A Distributed Energy Efficient Query Processing in Self-Organized Wireless Sensor Networks

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Abstract—**Spatial query execution is an essential functionality of a sensor network. Redundancy within a sensor network can be exploited to reduce the communication cost incurred in execution of such queries. Any reduction in communication cost would result in an efficient use of battery energy, which is very limited in sensors. One approach to reduce the communication cost of a query is to self-organize the network, in response to a query, into a topology that involves only a small subset of the sensors sufficient to process the query. In this paper, we design an efficient algorithm for the above problem of self-organization of a sensor network into an optimal logical topology, to reduce energy consumption, in response to a query. We introduce the EEDSOSC algorithm, a new Energy Efficient Distributed Self-organization approximation algorithm for Optimal Sensor Cover that produces a near-Optimal Sensor Cover with minimum consumed energy, minimum connected sensor cover and less message communication overhead. The performance of algorithm is tested for both dense and sparse sensor networks. Through extensive simulations, we have shown that our designed technique result in substantial energy savings in a sensor network. Moreover, experiments have been conducted on networks with different sensors transmission radius, different query sizes, and different network configurations. All experimental tests are evaluated using simulations and the experimental results showed that the proposed approach results in a significant communication cost reduction and an energy-efficient near-optimal connected sensor cover. Compared with other techniques, the results demonstrated a significant improvement of the proposed technique in terms of energy-efficient query cover with lower communication cost.**

Index Terms—**wireless sensor network, query cover, energy consumption, redundancy**

I. INTRODUCTION

Wireless sensor networks are often deployed for passive data-gathering or monitoring in geographical region. A sensor network [1]-[4] consists of sensor nodes with short range radios and on-board processing capability each sensor can also sense certain physical phenomena such as light, temperature, vibrations, or magnetic field around its location. The purpose of a sensor network is to process some high-level sensing tasks in a collaborative fashion, and is periodically queried by an external source to report a summary of the sensed data/tasks. Some work has been introduced in [5], but the mentioned centralized approach to query optimization and spanning tree construction has some deficiencies with respect to query optimization and routing. This centralized approach didn't generate an efficient query plans and resulted in high overhead as it requires that each node reports its metadata to the AP. Moreover, the routing tree infrastructure inefficiently aggregates the data packets and since that metadata (gathered by the access point) is in aggregated form, it may not precisely represent every nodes local metadata. While the technique presented in [6] results in energy savings, however the authors only present a centralized algorithm which does not extend easily to distributed. Some other related work can be found in [7]-[20]. Several new design schemes have emerged for sensor networks. On one hand, the network must be self-configuring and highly fault tolerant as the sensors may be deployed in an 'ad hoc' fashion. On the other hand, as each sensor has only limited battery energy, the network as a whole must minimize total energy usage in order to enable unattended operation for an extended time. One technique to optimize energy usage during query execution would be for the network to self-organize, in response to a query, into a logical topology involving a minimum number of sensor nodes that is sufficient to process the query. The technique of self-organization exploits sensors redundancy effectively to conserve energy. The query is then executed using only the sensors in the constructed topology. Only the sensors in the logical topology can participate (communicate with each other) during the query execution. The Self-organization technique is beneficial for queries that run sufficiently long to amortize the communication cost incurred in self-organization. This strategy is very effective for energy conservation, especially when there are many more sensors in the network than are necessary to process a given query. In this paper, we introduce a decentralized infrastructure to support query execution in sensor network. This infrastructure will distribute query optimization within the sensor network. We first define the problem and discuss the motivation of designing a decentralized query cover algorithm that overcomes many of the limitations of the centralized approach. Then we introduce a new distributed approach, the EEDSOSC algorithm, a new Energy Efficient Distributed **S**elf-organization algorithm with Optimal Sensor Cover that produces a near-Optimal Sensor Cover with minimum consumed energy. Efficient query plans will be generated that are more efficient in terms of energy consumption, cover size, message overhead, in addition to overcome many of the limitations of centralized approaches. The designed technique exploits the redundancy in the sensor

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network by selecting the optimal subset of sensors that is sufficient to process a given query. The rest of the paper is organized as follows. In Section II, we define and formulate the problem under investigation. In section III, we introduce a new distributed self-organization algorithm for efficient query cover in WSN and present the design and analysis of the proposed work. Section IV presents the simulation results and comparisons depicting the performance of our proposed algorithm, conclusions are presented in section V.

