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Efficient Cluster Head Selection and Connected Target Coverage Strategies for Real Time Requirements

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ABSTRACT

Clustering is one of the most efficient techniques for saving energy of wireless sensor networks (WSNs). However, in a hierarchical cluster based WSN, cluster heads (CHs) consume more energy due to extra overload for receiving and aggregating the data from their member sensor nodes and transmitting the aggregated data to the base station. Proper selection of CHs plays major role to conserve the energy of sensor nodes to increase the lifetime of WSNs. Coverage and connectivity must also be addressed to fulfil reliability and real- time requirements. In this paper, we propose an energy efficient cluster head selection algorithm and also analyze characteristics of energy-efficient coverage strategies. In the proposed approach, we consider various parameters such as sink distance and intra-cluster distance of sensor nodes for energy-efficiency. The results are compared with some existing algorithms to demonstrate the superiority of the proposed algorithm.

I. INTRODUCTION

Wireless sensor networks (WSNs) consist of autonomous sensor nodes, which cooperate themselves to collect and process the data from a target area and communicate to a remote base station. Due to recent advances in the micro-electro-mechanical-systems (MEMS) technology, low-cost sensors are available and as a result, WSNs have paid enormous attention for their wide range of applications in various fields, including industry, disaster management, health and military etc. However, the major constraint of WSNs is the limited power sources of the sensor nodes. The battery operated sensors are often deployed in an unattended hostile environment, so replacement of their battery is almost impossible which make the sensor node energy constraint. Therefore, energy conservation of the sensor nodes is the main challenging issue in the development of a large scale WSNs. Clustering sensor node is one of the most effective techniques which are employed to conserve the energy of the sensor nodes. In the process of clustering, the network is divided into several groups, called clusters. Each cluster has a leader referred as cluster head (CH). CHs are responsible to collect the local data from their member sensor nodes within the clusters, aggregate them and send it to a remote base station (BS) directly or through other CHs. The BS is connected to a public network such as Internet for public notification of the event. As an example, the functionality of cluster based WSN is shown in Figure 1.

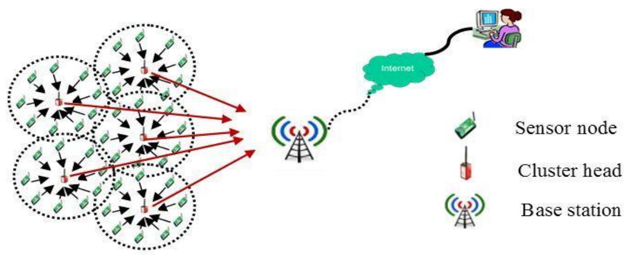

Figure 1. Cluster based WSN model

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Clustering has the following advantages.

(1) It enables data aggregation at CH level to discard the redundant data, thus reduces energy consumption of the network by preventing transmission of individual data from each sensor node.
(2) It improves the scalability of the network significantly.
(3) Exchange of redundant messages can be avoided because it conserves communication bandwidth as sensor nodes communicate with CHs.

However, in the process of clustering, selection of the CHs performs a very crucial role for longevity of the network lifetime as it has several impacts on the energy conservation of member sensor nodes. It has also the effect on the data routing process in an energy efficient manner which is the ultimate goal of any WSN. Therefore, proper care should be taken in the selection process of the CHs. CH-selection is an optimization problem which is NPhard in nature. Classical optimization algorithms are inefficient with the increasing size of the network. Particle swarm optimization (PSO) is one of the efficient nature inspired algorithms which can be a better choice for such NP-hard problem due to its ease of implementation, high quality of solution, ability to escape from the local optima and quick convergence.

Industrial applications require a high measure of reliability, so any sensing of essential equipment or processes must be prioritised and free of interruption. As a leading application of IAS, supervisory control and data acquisition require a high level of reliability in terms of data integrity and timely reporting. Therefore, an WSN should provide uninterrupted target coverage and connectivity among all sensor nodes and a sink node. This is referred as the Connected Target Coverage (CTC) problem. In this each discrete target in the network must be within the sensing range of at least one sensor node, and where at least one routing path must be found to connect any source node to the sink node. However, in industrial environments, the coverage area of a sensor node, as well as the link connectivity, may suffer from noise, co channel interferences and multipath propagation. Energy is also one of the main constraints of wireless sensor nodes. Therefore, the energy-efficient connected target coverage problem has become an important issue that urgently needs to be addressed.

