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Interference Reduction and Capacity Improvement in Collaborative Beamforming Networks via Directivity Optimization

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***Abstract*—Collaborative beamforming with finite number of collaborating nodes produces sidelobes that depend on the nodes' arrangement. Sidelobes cause interference when they occur at the directions of unintended receivers and thus reduce the transmission rate at these receivers. Peak sidelobe minimization does not effectively minimize the overall sidelobe of a beampattern formed by collaborative beamforming. Two main contributions are highlighted in this paper. First, we proposed a new fitness function based on directivity instead of the conventional peak sidelobe. Second, we applied the genetic algorithm (GA) to reduce the sidelobe in collaborative beamforming. This proposed solution is implemented without any feedback from the unintended receiver(s). In the light of reduced sidelobe, we recorded the resultant capacity and calculated its improvement. Results showing up to 14% of capacity improvement, proving the efficacy of the proposed methodologies: the GA and the new fitness function.**

Keywords*—*beampattern optimization; collaborative beamforming; genetic algorithm; capacity analysis

I. Introduction

Collaborative beamforming (CB) has been receiving favorable attention in the research community ever since the distributed antenna system was identified as a promising prospect in the 5G standard [1]. In CB, decentralized nodes act as a distributed transmit antenna array and adjust the initial phases of their carriers to form a beam collaboratively towards an intended receiver [2, 3].

The random placement of the collaborating nodes in CB results in high and asymmetrical sidelobes in its beampattern [3, 4]. High sidelobe is undesirable in a beamformer as it will cause interferences to unintended receivers and reduces the capacity of the network. A common solution to this problem is the use of peak sidelobe (PSL) minimization technique [5]. However, it is shown in [6] that minimizing PSL alone does not guarantee overall sidelobe reduction in the beampattern of a random antenna array such as collaborative beamforming.

Furthermore, previous research focused only on the beampattern analysis and do not investigate the impact of the sidelobe reduction in terms of network capacity. The significance of sidelobe control in improving the transmission rate of a network has been investigated in [7]. However, it was assumed that the collaborating nodes (CNs) have full knowledge of the unintended receivers' location and are able to receive feedbacks from these receivers. The function of the proposed algorithm in [7] is to create nulls in certain directions rather than overall sidelobe reduction in the CB beampattern. Moreover, the proposed node selection algorithm to form the nulls is feasible only when a large number of nodes is available for collaboration.

Therefore, this paper proposes a new directivity based fitness function for weight optimization to reduce sidelobes in CB, with no knowledge and feedback from unintended receivers in a network. The proposed method can be utilized in both small number and large number of CNs. The probability of interference rejection and capacity improvement at the unintended receivers are analyzed. A Genetic algorithm (GA) is used to perform the optimization in all cases.

II. System Model

A. Array Factor of Collaborative Beamforming

Consider a total of N collaborating nodes, noted as $\mathbf{C} = \{c_n, n = 1, 2, \ldots, N\}$, distributed randomly within a cluster with radius of R meters on a two dimensional plane as shown in Fig. 1. One of the collaborating nodes is selected as the cluster head and becomes the reference point to all other nodes. Hence, the cluster head is treated as the origin, with a polar coordinate $(0, 0)$. Therefore, the n^{th} node from the pool of collaborating nodes, located r_n meters away from the cluster head at an angle ψ_n radians has a polar coordinate of (r_n, ψ_n). Receiver nodes are positioned at locations far from the cluster of collaborating nodes such that far field can be assumed. When there are L intended receivers and K unintended receivers, the receiver nodes can be denoted as $\mathbf{D} = \mathbf{D}^i \cup \mathbf{D}^u$, where $\mathbf{D}^i = \left\{d_l^i, l = 1, 2, \ldots, L\right\}$ is a set of intended receivers and $\mathbf{D}^u = \left\{d_k^u, k = 1, 2, \ldots, K\right\}$ is a set of unintended receivers. The polar coordinate of a receiver, d is referenced to the cluster head as (A_d, ϕ_d).