II. FORMULATION OF THE PROBLEM

Given a query *Q* over a sensor network, select an optimal set of sensors that satisfy the conditions of coverage as well as connectivity, i.e., selecting a minimum number of sensors that are sufficient to answer the query such that: 1) the sensing region of the selected set of sensors cover the entire geographical region of the query, 2) the selected set of sensors form a connected communication graph where there is an edge between any two sensors that can directly communicate with each other, and 3) The selected set of sensors should form a minimum cover-size connected communication graph, so that they can form a logical routing topology for data gathering and transmission to the query source. In addition, (4) query processing must incorporate energy awareness into the system to extend the lifetime of the sensor nodes and network by reducing the total energy consumption. This is fulfilled by assigning a weight to every sensor in the network according to the amount of energy it consumes. During the selection of sensors into the cover the factor of energy consumption is taken into consideration by choosing the sensor with the minimum weight, i.e. minimum consumption of energy, because this guarantee a higher cover life time which is more suitable for long running queries. Further more, the required algorithm needs to reduce the number of exchanged messages for coordination and minimize the computation load on the sensor nodes.

A sensor network is modeled as a set N of a large number of sensors, |N|, distributed randomly in a geographical region. Each sensor has a unique identifier (ID) V_i and is capable of sensing a well-defined convex region *SR* around itself called *sensing region*. Each sensor also has a radio interface and can communicate directly with some of the sensors around it. Each sensor node has a different energy consumption attribute, the lower the consumption attribute the higher the sensor survivability. The sensor network is represented with an undirected graph *G* with set of vertices *V* and set of edges *E*. The sensor network consists of $|N|$ sensor nodes. If two sensors can communicate directly then they are connected with a virtual edge, i.e. their sensing disks intersects (connection edge). A Query *Q* in a sensor network asks for the summarization of some sensed data/events over some time window and geographical region, which is a subset of the overall region covered by the sensing regions of all the sensors in the network. A query is typically run multiple times, possibly, for different time windows

III. THE PROPOSED ENERGY-EFFICIENT DISTRIBUTED SELF-ORGANIZATION ALGORITHM FOR OPTIMAL SENSOR COVER (EEDSOSC)

In this section, a new **E**nergy-**E**fficient **D**istributed **S**elf-organizing algorithm is proposed with **O**ptimal **S**ensor **C**over that produces a near-Optimal Sensor Cover with minimum cover-size, less message communication overhead and minimum energy consumption. The network is assumed to have sensor nodes with different energy consumption capabilities. In this section, we present an alternate modified distributed approach that uses a lower number of messages and can scale well for large dense networks with the least consumption of energy, while maintaining a guarantee an upper-bound on the size of the connected sensor cover delivered by the applied algorithm.

It is assumed that every sensor is capable of sensing a well defined convex region around itself and can communicate directly with some of the sensors around it if the distance between them is within the transmission radius *t.* Fig. 1 illustrates an example of a query region *QR* and the region covered by *C*.

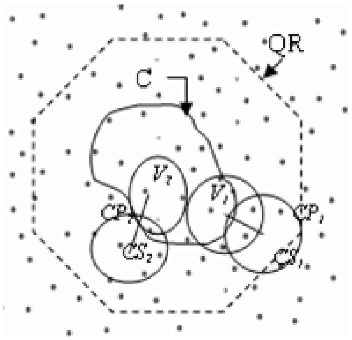


Figure 1 Geographic query region *QR* inside the network's boundary. *Candidate sensors:*CS_1 and CS_2; associated candidate paths: CP_1 and CP_2; cover: C.

