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Energy Efficient Ant Colony System for Packet Routing in Wireless Sensor Network

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Abstract. Routing packets in Wireless Sensor Network (WSN) is challenging due to the distribution of sensor nodes with different ability. Inefficient routing may lead to higher failure rate, higher latency and higher energy consumption. One of the common approaches to solve this problem is by using bio-inspired routing algorithms due to their abilities to adapt with dynamic environment. This paper proposed an improved ant colony system for packing routing in WSN that focuses on exploration and exploitation techniques. In the proposed routing algorithm, the best path to be used for packet transmission will be determined by considering the remaining energy of each sensor node to reduce the hotspot problem. Local pheromone update and global pheromone update are used with the aim to prevent imbalanced energy depletion of sensor nodes and to balance the packet distribution. The proposed routing algorithm was validated against several bio-inspired routing algorithms in medium and large sized networks. The results suggested that it has outperformed in terms of success rate, packet loss rate, latency and energy efficiency.

1. Introduction

Wireless Sensor Network (WSN) refers to a collection of sensor nodes that are heterogenous and interconnected to sense data, communicate with the other sensor nodes, and execute basic operations on the sensed data. Management of sensor nodes in WSN is the main aspect that needs to be considered in maximizing the network lifetime. There are several main issues in WSN such as packet routing, load balancing, fault tolerance, and energy efficiency [1]. Robustness and scalability are two main factors that need to be considered in implementing packet routing in WSN. Due to each sensor node in WSN having limited transmission range, packets can only be forwarded from the source node to the destination node through other sensor nodes using multi-hop technique [2].

Routing packets in WSN aims to optimize energy efficiency, latency, energy consumption, throughput, success rate, and load balancing. Finding an optimal path from the source node to the destination node is one of the main challenges in WSN which considers the distance between source node to destination node, energy level of sensor nodes, and capacity of each sensor nodes during packet submission [3]. Packet routing is classified as a Nondeterministic Polynomial (NP)-complete problem in which the optimal solution can be found by applying all possible solutions in a polynomial time. One of the most effective ways to solve this problem is to use metaheuristic algorithms such as Ant Colony

Optimization (ACO), Genetic Algorithm, Simulated Annealing, and Termite-hill that move from one solution to another in the process of constructing the best solution [4].

ACO algorithm is inspired by the foraging behavior of real ants in constructing the shortest path from the nest to the food source. Ants mark the journey from the nest to food source and vice versa by using a chemical substance called pheromone [5]. The shortest path or optimal path will be identified by the ant based on the level of deposited pheromone by the previous ants [6]. Ants are more attracted to the path with high pheromone value because it is shorter and more optimal than the path with low pheromone value.

There are many variations of ACO algorithm such as Ant System, Max-Min Ant System, and Ant Colony System (ACS). ACO has been successfully applied to solve many computational problems such as fault tolerance, sequential ordering, and data classification. Many researchers also applied ACO in optimizing the packet routing in WSN due to its adaptability on static, mobile, and dynamic WSN environments [7][8][9]. Several examples of ACO application in WSN include Energy-Efficient Ant-Based Routing Algorithm (EEABR), Improved Energy-Efficient Ant-Based Routing, Fish Swarm Ant Colony Optimization (FSACO), and Enhanced Ant Colony System (EACS).

This paper proposed ACS based packet routing algorithm in WSN that will optimize the success rate, latency, and energy efficiency. Section 2 presents recent research works that applied swarm intelligence algorithms in WSN while further elaboration on the proposed algorithm is covered in Section 3. Then, Section 4 discusses experimental result and followed by the conclusion in Section 5.

2. Swarm Intelligence Algorithms in Wireless Sensor Network

Swarm intelligence algorithm is inspired by the biological behaviour of natural system such as colonies of ants and bees, flocks of birds, and schools of fish that can be related to the optimization problem [10]. Swarm intelligence algorithms have successfully solved many distributed optimization problems such as packet routing, fault tolerance, and grid scheduling. There are several swarm intelligence algorithms that are commonly used to improve the performance of WSN packet routing such as ACO, Particle Swarm Optimization, Termite-hill, Artificial Bee Colony, and Cuckoo Search [11][12].