In Energy-efficient target coverage approaches selected nodes are prioritised and always connected to the control sink even if other nodes may die. These approaches could be used to monitor essential equipment with dedicated target sensor nodes. These nodes could be in hard-to-maintain areas, e.g. inside motors, pipes or furnaces, which places a premium on longer lifetime in addition to connection reliability. WSNs also need to be resistant to noisy environments, a requirement not commonly considered in consumer network design.

In this paper, we mainly concentrate on CH selection problem and present a PSO based algorithm. The proposed algorithm efficiently selects the CHs among the normal sensor nodes. We next propose the PSO based approach for the same. We also present the cluster formation phase. The proposed PSO algorithm is developed with an efficient particle encoding scheme. The fitness function is also derived by considering various distance parameters and residual energy to make the PSO based approach energy efficient. This paper also evaluates different connected target coverage in terms of reliability and real-time requirements.

II. LITERATURE RELATED WORK

A large number of clustering algorithm based on heuristic methods has been developed for WSNs. Among these LEACH is a well-known distributed clustering algorithm in which the sensor nodes elect themselves as a CH with some probability. LEACH provides significant energy saving and prolongs the lifetime of the network compared to static clustering and minimum transmission energy (MTE) protocol. However, the main disadvantage of this algorithm is that there is a possibility to select a CH with very low energy, which may die quickly and thus degrades the performance of the network.

Therefore, a number of algorithms have been developed to improve LEACH protocol; PEGASIS and HEED are popular among them. PEGASIS organizes the nodes into the chain so that each node transmits and receives the data only from its neighbour nodes. In each round, a randomly selected node from the chain is selected as a CH. PEGASIS is more energy efficient over LEACH but it is unstable for large size networks. Moreover the delay is significantly high. Recently, many algorithms have been developed for data gathering schemes for extending the lifetime of WSNs. Loscri et al., have proposed TL-LEACH protocol introducing a new level of hierarchy. It improves the network lifetime over LEACH, however, with an extra overhead for electing secondary CHs and also non-CH nodes assign to the CHs based on distance only, which may cause severe energy imbalance to the network. Xiaoyan et al., have proposed M-LEACH algorithm, it is similar to LEACH, the only difference is instead of sending the data directly to the BS, it forward to the next hop CH node, in this way it saves energy compared to LEACH and TL-LEACH. However, it doesn’t take care of cluster formation phase. Also, in multi-hop data transfer between CHs, it does not consider the important metrics like energy, node degree etc. Yassein et al., have proposed V-LEACH protocol for improving the LEACH protocol in which some CHs referred as vice CHs are selected along with the main CHs, when the main CHs die, the vice CHs act as a CHs. It is shown to perform better than original LEACH. However, sensor nodes need extra processing energy for selecting vice CHs. Also, it doesn’t take care of formation of clusters, which may cause severe energy inefficiency of the WSN.

There are numerous papers on optimizing routing and connectivity of networks in a number of different ways. For example, there are proposals that prioritize geographic area coverage as well as barrier coverage, rather than the coverage of discrete targets, and allow for network nodes to move after deployment. Due to energy constraint in IWSNs, the scope of our study is confined to CTC protocols with claims to energy efficiency. In this section, we briefly review some of the prominent existing CTC algorithms, which adopt different energy conservation technologies. Related research attempted to schedule sensor nodes to alternate between active and sleep mode by organizing nodes in sets. A maximum covers algorithm using mixed integer programming (MC-MIP) was proposed. Based on the output of MC-MIP, nodes are organized into disjoint set covers (DSC) which are activated successively. And a greedy algorithm designed for maximum set covers (MSCGreedy) was proposed. Cover sets generated from MSCGreedy are not required to be disjoint and are allowed to operate in different time intervals. Compared with MC-MIP, MSC-Greedy produces better results in terms of network lifetime, since the solution space of DSC problem is included in the solution space of the maximum set cover (MSC) problem. Another power saving method is to adjust transmission or sensing range of sensor nodes by making use of power control technology. A virtual backbone based (VBB) algorithm was proposed to solve adjustable sensing range connected sensor cover (ASR-CSC) problem. By determining the transmission range of each node, both target coverage and network connectivity can be guaranteed. In proposed adjustable range load balancing protocol (ALBP). Combing sleep-sense scheduling technique with adjustable range model, further improvement in network lifetime can be derived by ALBP. In the above mentioned related work, special features for industrial environments are not taken into consideration. Also, we observe that basic design ideas behind them determine their performances while a fair and reasonable comparison helps to reveal their characteristics.