Given a current cover C_i, the control is distributed over the set *B* of boundary sensors for the selection of the next candidate sensors. This selection of the next candidate sensors will be based on boundary node's local neighborhood information of the current cover. Our proposed algorithm goes through the following sequence of stages:

(1) ***Choosing the boundary sensors:*** at each iteration of the algorithm, the set *B* will be updated with the new boundary sensors by checking the location of every sensor C_i in *the current cover C* with respect to the center of the cover. If C_i falls within a certain threshold range then it will be considered a boundary sensor and added to the set *B*. The threshold range is between *Min_Boundary_dist* and *Max_Boundary_dist*. As illustrated in Fig. 2, all sensors that lie between boundary thresholds are defined as boundary sensors.

Only the boundary sensors *B* will be invoked in selection of the next candidate sensors without taking the rest of the sensors in the middle of the cover into consideration to reduce the number of messages broadcasted as will be mentioned next in phase (2). Experiments have shown that even if the sensors in the middle of the cover are taken into consideration will not add any benefit. As sensing regions of candidate sensors intersecting with these sensors will be approximately the same sensing regions of some sensors in the boundary set (i.e. will not give any additional uncovered areas to be added to the cover). Adding these candidate sensors to the cover will just increase the redundancy of sensors and waste energy.

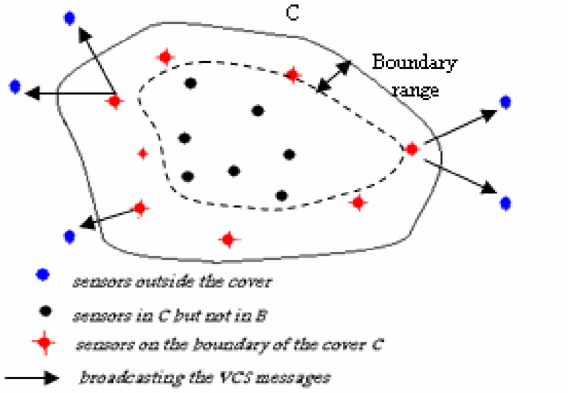


Figure 2 The cover *C* and the boundary sensors that will be selected in *B;* Sensors in *B* broadcasts VCS messages to the neighbor sensors

(2) *Finding possible Candidate sensors:* Every sensor B_L in the updated set *B* broadcasts a *View Candidate Sensors (VCS)* message to all the neighbor sensors, $V_i \notin C$, falling at a distance not less than *Boundary_Dist_threshold*. We choose this threshold to eliminate the number of broadcasted messages to sensors having nearly the same sensing regions as other sensors in C (i.e. reducing the consumption of energy by keeping sensors that will not add any gain to the cover inactive). The *VCS* message contains the ID of the originating sensor of the message.

***(3) Collecting Candidate paths*:** Any sensor V_i receives a VCS message checks to see if it is a new candidate sensor, i.e., if V_i*'s* sensing region intersects with the sensing region of some sensor in the boundary sensors set. Moreover, it checks whether the minimum distance between it and all other sensors in *C* is greater than or equals to the *Dist_threshold to avoid redundancy*. This will eliminate the redundancy of sensors having the same sensing region in the selected cover. If V_i is a candidate sensor CS_i, it unicasts a ***KEepAlive** (KEA)* message to the originating sensor of the *VCS* message informing that it is one of the candidate sensors. The *KEA* message contains the candidate path connecting CS_i to some sensor in C.

(4) ***Choosing the most beneficial candidate path/sensor***: Every sensor B_L in *B*, which was the originator of the *VCS* messages in the current stage, collects all the *KEA* messages sent to it by the candidate sensors. The fitness of every candidate path contained in each received *KEA* message is calculated. After finding the fitness of all candidate paths in this stage, the sensor with the highest fitness is added to the cover.

(5) Check for query coverage: The above process repeats until the selected set of sensors *C* covers the entire query region in the sensor network. One of the most principle features of the EEDSOSC algorithm is that the *Boundary_Dist_threshold* is dynamically adapted. The algorithm starts with an initial setting for the *Boundary_Dist_threshold.* Then, at each iteration in which the candidate set returns empty, the *Boundary_Dist_threshold is* decreased and the candidate selection process is repeated. This adaptive selection mechanism allows the EEDSOSC approach to dynamically adapt for different network distributions and density.

