

Research Article

Hybrid Ant Algorithm Based Query Processing with Multiagents in Sensor Networks

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The wireless sensor networks are usually deployed in various application-specific contexts, which can be treated as distributed databases with big data. The event-involved query responses can be obtained by issuing query requests to this kind of database. However, the constraints of the energy and delay have had a great impact on the operation of wireless sensor networks. How to design the query-involved network model and the corresponding query processing algorithms is extremely challenging. This work investigates query processing problem in resource-constrained wireless sensor networks with the two-tier architecture and multiple query agents, where the multiple nodes of query agents are configured in the networks and the corresponding source cluster-heads send collected events to only one optimum query agent. To reduce the energy consumption and shorten the delivery delay, an efficient query processing algorithm inspired by the swarm intelligence of ants is proposed, which takes advantage of the beneficial clustering and routing emerging in a hybrid self-organized way from the positive interaction of ants. The experimental results demonstrated that the proposed algorithm can deliver collected events to the optimum query agents efficiently. Not only is the energy cost reduced but also the delivery delay is shortened significantly when transmitting the named events to the appropriate query agents.

1. Introduction

The technologies of wireless sensor networks (WSN) have been developed rapidly in the most recent years. Because WSN can cover large areas and extract localized features, the applications involved are from a wide variety of areas such as environment monitoring and security [1–3].

As WSNs are characterized by data-centric routing under most circumstances, any application involved requires data processing technologies, especially the query processing [4]. Because of the severe constraints on energy and computation that are characteristics of WSNs, the centralized querying approach is often infeasible for large-scale networks, and it is crucial to propose energy-efficient distributed in-network querying protocols while providing an acceptable quality of information [5]. A decentralized infrastructure for supporting querying in WSNs was introduced in [6],

which utilizes sensor's spatial and semantic characteristics. The ACQUIRE mechanism in [7] provides superior query optimization for responding to particular kinds of queries. However, a one-size-fits-all approach is unlikely to provide efficient solutions for all types of queries [7]. In this paper, we focus on the solution for query processing with both the energy and the delay constraints in WSNs. To the best of our knowledge, when considering the multiple QoS constraints such as the query delay and the minimal energy required, the multiconstrained querying problem is NP-hard.

For a special application in WSNs, the event types are limited. When the events involved occur somewhere, the sensors nearby will collect the information and transmit it to the local cluster head. Each of the cluster-heads can identify the limited kinds of the events and transmit the event data to the queriers. Therefore, the process of issuing queries can

be omitted, and the routing problem of how can the cluster-head find the optimum querier and deliver the events to it becomes the focused topic in this paper. To promote the query performances, the query model with multiagents is presented in this paper, in which certain number of nodes are selected as the query agents and once the named events are delivered to one of the agents, the query routing is then completed. As the query agents is selected randomly, the location of them is unknown beforehand; how to search the optimum query agent when collecting the interested events is a challenge.

A distributed multiple ant colonies any cast algorithm was proposed in [8]. Though aiming at finding replicated service, it is revelatory to search replicated query agents in WSNs.

In this paper, we propose a distributed hybrid ant algorithm based query processing algorithm with multiple agents (HAAQP), which intends to overcome the inefficiency of those previous querying algorithms by reducing the expected search cost and shortening the query delay.

The remainder of the paper is organized as follows. Section 2 describes the preliminaries and the problem formulation. The novel HAAQP algorithm is proposed in Section 3. In Section 4, the proposed algorithm is evaluated by simulations. Finally, Section 5 concludes the paper.

2. Preliminaries and Problem Formulation

2.1. Ant-Based Routing Model. Swarm intelligence is a relatively new approach to problem solving that takes inspiration from the social behaviors of insects. In particular, ants have inspired lots of methods and techniques among which the most successful is ant colony optimization (ACO). The large majority of the applications of ACO are to NP-hard problem. ACO was applied to routing in various networks [9, 10]. Several improved ant-based routing algorithms for WSNs were proposed in [11].

2.2. Ant-Based Clustering Model. A special kind of ants divides their eggs based on the size. An ant-based clustering algorithm was studied [12] inspired by such behavior. Ant-based clustering is characterized by a probabilistic approach, where clustering is repeatedly realized by ants, and stochastically selected eggs are picked up or dropped. By the combination of the two ant-based models, we propose a hybrid ant-based HAAQP algorithm to solve the multiconstrained querying problem for WSNs.