III. PRELIMINARIES

3.1 Overview of PSO

Particle swarm optimization (PSO) is a nature inspired swarm intelligence based algorithm, modelled after observing the choreography of a flock of birds, i.e., how they can explore and exploit the multi-dimensional search space for food and shelter. PSO consists of a predefined number of particles say NP, called a swarm. Each particle provides a potential solution. A particle Pi, 1<=i<=Np has position X i,d and velocity V i,d, 1<=d<=D in the dth dimension of the search space. The dimension D is same for all particles. A fitness function is used to evaluate each particle for verifying the quality of the solution. The objective of PSO is to find the particle's positions that result best evaluation of the given fitness function. In the initialization process of PSO, each particle is assigned with a random position and velocity to move in the search space. During each iteration (generation), each particle finds its own best, i.e., personal best called Pbesti and also the global best called Gbest.

3.2 Energy-Efficient connected target coverage

Since wireless sensor networks (WSN) are application oriented, algorithms applied in different target applications are based on different design assumptions and objectives. It is unfair and misleading to compare algorithms without considering their assumptions and objectives. In addition, a general survey of literature ignores the characteristics of the algorithm itself. Therefore, a comparison analysis based on a set of sample algorithms which share the same design assumptions and objectives is considered as a better method to understand the algorithms

In this paper, the four connected target coverage algorithms CWGC, OCCH, OTCC and AR-SC, have a common design objective: to maximize network lifetime while maintaining sensing coverage and network connectivity. Furthermore, they share identical design assumptions including detection model, sensing area, transmission range, failure model, time synchronization, location information and distance information. The main difference of the four algorithms is the design ideas they adopted to save energy and prolong network lifetime. The four typical design ideas behind them can be respectively summarized as follows: 1) scheduling sensor node activity to allow redundant nodes to enter the sleep mode (CWGC), 2) monitor critical targets and protecting nodes from forwarding data (OCCH), 3) eliminating the redundancy caused by overlapped targets (OTCC), and 4) reducing power consumption to minimize the sensing range while the sensing coverage objective is met (AR-SC). In our study, the same design assumptions and objectives are recognized as constant factors while the idea used to conserve energy is the only variable factor whose effect needs to be determined. Therefore, it is fair to embody the properties of each power-saving idea by a detailed comparison. In the following subsections, the four typical connected target coverage algorithms are presented in detail.

IV. PROPOSED SYSTEM

The algorithm consists of two phases, i.e., CH selection and cluster formation. The CH selection is based on PSO. The CH selection algorithm based on residual energy and distance parameters. In the CH selection phase, initially all the sensor nodes send their location and residual energy to the base station to check whether it meets the threshold energy (average energy of the sensor nodes) to become eligible for a CH. The PSO based CH selection algorithm is then run at the base station followed by cluster formation phase. For the cluster formation, we derive the weight function based on various parameters such as distance, energy and node degree of CHs. We now first describe our proposed PSO based method for CH selection and present cluster formation phase in details as follows before that we presents the Linear programming formulation for the cluster head selection problem.

