

(4) $$of_{SLL}(\theta_{SLL}) = \Sigma|AF(\theta_{SLL1})|_{dB} + \Sigma|AF(\theta_{SLL2})|_{dB}$$

where $\theta_{SLL1}$ and $\theta_{SLL2}$ are the angles where the SLL is minimized in the lower band and in the upper band respectively. AF is the array factor as in equation (1). $of_{nu}$ is the objective function of null placement which is defined as:

(5) $$of_{nu}(\theta_{nu\varsigma}) = \Sigma|AF(\theta_{nu\varsigma})|_{dB}$$

where $\varsigma$ and $\theta_{nu}$ are the number of nulls and the location angles of null-placements. $of_{bw}$ is the objective function of FNBW as defined:

(6) $$of_{bw}(\theta_{bw}) = \Sigma|AF(\theta_{bw})|_{dB}$$

where $\theta_{bw}$ is the angle of desired FNBW which is the range of angles of the major lobe.To fulfil the objective function, the boundary constraint of spacing between sensor node is applied in this paper [37]. The following condition of minimum spacing between sensor nodes, $x_i$ and $x_j$ must be satisfied in order to overcome the mutual coupling:

(7) $$|x_i - x_j| > 0.25\lambda$$

(8) $$\min\{x_i\} > 0.25\lambda \qquad i = 1, 2, ...., N. \qquad i \neq j$$

To avoid grating lobe, the largest distance, $d_{max}$ between sensor nodes should be less than one wavelength [40]:

(9) $$d_{max} < \lambda$$

This paper also aimed to optimize the trade-off of the radiation pattern in terms of peak SLL, FNBW size and null placements. The trade-off is implemented into multi-objective fitness functions that evaluates the beampattern properties simultaneously. The multi-objective fitness function, *mulobj* is defines by considering the weightage function $w_i$ as:

(10) $$mulobj = (w_1 \cdot of_{SLL}) + (w_2 \cdot of_{nu}) + (w_3 \cdot of_{bw})$$

$w_i = 1, 2, 3$ is the user defined constant that controls the contribution of fitness function.

**Imperialist Competitive Algorithm (ICA)**

ICA is inspired by socio-political behaviours of modern colonialism in 1870 when developed countries attempted to take over less developed countries; colonize them or influence them to extend their power [39]. Figure 1 shows the flowchart of ICA.

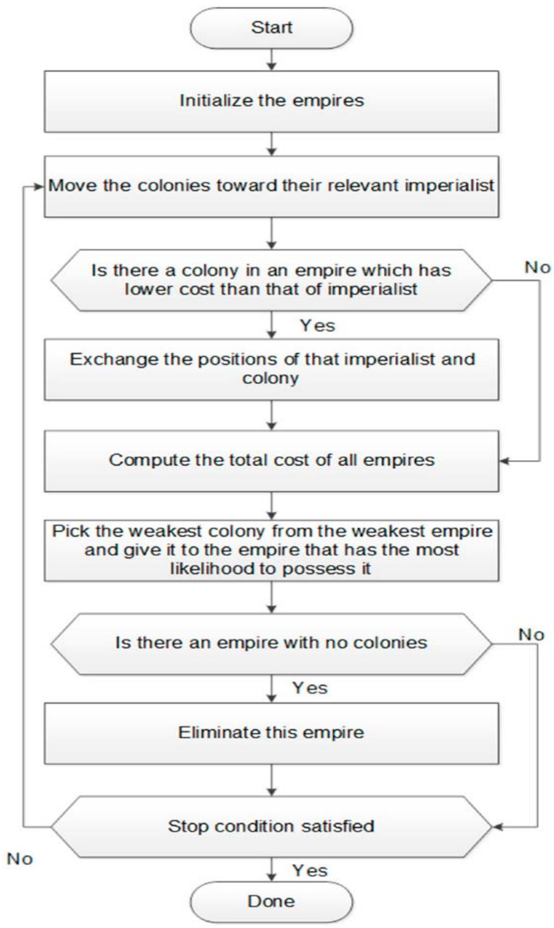


Fig.1. Flowchart of ICA [36]

**Simulation and Result Analysis**

Parameter tuning experiment is carried out to study the effect of the various parameters on the performance of ICA in optimizing element spacing of 10 and 28 sensor nodes to minimize peak SLL. The parameters involve are population size, revolution rate, direction assimilation, deviation assimilation and coefficient associated with the average power of empire's colonies as tabulated in Table 1. The range of parameters of ICA are chosen based on the previous studies [41]–[46]. The best and average fitness values of maximum SLL perform by ICA from 30 runs are shown in bold.