2.3. Network Model of WSN. As the WSNs considered in this paper are large-scale networks, the utilization of cluster can improve the scalability. A clustering protocol capable of providing uniformly distribution of cluster-heads was proposed in [13]. We adopt the similar approach for low-tier of the WSN. The cluster radius r_C and the number of cluster-heads N_C can be calculated according to [14].

To reduce the energy cost, only part of the sensors in each cluster stays alive. There are N_Q query agents in the network ($N_Q \leq N_C$). When completing clustering in the low-tier of the WSN, the up-tier of the network emerges composed of

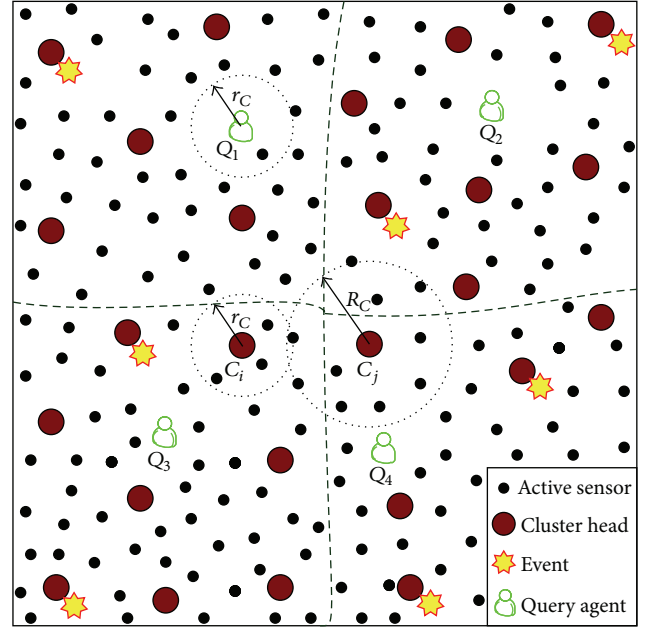


FIGURE 1: The network environment of the proposed HAAQP algorithm.

the cluster-heads including the query agents. Figure 1 shows the network environment of the problem.

In Figure 1, each cluster-head maintains several active sensors, and the sleeping sensors are omitted. The query agents Q_i are the special cluster-heads merely receiving the event packets, which are the destinations for all events. Other cluster-heads C_i act as both aggregation nodes and routers. Once an event occurs, the sensors collect the event and transmit it to the corresponding cluster-head. If the cluster-head is a query agent, the event is received successfully. Otherwise, it will be transmitted to another cluster-head till it reaches one of the query agents or it is dropped because of the constraints on it. To enhance the scalability, it is necessary to cluster on the up-tier of WSN, which makes each cluster-head C_i belong to one optimum query agent Q_i . An ant-based clustering method is adopted to work on the up-tier of the network.

2.4. Generation and Aggregation of Events. For specific application in WSNs, suppose that the maximum number of event types and the event attributes are M_0 and k , respectively. The event attributes are denoted as $(A_1, \dots, A_i, \dots, A_k)$ and $1 < i < k$. Each type of events has its special ranges of attributes. For example, the range of A_i is denoted as $|A_i| \in [a_i, b_i]$. The types of events are loaded into each sensor in advance.

The events are uniformly generated during the deployment period in WSN. To reduce the storage of sensors efficiently, the aggregation method is adopted according to the spatiotemporal attributes and sensing attributes of events [14].

When an event involved occurs, any sensor obtaining all the attribute values can infer the event type by matching the event list inserted into the node in advance.

