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Routing Protocols Based on Ant Colony Optimization in Wireless Sensor Networks: A Survey

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ABSTRACT Routing is one of the important topics in wireless sensor networks (WSNs), and has been attracting the research community in the last decade. Routing based on ant colony optimization (ACO) is a type of transmission method rich in characteristics. There are several survey papers that present and compare routing protocols from various perspectives, but the survey on ACO-based routing is still missing. This paper makes a first attempt to provide a comprehensive review on ACO-based routing protocols in WSNs. First, we offer a classification of these routing algorithms. Second, the most representative ACO-based routing protocols are described, discussed, and qualitatively compared. Finally, we put forward some open issues concerning the design of WSNs. This survey aims to provide useful guidance for system designers on how to evaluate and select appropriate routing schemes for specific applications.

INDEX TERMS Wireless sensor networks, routing protocol, ant colony optimization.

I. INTRODUCTION

Wireless sensor networks (WSNs) are composed of a large number of sensor nodes with limited energy capabilities that are located randomly or determinedly on a specific environment. WSNs are the foundation, key components, and important technologies of the Internet of Things (IoT) and Cyber-Physical Systems (CPSs) [1]–[4], where WSNs will play a significant role in various application scenarios of the future internet, such as environment surveillance, health care, military battlefield, agriculture monitoring, industrial control, and smart life [5]–[9].

There are some key techniques in WSNs, including node deployment (i.e. coverage and connectivity), node localization, topology control, time synchronization, data aggregation, routing scheme, security defending, and etc. As one of the key issues of WSNs, routing has attracted much attention in the field of WSNs. Different from that in traditional ad hoc networks, routing in WSNs is more challenging due to the inherent characteristics of WSNs. Firstly, resources of power supply, processing capability and transmission bandwidth are very limited in such networks. Furthermore, considering the limited resources, it is difficult to deal with unpredictable topology changes which usually exist in harsh environments. In addition, generally the many-to-one communication pattern, i.e., transmission from multiple sources to one sink, is easy to cause energy holes and accordingly diminish the network lifespan [10], [11].

The first consideration of routing design in WSNs is to improve energy efficiency and enhance network lifetime. Although wireless power transfer is a potential solution to lengthen the system lifetime of WSNs, and the benefits of using battery charging by harvesting environmental have been well recognized [12], [13], frequent battery recharging is apt to cause difficulties in creating and collecting production information, and in making instant cyber-physical decisions in the current industry framework [14]. In order to avoid frequent wireless recharging, energy consumption should be controlled, and the network lifetime is still a crucial factor in WSNs. Furthermore, with the application requirements of WSNs being lifted, the application difference must be taken into account in the design of WSNs [15], [16]. Quality of Service (QoS) is solution for satisfying specific requirements

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and QoS-based routing is a hot topic in WSNs. The QoS-based routing can be specified in the form of performance metrics, such as delay, reliability, and throughput.

There are a large number of routing protocols for WSNs, including classical routing and intelligent routing. Ant colony optimization (ACO) [17] is a well-known intelligent algorithm where complex collective behavior emerges from the behavior of ants. As one of the most successful swarm intelligence algorithms [18], it has also succeeded in some fields of the design of WSNs, such as activity scheduling [19]–[22], node deployment [23]–[26], target tracking [27], data aggregation [28], and attack detection [29]. There also exist some ACO-based routing protocols in WSNs, such as that in [30]–[38]. In ACO-based routing protocols, generally a colony of artificial ants travel through the network and look for paths between source nodes and a destination node, as shown in Fig. 1. Each ant chooses the relay node according to a probability with respect to pheromone trail and heuristic information. When an ant reaches the destination node, it travels backwards trough the path constructed and updates the pheromone trail.

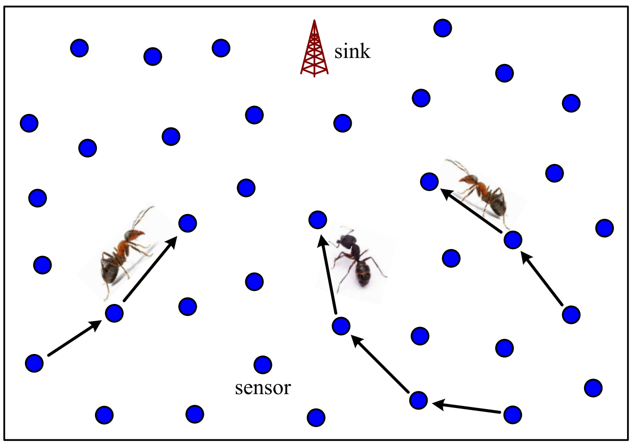

FIGURE 1. Path selection of ACO-based routing.

In the last few years, many routing protocols have been developed for WSNs, but no one focuses on ACO-based routing. In this paper, we make an attempt to survey the ACO-based routing protocols for WSNs. In sum, the main contributions of this paper are outlined as follows.

1) To the best of our knowledge, this survey is the first attempt to comprehensively review and critically evaluate the most prominent ACO-based routing methods developed for WSNs. This will contribute to making a large audience aware of the existence and the performance of these protocols.

2) We present a classification of ACO-based routing protocols of WSNs. As far as we know, this is the first classification of ACO-based routing protocols in WSNs. This will help readers to further comprehend these protocols.

3) We not only describe the representative ACO-based routing protocols in WSNs and summarize the strengths and weaknesses of these methods, but also compare these protocols with respect to a few metrics. This is beneficial for application designers to identify appropriate and alternative solutions.

4) We highlight some research challenges and identify some possible future trends for ACO-based routing protocols according to the latest developments of WSNs. This will contribute to the development of this research field.

The remainder of this paper is organized as follows: Section II provides an overview of surveys on routing protocols for WSNs. Section III offers a classification of ACO-based routing protocols in WSNs. Section IV provides a comprehensive review on some representative ACO-based routing protocols with respect to their characteristics, strengthens and drawbacks. These protocols with respect to their performances are compared in Section V. Finally, this paper is concluded and some open issues as well as challenges are discussed in Section VI.

II. RELATED WORK

Routing is a very important issue in the design of WSNs. There have been some survey papers on routing protocols of WSNs. These representative surveys are listed in TABLE I and summarized as follows.

Al-Karaki and Kamal [39] provided a survey on routing protocols in WSNs. According to the network topology, the authors divided the routing techniques into three categories: flat, hierarchical, and location-based routing protocols. These protocols are also classified into other types, such as multipath-based, query-based, and QoS-based routing techniques. Moreover, this survey presents several energy-efficient routing protocols that have been developed for WSNs.

Akkaya and Younis [40] surveyed some routing protocols for sensor networks and presents a classification for the various approaches pursued. The authors divided these routing protocols into three main categories, namely data-centric, hierarchical and location-based routing. Each routing protocol is described and discussed under the appropriate category. Additionally, they also discussed these protocols using contemporary methodologies such as network flow and quality of service modeling.

Abbasi and Younis [41] presented a taxonomy and general classification of published clustering protocols of WSNs. The authors described different clustering algorithms for WSNs and highlighted their objectives, features, complexity, etc. The authors also compared these clustering protocols on the basis of several metrics, such as convergence rate, cluster stability, cluster overlapping, location-awareness and support for node mobility.

Biradar *et al.* [42] discussed the design issues of WSNs and presented a classification and comparison of routing protocols of such network. The authors discussed that, to meet this general trend towards diversification, the following important design issues of such networks should be considered, such as fault tolerance, scalability, production costs and operating environment. This comparison provided by the

TABLE 1. Summary of previous surveys on routing protocols in WSNs.