Table 1. Peak SLL of 10 and 28 elements for various values of parameter tuning

| Parameter's variation | Peak SLL for 10 elements (dB) | Peak SLL for 28 elements (dB) |
|---|---|---|
| Population size (Number of countries): | | |
| 10 | -13.95 | -15.27 |
| 30 | -14.89 | -15.51 |
| 50 | -15.46 | -15.52 |
| 70 | **-15.68** | **-16.31** |
| Revolution rate: | | |
| 0.05 | -15.28 | -15.50 |
| 0.10 | -15.22 | -15.50 |
| 0.15 | **-15.68** | **-16.31** |
| 0.20 | -14.50 | -15.61 |
| Direction assimilation parameter, β: | | |
| 1.0 | **-15.68** | **-16.31** |
| 1.5 | -14.03 | -16.05 |
| 2.0 | -14.58 | -14.38 |
| Deviation assimilation parameter, θ: | | |
| 0.5 | -14.15 | -15.60 |
| 1.0 | -15.40 | -16.22 |
| 2.0 | **-15.68** | **-16.31** |
| Coefficient associated with average power of empire's colonies, ξ: | | |
| 0.05 | **-15.68** | **-16.31** |
| 0.10 | -15.42 | -16.01 |
| 0.15 | -14.85 | -15.96 |

Based on the results, the best value of parameters that gives the best performance of ICA are chosen. The best performance is evaluated based on the peak SLL reduction. The selected parameters' values are used to evaluate the next experiments which involve the peak SLL reduction with narrow FNBW and peak SLL reduction with single and multi null placement. The performance of ICA is compared with BSA with the same number of elements and objective function.

Table 2 tabulate the results of peak SLL, FNBW and element spacing of 10 and 28 elements which is optimized by ICA and BSA. Figure 2 shows the beampattern of ULA and optimized beampattern by ICA and BSA for 10 elements. From the results, it is seen that there is an improvement in the reduction of peak SLL for 10 elements that is optimized by ICA as compared to BSA. The maximum SLL of proposed ICA has been lowered from -13dB to -15.68dB (by about 2.68dB) as compared to ULA and from -13.60dB to -15.68dB (by about 2.08dB) as compared to BSA. FNBW optimized by ICA is reduced by 13.1% as compared to ULA (51.70º). Whilst, BSA gives the increment of FNBW by 1.7% as compared to ULA.

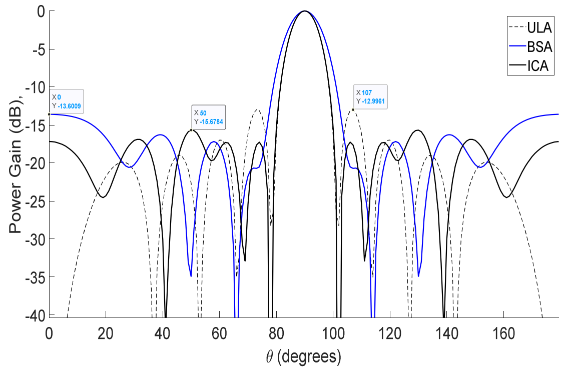


Fig.2. Beampattern optimized by ICA and BSA for 10 elements to minimize peak SLL.

Figure 3 shows the beampattern of ULA and optimized beampattern by ICA and BSA for 28 elements. ICA also shows a superiority in optimizing 28 elements as compared to BSA. ICA offers an improvement in suppression of peak SLL by around 3.04dB and 2.72dB as compared to ULA (-13.27dB) and BSA respectively. Besides, ICA successfully reduce FNBW by 16.9% as compared to ULA (30.70º), whereas BSA offers 16.0% reduction of FNBW which is narrower than ULA.