Let two functions f1 and f2 will be used to derive the fitness function for the proposed PSO based approach. The aim is to minimize both the functions f1 and f2. The best way is to minimize their linear combination. Therefore, the Linear Programming (LP) of the optimal CH selection problem is as follows:

Minimize $F = \alpha \times f1 + (1-\alpha) \times f2$

Subject to

dis(si, CHj)<=dmax; for all si $\in$ S; and CHj $\in$ C

dis(CHj, BS)<=Rmax; for all CHj $\in$ C

ECHj > TH; 1<=j<=m

$0< \alpha<1$

0< f1 , f2 <1

Where,

Dis(si; sj): The distance between two sensor nodes si and sj.

ECHj : The current energy of cluster head CHj, 1<= j<= m.

After selecting proper CHs a detailed comparison is needed to choose one of the four coverage methods, CWGC, OCCH, OTCC and AR-SC. The main idea of each algorithm is also introduced by highlighting the energy conserving mechanism they applied.

(A). Communication Weighted Greedy Cover (CWGC)

In Q. Zhao et al. modeled the CTC problem as a Maximum Cover Tree (MCT) problem. A fast heuristic algorithm called CWGC was proposed to solve the MCT problem. As shown in Fig. 4.1, a complete cover tree is a logical topology which has the following properties: 1) The root of the tree is a sink node, 2) each leaf of the tree is a source node, and 3) each target can directly connect to at least one source in the tree. CWGC consists of three steps: 1) select sources in a greedy manner that can cover all the targets, 2) calculate the communication overhead of each edge in the graph to generate the shortest routing path to the sink, and 3) update the communication overhead to avoid selecting nodes with low residual energy.

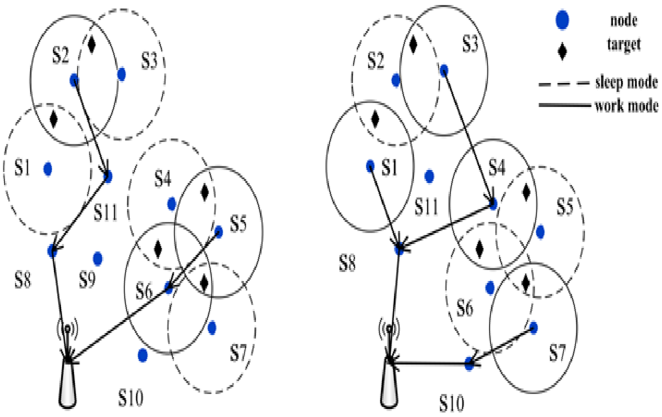


Figure 2. An example of a maximum cover tree

(B). Optimized Connected Coverage Heuristic (OCCH)

It can be observed that a target, which is covered by the minimum number of sensors, is the bottleneck in terms of the network lifetime. This kind of target is known as a critical target. The sensor nodes that monitor the critical targets are defined as critical nodes. D. Zorbas and C. Douligeris proposed an efficient algorithm called OCCH to protect the critical nodes from forwarding data. To increase the communication weight of critical nodes manually, the possibility that a critical node is selected to relay data can be decreased. As shown in Figure 3, once a critical node appears in the optimal route, a common node in the vicinity of the critical node will replace it and establish a sub-optimal route. Although using other nodes may increase the transmission cost, it makes sense to prolong the whole network lifetime.

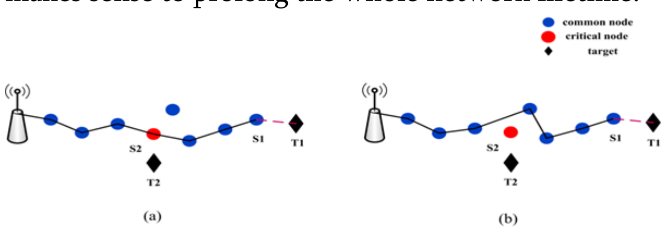


Figure 3. Avoid traversing a node that covers a critical target

(C). Overlapped Target and Connected Coverage (OTCC)

The energy a node consumes to sense and transmit is proportional to the number of targets within its sensing area. However, multiple transmissions of the same data is redundant and the energy used to process the redundant data is meaningless if we do not take data reliability into consideration. In Fig. 4.3, adjacent nodes may gather overlapped data from targets and deliver them to the sink node. This is referred to as the Overlapped Target issue.