Year	Authors	Reference	Literature title	Survey characteristics
2004	J.N. Al-Karaki A.E. Kamal	[39]	Routing techniques in wireless sensor networks: a survey	Energy-efficient routing
2005	K. Akkaya M. Younis,	[40]	A survey on routing protocols for wireless sensor networks	comprehensive routing
2007	A.A. Abbasi M. Younis	[41]	A survey on clustering algorithms for wireless sensor networks	Clustering routing
2009	R .V. Biradar, et al.	[42]	Classification and comparison of routing protocols in wireless sensor networks	comprehensive routing
2011	S. Ehsan B. Hamdaoui	[43]	A survey on energy-efficient routing techniques with QoS assurances for wireless multimedia sensor networks	Energy-efficient QoS routing
2011	M. Saleem, et al.	[44]	Swarm intelligence based routing protocol for wireless sensor networks: survey and future directions	Swarm-intelligence-based routing
2012	X. Liu, J. Shi	[45]	Clustering routing algorithms in wireless sensor networks: an overview	Clustering routing
2012	A.M. Zungeru, et al.	[46]	Classical and swarm intelligence based routing protocols for wireless sensor networks: a survey and comparison	Classical routing Swarm intelligence routing
2012	X. Liu	[47]	A Survey on clustering routing protocols in wireless sensor networks	Clustering routing
2013	N.A. Pantazis, et al.	[48]	Energy-efficient routing protocols in wireless sensor networks: a survey	Energy-efficient routing
2014	W. Guo, W. Zhang	[49]	A survey on intelligent routing protocols in wireless sensor networks	Intelligent routing
2014	M. M. Afsar M.H. Tayarani-N	[50]	Clustering in sensor networks: a literature survey	Clustering routing
2014	C. Tunca, et al.	[51]	Distributed mobile sink routing for wireless sensor networks: a Survey	Mobile sink routing
2014	S. Yu, et al.	[52]	Routing protocols for wireless sensor networks with mobile sinks: a survey	Mobile sink routing
2015	X. Liu	[53]	Atypical hierarchical routing protocols for wireless sensor networks: a review	Atypical hierarchical routing
2016	J. Yan, et al.	[54]	Recent advances in energy-efficient routing protocols for wireless sensor networks: a review	Energy-efficient routing

authors reveals the important factors that need to be taken into consideration while designing and evaluating a routing protocol for WSNs.

Ehsan and Hamdaoui [43] surveyed some energy-efficient routing techniques for Wireless Multimedia Sensor Networks (WMSNs). The authors outlined that the design challenges of routing protocols for WMSNs. Further, they provided a classification of recent routing protocols of WMSNs. This survey discusses some issues on energy efficiency in WSNs. However, it mainly discussed the energy efficient techniques with QoS assurance for WMSNs.

Saleem *et al.* [44] provided a survey of swarm-intelligence based routing protocols in WSNs. The authors discussed the general principles of swarm intelligence and of its application to routing. They also introduced a taxonomy for routing protocols in WSNs and used it to classify the surveyed protocols. They concluded the paper with a critical analysis of the status of the field, and pointed out a number of fundamental issues.

Liu and Shi [45] presented an overview on clustering routing algorithms of WSNs. The authors focused on differentiating these routing protocols according to diverse cluster shapes, and discussed the classification of clustering routing in WSNs. They also analyzed the typical clustering routing protocols and compare these approaches in terms of various metrics.

Zungeru *et al.* [46] presented a comprehensive survey and comparison of classical routing and swarm-intelligence-based one in WSNs. The authors surveyed state-of-the-art routing protocols in WSNs from classical routing protocols to swarm-intelligence-based protocols. These protocols are categorized according to their computational complexity, network structure, energy efficiency and path establishment. The authors also presented a comparison of several representative classical and swarm-intelligence-based routing protocols.

Liu [47] provided a comprehensively review of the most prominent clustering routing protocols in WSNs. The author presented a comprehensive and fine-grained taxonomy of

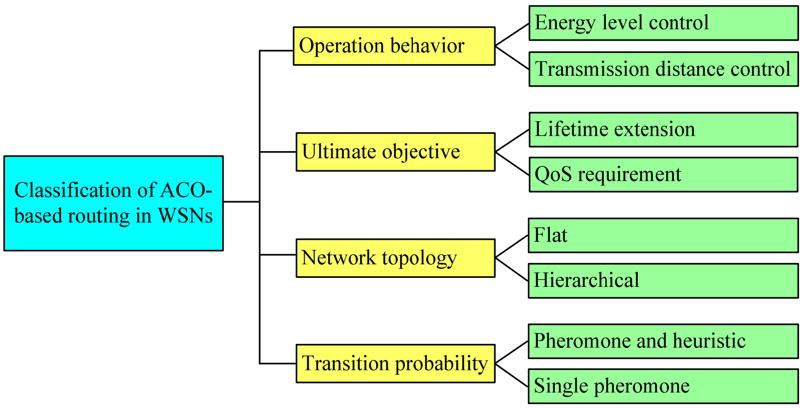

FIGURE 2. Classification of ACO-based routing protocols in WSNs.

clustering approaches, and also analyzed popular clustering routing protocols based on the classification of different operation stages of algorithms. The author also summarized the advantages and disadvantages of different clustering routing protocols.

Pantazis *et al.* [48] provided an comprehensive survey on the energy-efficient routing protocols of WSNs as well as their classification into four categories: network structure, communication model, topology-based and reliable routing schemes. The authors focused on how to minimize energy consumption and how to extend the system lifetime. Moreover, they discussed the advantages and disadvantages of each protocol, and provided a comparison among them including multiple metrics.

Guo and Zhang [49] surveyed intelligent routing protocols which contributed to the optimization of network lifetime in WSNs. The authors presented new ideas on the definition of network lifetime. Then, with a view of extending network lifetime, they analyzed the routing protocols based on intelligent algorithms. They discussed some representative intelligent routing algorithms and further analyzed the performance of network lifetime defined in multiple aspects.

Afsar and Tayarani-N [50] presented a comprehensive survey on clustering routing in WSNs. The authors provided a classification on the clustering algorithms in WSNs. They surveyed some clustering approaches proposed in the past few years in a classified manner and compared them on the basis of different metrics such as mobility, cluster count, cluster size, and algorithm complexity.

Tunca *et al.* [51] provided a survey of the existing mobile sink routing protocols in WSNs. In order to provide an insight to the mobile sink routing protocols, related design requirements and challenges are described and explained. A detailed categorization of these protocols is presented and the merits and drawbacks of these protocols are determined with respect to their applications.

Yu *et al.* [52] presented a survey of routing protocols in WSNs with sink mobility. The authors classified existing these routing protocols based on different design criteria, according to which these protocols can be divided into delay-sensitive and delay-tolerant protocols, and can also be categorized into centralized and distributed protocols. The authors illustrated how each of the protocols works, and discuss their advantages and disadvantages.

Liu [53] provided a comprehensive review on atypical hierarchical routing in WSNs. The author offered a classification of atypical hierarchical routing, and analyzed different logical topologies. The most representative atypical hierarchical routing protocols are described, discussed, and compared. The merits and defects of these protocols are analyzed with respect to the significant performances and application scenarios.

Yan *et al.* [54] discussed the energy-efficient routing problem and classify routing protocols of WSNs into two types according to their orientation toward either homogeneous or heterogeneous WSNs. The authors divided these protocols into static and mobile ones. They also provided an overview of these protocols in each category by outlining their characteristics, defects, and applications.