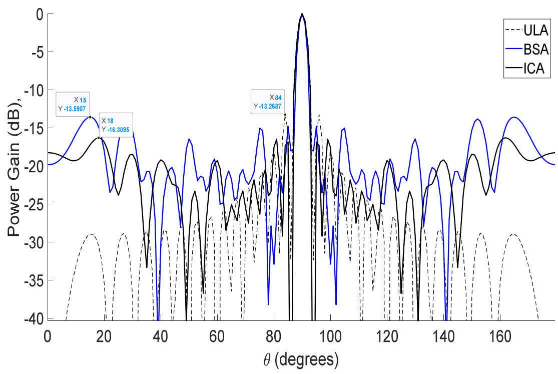


Fig.3. Beampattern optimized by ICA and BSA for 28 elements to minimize peak SLL.

Table 2. Peak SLL, FNBW and spacing between element for 10 and 28 elements optimized by ICA and BSA

| Number of elements | Algorithm | Peak SLL (dB) | FNBW (º) | Spacing between elements ($x_n - x_{n-1}$) |
|---|---|---|---|---|
| 10 | ULA | -13.00 | 51.70 | [1, 1, 1, 1, 1, 1, 1, 1, 1, 1] |
| | ICA | -15.68 | 49.30 | [1.1374, 1.4798, 0.9259, 1.0220, 0.9678, 0.9419, 0.7028, 1.0757, 1.3412, 0.9607] |
| | BSA | -13.60 | 52.60 | [0.84082, 1.5052, 1.2107, 0.6929, 0.54952, 0.87094, 0.50008, 0.69084, 0.97159, 0.87011] |
| 28 | ULA | -13.27 | 30.70 | [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1] |
| | ICA | -16.31 | 28.60 | [1.0542, 1.5000, 0.9115, 1.2761, 1.0787, 1.1782, 1.0922, 1.3678, 0.8028, 0.8066, 1.3188, 1.4038, 0.6747, 1.2754, 0.6991, 1.1299, 0.6902, 0.5584, 0.8310, 1.3780, 1.2512, 1.3071, 0.9676, 1.5000, 0.7697, 1.5000, 1.1059, 0.9167] |
| | BSA | -13.59 | 25.79 | [0.84879, 1.2646, 1.9788, 1.8074, 1.7025, 0.87964, 1.4905, 0.54479, 0.5, 1.6705, 1.7483, 1.3258, 0.68747, 0.60323, 0.78763, 1.6952, 1.4467, 1.7358, 1.3799, 0.53038, 1.5153, 1.368, 0.99657, 1.1538, 1.6433, 1.1896, 0.87634, 1.8083] |

Figure 4 shows the beampattern of 8 elements that are optimized by ICA and BSA which is subjected to peak SLL reduction and single null placement at θ = 52º. The result shows that ICA and BSA are successfully minimized the SLL peak of LAA by 3.88dB and 1.38dB respectively as compared by ULA (-12.8dB). Besides, ICA successfully place a null at the desired direction which leads to a reduction power gain about 69.25dB as compared to ULA. BSA achieve a power gain reduction of only 1.44dB from ULA.

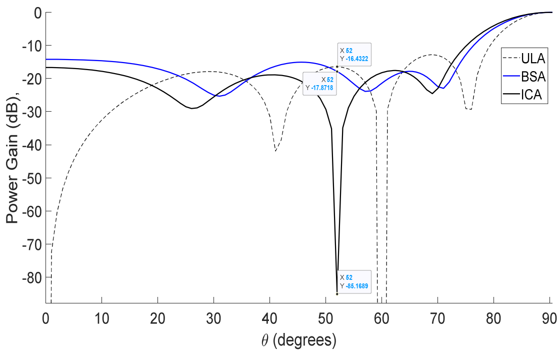


Fig.4. Beampattern optimized by ICA and BSA for 8 elements to minimize peak SLL and single null placement at θ = 52º.

Figure 5 represents the optimized beampattern by ICA and BSA for 32 elements. A single null is places at θ = 81º. Based on the results, it is shown that ICA and BSA successfully reduce the peak SLL by 3.1dB and 2.34dB respectively as compared to ULA (-13.29dB). Besides, ICA and BSA also offers reduction in power gain of SLL at null placement by 47.86dB and 1.22dB respectively.