In this paper, only single link communications are considered, thus $L = 1$. Thus, the array factor (AF) of N nodes collaboratively beamforming with a carrier wavelength of λ towards a destination, d^i, at the incident angle, $\theta = [-\pi, \pi]$ is

$$\mathrm{AF}(\theta) = \sum_{n=1}^{N} e^{j\frac{2\pi}{\lambda} r_n [\alpha_n - \beta_n(\theta)]} \tag{1}$$

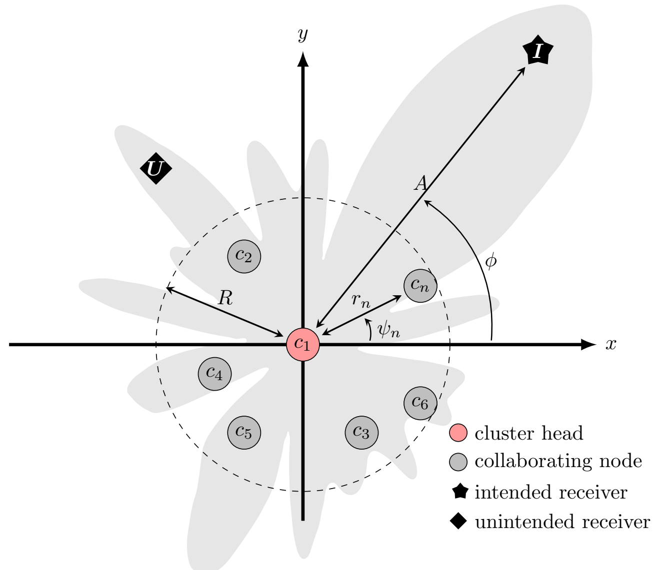

Fig. 1. Array geometry of collaborative beamforming.

where $\beta_n(\theta) = \cos(\theta - \psi_n)$ and ψ_n is the phase delay due to the propagation from node c_n to the far field point of the receiver [3]. The coefficient α_n is the initial phase of a n^{th} collaborating node. In a closed-loop scenario, α_n is chosen to compensate the phase offset between a collaborating node and the intended receiver. Therefore, $\alpha_n = \cos(\phi_{d^i} - \psi_n)$.

B. Received SNR in Collaborative Beamforming

Assuming that each collaborating node transmits a common data symbol, x using an isotropic reciprocal antenna with a power, P_n, the corresponding received baseband signal, y at a receiver d located at (A_d, ϕ_d) is

$$y(\phi_d) = x \sum_{n=1}^{N} \sqrt{P_n} h_{d_n} e^{j[\alpha_n - \beta_n(\phi_d)]} + \mathbf{w} \tag{2}$$

where $\mathbf{w} \sim \mathcal{CN}(0, \sigma_{w^2})$ is additive white Gaussian noise (AWGN) and h_{d_n} is the channel coefficient between the n^{th} node and the receiver. The channel coefficient is a product of the fading effect, a_{d_n} and the attenuation effect, b_{d_n} due to the propagation distance between c_n and d. Thus $h_{d_n} = a_{d_n} \cdot b_{d_n}$.

At the direction of the intended receiver, $\phi_d = \phi_{d^i}$, leading to $\alpha_n - \beta_n(\phi_d) = 0$, therefore the signal- to - noise ratio (SNR) at the receiver is

$$SNR_{d^i}(\xi, \phi_{d^i}) = \frac{\left\| \sum_{n=1}^{N} \sqrt{P_n} h_{d_n} \right\|^2}{\sigma_{w^2}} \tag{3}$$

where $\xi = \{\sqrt{P_n}, n = 1, 2, \ldots, N\}$ is the energy set of every collaborating node.

III. Sidelobe Reduction via Directivity Optimization in Collaborative Beamforming

The analysis and design of CB beampattern are non-linear and non-convex since its array factor depends on the collaborating nodes' position and initial phases, that are both random. Hence, standard convex optimization tool cannot be implemented to achieve the globally optimum beampattern with reduced sidelobe [8]. In this paper, the use of metaheuristic optimization method, namely genetic algorithm (GA) is proposed to find the globally optimum solution to the proposed objective function.