III. CLASSIFICATION of ACO-BASED ROUTING IN WSNs

The ACO-based routing protocols in WSNs can be classified into multiple types. In this section, we propose a comprehensive classification of ACO-based routing protocols in WSNs. As shown in Fig. 2, the classification is achieved from different points of view and is analyzed as follow.

A. OPERATION BEHAVIOR

The ACO-based routing in WSNs can be categorized into routing of energy level control and that of transmission distance control, according to the operation behavior of the routing. The main operation of the former is to select relay nodes with more energy level, but the latter mainly aims to select appropriate transmission distance for each node.

B. ULTIMATE OBJECTIVE

On the basis of the ultimate objective, the ACO-based routing protocols in WSNs can also be classified into routing of lifetime extension and that with QoS requirement. The ultimate goal of the former is to maximize the network lifespan, while the latter aims to provide specific QoS services.

C. NETWORK TOPOLOGY

According to the network topology, the ACO-based routing in WSNs includes two types, Flat routing and hierarchical routing. In flat routing, each node perform the same task of path search. However, in hierarchical routing, several nodes are formed into a group and path selection is carried out among different groups.

D. TRANSITION PROBABILITY

According to the transition probability of the ants, the ACO-based routing in WSNs can be divided into routing of pheromone and heuristic and that with single pheromone. In the former, path selection is performed by both pheromone trail and heuristic information of the path, while path searching is carried out only by pheromone trail of the path.

IV. ANALYSIS OF REPRESENTATIVE ACO-BASED ROUTING PROTOCOLS IN WSNs

In this section, we present a comprehensive survey of the representative ACO-based routing protocols in WSNs. We analyze 10 routing algorithms in detail based on the classification of operation behavior, and highlight their advantages and disadvantages.

A. ACO ROUTING PROTOCOLS BASED ON ENERGY LEVEL CONTROL

1) BABR

a: PROTOCOL DESCRIPTION

Camilo *et al.* presented the Basic Ant-Based Routing (BABR) [30], which is an ACO-based routing protocol and aims to reduce the path distance and achieve load balance to some extent. During the process of path creation, both the energy levels of nodes and the path lengths to be constructed are taken into account to update the pheromone trail. The paths are created by forward ants and backward ants. When the ant arrives at the destination node, it travels backwards through the visited path and updates the pheromone trail based on the energy quality and the number of nodes of the path.

At regular intervals, a forward ant k is generated with the mission to find a path until the destination. The identifier of every visited node is stored onto a memory M_k of the ant. The forward ant selects the next-hop node on the basis of the following probability

$$p_k(r,s) = \begin{cases} \dfrac{[T(r,s)]^\alpha [E(s)]^\beta}{\sum\limits_{u \notin M_k} [T(r,s)]^\alpha [E(s)]^\beta} & \text{if } s \notin M_k \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $p_k(r,s)$ is the probability with which ant k chooses to move from node r to node s, $T(r,s)$ is the routing table at each node that stores the pheromone amount on path (r,s), $E(s)$ is the visibility function given by

$$E(s) = \frac{1}{C - e_s} \quad (2)$$

where C is the initial energy level of the node s, e_s is the actual energy level of node s, and α and β are weight parameters which reflect the relative importance of the pheromone trail versus visibility function.

When the forward ant reaches the destination node, it is transformed into a backward ant, whose mission is to update the pheromone trail of its visited path that is stored in its memory. It is noted that, the memory of each ant is reduced to just two records, i.e. the last two visited nodes. Before the backward ant starts its return journey, the destination node computes the following pheromone amount that the ant will drop during the trip.

$$\Delta T_k = \frac{1}{N - Fd_k} \quad (3)$$

where N is the total number of nodes, and Fd_k is the distance travelled by the forward ant k, i.e. the number of nodes stored in its memory.

When a node receives a backward ant coming from a neighboring node, it updates its routing table in the following way

$$T_k(r,s) = (1-\rho)T_k(r,s) + \Delta T_k \quad (4)$$

When the backward ant reaches the node where it was created, it has completed its whole mission.

b: PERFORMANCE ANALYSIS

BABR has the following advantages. (1) The ant chooses the nodes with more residual energy as relay nodes. This mechanism contributes to constructing paths with load balance to some extent and accordingly prolonging the network lifespan. (2) Each ant selects path with as less visited nodes as possible. This mechanism can reduce the energy consumption of hop-by-hop communications to some extent.

However, there are some disadvantages in BABR: (1) The relay selection in the beginning is equivalent to random search, because all nodes possess the same residual energy and there are equal pheromone trail in all paths at that time. (2) According to the pheromone updating rule, the ant prefers to complete its whole trip by using less relay nodes. This will increase the average transmission distance of each hop and accordingly increase the energy depletion of data transmission. (3) The path selection is performed according to the residual energy and the total number of hops, but the energy dissipation of data transmission and data reception has not been taken into account. (4) BABR follows the traditional many-to-one transmission pattern, in which the nodes near the sink bear much more communication load compared with those far from the sink, but there is no any load balancing strategy.

2) EEABR

a: PROTOCOL DESCRIPTION

Camilo *et al.* also presented the Energy-Efficient Ant-Based Routing (EEABR) [30], which is an improvement of BABR. The algorithm aims to reduce the communication load of ants and the energy depletion of data communication. During the process of path creation, both the energy levels of nodes and the path lengths to be constructed are taken into account to update the pheromone trail.

In EEABR, each ant possesses a memory which stores all the visited nodes. To avoid storing excessive information of sensor nodes, each ant only stores the last two visited nodes in its memory. Each node keeps records of its received ant and sent ant in its memory. The memory record consists of the previous node, the forward node, the ant identification and a timeout value. Once a node receives a forward ant, it looks into its memory and saves the required information. Then it restarts a timer and forwards the ant to its next node. Once a node meets a backward ant, it searches its memory to determine the next node that the ant would be sent to.

Similar to that of BABR, the transition probability of the ant is

$$p_k(r,s) = \begin{cases} \dfrac{[T(r,s)]^{\alpha}[E(s)]^{\beta}}{\sum\limits_{u \notin M_k}[T(r,s)]^{\alpha}[E(s)]^{\beta}} & \text{if } s \notin M_k \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

where $p_k(r,s)$ is the probability with which ant k chooses to move from node r to node s, $T(r,s)$ is the routing table at each node that stores the pheromone amount on path (r,s), $E(s)$ is the visibility function.

When the forward ant arrives at its destination, a backward ant is created and its mission is to update the pheromone trail of the path visited by the forward ant. The amount of pheromone trail to be stored by the backward ant is given by

$$\Delta T_k = \frac{1}{C - \frac{E_k^{\min} - Fd_k}{E_k^{\text{avg}} - Fd_k}} \tag{6}$$

where C is the initial energy level of the nodes, Fd_k is the number of nodes visited by the forward ant k, $E_k^{\min}$ and E_k^{avg} are respectively the minimum and average value of the vector E_k.

The above equation is used to update the routing table of each node in the following way

$$T_k(r,s) = (1-\rho)T_k(r,s) + \left[\frac{\Delta T_k}{\varphi Bd_k}\right] \tag{7}$$

where φ is a coefficient, Bd_k is the travelled distance, represented by the number of visited nodes of the backward ant k until node r.

