Bacteria Foraging Algorithm for Optimal Topology Construction in Wireless Sensor Networks

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ABSTRACT

Topology control is a significant method to reduce energy consumption and prolong the network lifetime. Connected Dominated Sets (CDS) are the emerging technologies to construct the energy-efficient optimal topology. Traditional topology construction algorithms are not utilized suitable in optimization techniques for finding the optimum location of the active nodes in the networks. In this paper, Bacteria Foraging Algorithm (BFA) identifies the optimal location for active nodes to form the virtual backbone of the network. Residual energy and network connectivity are considered to evaluate the fitness function. The performance of the BFA is compared with other algorithms, namely A3, A1, Genetic Algorithm (GA), and Gravitational Search Algorithm (GSA) algorithms for considering the performance metrics of the active nodes, residual energy, and connected sensing area coverage. Simulation results show that the proposed methodology performs well for reducing energy consumption and improving the connected sensing coverage area in the wireless sensor network.

KEYWORDS

Bacteria Foraging Algorithm (BFA), Connected Sensing Coverage Area, Energy Consumption, Topology Construction, Wireless Sensor Networks

1 INTRODUCTION

Wireless Sensor Networks (WSN) have been more popular for processing information in risky environments such as health care monitoring systems, intruder surveillance, and environmental control systems. The sensor nodes execute the process of sensing, communication, and computing for the information. The nodes have limited computation and communication capabilities. Energy is an important factor to perform the communication and computation process. Many of the algorithms and methods were used to provide energy-efficient infrastructure.

The topology control technique is mainly used for providing the energy-efficient infrastructure, to consume the minimum energy for the communication that also improves the network lifetime. The main goal of topology control is to form the good connectivity of the network topology and to minimize the energy consumption. This method forms the virtual backbone that connects the set of active nodes for sending the information to the destination through intermediate nodes. The set of active nodes is used to reduce the routing path from source to destination. This method reduces the nodes to participation and forwards the routing information to the destination node.

The biologically inspired algorithms (Selvakennedy et al., 2007) are utilized to design the sensor networks. The complex behavior of the system is modified into the new environment and to find a solution by using simple rules. The insect or spics behavior is used to achieve the optimal solution

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to the problem. Some of the biologically inspired techniques are applied to obtain the solution for clustering and multi sink placement problem in wireless sensor networks.

Bacteria Foraging Algorithm (BFA) is one of the methods for the biologically inspired algorithm which is used to form the optimal nodes for connected dominating set in the topology construction. The performance of the BFA is evaluated with other algorithms such as A3, A1, GA, and GSA algorithms. The optimal topology generated by the BFA algorithm is used for extending the network lifetime and improving the connected sensing coverage area in the network.

The objectives of this paper can be summarized as follows:

1. Topology control problem is formulated to prolong the network lifetime with the help of the number of the active nodes
2. Bacteria Foraging Algorithm is utilized to find the optimal node position of connected dominating set in the topology construction.
3. The proposed methodology is evaluated by using simulation studies. The simulation results achieve better results with the comparison of A3,A1,GA, and GSA algorithms by considering the performance metrics such as the number of active nodes, energy consumption, total connected sensing coverage area.

The motivation of the proposed work is presented as follows:

The energy-efficient structure is generated by using the topology control technique for consuming the minimum energy for the communication and also improving the network lifetime. The main goal of the topology control is to generate good connectivity of the active nodes for minimizing the energy consumption. By using the bacteria foraging algorithm produces the virtual backbone that connects the optimal set of active nodes for sending the information to the destination through intermediate nodes. The optimal set of active nodes is used to reduce the routing path from source to destination and also to increase the total connected sensing coverage area of the network.

The rest of the paper is organized as follows. Section 2 describes the methods and techniques used for the topology construction and biological inspired methods. Section 3 describes the bacteria foraging algorithm for finding the optimal node position that forms the connected dominating set for topology construction. Section 4 presents the performance evaluation of the bacteria foraging algorithm for generating the optimal topology construction. Section 5 provides the conclusion.

2. RELATED WORKS

The following papers for topology control algorithms in wireless sensor networks are summarized and shown in Table 1.