It is assumed that the location of the collaborating nodes are static, and all the nodes are aware of each others' position. The optimization model proposed in this paper is solved during the network deployment stage [7]. The optimization process is performed by the node that is chosen as the cluster head. The network is periodically monitored, and changes in the network configuration will require a reconfiguration of the optimization.

A. Synthesis of the Proposed Objective Function

Beampattern is the power distribution of a beamformer obtained through the pattern multiplication of every element factor to the array factor of the collaborating nodes' antenna. Since it assumed that identical isotropic antenna elements were used in all the collaborating nodes, the element factor for all collaborating nodes is unity, and hence, the beampattern, B is

$$B(\xi, \theta) = \left\| \sum_{n=1}^{N} \sqrt{P_n} e^{j \frac{2\pi}{\lambda} r_n [\alpha_n - \beta_n(\theta)]} \right\|^2 \tag{4}$$

The goal of the optimization in this paper is to choose the best values of the energy at each collaborating node such that the collaborative beamformer produces a beampattern that has maximum power pointed towards the intended direction, ϕ_{d^i}, while maintaining low power in all other directions.

Hence, the general constrained optimization problem in this paper is

$$\begin{aligned} \underset{\xi}{\text{minimize}} \quad & f(\xi) \\ \text{subject to} \quad & g(\xi) \end{aligned} \tag{5}$$

where $f(\xi)$ is the objective function, $g(\xi)$ is the constraint function and the input energy at all nodes $\xi = \{\sqrt{P_n}, n = 1, 2, \ldots N\}$ is the decision variable with the search space $[0, 1]$.

Since the optimization task is sidelobe minimization, the usual approach adopted would be to minimize the peak sidelobe level (PSL) [5, 9], hence, the objective function used would be

$$f_{PSL}(\xi) = \max|B(\xi, \theta)|; \theta \neq \phi_{d^i} \tag{6}$$

However, since collaborative beamforming is usually a random array, minimizing the PSL results in increased width in the main lobe [6]. In such cases, if an undesired receiver is located at a plane angle close to the desired receiver, the possibility of interference in the undesired direction is very high. Furthermore, there is a possibility that the optimized beampattern achieves low PSL but end up with higher sidelobes at other positions.

Therefore, instead of resorting to minimizing only the PSL, this paper proposes to maximize the directivity, D of the beampattern to achieve lower overall sidelobes. Directivity characterizes the amount of energy that is concentrated in the desired receiver's direction, and a higher directivity signifies that the average energy at plane angles other than the desired receiver's direction is kept to the minimum. Based on the formulation in [3], the directivity of a collaborative beampattern is

$$D(\xi) = \frac{2\pi}{\displaystyle\int_{-\pi}^{\pi} \frac{|B(\theta,\xi)|}{|B(\phi,\xi)|} \mathrm{d}\theta} \tag{7}$$

Since the directivity has to be maximized to obtain lower overall sidelobes, the minimization problem in Eq. (5) is modified into a maximization problem by negating the proposed objective, hence $f_D(\xi) = -D(\xi)$.

In order to ensure that the received symbol is decoded correctly at the intended receiver d^i, the SNR at $\theta = \phi_{d^i}$, $\text{SNR}_{d^i}(\xi, \phi_{d^i})$ must be higher than the receiver's threshold SNR, SNR_{thr}. Therefore, the constraint function in Eq. (5) is $g(\xi) = \text{SNR}_{d^i}(\xi, \phi_{d^i}) \geq \text{SNR}_{thr}$.