The idea behind the routing table updating is to build better pheromone distributions. Specifically, this idea is to make the nodes near the sink possess more pheromone levels and force the nodes far from the sink to find better paths.

b: PERFORMANCE ANALYSIS

EEABR has the following advantages. (1) The ant chooses the nodes with more residual energy as the relay nodes. This mechanism contributes to constructing paths with load balance to some extent and accordingly prolonging the network lifespan. (2) Each ant only stores the last two visited nodes in its memory. This method is effective to reduce the communication load of ants to some extent.

However, there are some disadvantages in EEABR: (1) According to the pheromone updating rule, the ant prefers to complete its whole trip by using less relay nodes. This will increase the average transmission distance of individual hops and accordingly increase the energy depletion of data transmission. (2) The path selection is performed according to the residual energy and the total number of hops, but the energy dissipation of data transmission and data reception has not been taken into account. (3) It is easy to result in energy holes near the sink, due to the traditional many-to-one transmission pattern. Therefore, this will dramatically diminish the network longevity.

3) ACO-QoSR

a: PROTOCOL DESCRIPTION

ACO-QoSR, proposed by Camilo *et al.* [31], is a reactive routing protocol whose goal is to cope with both strict delay requirements and the limited energy and computational resources limitation at the sensor nodes. The addressed problem is to find paths from a sensor to the sink and guarantee two constraints: The first one is that the total end-to-end delay is less than a bounding value D. The second one is that the energy residual ratio, ERR $= E_{\text{residual}}/E_{\text{initial}}$, is above a certain threshold value.

In ACO-QoSR, when a source/sensor node wants to deliver data, it checks its routing table for a suitable path. If there is no such a path in the routing table, a path probe to find a new route is initiated by ants. These ants are unicast to its next hop nodes by the following selection probability

$$p_{ij} = \frac{\left[\tau_{ij}\right]^{\alpha}\left[\eta_{ij}\right]^{\beta}}{\sum\limits_{k \in N_i}\left[\tau_{ik}\right]^{\alpha}\left[\eta_{ik}\right]^{\beta}} \tag{8}$$

where the heuristic information is defined as the ratio between the residual energy of node j and the total residual energy of all the neighbor nodes of node i:

$$\eta_{ij} = \frac{E_{\text{residual}}(j)}{\sum\limits_{k \in N_i} E_{\text{residual}}(k)} \tag{9}$$

Eq. (9) is designed to favor the nodes with higher level of residual energy and accordingly balance energy usage.

If the forward ant finishes its trips, the pheromone intensity on every path (i,j) is updated by

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{10}$$

where the pheromone increment of ant k is

$$\Delta\tau^k = \begin{cases} f\left(ERR_k^*, \Delta\tau^{k-1}\right) & \text{Delay}(k) \leq D \\ 0 & \text{Delay}(k) > D \end{cases} \quad (11)$$

In Eq. (11), Delay(k) is the path delay of the ant k, ERR_k^* is the normalized energy residual ratio of the path, i.e.

$$ERR_k^* = \frac{ERR_k}{Hop_k} \quad (12)$$

where ERR_k is the ratio of the total residual energy of the path, Hop_k is the total hops visited by the forward ant k. In Eq. (11), the pheromone increment is further described as

$$f(ERR_k^*, \Delta\tau^{k-1}) = \begin{cases} \Delta\tau^{k-1} + \lambda(ERR_k^* - ERR_{k-1}^*), & ERR_k^* > ERR_{k-1}^* \\ \Delta\tau^{k-1}, & ERR_k^* \leq ERR_{k-1}^* \end{cases} \quad (13)$$

It is revealed from Eq. (6) that, if the delay is larger than the permitted threshold, the pheromone of the path will not be increased. Moreover, the pheromone tends to be added to the path with larger ratio of the total residual energy.

b: PERFORMANCE ANALYSIS

The merits of ACO-QoSR are described as follows. (1) It is a QoS-based routing protocol which can satisfy the time constraints of some applications and has higher packet delivery ratio than similar routing protocols. (1) The path with more residual energy ratio will be selected to construct the routing of data transmission. This selection will benefit for the ant to establish paths with load balance to some extent and accordingly extend the network longevity.

The defects of ACO-QoSR are described as follows. (1) delay-constrained path search in ACO-QoSR is not energy efficient, because the forward ants must keep the routing information and this will result in large energy depletion. (2) The path selection is performed according to the residual energy ratio and the delay constraints, but the energy dissipation of data transmission and data reception has not been taken into account. (3) The delay guarantees may not be available in large-scale networks, where the whole round trip of the ants will result in large delay.

4) E&D ANTS

a: PROTOCOL DESCRIPTION

Wen *et al.* [32] proposed an Energy*Delay model based on ant algorithms (E&D ANTS) to minimize the time delay in data transmission through an energy-constrained manner in one round. The goal of E&D ANTS is not only to extend the system lifetime but also to provide real-time transmission services. Considering the tradeoff of energy and delay in wireless network systems, the reinforcement learning (RL) algorithm is adopted to train the model.

E&D ANTS is a reactive protocol in which multiple forward ants are used to discover paths with minimum energy and delay. In other words, the best solution is to minimize the following Energy*Delay model.

$$g(t) = \min\{Energy \times Delay\} \quad (14)$$

The residual energy level and the hop delay experienced at each node are stored in the local memory of each forward ant. For any node i, the next-hop node j is selected according to the following probability

$$p_{ij} = \frac{\omega\tau_{ij} + (1-\omega)\eta_{ij}}{\omega + (1-\omega)(|L_i| - 1)} \quad (15)$$

where ω $(0 \leq \omega \leq 1)$ is a weighting factor of the pheromone trail and the heuristic information, and L_i is the neighbor set of node i. In Eq. (15), the heuristic information is defined as

$$\eta_{ij} = \frac{e_j}{\sum\limits_{k \in L_i} e_k} \quad (16)$$

where e_j is the residual energy level node j. The next hop is selected as the one with the best trade-off between expected latency and residual energy. The pheromone of the path is updated by the following equation:

$$\tau_{ij} = \rho\tau_{ij} + \Delta\tau_{ij} \quad (17)$$

where the pheromone increment $\Delta\tau_{ij}$ is calculated accordingly to the relative goodness between the new finding and the near past. More specifically, the increment of pheromones is designed as

$$\Delta\tau_{ij} = \tau_0\left(1 - \frac{z_{\text{new}} - g(k)}{\bar{z} - g(k)}\right) \quad (18)$$

where τ_0 is the initial pheromones value, z_{new} is the new solution of the $(k+1)$ iteration, $\bar{z}$ is the average of the last k solutions. It is demonstrated from Eq. (18) that, if the new solution is lower than the average one, the pheromone trail of the last path will increase, otherwise it will decrease.

The homeostasis strategy is used to make out the past optimal solution and enhance the exploration ability of new paths. So the authors use the RL algorithm to find the best solution.

b: PERFORMANCE ANALYSIS

The merits of E&D ANTS are described as follows. (1) It can also be regarded as a QoS-aware routing protocol which can satisfy specific delay and energy requirements. (2) The nodes with more residual energy have greater priority of being selected as the relay nodes of the routing. This selection mechanism will benefit for prolonging the network lifespan due to the load equilibrium idea.

The defects of E&D ANTS are described as follows. (1) The delay and energy requirements in E&D ANTS may not be achieved, because the RL process may need much energy depletion. (2) The path is selected according to the residual energy ratio and the delay constraints, but the energy dissipation of data transmission and data reception has not been taken into account. (3) The delay and energy guarantees may not be achieved in large-scale networks, where the whole round trip of the ants will result in large delay and energy dissipation.