From the above survey, Many of the existing algorithms are not considered the energy-efficient parameters for topology construction process. Bacteria Foraging Algorithm has not been applied for topology construction in WSN. Therefore, the author has proposed the Bacteria Foraging Algorithm to address the effective topology construction in WSN. This describes the novelty of this paper.

3 PROPOSED METHOD

3.1 Bacteria Foraging Algorithm

BFA algorithm developed by Passino K.M et al., 2002. This algorithm is used to provide the solution for optimization problems. Animals are improving energy utilization over the period for finding and searching the food resources. The E.Coli bacteria behavior is mimicked as a BFA algorithm for the food searching and handling process. This algorithm has four important steps such as chemotaxis, swarming, reproduction, and elimination and dispersal processes.

Table 1. Papers on topology control algorithms in wireless sensor networks

Author	Technique	Performance metrics	Advantages	Disadvantage
Wightman P.M et al., 2008	A3 tree algorithm	Number of active nodes Energy used in CDS Number of messages	Simple No synchronization scheme is required	Consumes more time for constructing the virtual backbone.
Rizvi et al., 2012	A1 topology construction	Number of messages Residual energy Total connected sensing area	Achieves better Sensing Coverage connectivity	The transmission range can not be considered.
Lee C Y., et al 2013	Distributed and reliable efficient topology control algorithm	Average packet delivery ratio Communication radius Maximum Remaining Energy	Automatically create and maintain the energy-efficient links	Network link failure can't be considered for the processing
Saha S et al., 2014	Energy-Aware Spanning Tree for balancing the load and also reducing the energy utilization of the network	Maximum transmission range Initial energy of the node Number of nodes	Generating the energy-aware spanning tree in an effective manner	Energy-efficient related parameters can not be addressed
Torkestani, J. A et al., 2013	automata based on the heuristics for degree constrained minimum connected dominating set problem	Active nodes Average residual energy Network lifetime	Balanced the network topology with maximum energy.	Communication coverage and sensing coverage are not addressed.
Xing G et al., 2013	configurable topology control in lossy WSN	Dilation of transmission count Total number of nodes Packet delivery ratio End to end communication delay	Achieved the quality path in lossy networks.	Topology maintenance can not be addressed for the lossy networks.
Qureshi, H. K et al., 2011	The polygon-based topology construction method	Message overhead Energy overhead Residual energy Connectivity	By using this method the network reliability is achieved	Communication coverage and Energy-efficient parameters can not be addressed.
Fiaz M et al., 2014	poly3 technique maintains the group size of three for achieving the network reliability	Packet delivery reliability Link success reliability Message and energy overhead. Connected sensing coverage area	Achieved the network reliability and energy efficiency of the network.	Energy-efficient parameters are not considered more for developing the algorithm.
Hou et al., 2018	Mobile service computing based network topology control algorithm	Energy consumption Packet loss rate	This method reduced the network traffic and prolonged the network lifetime.	This method is not addressed the energy efficiency parameters.
Ahmed, M et al 2017	Whale Optimization algorithm for topology control algorithms	Number of active nodes Energy consumption The average rate of the conversion process	This optimization method was achieved to minimize the active nodes with low energy consumption.	Communication coverage and total sensing coverage are not addressed.
Gui et al., 2017	Link quality in the lossy wireless networks based on link quality and neighborhood discovery	Energy consumption Delivery ratio End to end delay Transmission power	Generated the link quality based on the demand. Achieved better results in communication overhead.	Energy-efficient parameters and network reliability have not been addressed.
Javadi et al., 2018	Learning automata-based topology control	Average transmission range Average number of neighbors Node density Residual energy	The selected smallest transmission range for enhancing the overall network lifetime.	Mobility of the nodes are not considered
Khalily-Dermany et al., 2017	Optimal topology control with network coding based multicast processing	Energy consumption Packet intervals	Achieved to reduce the energy consumption and provide the network reliability	Communication coverage and Network reliability parameters are not considered
Hao et al., 2018	Topology control with the help of Markov lifetime prediction model	Average transmission power Average node degree Number of nodes	Achieved the real-time prediction by using the mode transition	More energy-related parameters are not addressed
Varsa et al., 2019	Balanced energy-efficient virtual backbone construction by using Genetic algorithm	Average number of nodes in CDS Average energy consumption Network lifetime Packet delivery ratio	This method achieved to prolong the network lifetime and minimize the average energy consumption	Topology maintenance and communication coverage parameters can not be addressed.
Fouad et al., 2019	Grey wolves and chicken swarm optimization based on generating the optimized topology control.	Number of active nodes Surplus energy Network size	This method achieved to minimize the number of active nodes and residual energies for solving the network coverage	Convergence rate and more energy- related parameters are not considered.
Fu et al., 2020	Sink oriented cascading model by using memetic algorithm	Clustering coefficient Average shortest path length Network communication efficiency	This method is mainly used to achieve network robustness by using topology optimization	Sensing coverage and energy-related parameters are not considered for optimizing the topology.