2.5. Problem Formulation. As the WSN is treated as a two-tier network, constrained query routing among the cluster-heads on the up-tier has become the focus to be considered. There are two constraints when delivering the events to the corresponding query agent. One is energy constraint ENE_C of nodes and the other is query delay constraint DUR_C of events. Their values are different according to the different event types. When an intermediate cluster-head C_i receives an event E_r with the $ENE_C(E_r)$ and $DUR_C(E_r)$, the event will be forwarded only if the current query delay of the event is smaller than $DUR_C(E_r)$ and there exist a neighbor of C_i whose energy is more than $ENE_C(E_r)$. The up-tier of the WSN can be viewed as a connected graph $G' = (V', E')$, where $V' = \sum C_i \cup \sum Q_j$ and E' is the set of the links between cluster-heads. How to transmit the events with different constraints from local C_i to one of the query agents Q_j energy efficiently and quickly is the focused problem. To solve the NP-hard problem, an ant-based HAAQP protocol is proposed as follows.

3. Hybrid Ant-Based Query Processing for WSNs

3.1. Management of Ants. Three kinds of ants are to be considered in HAAQP, namely, the forward ants (FAs), the backward ants (BAs) and the clustering ants (CAs). The FAs can be viewed as events to be transmitted. Once an event E_r occurs, the local cluster-head C_j completes aggregation and generates a $FA_{C_s}(ID_F, E_r, T_F, ID_{F,Cur}, VL_F)$ where the $E_r = (DT_E, T_E, ENE_C(E_r), DUR_C(E_r))$ and C_s is the source cluster-head. ID_F is the identifier of the FA, and T_F is the beginning time of the FA. $ID_{F,Cur}$ denotes the current sensor node which the ant arrives at. The VL_F denotes the cluster-head list ant visited. The DT_E denotes the event data, and the T_E denotes the time E_r generated. The $ENE_C(E_r)$ and $DUR_C(E_r)$ denote the energy constraint and delay constraint of the E_r respectively. The generation rate of the initial FAs in one cluster-head C_j is determined mainly by the event rate. We consider that the values of the two constraints are uniformly distributed. Each ant nest corresponds to a source cluster-head, and each ant in an ant colony corresponds to an event packet. Each FA will generate a new FA when it makes a move forward. Each current FA assigns its next hop as the $ID_{F,Cur}$ of the new FA then puts the $ID_{F,Cur}$ into the VL_F of the new FA. Assume that the delay of the current C_i to its next hop C_j is $\text{delay}(C_i, C_j)$; current ant will add $\text{delay}(C_i, C_j)$ to its T_F and assign it to the T_F of the new FA.

Both the FAs and the BAs can update the pheromone. There are two kinds of pheromones in HAAQP, namely, the search pheromone τ and the clustering pheromone π . The BAs update both of the τ and π when they come back. Each cluster-head maintains a buffer of ants including the FAs and BAs. The ants that arrive to it are arrayed in the buffer ordered by the T_F . There are special ants CAs in each cluster-head C_i , which determine the membership of C_i according to the clustering pheromone to different query agents. The CAs

issue from the C_i only communicate with the neighbors of the C_i .

3.2. Initiation of HAAQP. Suppose that the energy cost for querying is to be proportional to the number of transmissions. The query delay is the end-to-end delay between the source cluster-head and the optimum query agent. The initial values of the τ and π should be initiated beforehand. In the initial phase, each query agent Q_j assigns the initial values of $\tau_{C_i}(Q_j) = \tau_{\max}$ and $\pi_{C_i}(Q_j) = \pi_{\max}$ on the directly connected links, where the C_i is the neighbor of Q_j , $1 < i \leq N_C$ and $1 < j \leq N_Q$. Meanwhile, the C_i declares that it is a member of Q_j . The initial values of pheromone on the other links are set as $\tau_{C_j}(C_i, Q_{C_i}) = \tau_{\min}$ and $\pi_{C_j}(Q_{C_i}) = 0$, where the C_j is the neighbor of C_i belonging to Q_{C_j} and τ_{\min} is a small positive value.