5) ACORC

a: PROTOCOL DESCRIPTION

Selcuk and Dervis [33] presented the ant colony optimization router chip (ACORC) which aims to construct an effective multi-path routing and improve the reliability of the network in the case of node faults.

In ACORC, each ant tries to find a path with minimum cost. Ants are launched from a source node and move through neighbor repeater nodes, and reach a final destination, the sink. After launching, the choice of the next node is made according to the following probability

$$p_k(r,s) = \begin{cases} \dfrac{[\tau(r,s)]^{\alpha} \cdot [\eta(r,s)]^{\beta}}{\sum\limits_{r \in R_s} [\tau(r,s)]^{\alpha} \cdot [\eta(r,s)]^{\beta}} & \text{if } k \notin tabu^r \\ 0 & \text{otherwise} \end{cases} \tag{19}$$

where $\tau(r,s)$ and $\eta(r,s)$ are respectively the pheromone value and the heuristic information of the path (r,s).

In Eq. (19), the heuristic information $\eta(r,s)$ is the energy factor, which is defined as

$$\eta(r,s) = \frac{(I - e_r)^{-1}}{\sum_{n \in R_s} (I - e_n)^{-1}} \tag{20}$$

where I is the initial energy of the node, and e_r is the current energy level of the receiver node r. This energy factor means that, the node with lower energy source has lower probability of being selected as a relay node. If nodes sense any change in their energy levels, they will inform their neighbors about the changes.

After all ants have completed their tour, the pheromone will be updated as follows

$$\tau(r,s)(t+1) = \tau(r,s)(t) + \Delta\tau(r,s)(t) \tag{21}$$

$$\Delta\tau^k(t) = \frac{1}{J_w^k(t)} \tag{22}$$

where $J_w^k(t)$ is the length of the tour $w_k(t)$, which is done by ant k at iteration t. Pheromone values are stored in the memory of any ant. Each node is aware of the pheromone amount on the paths to its neighbor nodes. The pheromone increment on the paths based on the lengths of tours, would continuously cause an increasing positive feedback. In order to control the operation, the operation of pheromone evaporation after the tour is also performed as follows

$$\tau_{ij}(t) \leftarrow (1-\rho)\tau_{ij}(t) \tag{23}$$

Once an event takes place, several nodes become sources and know about the event information, which will be delivered to the base node by repeaters. The data about an event, provided by the source node, is named raw data, which contains such information as source node identification, event identification, time and data about the event. The raw data from each source is split to multiple pieces called data parts.

After the dissemination operation of multiple-piece data, the base gets data in parts from several paths. The main idea of multiple-path delivery is to provide reliable transfer in case of breakdown of the major routes. To prevent package loss, acknowledgement signals are used. If a node receives an acknowledgement signal, it first checks the data. If the data information is found in the node memory, this signal is broadcasted to other neighbors along the path. In case of an absent acknowledgement signal which is caused by errors in the path, that package will be disseminated again.

b: PERFORMANCE ANALYSIS

The advantages of ACORC are summarized as follows. (1) This protocol creates a multi-path transmission scheme, which can advance the reliability of the network in the case of node faults. (2) The nodes with more residual energy have higher probabilities of being selected as repeater nodes. This mechanism can achieve load equilibrium to some extent and accordingly extend the network lifetime.

The disadvantages of ACORC are outlined as follows. (1) The multi-path transmission scheme with its acknowledgement operation will result in more information exchange and energy depletion, compared with other ACO-based routing protocols. (2) The path selection is performed according to the residual energy and the path lengths, but the energy depletion in terms of data transmission and data reception has not been taken into account. (3) This protocol adopts the traditional many-to-one transmission pattern, which easily generates energy holes near the sink. Therefore, the network lifespan will be shortened.

6) EAACA

a: PROTOCOL DESCRIPTION

Cheng *et al.* [34] proposed the energy aware ant colony algorithm (EAACA) for the routing of WSNs. The goal of EAACA is to create paths with low energy dissipation, balanced energy depletion, and low transmission distance. In the process of path creating in EAACA, the next neighbor node is selected according to the distance of sink node, the residual energy of the next node, and the average residual energy of the path.

The EAACA protocol includes two steps, the route discovery and route maintenance process. In the route discovery process, nodes establish all valid paths to the destination node by sending a query packet through the forward ants. If the ants find the destination node, the destination node generates a response packet through the backward ants. The backward ants go back to the sending node along the reverse path, and releases their pheromone. In route maintenance process, nodes send several probe packets to the destination node periodically to monitor the quality of the existed paths, meanwhile probe new path to the destination node. In order to lessen the control packet overhead, the number of probe packets is restricted by the pheromone concentration.

In EAACA routing algorithm, the transition probability of the ant is defined as

$$P_{\mathrm{n,d}} = \begin{cases} \dfrac{\tau_{n,d}^{\alpha} E^{\beta}(n)}{\sum\limits_{n \notin nodes\_visit_p} \tau_{i,d}^{\alpha} E^{\beta}(i)} & i \in N_m - v\_node_p \\ 0 & otherwise \end{cases} \tag{24}$$

where $E = 1/(Einitial\text{-}Es)$, and $Einitial$ is the initial energy of nodes; E_s is the actual energy of the nodes; α and β are importance parameters to control pheromone concentration, which represent weights of more residual energy and shorter path.

In Eq. (24), the pheromone evaporation method is defined as

$$\tau_{n,d} = \begin{cases} \tau_{n,d} \times \rho_1 & if\ \tau_{n,d} \times \rho_1 >= \tau_{n,d}\_default \\ \tau_{n,d}\_default & if\ \tau_{n,d} \times \rho_1 <= \tau_{n,d}\_default \end{cases} \tag{25}$$

which guarantees the pheromone is no lower than the lower limit of the pheromone concentration $\tau_{n,d}\_default$. During the process of path searching, $\tau_{n,d}\_default$ ensures that every neighbor could be the next-hop node.

In EAACA, each node updates pheromone table as follows

$$\tau_{n,d} = (1 - \rho)\tau_{n,d} + \frac{\Delta\tau}{\omega \times hop_{count}} \tag{26}$$

where ω is the control factor; hop_{count} is hops of the current node packet to the destination node, i.e. the number of nodes visited by backward ants.

In Eq. (25), the pheromone increment is defined as

$$\Delta\tau = c \times (HOP_{\max} - hop_{count}) \times Eavg_n \tag{27}$$

where c is the variable parameter, HOPmax represents the maximum allowed number of hops for query data packets and probe data packets in the network; $Eavg_n$ is the average energy level of the path. It is concluded from Eq. (27) that, EAACA not only considers the distance of the path, but also takes into account the energy level of the path.

b: PERFORMANCE ANALYSIS

EAACA has the following advantages. (1) This protocol aims to create routing with low energy dissipation, balanced energy depletion, and low transmission distance. This is a relatively comprehensive consideration, which can improve multiple aspects of network performance. (2) The nodes with more residual energy have higher probabilities of being selected as repeater nodes, and the paths with higher energy level have more chance of being the final routing. This mechanism can achieve high energy efficiency and good load balance to some extent and accordingly extend the network lifetime.

EAACA has the following disadvantages. (1) In route maintenance process, several probe packets are sent to the destination node periodically. Although the probe packets are restricted to some extent, this is a large overhead and will increase the energy consumption. (2) The path selection is performed according to the residual energy and the path lengths, but the energy depletion in terms of data transmission and data reception has not been taken into account. (3) This protocol adopts the traditional many-to-one transmission pattern, in which there is uneven load distribution throughout the network. This will reduce the system lifetime.