EEABR was proposed by [13] to reduce the energy consumption and communication load in WSN. The probabilistic decision rule is applied in EEABR to evaluate the capacity of sensor nodes during node selection process. Meanwhile, the global pheromone update is employed to encourage the next ants to select an optimal path. Experiment results showed that EEABR performed better than Basic Ant-Based Routing and Improved Ant-Based Routing in static network, mobile network, and mesh network. However, EEABR did not consider the exploration of alternative potential path in reducing the hotspot problem.

BeeSensor routing algorithm that is inspired by the foraging behaviour of bees was proposed by [14]. There are three types of agents used in BeeSensor which are scouts, packers and foragers. Packers are responsible to sense data from neighbour nodes and broadcast the information by using the waggle dance to scouts which are responsible to find the optimal path to the destination node. Foragers which are launched once scouts returned to the source node will evaluate the quality of the visited path to transmit packets from the source node to the destination node. From the experiment, BeeSensor achieved the best performance for control-overhead, energy efficiency, and network lifetime. However, the hotspot problem was not considered that may affect the packet delivery ratio and latency.

[15] proposed Termite-hill routing algorithm to improve the packet routing in static, dynamic and mobile WSN environment. Termite-hill uses autocatalytic behaviour of termite in finding a solution in a reasonable time. Three types of pheromones are used by Termite-hill which are initial pheromone, lower pheromone, and upper pheromone. Probability distribution of packets are measured in the early stage by using initial pheromone where pheromone update and pheromone evaporation are controlled by the range between lower pheromone and upper pheromone. Experimental results showed that Termite-hill outperformed in terms of energy consumption, energy efficiency, and throughput. However, the performance of Termite-hill in large sized networks was not validated since the experiments only covered small number of sensor nodes.

EACS was proposed by [16] to reduce the packet loss and latency while considering the energy efficiency of packet routing in WSN. EACS, which is one of the ACO variants, is inspired by the foraging behaviour of ants and used pheromone as a communication medium in finding the optimal path to the destination node. EACS obtains information from the neighbour nodes and applies probabilistic decision rule to determine the next neighbour node during routing path construction. Global pheromone update and local pheromone update are used by EACS to encourage the selection of optimal path and to reduce the hotspot problem. However, EACS did not consider the state transition rule that can control the exploration and exploitation in the early stage of packet routing. Additionally, its performance was not compared with the other swarm intelligence algorithms.

FSACO that combined Artificial Fish Swarm Algorithm (AFSA) and ACO to enhance packet routing in WSN was proposed by [17]. Crowd factor is adapted from AFSA for initial route discovery process and pseudorandom proportional route selection model is adapted from ACO to find the optimal solution. Crowd factor is used to determine the congestion degree within sensor nodes radius. Global pheromone update is applied during searching process by considering sensor nodes remaining energy and path length. Experimental results showed that FSACO achieved better performance in terms of convergence time, energy consumption, throughput, and energy deviation. However, the local pheromone update which can potentially reduce hotspot problem was not considered.

As discussed in this section, swarm intelligence algorithms have been used by many researchers to solve packet routing problem in WSN. However, there are still many rooms for improvement to further optimize the performance of the algorithms in this application domain.

3. Improved Ant Colony System for Wireless Sensor Network

The concept of ant-based routing in WSN is similar to the natural behaviour of ants in which paths are constructed from the nest (source node) to the food source (destination node). The path construction by ants represents the network routing scheme where the shortest path or path with minimal error is more preferred and optimal. Figure 1 depicts an overview of a network used by ants in a WSN system. Sensor nodes are represented by circles and ants that carry packet information move from one sensor node to another to construct routing path between the source node and the destination node.