1. **Chemotaxis:** In the foraging process, bacteria movement is performed by using the group of flagella with two methods such as tumble or swim. Bacteria move to the desired position or different position through the swim or tumble method to search the food source. The swim or tumble method is executed simultaneously for the entire life.
2. **Swarming:** In the food searching process, bacteria reach the best location and attract the nearest bacteria by using the attractant signals. The relative distance between the bacteria is calculated and the cost value is updated. The minimum cost value of the bacteria is selected and joined together for forming the bacterial colony.
3. **Reproduction:** In this method, all the bacteria go to reproduction. The most healthy bacteria are divided into two bacteria and the least healthy bacteria are moved into the dead state. The newly formed bacteria are placed in the same position.
4. **Elimination and dispersal:** The unexpected or slow changes in the environment are implemented in the elimination or dispersal. The most healthy bacteria are split into two bacteria and moved into the same location. The least healthy bacteria are eliminated from the execution environment.

3.2 Bacteria Foraging Algorithm for Optimal Topology Construction

Step 1: Assign the sink node and parameters used for the BFA algorithm.

Step 2: Elimination and dispersal of the bacteria l

Step 3: Reproduction of the bacteria k

Step 4: Chemotaxis of the bacteria j

a) For each i^{th} bacteria

b) Calculate the cost value of the current position of the bacteria

c) Tumble

Randomly generate the different directions of the bacteria.

d) Move

Find the next position of the bacteria.

e) Swim

Initialize the swim length is zero

While (swim length is less than the number of swims)

if the new position of the bacteria is less than the old position of the bacteria then

old position of the bacteria = new position of the bacteria

end if

else

Assign the number of swims to the swim length.

Increment the swim length

end while

Compute the cost value of the new position of the bacteria

Repeat the steps from a to e for the chemotaxis process.

Step 5: Reproduction:

The position of the bacteria is displayed in ascending order based on the health value.

The healthy bacteria are split into two and placed in the same position.

If the reproduction value is less than the number of reproductions then

goto step 3

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else
goto step 6
end if
Step 6: Elimination and dispersal:
for each  $i^{th}$  bacteria
Generate the random value  $r$ 
If  $r$  is less than the probability value of elimination dispersal,
then
bacteria are moved to the new position.
Else
bacteria retain the same position.
End if
end for
Step 7:
If the elimination dispersal value is less than the number of
elimination dispersal then
goto step 2
else
stop
end if
Step 8: Calculate the time-out period for the node from the value
of the remaining energy and signal strength.
Step 9:
If the node gets the message with parent ID then
goto active mode.
Else
goto sleep mode
Step 10: Repeat steps 4 to 9 for the remaining number of nodes.
Step 11: Identify the optimal node position for the optimal
topology construction.

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The main aim is to construct the optimal topology with the help of a bacteria foraging algorithm in the connected dominating set. The optimal topology is generated by reducing the network size with the residual energy and signal strength. The following equation is used for computing the timeout period T for the nodes in the optimal topology construction.

$$T = \frac{E_c}{E_i} + \frac{SS_p}{SS_m}$$

Where, p and c denotes the parent and children node and E_c is the remaining energy of the children node, E_i is the initial energy of the node, SS_p is the signal strength of the parent node, SS_m is the minimum signal strength used to provide the network connectivity. The selection process of the node contains more energy and good signal strength. Optimal nodes are selected using a bacteria foraging algorithm for constructing the CDS formation in the network topology.