3.3. Path Construction Policy of HAAQP. When dealing with the initial or intermediate FAs, how to select the next hop of the cluster-head is important. Because the global information of the large-scale sensor network is unknown, only the local information of the neighbors can be used during the selection. As the ordinary sensors have been ignored on the up-tier of the network, the neighbors are sure to be the cluster-heads or query agents, which can improve the computational efficiency because the number of candidates to be selected is shrunk sharply. We first calculate the weight of the current C_i to all its possible neighbors by the search pheromone, residual energy of the neighbor, and link cost then select the next hop C_j according to the following equation:

$$j = \begin{cases} \arg \max \left\{ \tau_{C_i}(C_j, Q_{C_j}) + \alpha \cdot \lambda(C_i, C_j) + \beta \cdot \mu(C_i, C_j) \right\} & \text{if } q \leq q_0, \\ J & \text{else,} \end{cases} \quad (1)$$

where $\tau_{C_i}(C_j, Q_{C_j})$ is the search pheromone of the link (C_i, C_j) , $\lambda(C_i, C_j) = 1/c(C_i, C_j)$, and $c(C_i, C_j)$ is the cost of link (C_i, C_j) ; $\mu(C_i, C_j)$ is the residual energy of the C_j ; α and β are parameters controlling the relative importance of the link cost and residual energy, respectively. The parameter $q_0 = 0.8$ and $q \in (0, 1]$. The value of J is a stochastic variable, which is determined by the probability of $P_k(C_i, C_j)$. The $P_k(C_i, C_j)$ for the k th FA in C_i to the neighbor C_j is defined as follows:

$$P_k(C_i, C_j) = \frac{\tau_{C_i}(C_j, Q_{C_j}) + \alpha \cdot \lambda(C_i, C_j) + \beta \cdot \mu(C_i, C_j)}{\sum_{d \in L^k(C_i)} [\tau_{C_i}(d, Q_d) + \alpha \cdot \lambda(C_i, d) + \beta \cdot \mu(C_i, d)]}, \quad (2)$$

where $L^k(C_i)$ is the set of the optional neighbors to the cluster-head C_i . From (1) and (2), we can see that FAs tend to select the links with smaller cost, more available energy of neighbor, and stronger pheromone. If an ant FA finds that the neighbor

is in its path, it discards the neighbor to prevent loop. To judge whether the path satisfies the constraints, the energy level of the neighbors needs to be recorded timely, as well as the T_F of the ants. If $\mu(C_i, C_j) < ENE.C(E_r)$ or $(T_F - T_E) > DUR.C(E_r)$, apparently the event packet is unable to reach the query agent via C_j . If none of the neighbors satisfies the constraints, the ant dies. The illustration is shown in Figure 2.

3.4. Pheromone Update Rules of HAAQP. Two updating rules for search pheromone are introduced herein: the global updating and the local updating. Ants will intensify the pheromone of the link when moving forward each step, so that the ants sent from the same nest can tend to select the same path. Because each ant has different constraints according to different events, they perhaps select another path. Suppose that FA at C_i select C_j as its next hop, the formula of updating local pheromone is as follows.

$$\tau_{C_i}(C_j, Q_{C_j}) \leftarrow (1 - \rho_1) \cdot \tau_{C_i}(C_j, Q_{C_j}) + \Phi \cdot \Delta\tau_{C_i}^k(C_j, Q_{C_j}). \quad (3)$$

Note that $\tau_{C_i}(C_j, Q_{C_j})$ is the search pheromone of the link (C_i, C_j) to the query agent Q_{C_j} ; ρ_1 is the factor of the pheromone volatilization ($0 < \rho_1 < 1$). The Φ is an adjustable parameter. We consider that $\Delta\tau_{C_i}^k(C_j, Q_{C_j}) = 1/\text{delay}(C_i, C_j)$, where the $\text{delay}(C_i, C_j)$ is the delay of link (C_i, C_j) . The pheromone can be adjusted dynamically based on the delay. Accordingly, the subsequent ants will not select the link with larger delay.

When an ant finds an eligible path, it intensifies the pheromone of the path and evaporates the pheromone of the involved links that are not in the path meanwhile. The global pheromone updating is defined as follows:

$$\tau_{C_i}(C_j, Q_{C_j}) \leftarrow \begin{cases} (1 - \rho_2) \cdot \tau_{C_i}(C_j, Q_{C_j}) + \Delta\bar{\tau}_{C_i}(C_j, Q_{C_j}), & \text{if } (C_i, C_j) \in p, \\ (1 - \rho_2) \cdot \tau_{C_i}(C_j, Q_{C_j}) & \text{else,} \end{cases} \quad (4)$$

where p is the path from source cluster-head C_S to one of the query agents. We consider that $\Delta\bar{\tau}_{C_i}(C_j, Q_{C_j}) = (\mu_{\min})^\sigma/\theta$, where μ_{\min} is the bottle-neck energy level on the path p , θ is an adjustable parameter, σ is the response degree of pheromone to energy, and ρ_2 is the pheromone volatilization factor ($0 < \rho_2 < 1$) and it also simulates the volatilization of search pheromone.