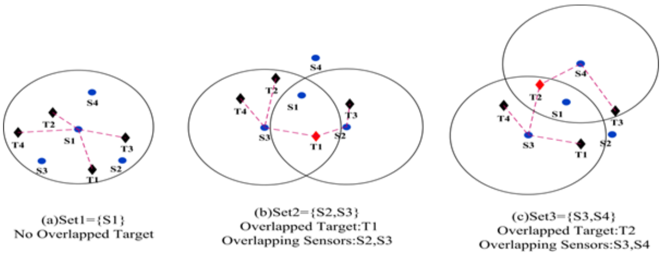
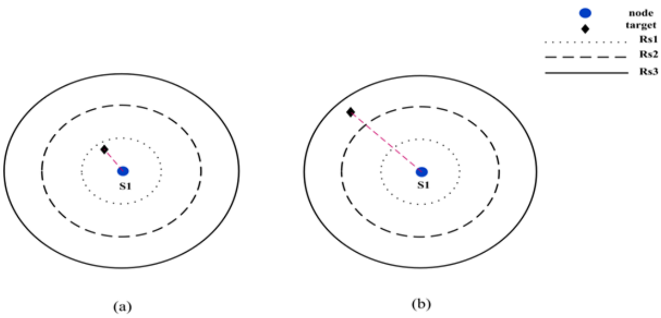


Figure 4. Overlapping sensors in joint sets in overlapped target.

(D). Adjustable Range Set Covers (AR-SC)

M. Cardei et al. addressed the target coverage problem with adjustable sensing radius. As shown in Fig. 4.4, the sensing radius of each node can be adjusted by working on different power levels. Since energy resources are conserved, working on a low power level allows the sensor to be operational longer (Figure 5(a)). In addition, the ability to adjust the sensing radius helps the network to be more flexible. When a node with enough residual energy cannot monitor any target in the current state, it has the possibility to join the sensing task by increasing its power level (Figure 5(b)).



Figuer 5. Example with one node, one target and three power levels

V. PERFORMANCE EVALUATION

The proposed algorithm was tested using C programming and the results are plotted using MATLAB (version 7.11) and on an Intel core i7 processor with chipset 2600, 3.40 GHZ CPU 2 GB RAM running on the platform Microsoft Windows 7. The simulations were performed over varying number of sensor nodes from 300 to 700 with 15 to 50 CHs. It was assumed that each sensor node has the initial energy of amount 2 J. In the simulation run, we have used following parameter values as used by Heinzelman et al. as shown in Table 1. We have considered various network scenarios, three of which are presented here as follows.

Table 1

Parameter	Value
Target area	200 9 200 m2
Base station location	(100–300, 100–300)
Number of sensor nodes	300–700
Energy of sensor node	2 J
Percentage of CHs	5–10
Eelec	50 nJ/bit
efs	10 pJ/bit/m2
emp	0.0013 pJ/bit/m4
dmax	100 m
d0	30 m
Packet length	4000 bits
Message size	500 bits

For the first scenario the position of base station was taken in the centre of the field, i.e., at (100,100), for the second scenario, it was placed at (200, 200), i.e., top right corner of the field and finally outside of field at (300, 300). We also considered four different cases of WSN, namely WSN#1, WSN#2 and WSN#3.

In WSN#1, number of sensor nodes were 300, 400 sensor nodes in WSN#2, in WSN#3 the number of sensor nodes were 500. We analyze the performance of the algorithm over various scenarios and varying number of sensor nodes. For example, here we present some of the cases with 5 and 10 % of sensor nodes as CHs. In WSN#1 and WSN#3, we have considered 5 and 10 % of sensor nodes as CHs for both the cases. In WSN#2, we have considered only 10 % of sensor nodes as CHs. We ran the algorithms for 30 times, and average of these instances of data was considered for plotting the results. We tested our algorithm at variable size of the initial population ranging from 30 to 70, however, we used the predefined swarm size of particles as 30. In the weight sum approach we had tested different values of weight factors, ranging 0<=a<=1, however, a = 0.3 was showing comparably better results.