IV. EXPERIMENTAL RESULTS

Experiments have been conducted to illustrate the efficiency of the proposed algorithm. A simulator is constructed to evaluate the performance and compare with other algorithms in terms of average consumed energy, communication overhead and solution cover size. We ran our algorithms on randomly generated sensor networks wherein a certain number of sensor nodes $|N|$ are placed randomly in an area of 100×100 unit square. All sensor nodes have a circular sensing region of radius r_s associated with them. The size of rectangular region, number of nodes $|N|$, sensing radius r_s, and transmission radius *t* are input parameters of the simulator.

We vary the network size $|N|$ from 100 to 800 (which provides substantial redundancy) randomly placed sensors. Also, we vary the transmission radius *t* of sensor nodes from 10 to 20 units. The query region is a circular region of radius r_q within the rectangle area. Experiments have been conducted with different generated query radius ($r_q = 10, 15, 20, \ldots, 50$). Each sensor node has a different energy consumption attribute, the lower the consumption attribute the higher the sensor survivability. Sensors have a sensing region of radius $r_s = 10$. This range of parameters allows us to study the performance for sparse to dense networks. Our experiments with lower values of *t* and $|N|$ showed that the network was too sparse that a connected sensor cover did not exist (Query Not Covered (*QNC*)). For $t > 10$, the sensors with intersecting sensor disks are reachable within one hop (i.e. link radius $r=2$). Thus, one set of experiment for $t > 10$ is sufficient.

The algorithm computes the total energy consumption of the selected cover (*En*), the number of messages transmitted during the algorithm (a measure of the communication overhead of the algorithm), and the size of the connected sensor cover constructed, for a given set of input parameters. Let *D* be the number of messages needed to compute a connected sensor cover and *c* be the size of the computed connected sensor cover. Query source is randomly selected sensor. Furthermore, we compare the performance of our proposed EEDSOSC algorithm with the centralized and decentralized greedy algorithms [4].

Let *c* be the cover size returned by the decentralized greedy algorithm and let c_c be the cover size returned by the centralized greedy version. Fig. 3 illustrates the change in the ratio c/c_c versus *t*. The figure depicts excellent performance of the decentralized approximation algorithm relative to the greedy centralized one. The ratio c/c_c always remains close to the ideal value of 1. Thus the optimizations induced in the decentralized approximation algorithm to reduce communication cost do not impact the c/c_c ratio, which remains close to the ideal. Moreover, for dense WSN (high $|N|$ and *t*) there is a significant decrease in the number of messages produced by the decentralized version. The above observation validates the approach for both dense and sparse WSN.

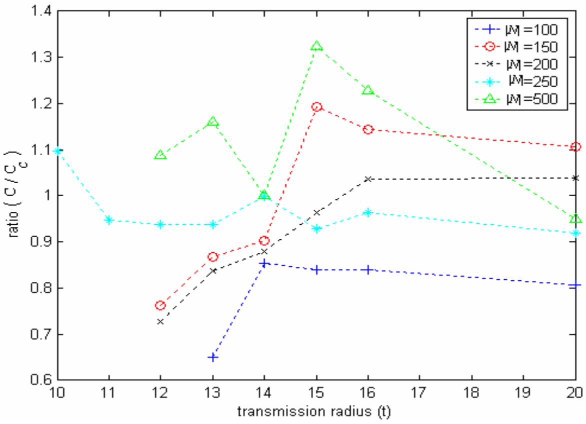


Figure 3 Cover size ratio of the distributed versus. centralized (c / c_c)

Note that c is very small relative to the network size $|N|$, except for low $|N|$ and t when the communication graph is very sparse and there is low redundancy in the network. A random network for some low values of t and $|N|$ may not have a connected communication graph with high probability.