In order to determine the membership of each cluster-head C_i dynamically in terms of the clustering pheromone $\pi_{C_i}(Q_j)$, the clustering ants CAs should be launched from each C_i to their neighbors in fixed interval ΔT_{CA} to update the values of the $\pi_{C_i}(Q_j)$, which reflects the attractiveness of the query agent Q_j . The rule of updating the $\pi_{C_i}(Q_j)$ is as follows:

$$\pi_{C_i}(Q_j) = \frac{\sum_{k \in \nabla_{C_i}(Q_j)} \pi_k(Q_j) + \bar{\tau}_{C_i}(Q_j)}{|\nabla_{C_i}(Q_j)| + 1}, \quad (5)$$

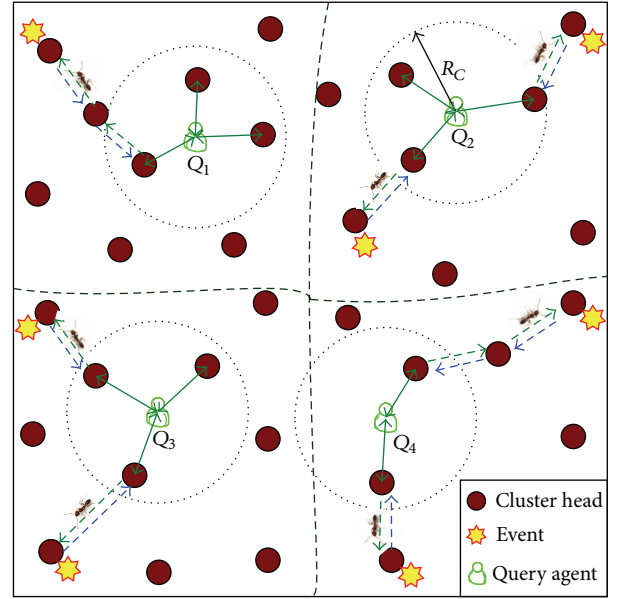


FIGURE 2: The path construction process of the proposed HAAQP algorithm.

where the $\nabla_{C_i}(Q_j)$ denotes the set of the cluster-heads which are neighbors of C_i that belong to the members of the query agent Q_j and the $|\nabla_{C_i}(Q_j)|$ denotes the size of the $\nabla_{C_i}(Q_j)$; $\bar{\tau}_{C_i}(Q_j)$ is the average value of the search pheromone in the outgoing links of the C_i , which is represented as follows:

$$\bar{\tau}_{C_i}(Q_j) = \frac{\sum_{k \in \nabla_{C_i}(Q_j)} \tau_{C_i}(k, Q_j)}{|\nabla_{C_i}(Q_j)|}. \quad (6)$$

From (5), and (6), we can see that the search pheromone affects the clustering pheromone to some degree. If an optimum path to the query agent Q_j is explored, the $\pi_{C_x}(Q_j)$ of the cluster-heads C_x nearby the path will increase with the $\bar{\tau}_{C_i}(Q_j)$. The events that occurred near the optimum path can be attracted to the path efficiently. When there are no explored optimum paths near the C_x of the events, FAs are launched to search the optimum neighbor till an optimum path or a query agent is found. If more optimum paths are explored, the search efficiency of FAs to one of the query agents can be improved significantly.

3.5. Approaches of HAAQP Algorithm. The HAAQP algorithm for the WSNs is described as follows.

Step 1. Initialize the values of the search pheromone on each link on the up-tier when completing the two-tier structure of the WSN by existing clustering protocol. The values of the clustering pheromone on each cluster-head C_i are also initialized beforehand.

Step 2. Each source cluster-head generates events with the query constraints of the $ENE.C$ and $DUR.C$ according to Poisson distribution. These events are buffered in the queue of ant-manager ordered by the generating time T_F of the FAs.