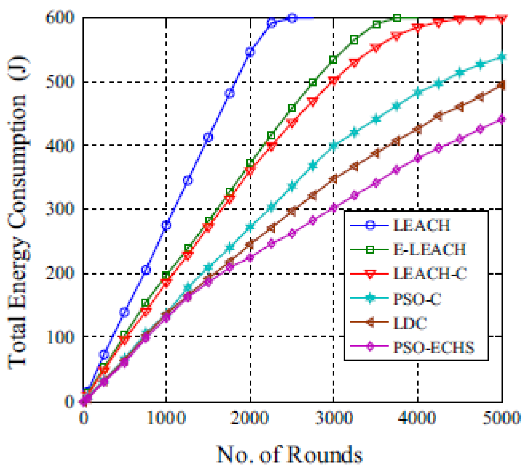


Figure 6. Comparison in terms of total energy consumption for WSN#1 with 15 CHs.

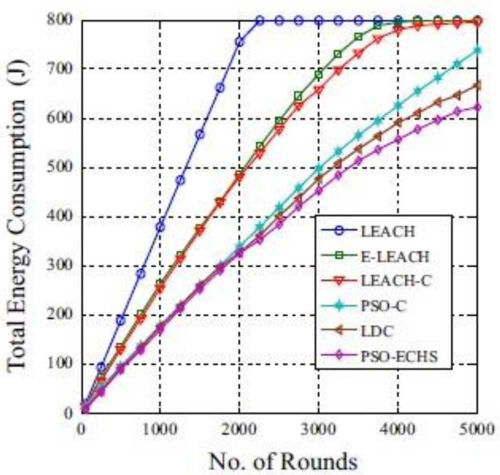


Figure 7. Comparison in terms of total energy consumption for WSN#2 with 40 CHs.

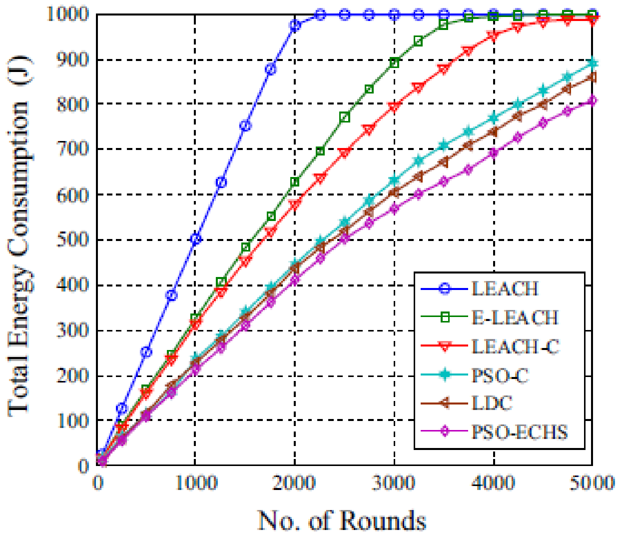


Figure 8. Comparison in terms of total energy consumption for WSN#3 with 50 CHs.

We also conduct simulations in Matlab to compare the four coverage algorithms. Although there are several network simulators available, our major focus is on the effects of industrial noise in harsh environments on the physical layer communication and how it affects these protocols. We take the advantage of Matlab's built in ability to model and visualize channels with various realistic noise models, although this requires us to implement our own model for other network operations. Both shadowing and pass loss effect are considered in our simulation to describe signal attenuation. Due to reflections of walls and machines in industrial environments, multipath effects (Rayleigh fading in our simulation) that severely affect the signal strength is also taken into account. As it is a common physical layer for industrial control and monitoring networks, a sensor network communicating with IEEE 802.15.4 is simulated that encounters various noise environments. Both sensor nodes and targets are randomly deployed in a square area. We envisage that the targets, such as motors, pumps or furnace, are essential industrial equipment within which sensor nodes are located. Since the targets are hard to maintain and require long service life, critical parameters such as temperature, pressure, vibrations or power usage need to be continuously monitored.

The rest of nodes will function as relay nodes to upload data to a sink node, while ensuring that the target always remains connected to the network. The communication radius of each node is 30m. The maximum sensing radius is 10m and can be adjusted by the power level. The position of the sink is fixed at the centre of the square area to notify any potential problem caused by failures or malfunctions in machinery. Simulation parameters are listed in Table 2.