In this paper, we construct the optimal topology by using the bacteria foraging algorithm with the sample network shown in Figure 1. The optimal topology construction is started by selecting the random node in the network. The random node acts as a bacteria which is used to initiate the tumble

or swim mode. These two modes are mainly used to perform the movement of the bacteria from one position to another position.

Bacteria make a move into different directions of the node position for the swim mode. During the tumbling mode, bacteria do not move into the specified directions but make a little movement from the current position. The bacteria find the better node position by selecting any one of the modes such as tumble or swim. After the execution of the tumble or swim mode, bacteria sends the attractive signal to the neighboring node position within the transmission range and finds the relative distance between the nodes. The cost value of the old and new positions of the bacteria is compared and the node position is updated with the minimum cost value.

Figure 1. Sample topology

The chemotaxis process is executed for the remaining swim length value. The position of the nodes is located in ascending order with the help of health value and maximum health value of the bacteria and is separated into two copies and positioned in the same location. The reproduction process is executed for the maximum value of the process. The random value is generated and compared with the probability value, and the bacteria move either in the direction of the new node position or reside on the same node position. The entire process is executed for all remaining nodes to find the optimal position of the neighbor nodes in the topology.

In the initial stage of the process, the parent ID is set to empty and assign the parent as their id. The nodes B,C,K are available within the transmission range of node A. After receiving the attractant signal, the neighbor nodes such as B,C and K calculate the relative distance and period and select the node B that has minimum distance among the neighboring nodes. The nodes C and K have sent the message to node A. Therefore, node A acts as an active node and other nodes C and K enter into the sleep mode for the calculated time-out period.

Node B finds its neighbors by sending the attractant signal for a period of the time interval. During this period, nodes have a minimum relative distance identified among the neighbors and set the node as the active mode for the processing. After identifying the active nodes, the remaining nodes send the message to the parent node and enter into the sleep mode for the calculated time-out period. The nodes E and F receive the message from nodes C and E respectively. Figure 3 shows nodes G and F act as an active nodes for their neighbors. Figure 4 indicates the reduced topology of the network.

Figure 2. Find the neighbor of node B

Figure 3. Find the active node

Finally, the nodes D,H,I and K do not find any message along with the parent ID and move into the sleep mode for the calculated the time out. The optimal and reduced topology is generated by using a bacteria foraging algorithm to identify the optimal position of the neighborhood nodes. The set of active nodes used for forming the virtual backbone in the optimal and reduced topology construction. The flowchart for the construction of optimal topology is shown in figure 5.

4 PERFORMANCE EVALUATION

4.1 Simulation Setup

The simulation was implemented by using the Atarraya topology control simulator for the wireless sensor networks. The nodes are placed randomly in the area of 600 X 600m² and the nodes have equal

Figure 4. Reduced topology

energy at the initial phase. The initial energy of the sensor node was set to 1 Joule. The performance of the BFA algorithm is compared with other algorithms such as A3, A1, GA, and GSA algorithms. Simulation experiments are executed with different random topologies and plotted the graph from the average values. The parameters utilized for the simulation setup and bacteria foraging algorithm are shown in Table 2 and Table 3.

There are two different ideal grid topology such as Grid HV and Grid HVD topology. The nodes are connected with horizontal and vertical neighbor directions in the Grid HV topology. For considering the Grid HVD topology, nodes are connected with horizontal, vertical, and diagonal neighbor directions.

4.2 Performance Metrics

The following metrics are used for evaluating the performance of the algorithms.

1. **Active node:** It is defined as the number of nodes active for the optimal topology construction.
2. **Energy consumption:** The amount of energy is consumed for constructing an optimal topology in the data communication process.
3. **Residual energy:** It is defined as the remaining energy from the active nodes in the virtual backbone.
4. **Connected sensing area coverage:** It is defined as the area covered by the nodes in the optimal topology construction.

4.3 Simulation Results

Figure 6 illustrates the transmission range versus the number of active nodes. In this experiment, the transmission range is varied from 28m to 84m in the network, while maintaining the number of sensor nodes as 100. Active nodes are more important for constructing the optimal connected dominating set in the network. Figure 6 shows that the BFA method increases the number of active nodes when compared to A3, A1, GA, and GSA algorithms. BFA algorithm quickly finds the optimal CDS and improves the performance of topology construction. Table 4 represents the number of active nodes by varying the transmission range for different algorithms.