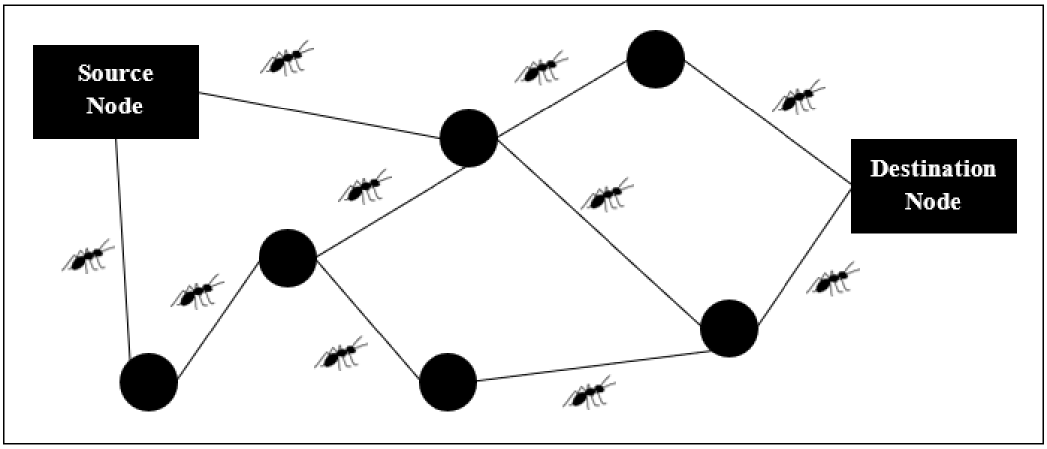

Figure 1: Ants in WSN system

Energy Efficient ACS (EEACS) algorithm is proposed to enhance the packet routing process in WSN by applying techniques from ACS to increase success rate, reduce packet loss rate, reduce latency and increase energy efficiency. The proposed routing algorithm consists of state transition rule, local pheromone update, and global pheromone update. The searching agent consists of forward ant and backward ant. Initially, forward ant is launched to construct a potential optimal path from the source node to the destination node where the information of visited sensor nodes will be stored in the ant's memory. The state transition rule that considers the pheromone value and remaining energy of sensor nodes is used in node selection process. State transition rule is calculated using the following equation:

$$P^k{}_{(r,s)} = \begin{cases} argmax\,\{[\tau_{(r,s)}][E_v]^{\beta}\} & if\ q \leq q_0 \quad (exploitation) \\ S & otherwise \quad (exploration) \end{cases} \tag{1}$$

where $P^k{}_{(r,s)}$ is the probability value of ant k to move from node r to node s. $\tau_{(r,s)}$ is the pheromone value of the edge between node r and node s. E_v is the heuristics value defined by $\frac{1}{E_r}$, where E_r is the remaining energy of node s. q is a random variable ranging from 0 to 1 and q_o ($0 \leq q_o \leq 1$) is a parameter to control the possibility of exploration or exploitation. S is a random variable controlled by the probabilistic decision rule using the following equation:

$$\boldsymbol{S^k}{}_{(\boldsymbol{r},\boldsymbol{s})} = \frac{[\boldsymbol{\tau}_{(\boldsymbol{r},\boldsymbol{s})}][\boldsymbol{E_v}]^{\boldsymbol{\beta}}}{\sum[\boldsymbol{\tau}_{(\boldsymbol{r},\boldsymbol{s})}][\boldsymbol{E_v}]^{\boldsymbol{\beta}}} \tag{2}$$

The local pheromone update is performed by the forward ant on each visited sensor nodes to reduce the pheromone strength while encouraging exploration of other potential nodes. This technique can potentially reduce the hotspot problem where some sensor nodes are being overutilized and eventually cause their energy to drain drastically. The local pheromone update is defined by:

$$\tau_{(r,s)} = (1-\rho) * \left(\tau_{(r,s)}\right) + \rho(E_{i-}E_r) \tag{3}$$

where the range of pheromone values is controlled by the coefficient value ρ ($0 \leq \rho \leq 1$), E_i is the sensor node initial energy, and E_r is the sensor node remaining energy. Once the forward ant arrives at the destination node, it will be transformed into the backward ant which will return to the source node through previously visited path and at the same time apply the global pheromone update to each node along the path. This update will reinforce the pheromone value on the potential optimal path so that the path becomes more attractive to next ants. The global pheromone update is defined by:

$$\tau_{(r,s)} = (1-\alpha) * \tau_{(r,s)} + \alpha\left(\Delta\tau_{(r,s)}\right) \tag{4}$$

where α ($0<\alpha<1$) is the evaporation rate value and $\Delta\tau_{(r,s)}$ is defined by the following formula:

$$\Delta\tau_{(r,s)} = \frac{1}{N_r} \tag{5}$$

where N_r is the number of visited nodes from node r until the destination node. The optimal values for α, β, ρ, and q_0 of EEACS are adopted from [18].