Let c_{eeds} be the size of the connected sensor cover returned by the proposed EEDSOSC algorithm and c is the sensor cover returned by the decentralized greedy algorithm. Fig. 4 plots the ratio c_{eeds}/c versus t for different network sizes. Since the ratio is almost less than or close to 1, the new distributed EEDSOSC algorithm, which depicts excellent performance in consumed energy reduction and in reducing the number of messages, either is combined with reducing the cover size or does not impact the c_{eeds}/c ratio, which remains close to the ideal. Moreover, Fig. 5 illustrates the performance of the decentralized greedy algorithm in terms of the number of messages, D. It plots D versus t for various values of network size.

Fig. 6 plots the ratio between the number of messages of EEDSOSC and the decentralized greedy query cover algorithm versus t, for different network sizes. It is observable from the chart that there is a dramatic decrease in the number of messages for the proposed EEDSOSC algorithm compared to the decentralized greedy query cover version for different network configurations and different t values. Moreover, for large dense networks (large $|N|$ and high values of t) the improvement is noticeable. It is observable from Fig. 6 that the ratio is more less than 1.

Let En_{eeds} be the total energy consumption of the query cover produced by the proposed EEDSOSC algorithm, and En_{ds} be the total energy consumption of the query cover using the distributed minimum-size cover algorithm (DSOSC), where the DSOSC is another version of our proposed algorithm in which the sensor nodes energy consumption are not considered in the candidate selection for minimum query cover. This version is implemented to illustrate a fair comparison with such algorithms that do not consider the sensor energy consumption factors**.**

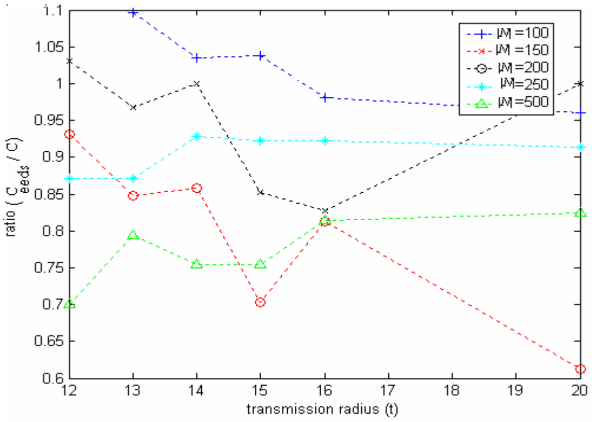


Figure 4 Cover size ratio of the proposed distributed EEDSOSC algorithm vs. decentralized greedy algorithm (c_{eeds} / c)

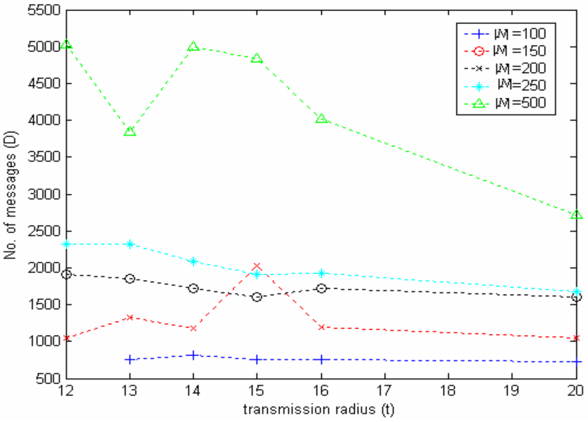


Figure 5.The performance of the decentralized greedy algorithm in terms of number of messages *D*. The graph illustrates the number of messages *D* versus *t*, for different WSN sizes.

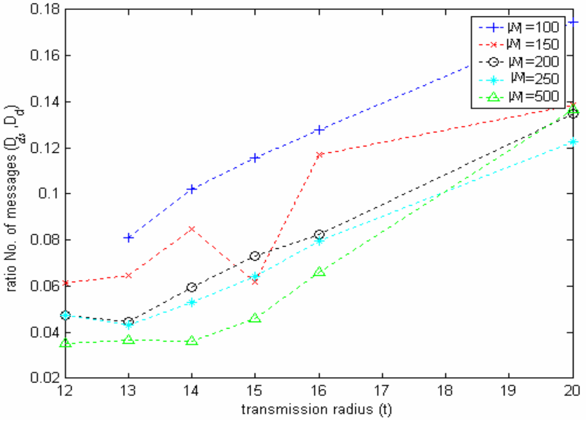


Figure 6 The relation between the number of messages of EEDSOSC and Decentralized greedy algorithm, for different network sizes.