B. Genetic Algorithm

In this paper, the genetic algorithm (GA) is applied to solve the optimization problem in Section III-A. Works in [10, 11] utilized this mechanism to approach the resource allocation problem in OFDMA system. First, M parent populations, uniformly distributed in the parameter space $\xi \in [0,1]$are initialized. The parent population is tested for its fitness function according to Eq. (5). The parent population is then sorted according to the value of its fitness function and a fraction of these parents are selected using rank selection. Child population is selected from the parent population and is subjected to mutation with the rate of μ. The selected child population is promoted as the parent population for the next generation. When the number of generations reaches the maximum specified generations, g, the optimization is terminated. For the optimization in this paper, the parameters $g = 100$, $M = 20$, and $\mu = 0.1$ are applied. The complexity of the algorithm is $\mathcal{O}(MN)$ and since M is fixed, the complexity only increases linearly with the number of collaborating nodes.

It has to be highlighted that though the GA is used as the optimization algorithm in this paper, any other suitable optimization method can be applied to solve the proposed optimization problem, according to the limitations of the system. For further reading on the operations of the GA or other metaheuristic algorithms, as well as the choice of parameters, readers may refer to [12].

IV. CCDF, SINR AND CAPACITY AT AN UNINTENDED RECEIVER

The communication between the collaborating nodes and the intended receiver d_i will cause interference at the unintended receiver(s) d_k^u if the power from the cluster of nodes performing collaborative beamforming exceeds the interference-to-noise ratio (INR) threshold, INR_{thr} of the unintended receiver(s).

The complementary cumulative distribution function (CCDF) of the interference at an unintended receiver is the probability of the power from the collaborative beamforming at the direction of an unintended receiver exceeding the INR_{thr}, where d_k^u can be located at $\phi_{d_k^u} \in [-\pi,\pi]; \phi_{d_k^u} \neq \phi_{d^i}$ [7]. In this paper, the effect of the collaborative beampattern's power on all the unintended receivers is analyzed using the CCDF where the joint probability interference occurring at unintended receivers is

$$\text{CCDF} = \prod_{k=1}^{K} \mathbf{Pr}\left\{B(\xi,\phi_{d_k^u}) > \text{INR}_{thr}^k\right\} \tag{8}$$

A CCDF=1 in this case signifies that interference occurs on all unintended receivers whereas CCDF=0 signifies that interference does not occur on at least one of the unintended receiver.

To gauge the capacity improvement at the unintended receivers, the channel effect should also be considered. A near ground WSN application is considered. Therefore, a time-invariant channel with predominantly large-scale fading is assumed [7]. Hence, a lognormal distributed random variable is assumed for the channel, $a_{d_n} \sim \exp[N(0,\sigma^2)]$, where $\sigma^2 = 0.5$. Since the distance between the collaborating nodes and the receiver is far greater than the distance between the collaborating nodes, it can be assumed the path loss component is the same for all the nodes such that $b_{d_n} = b_{\mathbf{D}} = 1$ for $n = \{1, 2, \ldots N\}$.

The corresponding transmission rate at an unintended receiver can be calculated if the input SNR at that receiver is known. Provided that the receiver receives a useful signal at the power γ^2, the SNR is γ^2/σ_{w^2}. If the communication is interfered by far field collaborative beamforming, the SINR becomes

$$\text{SINR} = \frac{\gamma^2}{\varepsilon^2 + \sigma_{w^2}} \tag{9}$$

where

$$\varepsilon^2 = \left\| \sum_{n=1}^{N} \sqrt{P_n} a_{d_n} e^{j[\alpha_n - \beta_n(\phi_{d_k^u})]} \right\|^2 \tag{10}$$

With the SINR information, the capacity, C at the unintended receiver can be calculated by

$$C = \log_2\{1 + \text{SINR}\} \tag{11}$$

V. SIMULATION RESULTS AND DISCUSSIONS

Simulations results presented in this section are performed with the aid of MATLAB ® software. All angular directions are mentioned in degree (°), whereas the radius of the collaborating nodes' cluster, R, is normalized so that $\widetilde{R} = R/\lambda$.