Step 3. In each buffer of the cluster-heads, the ant-manager deals with the intermediate FAs in order. When dealing with initial FAs, new intermediate FAs are generated and inserted into the buffer queue according to the T_F of the new FAs.

Step 4. Ant-manager goes on dealing with subsequent ants. They may be initial FAs, new intermediate FAs, or BAs, which is up to the T_F or T_B of the ants.

Step 5. Before dealing with ants of current cluster-head, whether the neighbors satisfying the constraints of the packets exist or not must be judged. If there is no such neighbor node, the ant dies; otherwise, we judge the type of ants and deal with them, respectively.

- (1) For the initial or intermediate FAs, the ants first determine whether the current cluster-head is a query agent or a neighbor of query agents. If yes, the events are accepted directly or through one hop. Meanwhile, the BAs are triggered to update the search pheromone on the corresponding paths. Otherwise, the ants select next hop according to the probability of each possible neighbor sensor and prevent loop. Ants update the local information on the selected link. When completing the FAs, the new FAs are generated. Judge whether the new FAs are satisfied with the constraints. If no, they will be discarded; otherwise, they are inserted into the queue according to their beginning time T_F .
- (2) For the BAs, they are adopted to output the paths by which events are delivered to the query agents and update the energy on the path and search pheromone on all the links.
- (3) For the CAs, they are launched to collect the value of the neighbors' clustering pheromone in a fixed interval and determine the membership of the current cluster-head.

Step 6. If there are no ants to be processed, we count the total energy cost and the query delay in the simulation.

4. Simulations

We have simulated the HAAQP and evaluated the performance by comparing with the other query algorithms derived from [15–17], namely, the SARP-based query processing (SARPQP), the TBA-based query processing (TBAQP), and the ABS-based query processing (ABSQP). A topology generator is adopted to obtain various sensor networks. The number of sensor nodes N varies from 1000 to 6000, which is deployed in a square area with $\|A\| = 500 \text{ m} \times 500 \text{ m}$ and clustered into N_C clusters with N_Q query agents uniformly ($2 \leq N_Q \leq 12$). The simulation time $T = 3000$ units divided into T/w segments, where w is the event interval and can vary between 50 and 300 time units. The smaller the value w is, the heavier the network load is and vice versa. The values of the T and w determined the number of events together. There

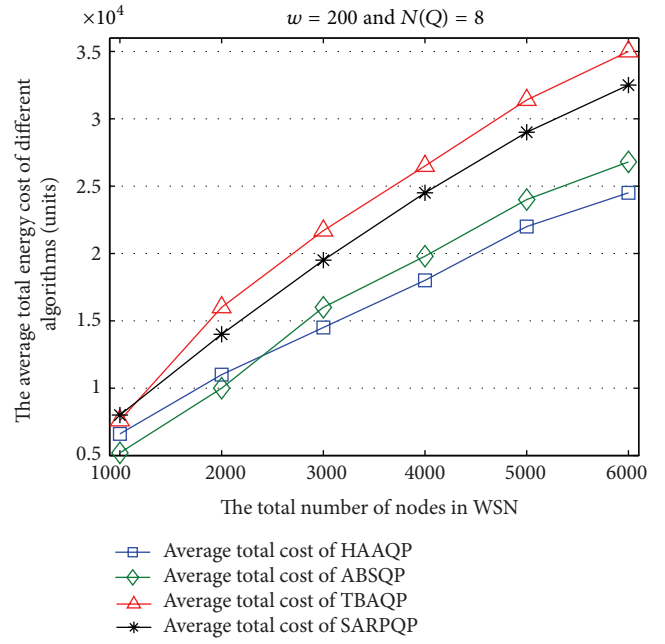


FIGURE 3: The average total energy cost of HAAQP and other algorithms.

are about 5% of the cluster-heads as sources. About 10 events issue from each source in each segment according to Poisson distribution.

The initial energy value of each sensor is 400 units. The values of ENE_C are uniformly distributed between 20 and 80 units and that of the DUR_C are between 60 and 100 time units. The link cost between cluster-heads is set $c(C_i, C_j) \in [2, 5]$, and the initial link delay is assigned between 2 and 8 time units. The parameter values of the $\alpha = 100$, $\beta = 0.5$, $\rho_1 = \rho_2 = 0.1$, $\sigma = 1$, $\theta = 5$, $\tau_{\min} = 5$, and $\tau_{\max} = \pi_{\max} = 100$. The metrics we investigated are the energy cost and the query delay. For each different configuration of the sensor networks, the algorithm is carried out 200 times, and the average values of the metrics are obtained. The simulation results are shown as in Figure 3 to Figure 5.