Figure 7 illustrates the residual energy for the optimal CDS construction. In this experiment, the network density is increased by the sensor nodes from 50 to 250 while considering the transmission

Figure 5. Flowchart for optimal topology construction using BFA

range as 42m. In figure 7, BFA provides better results for residual energy when compared to A3, A1, GA, GSA algorithms. BFA method finds the minimum distance from the nodes by using the chemotaxis process and to form the optimal CDS in the virtual backbone. Table 5 represents the residual energy for the sensor nodes.

Figure 8 demonstrates the total number of sensor nodes versus total connected sensing covered area. In this experiment, the sensor nodes are varied from 50 to 250 and the performance of the five algorithms is evaluated for measuring the communication coverage. Communication coverage is measured by identifying the active nodes connected in the topology construction. From figure 8, the BFA algorithm covered more sensing areas than A1, A3, GA, and GSA algorithms. BFA technique quickly constructs the optimal connected dominating sets and reaches more communication coverage for the process of communication. Table 6 represent the total connected coverage area for the number of sensor nodes.

In this experiment, homogeneous grid topology is considered with two different types such as Grid HV and Grid HVD. This topology maintains the ideal value of node degree and node density.

Figure 9 shows the number of active nodes for Grid HV and Grid HVD topology. From this figure 9, the BFA method increases the number of active nodes compared to A3, A1, GA, and GSA algorithms. BFA technique quickly identifies the optimal connected dominating sets that help to form the optimal topology construction. Table 7 represents the number of active nodes.

Table 2. Simulation parameters

Parameter	Value
Area of deployment	600X600m ²
Number of sensor nodes	50 to 250
Initial energy of the node	1 Joule
Communicationradius	28 to 84m
Sensing radius	20m
Node distribution	Uniform
Simulation time	600 sec

Table 3. BFA parameters

Parameter	Value
Number of bacteria	100
Swim length of bacteria	4
Chemotaxis steps	100
Reproduction steps	4
Elimination and dispersal step	2
Value of Ped	0.25
Run length parameter	0.05

Figure 6. Transmission range vs number of active nodes

Figure 7. Number of sensor nodes vs residual energy

Table 4. Transmission range vs Number of active nodes

	A3	A1	GA	GSA	BFA
1	32	34	36	39	43
1.5	21	23	25	27	29
2	13	16	18	20	23
2.5	9	11	13	15	18
3	5	6	8	10	12

Table 5. Number of sensor nodes vs residual energy

	A3	A1	GA	GSA	BFA
50	0.339157	0.341732	0.36793	0.39873	0.435868
100	0.227573	0.232952	0.25567	0.28456	0.310348
150	0.127652	0.139714	0.14567	0.16751	0.195964
200	0.101982	0.119316	0.13546	0.15423	0.178625
250	0.081594	0.091726	0.11235	0.13674	0.161728

Figure 8. Number of Sensor nodes vs Total connected sensing area

Table 6. Number of Sensor nodes vs Total connected sensing area

	A3	A1	GA	GSA	BFA
50	0.023851	0.024552	0.026342	0.028435	0.031475
100	0.027459	0.028284	0.029432	0.031103	0.033191
150	0.031893	0.033164	0.034234	0.035123	0.036531
200	0.034864	0.035196	0.036451	0.037122	0.039172
250	0.035865	0.036364	0.037123	0.039467	0.043534

Figure 10 illustrates the energy consumption for Grid HV and Grid HVD topology. BFA method finds the optimal position of the connected dominating set in the topology. BFA technique consumes the minimum energy for the optimal topology construction when compared to A3, A1, GA, and GSA algorithms and provides support for extending the network lifetime. Table 8 shows the energy consumption for A3, A1, GA, GSA, and BFA.

4.3.1 Wilcoxon Rank Sum Calculator

Wilcoxon rank-sum calculator is used to find the solution for two independent samples. Energy consumption and total connected sensing coverage of BFA are taken as the two independent samples and also to consider the 0.05 significance level. Table 9 and 10 represents the two independent samples and average rank values.