Table 2

Parameter	Value
Physical layer	IEEE 802.15.4
Channel model	AWGN
Shadowing Mode	Constant
Multipath effect	Rayleigh
Path loss factor	2
Transmit amplifier	100pJ/bit/m2
Sensing energy	150nJ/bit
Receiving energy	150nJ/bit
Transmission energy	50nJ/bit
Packet	500bytes
Data rate	1Kbps
Initial power	20J

Evaluation Metrics

In order to evaluate the algorithms comprehensively, we investigate their properties through the following five metrics:

Network lifetime: Network lifetime is defined as the duration until there exists one target that can no longer be monitored by any node or the sensed data cannot be forwarded to the sink any longer by multi-hop.

Coverage time: Coverage time, which is used to reflect the convergence speed of the algorithm, is defined as the running time of the coverage algorithm.

Average energy consumption: Average energy consumption is defined as the overall energy consumption in the network divided by the number of deployed sensor nodes.

Ratio of dead nodes: The ratio of the number of nodes that run out of energy to the number of deployed nodes.

Balancing characteristic in energy consumption: The topology of remaining energy distribution is used to describe the characteristic of energy balance

Since sensor nodes are typically battery equipped, an important issue of CTC Algorithms is how to optimize energy consumption for data sensing, relaying and transmission. We mainly focus on comparing network lifetime under different network conditions, i.e. the number of sensor nodes, the number of targets, the network size, the communication radius, etc.

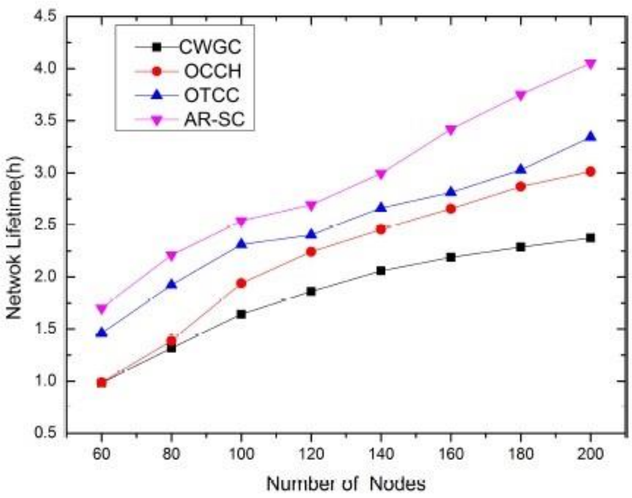


Figure 9. Network lifetime versus the number of nodes

VI. CONCLUSION AND FUTURE WORK

`In this paper, we have presented an energy efficient CH selection algorithm based on PSO using efficient particle representation and fitness function and also analyzed different energy-efficient coverage strategies designed for industrial environments. For the energy efficiency of the algorithm, we have considered intra-cluster distance, sink distance and the residual energy of nodes. Then, we derived the weight function for the formation of clusters. We have compare with various existing algorithms, namely, LDC, PSO-C, LEACH-C, E-LEACH and

LEACH. The algorithm has been extensively tested with several scenarios and various cases of WSNs. The experimental results have shown that the proposed algorithm performs better than the existing algorithms in terms of total energy consumption, network lifetime and the number of data packets received by the base station. Through comparing four representative CTC algorithms, properties of each strategy are embodied under different conditions. Since coverage performance is difficult to obtain uniformly, the selection of coverage algorithms should consider which factor (convergence speed, maximum lifetime, etc.) is the focus in a specific practical application.

However, we have not considered any routing algorithm in the proposed algorithm. Our future works will aim to develop a routing algorithm using appropriate meta-heuristic approach. For such algorithm, we shall consider various issues such as energy balancing and fault tolerance of WSNs. We also intend to develop the same for the heterogeneous WSNs in contrast to the proposed algorithm which works only for homogeneous networks. Additional work is required to bridge the gap between ideal simulations and real-world coverage systems. For instance, mobility should be introduced to a WSN.

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