Figure 3 shows the comparison of average total energy cost. It indicates that the ant-based HAAQP is more energy efficient than the other algorithms in most cases. The reason is that the ant-based search can provide more intelligence, especially for large-scale wireless sensor networks. The ABSQP algorithm is more energy efficient than both SARPQP and TBAQP for its heuristic design.

Figure 4 plots the curve of the energy cost of HAAQP with the values of the w and N_Q . From Figure 4, we can see that the energy cost is reduced with the increase of w and N_Q . This is because the paths can be shorter with bigger value of N_Q , and the number of events is reduced with the increase of w .

Figure 5 shows the comparison of the average query delay. It indicates that the delay of HAAQP is smaller than that of other algorithms. This is because that the ant-based querying with positive feedback can find short enough paths under multiconstraints.

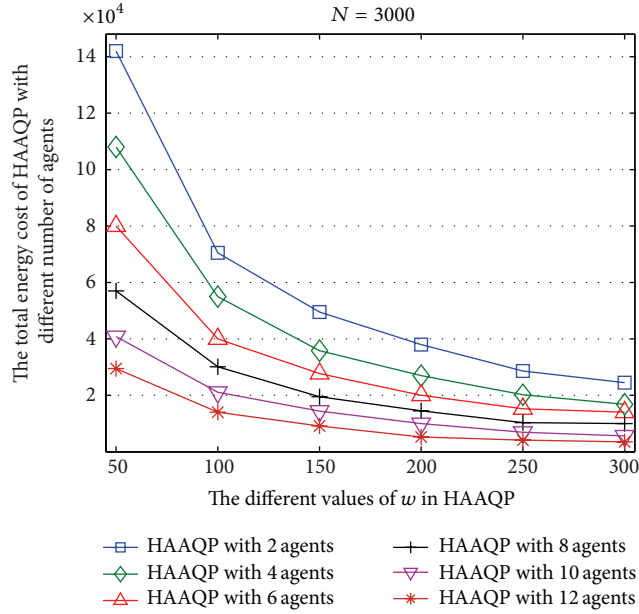


FIGURE 4: The total energy cost of HAAQP with a different number of agents.

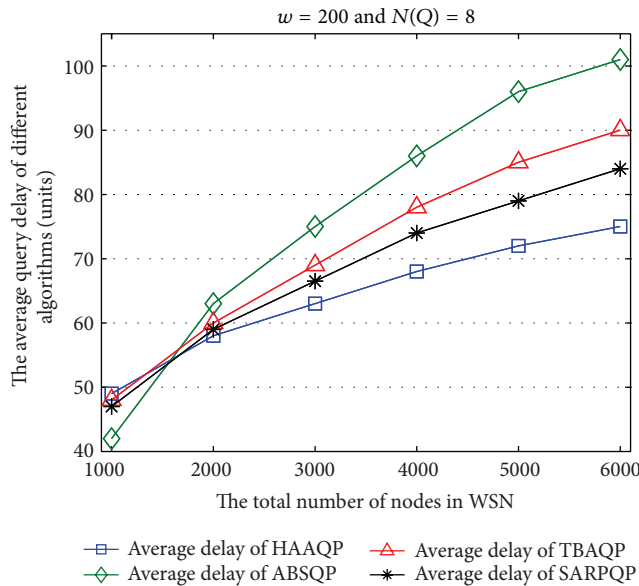


FIGURE 5: The average query delay of HAAQP and other algorithms.

5. Conclusions

The multi-constrained query processing is one of the most challenging problems for resource-constrained WSNs with multiple query agents. Considering the constraints of the node energy and query delay of different applications, an ant-based query processing algorithm HAAQP with positive feedback is proposed for WSNs in this paper. The simulation results show that significant energy gains are achieved by HAAQP, as well as the query delay. Our future work is to optimize the parameters to achieve better performance.

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