B. ACO ROUTING PROTOCOLS BASED ON TRANSMISSION DISTANCE CONTROL

1) ASTRL

a: PROTOCOL DESCRIPTION

Liu and Song [35] proposed the ant-based heuristic algorithm (ASTRL), which aims to address the transmission range assignment problem and ultimately maximize the lifetime of WSNs.

It is assumed that sensor nodes are deployed in a circle area which is partitioned into m concentric sectors, denoted as $C_1, C_2, \ldots, C_m$, centered at the sink. The raddi of different sectors satisfy $r_1 < r_2 < \cdots < r_m$. Each sensor has a maximum transmission range, which is divided into k levels. Each sector C_i selects a node as a corona head H_i to determine the transmission range of all nodes of this sector.

The ASTRL is performed by two types of ants: forward ants and backward ants. Each forward ant moves from the source to the sink according to the following probability

$$P_{i,j} = \frac{\tau_{i,j}^{a}\eta_{i,j}^{b}}{\sum_{l=1}^{k}\left(\tau_{i,j}^{a}\eta_{i,j}^{b}\right)} \tag{28}$$

where τ_{ij} ad η_{ij} respectively the pheromone trail and heuristic information of the path (i, j).

In Eq. (28), the initial pheromone trail is defined as

$$\tau_{i,j} = \frac{1}{W_{i,j}(0)} = \frac{1}{L\left[\beta_1 + \beta_2 (x_i d)^{\alpha}\right]} \tag{29}$$

where $W_{i,j}(0)$ denotes the per node energy consuming rate (ECR) of sending data generated by itself with transmission from sector i to sector j.

When the forward ant reaches the sink, it generates a backward ant, and the memory of the forward ant is transferred to the backward ant. The backward moves in the same path as that of its corresponding forward ant, but in the opposite direction. When the backward ant arrived another node, the pheromone of the path will be updated as follows.

$$\tau_{i,j} = \tau_{i,j} + \Delta\tau_{i,j} \tag{30}$$

where the pheromone increment is defined as

$$\Delta\tau_{i,j} = \frac{1}{\sum_{(i,(i-j))\in \mathrm{path}_g} W_{i,j}} \tag{31}$$

In Eq. (31), the ECR of data transmission from sector i to sector j is defined as

$$W_{i,j} = L\left[\beta_1 + \beta_2 (x_i d)^{\alpha}\right] + \left(\sum_{j=1}^{v} \sum_{j \in \mathrm{path}_j} L_{i,j}\right) \times \left[\beta_1 + \beta_2 (ud)^{\alpha} + \beta_3\right] \tag{32}$$

In Eq. (32), $L_{i,j}$ is the outer corona of corona C_i, the set path$_j = j_1, j_2, \ldots, j_n$, includes the coronas that ant g_j arriving at corona C_i has passed through.

Each corona generates data and forward the data generated by outer coronas to the sink. The nodes of corona C_i can receive data generated from $C_{i+1}, C_{i+2}, \ldots, C_m$ and store the per node traffic load generated from these coronas, denoted as $L_{i,i+1}, L_{i,i+2}, \ldots, L_{i,m}$.

When the backward ant arrive at a node from a neighbor node, the pheromone of the path is updated, the routing table is changed, and the transition probabilities are varied. The amount of the variation of the probabilities depends on the goodness associated with the energy consumption experienced by the forward ants.

b: PERFORMANCE ANALYSIS

ASTRL possesses the following advantages. (1) The maximum transmission distance is divided into multiple levels, and multiple transmission distances can be selected in ASTRL. This helps to increase the flexibility of routing selection. (2) The path selection is performed according to the energy depletion of data transmission associated with the outer coronas. This mechanism helps to reduce energy dissipation and enhance the system lifespan.

ASTRL possesses the following disadvantages. (1) It is described in [35] that the transition probability of the forward ant is associated with the pheromone trail and heuristic information. However, how to design the heuristic information is missing in ASTRL. (2) This protocol adopts the traditional many-to-one transmission pattern, in which there is larger load distribution near the sink. ASTRL only consider how to minimize the total energy consumption of data transmission, so energy holes may happen in the network. (3) It is assumed that nodes are uniformly deployed in the regular area. If this condition is not met, it is hard to acquire the data amount and energy consumption of all different area. (4) There is also a large amount of computation of the value of the energy consumption of different coronas and its maximum value.

2) UMM

a: PROTOCOL DESCRIPTION

UMM [36] is an ACO-based routing method which aims to realize the unity of the maximum possible energy efficiency (MPEE) and the maximum possible energy balancing (MPEB), and ultimately to maximize the lifetime of WSNs. This transmission scheme is performed by ACO, but it is quite different from general ACO algorithms in two aspects: 1) only one step is needed for a complete trip of the ant; and 2) no heuristic information exists in the transition probability of the ACO.

Sensor nodes are evenly distributed on a corona-shaped area. The sink is on the center of the area. All nodes have the same maximal transmission range, which is divided into K_0 levels, and the unit transmission range is the corona thickness ω. Nodes in different coronas have different selectable maximal transmission range, but nodes in the same corona have the same one. There is an ant in each sector. Every ant moves from Sector C_i to C_j according to a specific probability, and creates a corresponding path. After finishing the whole trip of the ant, a series of path have been constructed.

For energy depletion equilibrium, the author designed a preliminary energy balancing (PEB) mechanism, which makes a difference in the selectable maximal transmission range of different sectors. Specifically, the selectable maximal transmission level of the sector rises with the increase of the distance to the sink.

For further energy depletion equilibrium, the author designed an accurate energy balancing (AEB) mechanism, where each ant chooses its destination sector with a probability. For the t-th iteration, the transition probability from Sector C_i to C_j is

$$p_{ij}(t) = \frac{\tau_{ij}(t)}{\sum\limits_{r \in S^i_{\text{candidate}}} \tau_{ir}(t)} \tag{33}$$

where $\tau_{ij}(t)$ is the pheromone value of the path, and $S^i_{\text{candidate}}$, defined by PEB, is the set of candidate sectors of Sector C_i. Different from conventional ACO algorithms, there is no heuristic information in the transition probability. This form of transition probability can reduce the computation complexity of the algorithm.

AEB is achieved by the pheromone updating rule according to which the energy balancing degree is accurately evaluated. After all ants finish their trips, the pheromone intensity on every path $\Phi(i, j)$ is updated by

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{34}$$

where the added pheromone of path $\Phi(i, j)$ is given by

$$f(t) = \Delta\tau_{ij}(t) = \left[\frac{1}{\sum\limits_{i=1}^{M} \bar{E}_i(t)}\right]^{\mu} \left[\frac{1}{\bar{E}_i^{(\max)}(t) - \bar{E}_i^{(\min)}(t) + \delta}\right]^{\psi} \tag{35}$$

where $\bar{E}_i(t)$ is the average energy consumption per node (AECPN), and $\bar{E}_i^{(\max)}(t)$ and $\bar{E}_i^{(\min)}(t)$ are respectively the maximum and minimum of $\bar{E}_i(t)$ of different sectors.