Fig. 7-(a) and fig. 7-(b) plot the average energy consumption for both the EEDSOSC and DSOSC algorithms compared to the decentralized greedy, for networks of sizes 250 and 500, respectively. The figures illustrate a significant reduction in the total energy consumption of the resulted query cover using the EEDSOSC algorithm.

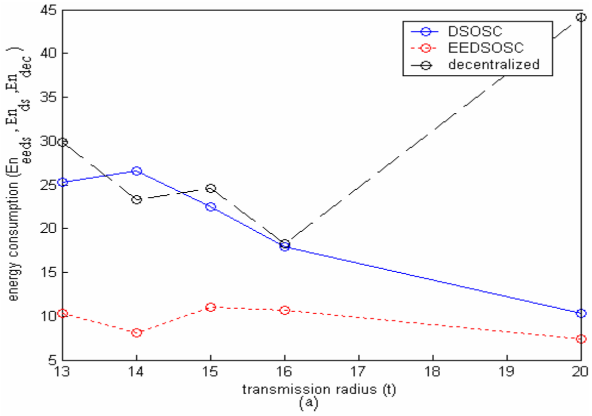


Figure 7-(a) The total energy consumption of query cover, for a network of size 250, for various transmission radius *t*.

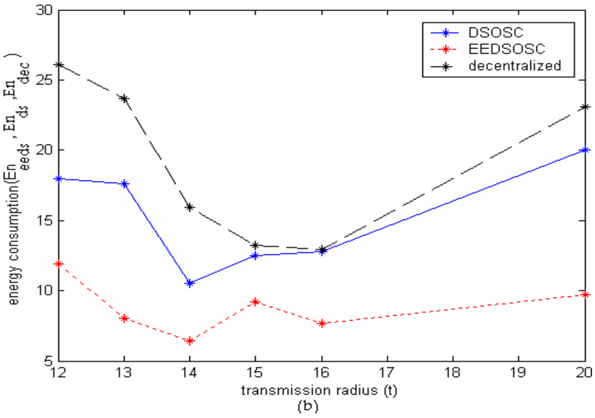
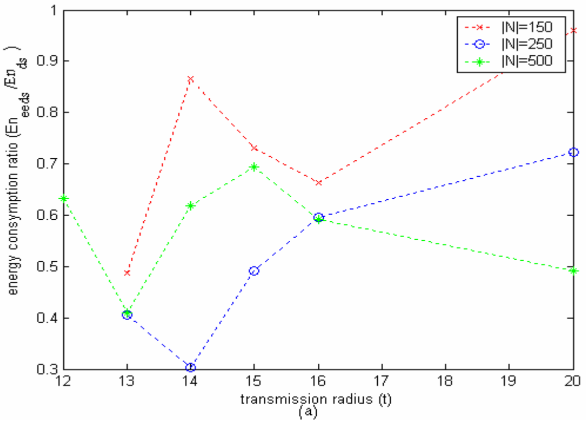


Figure 7-(b) The total energy consumption of query cover, for a network of size 500, for various transmission radius *t*.

Fig. 8-(a) plots the ratio En_{eeds}/En_{ds} versus t for different network sizes. Since the ratio is almost less than or close to 1, the new distributed EEDSOSC algorithm, which depicts excellent performance in reducing the number of messages, is combined with a great reduction in the energy consumption of the query cover.

Let C_{eeds} be the sensors cover size produced by the EEDSOSC algorithm, and C_{ds} is the cover size produced by DSOSC.