The two independent samples are considered as follows:

The average rank values with the rank ties are shown below

The sum of the ranks of sample1 is $1+2+3+4+5=15$

The sum of ranks sample is $6+7+8+9+10=40$

Figure 9. Number of active nodes

Table 7. Number of active nodes

Grid topology	A3	A1	GA	GSA	BFA
Grid HVD	21	23	26	30	38
Grid HV	33	35	37	38	42

Figure 10. Energy Consumption

Table 8. Energy Consumption

Grid Topology	A3	A1	GA	GSA	BFA
Grid HV	0.04523	0.03941	0.0302	0.02521	0.02027
Grid HVD	0.06823	0.05314	0.04813	0.04223	0.03128

Table 9. Two independent samples

Sample1 (Total Connected Sensing coverage)	Sample2 (Energy Consumption)
0.0314	0.4358
0.0331	0.3104
0.0365	0.1959
0.0391	0.1786
0.0435	0.1617

Table 10. Average rank values

Sample	Value	Rank	Rank (adjusted for ties)
1	0.0314	1	1
1	0.0331	2	2
1	0.0365	3	3
1	0.0391	4	4
1	0.0435	5	5
2	0.1617	6	6
2	0.1786	7	7
2	0.1959	8	8
2	0.3104	9	9
2	0.4358	10	10

Hence, the test statistic is $R = R_1 = 15$

Null Hypothesis: The difference of the median is less than or equal to zero

Alternate Hypothesis: The difference of the median is greater than zero.

The critical value for the significance level is provided and the type of tail is $R_c = 19$ and the null hypothesis is rejected for $R < 19$. For this cases $R = 15 \leq 19$, there is evidence to claim that the difference between population medians is greater than zero, at the 0.05 significance level,

It is concluded that the null hypothesis H_0 is not rejected. Therefore there is no an evidence to claim that the difference between population medians is greater than zero, at the 0.05 significance level.

The summary of the simulation results are provided as follows:

1. The number of active nodes determined by varying the transmission range from 1m to 3m. The proposed methodology achieves the maximum value when compared to the A3, A1, GA, and GSA algorithms.
2. The residual energy in connected dominated sets is calculated by varying the sensor nodes. This performance metric is computed for different algorithms such as A3, A1, GA, GSA, and BFA algorithms. The proposed methodology achieves the maximum residual energy when compared to the A3, A1, GA, and GSA algorithms.
3. Total connected sensing coverage area computed by varying the sensor nodes with the help of different algorithms such as A3, A1, GA, GSA, and BFA. The proposed methodology covers the maximum sensing coverage area when compared to A3, A1, GA, and GSA algorithms.
4. The number of the active nodes measured for the Grid HV and Grid HVD topology by comparing the A3, A1, GA, GSA, and BFA algorithms. BFA algorithm improves the number of active nodes when compared to the A3, A1, GA, and GSA algorithms
5. Energy consumption was measured for the five different algorithms such as A3, A1, GA, GSA, and BFA algorithm in the Grid HV and Grid HVD topology. The proposed methodology consumes minimum energy for the data communication when compared to A3, A1, GA, and GSA algorithms.

5. CONCLUSION

In this paper, Bacteria Foraging Algorithm (BFA) is proposed for selecting the suitable optimal nodes in wireless sensor networks. The optimal nodes are utilized for forming the connected dominating set for the topology construction by using residual energy and network connectivity. Bacteria Foraging Algorithm is compared with A3, A1, Genetic Algorithm (GA), and Gravitational Search Algorithm (GSA). The performance of the bacteria foraging algorithm is evaluated by utilizing the performance metrics of the number of active nodes, residual energy, and connected sensing coverage area. The proposed methodology achieves better results for reducing energy consumption and also increasing the number of active nodes for constructing the virtual backbone process. This methodology improves the network lifetime by forming the virtual backbone in wireless sensor networks.

In further enhancement, other metaheuristic techniques can be applied for designing the optimal topology construction. This work can be extended further for implementing and testing the real-time applications in wireless sensor networks. The proposed methodology can be implemented and tested for heterogeneous and mobility-based environments.

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