In Formula (13), the smaller the sum of AECPN, $\sum\limits_{i=1}^{M} \bar{E}_i(t)$ is, the more the added pheromone is. Analogously, the smaller the maximal difference of AECPN, $\bar{E}_i^{(\max)}(t) - \bar{E}_i^{(\min)}(t)$ is, the more the added pheromone is. Here the sum of AECPN represents the degree of MPEE, and the maximal difference of AECPN embodies the degree of MPEB. The two parameters μ and ψ determine the level of importance of MPEE and MPEB respectively. It is clear that the realization extent of MPEE and MPEB can be assessed by Formula (13), which can be used to judge whether the solution is good or not.

b: PERFORMANCE ANALYSIS

UMM possesses the following advantages. (1) Different from that of traditional ACO, the heuristic information is removed in the transition probability of ACO. This can reduce the computation complexity to some extent. (2) The PEB mechanism designs a difference in the selectable maximal transmission range of different sectors. This design decreases the candidate space of path selection for the ant, and accordingly speeds up the search speed. (3) The AEB mechanism helps to construct paths with both high energy efficiency and good energy balance. This clearly contributes to extending the network lifetime.

UMM possesses the following disadvantages. (1) Due to the absence of the heuristic information, the simplex pheromone updating of ACO may have limited ability of finding good paths in limited iterations. (2) It is assumed that nodes are uniformly deployed in the regular area. If this condition is not met, such as in an irregular zone, the difference in the selectable maximal transmission range in PEB may be no longer applicable. (3) There is a big computation for the value of AECPN, the maximum AECPN, the minimum AECPN. Therefore, UMM may suffer from the problem of scalability.

3) ODTS

a: PROTOCOL DESCRIPTION

The optimal-distance based transmission strategy (ODTS) [37] is an ACO-based routing protocol with goal of maximizing the lifetime of WSNs. The novelty of ODTS consists of two aspects. First, the author introduced two notions, most energy-efficient distance (MEED) and most energy-balanced distance (MEBD), by which a local optimal transmission-distance acquirement mechanism for both high energy efficiency and good energy balancing is designed. Second, a global optimal transmission distance acquirement scheme is in order to achieve energy depletion minimization for nodes with maximal energy consumption throughout the network.

It is assumed that nodes are evenly deployed on a disk which is divided into several disjoint concentric coronas. All nodes have the same initial energy and the same maximal transmission range. The maximal transmission range is divided into K levels, and the unit transmission range is the corona thickness ω. Nodes in different corona may use different transmission distances, but nodes in the same corona have the same one. The transmission distance is obtained by ACO, where each ant in different sectors selects appropriate path.

The MEED is obtained by minimizing the total energy consumption of data transmission from a specific starting point to a specific end point. By optimizing the number of hops associated with the transmission distance per hop, the value of MEED is achieved. The MEBD is gained by making the energy depletion of different corona equaling that of the most outer corona. The most outer corona selects an appropriate transmission level among its multiple candidates of transmission destination, and determines the equal energy consumption of each corona.

In ACO of ODTS, the transition probability of the ant from sector Ω_i to sector Ω_j is

$$p_{ij}(t) = \frac{\left[\tau_{ij}(t)\right]^{\alpha}\left[\eta_{ij}(t)\right]^{\beta}}{\sum\limits_{\Omega_r \in S_i}\left[\tau_{ir}(t)\right]^{\alpha}\left[\eta_{ir}(t)\right]^{\beta}} \tag{36}$$

where $\tau_{ij}(t)$ and $\eta_{ij}(t)$ are the pheromone intensity and the heuristic value of the path respectively.

The heuristic value of the path from sector Ω_i to sector Ω_j is defined as

$$\eta_{ij}(t) = \left[\frac{1}{(d_{ij} - d_{\mathrm{MEED}})^{\gamma} + \lambda_1}\right]^{\psi_1}\left[\frac{1}{(d_{ij} - d_{\mathrm{MEBD}(i)})^{\gamma} + \lambda_2}\right]^{\psi_2} \tag{37}$$

where d_{ij} is the distance from sector Ω_i to sector Ω_j; d_{MEED} is the MEED; $d_{\mathrm{MEBD}(i)}$ is the MEBD of sector Ω_i.

According to formula (14), the definition of the heuristic guides the ant to select the path that can achieve both high energy efficiency and good energy equilibrium. This contributes to extending the network lifespan.

In ODTS, the network lifetime is defined as

$$f(t) = \frac{\varepsilon_0}{\max\{\bar{E}_i(t), i = 1, 2, \cdots, M\}} \tag{38}$$

where the constant ε_0 is the initial energy of each node; $\bar{E}_i(t)$ is the per node average energy consumption (PNAEC) of sector Ω_i; $\max\{\bar{E}_i(t), i = 1, 2, \cdots, M\}$ is the maximum PNAEC among different sectors.

After all the ants finish their trips, the pheromone intensity on the path is updated according to

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{39}$$

where the pheromone increment on the path is defined as

$$\Delta\tau_{ij}(t) = \mu f(t) \tag{40}$$

It is concluded from formula (17) and (19) that, the smaller $\max\{\bar{E}_i, i = 1, 2, \cdots, M\}$ is, the more the pheromone increment is. This pheromone updating rule makes ants to select an efficient path with minimal value of the maximum PNAEC of different sectors.

b: PERFORMANCE ANALYSIS

ODTS possesses the following advantages. (1) The two concepts, MEED and MEBD, are important references which are effective in respectively achieving high energy efficiency and good energy balance. (2) The global optimization mechanism takes into account the maximum energy depletion which determines the network lifetime. This helps to construct paths with energy saving and accordingly prolong the system lifespan. (3) Compared with others, such as BABR [30] and EEABR [30], ODTS takes into account the energy consumption of data reception and data transmission. This can prevent constructing paths with excessive energy depletion during the process of data communications.

ODTS possesses the following disadvantages. (1) The MEBD is achieved by the selection of the transmission level of the most outer corona. This distance selection mainly depends on the experience. If it lacks experience, it is hard to determine the value of the MEBD, especially in the network with a large number of sectors. (2) It is assumed that nodes are uniformly deployed in the regular area. If this condition is not met, it is a complex computation of the data amount and energy consumption of all sub-zones. (3) There is also a large amount of computation of the value of the energy consumption of different coronas and its maximum value. Hence, the scalability of ODTS is also limited.

4) MMBEC

a: PROTOCOL DESCRIPTION

The multilevel minimization and balancing for energy consumption (MMBEC) [38] is a ACO-based transmission range adjustment strategy. The goal of this transmission strategy is to take full consideration of energy consumption minimization (ECM) and energy consumption balancing (ECB) and accordingly prolong the network lifespan. There are two important concepts in MMBEC. One is the reference transmission distance (RTD) which helps to realize local ECM and ECB. The other is the energy per node (EPN) which is used to achieve global ECM and ECB.

In the network model, sensor nodes are randomly and uniformly deployed on a disk which is divided into M disjoint concentric coronas. An arbitrary wedge is partitioned into M sectors, denoted as $C_1, C_2, \ldots, C_M$. Each sensor has K levels of transmission range to choose and the unit transmission range is the corona thickness ω. The problem is to search an optimal transmission range sequence for all sectors.

It is proved in [38] that The MEED makes the total energy consumed achieve the minimal value. However, for energy depletion equilibrium throughout the network, the sensors close to the sink should send data by relatively smaller distance than that far from the sink. For this reason, the advisable transmission manner should follow the rule that all sensors send data based on MEED, while more closer to the sink, more smaller the transmission distance is. On contrast, more far from the sink, more longer the transmission distance is. According to the above rule, the author designed the RTD d_{refer}, which is a linear function of the distance to the sink, d_{toSink}. The definition of RTD involves the idea of both ECM and ECB.