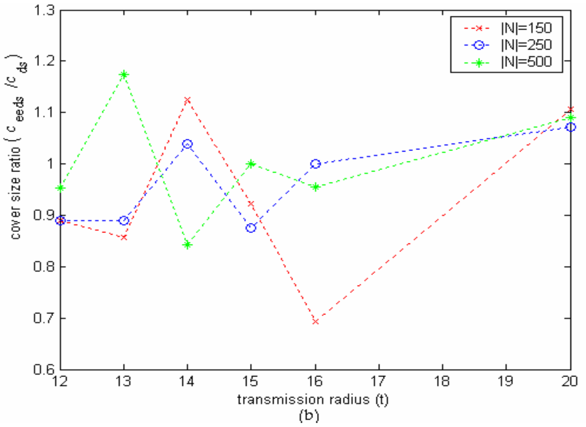


Figure 8 Comparison between EEDSOSC and DSOSC for different network sizes and transmission radius t;(a) shows the ratio En_{eeds}/En_{ds}; (b) shows the ratio c_{eeds}/c_{ds}

As shown from fig. 8-(b), cover size returned by the EEDSOSC is not much higher than that returned by DSOSC. The ratio c_{eeds}/c_{ds} remains approximately close to 1.

As observed from fig. 8-(a) and fig. 8-(b), while there is a great reduction the total energy consumption using the EEDSOSC, the optimizations induced in the algorithm to reduce energy consumption do not impact the c_{eeds}/c_{ds} ratio, which remains close to the ideal. Moreover, for dense WSN (high $|N|$ and t) there is a significant decrease in the consumed energy produced by the EEDSOSC. The above observation validates the approach for both dense and sparse WSN.

Fig. 9 illustrates the energy consumption of the resulted query cover for different values of generated query radius (queries of different sizes), applied for both the EEDSOSC and DSOSC algorithms. As shown in fig. 9, the energy consumption of the query cover in case of EEDSOSC is considerably lower than the corresponding value in case of the distributed DSOSC version. Moreover, the improvement is noticeable in case of large generated queries (with wide diameters), where the energy consumption of the cover is getting more reduced for EEDSOSC while there is a dramatic increase in the consumed energy in case of the DSOSC version.

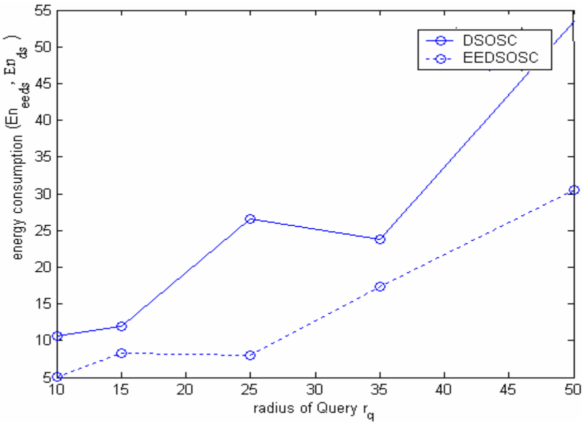


Figure 9 Comparison between the energy consumption of the query cover for both the EEDSOSC and DSOSC algorithms, for different query radius r_q.

V. CONCLUSION

In this paper we have introduced the EEDSOSC algorithm, a new **E**nergy **E**fficient **D**istributed **S**elf- organized approximation algorithm with **O**ptimal **S**ensor **C**over that produces a near-Optimal Query Cover with minimum consumed energy and minimum message communication overhead. Efficient query plans are generated that are more efficient in terms of energy consumption, cover size, message overhead, in addition to overcome many of the limitations of centralized approaches. The designed technique exploits the redundancy in the sensor network by selecting the optimal subset of sensors that is sufficient to process a given query. Select an optimal set of sensors that satisfy the conditions of coverage as well as connectivity. In addition, the proposed algorithm has reduced the number of exchanged messages for coordination, the number of broadcast View Candidate Sensors (VCS) messages, and minimizes the computation load on the sensor nodes. The presented alternate modified distributed approach uses a lower number of messages and can scale well for large dense networks while maintaining a guarantee on the size of the connected sensor cover. Through extensive simulations, we have shown that our designed techniques result in substantial energy savings in a sensor network. Compared with other techniques, the results demonstrated a significant improvement of the proposed techniques in terms of energy-efficient query cover with lower communication cost.

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