Fig. 2 shows a sample radiation pattern in collaborative beamforming for three scenarios: without any beampattern optimization, with beampattern optimization using f_{PSL} and the proposed beampattern optimization using f_D. The beampatterns in Fig. 2 are obtained for a node distribution of $N = 128$, $\widetilde{R} = 2$. The position of the intended receiver, $\phi_{d_1^i} = 0°$. Let the number of far field unintended receivers, $K = 3$. The first unintended receiver, d_1^u is located at the position where the peak sidelobe occurs, $\phi_{d_1^u} = 40°$. The power of the interference at unintended receiver d_1^u is reduced from the original value -11.42 dB to -15.71 dB with the use of the proposed f_D and to -20.65 dB by using the f_{PSL}. Since $\phi_{d_1^u}$ is the location of the peak sidelobe, it is natural that the beampattern obtained using the f_{PSL} minimization cost function provides 5dB lower interference power compared to the proposed method.

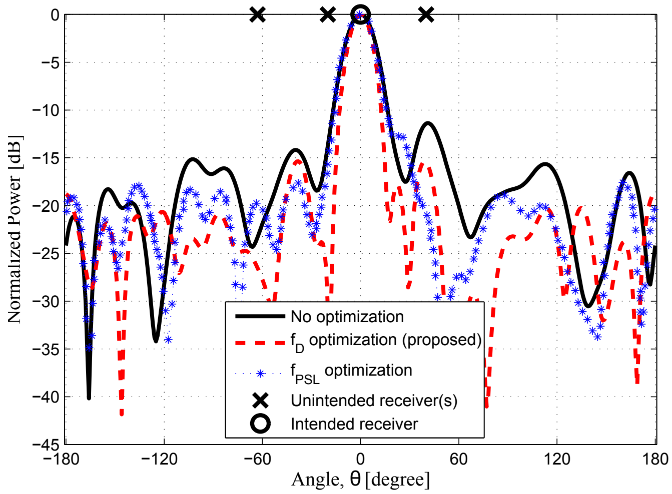

Fig. 2. Beampattern comparison for $N = 128$, $\widetilde{R} = 2$: The intended receiver is located at $0°$ and three unintended receiver is located at $40°$, $-20°$ and $-63°$.

The second unintended receiver, d_2^u is located very close to the intended receiver, at $\phi_{d_2^u} = -20°$. An improvement of 17.2 dB in interference power is seen at the unintended receiver when the proposed f_D is employed. Using the cost function f_{PSL}, on the other hand, provides no improvement at this position.

The final unintended receiver, d_3^u is placed a little further from the main lobe, at $\phi_{d_3^u} = -63°$. At this receiver, the received interference power is -23.32 dB when no optimization is attempted. Since the f_{PSL} only focuses on minimizing the peak sidelobe, the location d_3^u was neglected, and the interference increased by 3.5 dB. The proposed directivity based cost function successfully reduced the interference power by 3.2 dB. This proves that the PSL minimization based cost function is only effective in reducing the power at the peak sidelobe and does not guarantee lower power at all other locations.

Fig. 3 shows the CCDF for INR_{thr} between a range of -40dB to 5dB. For simplicity, it is assumed that the INR_{thr} at all unintended receiver is the same. Two scenarios are considered. In the first scenario, only one unintended receiver exists at a random location $\phi_{d_1^u}$ whereas, in the second scenario, four unintended receivers, $K = 4$ exist at four random and independent locations. Two node distributions are considered in both scenarios: $N = 128$, $\widetilde{R} = 2$ and $N = 16$, $\widetilde{R} = 1$.

Perfect channel conditions are assumed, where there is no similar path loss, and no small or large scale fading, hence, $h_{d_n} = 1$.

In the case of the first scenario, the Eq. (8) can be simplified to

$$\text{CCDF} = \mathbf{Pr}\left\{B(\xi, \phi_{d_1^u}) > \text{INR}_{thr}^1\right\} \tag{12}$$

The CCDF for the first scenario, as illustrated in Fig. 3(a) shows that proposed optimization method improves the CCDF (the probability of interference). It can be seen that for the node distribution $N = 128$, $\widetilde{R} = 2$, using the proposed f_D optimization reduces the probability of an interference from 0.41 to 0.31 at $\text{INR}_{thr} = 10$ dB compared to when no optimization is implemented. Similar improvement is also seen for $N = 16$, $\widetilde{R} = 1$, where the CCDF is reduced from 0.15 to 0.06 when $\text{INR}_{thr} = 10$ dB.