In MMBEC, the transition probability of the ant from sector C_i to sector C_j is given by

$$p_{ij}(t) = \frac{[\tau_{ij}(t)]^{\alpha}\,[\eta_{ij}(t)]^{\beta}}{\sum\limits_{r \in S^{i}_{\text{candidate}}} [\tau_{ir}(t)]^{\alpha}\,[\eta_{ir}(t)]^{\beta}} \tag{41}$$

where $\tau_{ij}(t)$ and $\eta_{ij}(t)$ are respectively the pheromone intensity and the heuristic value of the path.

The heuristic value $\eta_{ij}(t)$ of formula (41) is defined as

$$\eta_{ij}(t) = \frac{1}{\lambda_1 + \lambda_2 [d_{ij} - d_{\text{refer}(i)}]^2} \tag{42}$$

where d_{ij} is the distance between sector C_i and sector C_j and can be achieved by

$$d_{ij} = \frac{R}{M}(i-j) \tag{43}$$

$d_{\text{refer}(i)}$ is the RTD of sector C_i and can be written by

$$d_{\text{refer}(i)} = d_{\text{opt}} + \left(i\frac{R}{M} - \frac{R}{2}\right)\tan\theta \tag{44}$$

In Eq. (42), the more the value of d_{ij} is closer to that of $d_{\text{refer}(i)}$, the higher the probability of the path to be selected is, i.e. greater the degree of the ECM and ECB is.

In Eq. (41), the pheromone intensity is updated according to

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \tag{45}$$

where the added pheromone on the path is given by

$$\Delta\tau_{ij}(t) = \left[\frac{1}{\sum\limits_{i=1}^{M} \bar{E}_i(t)}\right]^{\mu} \left[\frac{1}{\bar{E}_i^{(\max)}(t) - \bar{E}_i^{(\min)}(t) + \xi}\right]^{\psi} \tag{46}$$

where $\bar{E}_i(t)$ is the EPN of sector C_i, and $\bar{E}_i^{(\max)}(t)$ and $\bar{E}_i^{(\min)}(t)$ are respectively the maximum and minimum EPN among all sectors.

In Eq. (46), the smaller the sum of EPN is, the more the pheromone increment is. The smaller the maximal difference of EPN is, the more the pheromone increment is. Hence, the sum of EPN represents the degree of ECM, and the maximal difference of EPN embodies the degree of ECB.

According to Eq. (46), the realization degree of ECM and ECB can be evaluated by

$$f(t) = \left[\frac{1}{\sum\limits_{i=1}^{M} \bar{E}_i(t)}\right]^{\mu} \left[\frac{1}{\bar{E}_i^{(\max)}(t) - \bar{E}_i^{(\min)}(t) + \xi}\right]^{\psi} \tag{47}$$

which is used to judge whether the solution is good or not.

b: PERFORMANCE ANALYSIS

The merits of MMBEC are summarized as follows. (1) The concept of RTD is very significant and effective to establish paths with both high energy efficiency and good energy balance. (2) The global optimization mechanism takes into account the total energy consumption and the difference of energy depletion of different sectors. This contributes to constructing paths with both high energy efficiency and good energy balance and accordingly prolonging the system lifespan. (3) Compared with others, such as BABR [30] and EEABR [30], MMBEC takes the energy consumption of data reception and data transmission. This can prevent constructing paths with excessive energy depletion during the process of data communications.

The defects of MMBEC are summarized as follows. (1) The concept of RTD is achieved by estimation, by which

TABLE 2. Comparison of ACO-based routing protocols in WSNs.

Reference	Protocol	Operation behavior	Ultimate objective	Network topology	Transition probability	Location awareness	Energy efficiency	Load balance	Computation complexity
[30]	BABR	Energy level control	Lifetime extension	Flat	Pheromone and heuristic	No	Low	Weak	Moderate
[30]	EEABR	Energy level control	Lifetime extension	Flat	Pheromone and heuristic	No	Low	Weak	Moderate
[31]	ACO-QoSR	Energy level control	QoS requirement	Flat	Pheromone and heuristic	No	Low	Weak	Moderate
[32]	E&D ANTS	Energy level control	QoS requirement	Flat	Pheromone and heuristic	No	Low	Weak	Moderate
[33]	ACORC	Energy level control	QoS requirement	Flat	Pheromone and heuristic	No	Low	Weak	Moderate
[34]	EAACA	Energy level control	Lifetime extension	Flat	Pheromone and heuristic	No	Low	Weak	Moderate
[35]	ASTRL	Transmission distance control	Lifetime extension	Hierarchical	Pheromone and heuristic	No	High	Weak	High
[36]	UMM	Transmission distance control	Lifetime extension	Hierarchical	Single pheromone	No	High	Strong	High
[37]	ODTS	Transmission distance control	Lifetime extension	Hierarchical	Pheromone and heuristic	No	High	Strong	High
[38]	MMBEC	Transmission distance control	Lifetime extension	Hierarchical	Pheromone and heuristic	No	High	Strong	High

the RTD is designed as a linear function of the distance to the sink. However, this estimation may not the optimal one. (2) It is assumed that nodes are uniformly deployed in the regular area. If this condition is not met, it is a complex computation of the data amount and energy consumption of all sub-zones. (3) There is also a large amount of computation of the value of the energy consumption of different coronas, and its maximum value as well as its minimum value. Hence, the scalability of ODTS is also limited.

V. COMPARISON OF ACO-BASED ROUTING PROTOCOLS IN WSNs

Table II shows the main characteristics of the different ACO-based routing protocols of WSNs. These protocols are compared according to their operation behavior, ultimate objective, network topology, transition probability, location awareness, energy efficiency, load balance, and computation complexity.

VI. CONCLUSION

In this paper, we have presented a survey on ACO-based routing protocols in WSNs. We have also developed a classification of these protocols. We have systematically analyzed a few representative ACO-based routing protocols and compared these approaches based on the classification and some primary metrics.

Finally, we want to sketch the following future directions for this research field.

A. EVALUATION IN REAL SCENARIOS

Most ACO-based routing are tested by simulations rather than real environments. However, there are difference between simulations and real environments. With the trend of WSNs from academic research to practical applications, ACO-based routing should be evaluated in real environments. A good example is that in [55], in which ACO-routing is applied to the wireless body area network (WBAN). Whenever the patient needs any critical care or any other medical issue arises, emergency messages can be quickly sent to the doctor's destination.

B. APPLICATIONS IN SPECIAL ENVIRONMENTS

It is assumed that nodes are deployed in common areas, such as square and circular zones. Nevertheless, nodes may be distributed in some special environments, such as three-dimensional scenarios [56], strip zones [57] and curved areas [58]. How to design appropriate routing in special environments is a challenging, because there exist a few thorny issues in such special environments. For example, the long-distance paths in mountain environments will lead to too much data accumulation near the sink and too long transmission delay [58].

C. DESIGN OF OTHER QoS-AWARE ROUTING

There are several ACO routing protocols that provide QoS services, such as ACO-QoSR [31], E&D ANTS [32], and ACORC [33]. These protocols focus on the guarantee of delay and reliability. However, routing with multiple types of QoS services is needful, including requirement of delay [31], guarantee of security [59], survival ability [60], etc. For instance, in recent years, because of the surge in cyber attacks, enhancing the robustness of the WSNs has become a critical issue [61], [62]. For another example, alert message like forest fire and property loss should be rapidly delivered to the destination nodes [63]–[65].

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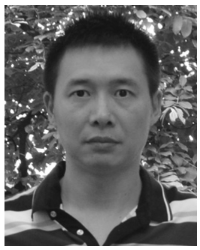

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