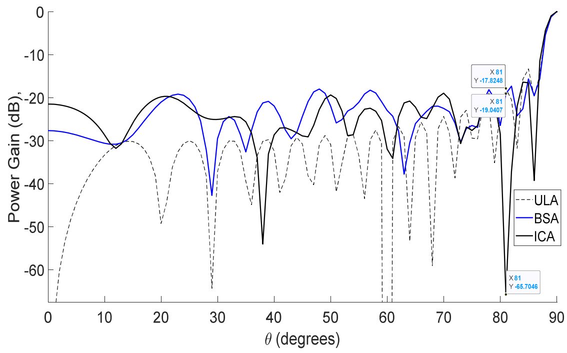


Fig.5. Beampattern optimized by ICA and BSA for 32 elements to minimize peak SLL and single null placement at θ = 81º

Figure 6 illustrates the results of optimized beampattern by ICA and BSA for 12 elements. Multiple nulls are placed at θ = 54º, 76º, 104º, 126º. It is shown that ICA and BSA successfully reduce the peak SLL by 2.71dB and 0.62dB as compared to ULA (-13.07dB). Besides, ICA and BSA also offer reduction in power gain of SLL at overall null placement as compared to ULA. ICA able to place a multiple nulls at the desired directions with power gain reduction of 67.04dB (θ = 54º, 126º) and 3.63dB (θ = 76º, 104º) as compared to ULA. BSA achieve a power gain reduction about 3.27dB and 0.69dB for θ = 54º, 126º and θ = 76º, 104º respectively.

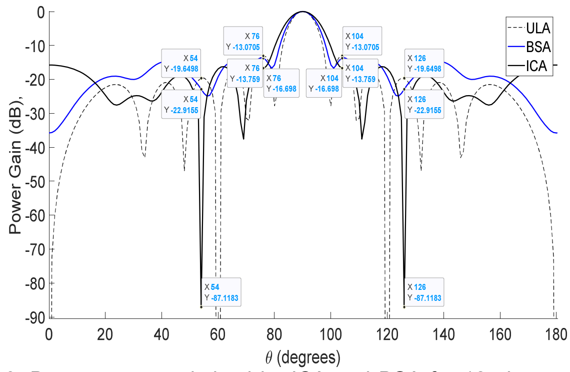


Fig.6. Beampattern optimized by ICA and BSA for 12 elements to minimize peak SLL and multiple null placements at θ = 54º, 76º, 104 º, 126º

## Simulation and Result Analysis

This paper proposes a beampattern optimization technique by optimizing the spacing between element to fulfil the MOO which are reducing peak SLL, increasing directivity by narrowing FNBW and mitigation with nulls placement at unintended lobe. Based on the overall experiments, ICA and BSA able to give the optimum element spacing which is between 0.5 to 2.0. It is important to avoid mutual coupling and grating lobe that increase interference of communication. Thus, the optimum element spacing able to produce desired beampattern with minimum peak SLL and narrow FNBW as well as reducing power gain at single or multi-null placement.

The results show that ICA able to produce narrow FNBW as well as peak SLL reduction as compared to ULA and BSA for 10 and 28 elements, which fulfil the requirement of MOO. Through the findings obtained, it is also can be seen that ICA gives better peak SLL reduction and null depth for single and multiple null placements which is superior than BSA. On top of being able to achieve the objectives, the ICA parameter tuning should be done in the first place to get the best final fitness value. Thus, a balance in exploitation and exploration of ICA is achieved which leads to the best results in optimizing beampattern throughout all experiments. The elements spacing optimized by the algorithms can be used as a reference array in node selection or position of VAA in WSN to perform CB.

## Conclusion

CB able to overcome the communication delay and increase reliability of WSNs. Thus, it can be replaced the multi-hop communication. CB is achieved when sensor nodes form a VAA to communicate with the BS. However, the random distribution of sensor nodes in WSN causes high SLL that leads to high interference at receivers. Therefore, a spacing between element optimization of a regular-shaped of VAA is proposed to produce desired beampattern. From the results obtained, it is proven that ICA effectively reduce maximum SLL, maintain or reduce FNBW and placing nulls at desired lobe.

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