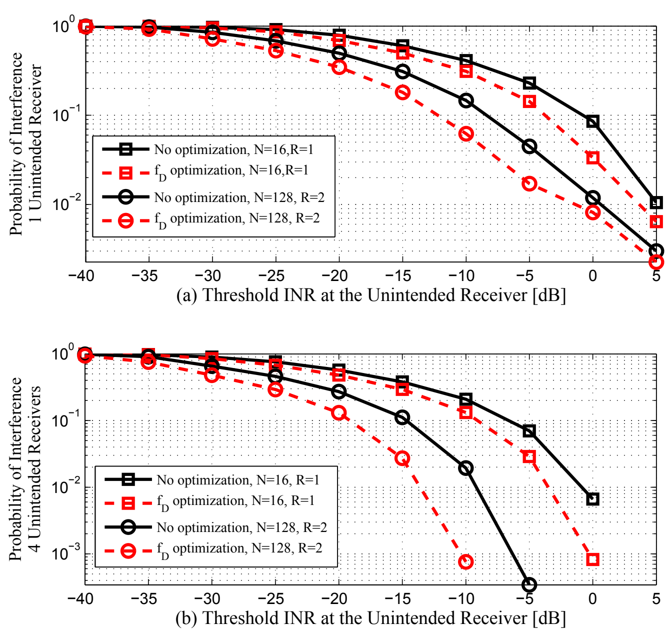

Fig. 3. The CCDF of the INR_{thr} at the unintended receiver(s): (a) only one unintended receiver, (b)four unintended receivers.

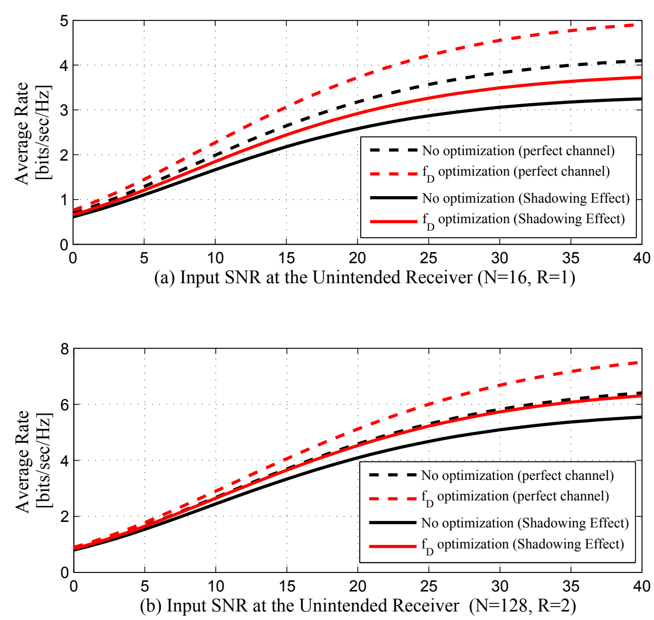

Fig. 4. The average transmission rate at the unintended receiver, with and without weight selection; under perfect channel and shadowing effects.

Fig. 3(b) depicts the CCDF when there are four independently located unintended receivers. The CCDF for the collaborative node distribution $N = 128$, $\widetilde{R} = 2$, is lower compared to $N = 16$, $\widetilde{R} = 1$. This is because the sidelobe level is naturally lower when N is larger [3]. It can be seen that for both node distributions, the proposed method has lower CCDF compared to the CCDF where there is no optimization.

The improvement in terms capacity at an unintended receiver is analyzed within the interference limited input SNR range (0 to 40 dB), as shown in Fig. 4. The average transmission rate at the unintended receiver, with and without the proposed optimization, and under both perfect channel and shadowing effects are depicted. The capacity in the presence of shadowing for $N = 16, \widetilde{R} = 1$ improves from 3.248 bits/sec to 3.727 bits/ sec when the proposed f_D based optimization is applied to the collaborative beamforming. Similarly, at $N = 128$, $\widetilde{R} = 2$ the capacity at the unintended receiver improves from 5.542 bits/sec to 6.350 bits/sec. A consistent improvement in capacity of 10% to 14% is recorded for both cases when the input SNR range at the unintended receiver ranges from 5 to 40 dB.

VI. CONCLUSION

This paper proposed the use of a new directivity based fitness function formulation for the sidelobe reduction in collaborative beamforming when the position of unintended receiver is unknown to the collaborating nodes. Having had applied the well-known global optimizer−GA, feasible solutions are obtained; the reduced sidelobes were clearly observed. And to our encouragement, we obtained improved transmission rates at the unintended receivers, with the calculated 14% for the overall capacity improvement.

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REFERENCES

[1] J. G. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, “What will 5g be?” 2014.

[2] I. Thibault, A. Faridi, G. E. Corazza, A. V. Coralli, and A. Lozano, “Design and analysis of deterministic distributed beamforming algorithms in the presence of noise,” *Communications, IEEE Transactions on*, vol. 61, pp. 1595–1607, 2013.

[3] H. Ochiai, P. Mitran, H. V. Poor, and V. Tarokh, “Collaborative beamforming for distributed wireless ad hoc sensor networks,” *Signal Processing, IEEE Transactions on*, vol. 53, no. 11, pp. 4110–4124, 2005.

[4] J. Huang, P. Wang, and Q. Wan, “Collaborative beamforming for wireless sensor networks with arbitrary distributed sensors,” *Communications Letters, IEEE*, vol. 16, no. 7, pp. 1118–1120, 2012.

[5] S. Jayaprakasam, S. Rahim, and C. Y. Leow, “Psogsa-explore: A new hybrid metaheuristic approach for beampattern optimization in collaborative beamforming,” *Applied Soft Computing*, vol. 30, pp. 229–237, 2015.

[6] S. Jayaprakasam, S. K. A. Rahim, and C. Y. Leow, “A pareto elite selection genetic algorithm for random antenna array beamforming with low sidelobe level,” *Progress In Electromagnetics Research B*, vol. 51, pp. 407–425, 2013.

[7] M. F. A. Ahmed and S. A. Vorobyov, “Sidelobe control in collaborative beamforming via node selection,” *Signal Processing, IEEE Transactions on*, vol. 58, no. 12, pp. 6168–6180, 2010.

[8] D. G. Kurup, M. Himdi, and A. Rydberg, “Synthesis of uniform amplitude unequally spaced antenna arrays using the differential evolution algorithm,” *Antennas and Propagation, IEEE Transactions on*, vol. 51, no. 9, pp. 2210–2217, 2003.

[9] S. Jayaprakasam, S. k. A. Rahim, C. Y. Leow, and M. F. Mohd Yusof, “Beampattern optimization in distributed beamforming using multiobjective and metaheuristic method,” in *Wireless Technology and Applications (ISWTA), 2014 IEEE Symposium on*. IEEE, 2014, pp. 86–91.

[10] S. F. Chien, T. O. Ting, X.-S. Yang, A. K. N. Ting, and D. W. Holtby, “Optimizing energy efficiency in multi-user ofdma systems with genetic algorithm,” in *Advances in Computing, Communications and Informatics (ICACCI), 2013 International Conference on*. IEEE, 2013, pp. 1330–1334.

[11] T. O. Ting, S. F. Chien, X.-S. Yang, and N. Ramli, “Resource allocation schemes in energy efficient ofdma system via genetic algorithm,” in *Communications (APCC), 2013 19th Asia-Pacific Conference on*. IEEE, 2013, pp. 723–727.

[12] X.-S. Yang, *Nature-Inspired Metaheuristic Algorithms*, 2nd ed. United Kingdom: Luniver Press, 2010.