4. Experimental Result

EEACS was evaluated in the simulated WSN environment supported by a Routing Modelling Application Simulation Environment (RMASE) framework that was written and run in MATLAB [19]. The performance of EEACS with different number of sensor nodes was compared with EACS, EEABR, BeeSensor, and Termite-hill. Experiments were done to measure the effect of the number of sensor nodes towards energy efficiency, latency, success rate and packet loss rate when routing packets in the same simulation time. Packets were submitted to the destination node in simulation grid of 49 (7×7), 64 (8×8), 81 (9×9), and 100 (10×10) sensor nodes for 300 seconds based on the parameter specifications described in Table 1.

Table 1. Simulation parameter

Parameters	**Values**
Number of nodes	49, 64, 81, 100
Node energy	50 J
Simulation Time	300 seconds
Performance Metric	Success rate, packet loss rate, latency, energy efficiency
Routing algorithm	EEACS, EACS, EEABR, BeeSensor, Termite-hill

Success rate refers to the number of successful packets received by the destination node over the number of submitted packets by the source node. Figure 2 shows that EEACS achieved the highest success rate when using 100 sensor nodes and slightly lower than Termite-hill and BeeSensor when using 49, 64, and 81 sensor nodes in submitting packets to the destination node. EACS which is another ACS variant also achieved good result in these experiments. The absence of local pheromone update in EEABR that could prevent the hotspot problem gives a significant impact to the success rate value compared to the EEACS and EACS. However, EACS does not consider the state transition rule that can balance the exploration and exploitation of optimal routing path. State transition rule used in the EEACS combines the pheromone value and sensor nodes remaining energy to select the next node.

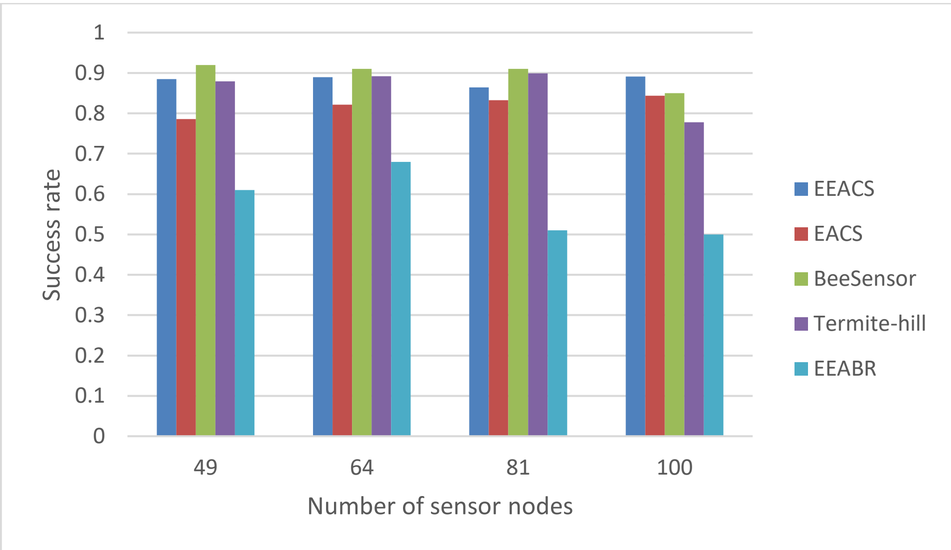

Figure 2. Success rate of different routing algorithms by using different number of sensor nodes

In addition to representing the performance in the form of success rate, representation using packet loss rate is also possible as shown in Figure 3. Packet loss rate is the number of unsuccessful received packets per the number of submitted packets by source node which contradicts the results in Figure 2. The results suggest that EEACS achieved the lowest packet loss rate when using high number of sensor nodes. These results also prove that EEACS is more suitable to be used in large networks. This is because in a large network, EEACS that applies state transition rule, local pheromone update and global update has better approach to reduce hotspot problem. Simultaneously, EEACS can balance between exploration and exploitation by considering the remaining energy and pheromone value of available sensor nodes. On the other hand, EEABR and Termite-hill do not effectively deal with the hotspot problem in large sized network.

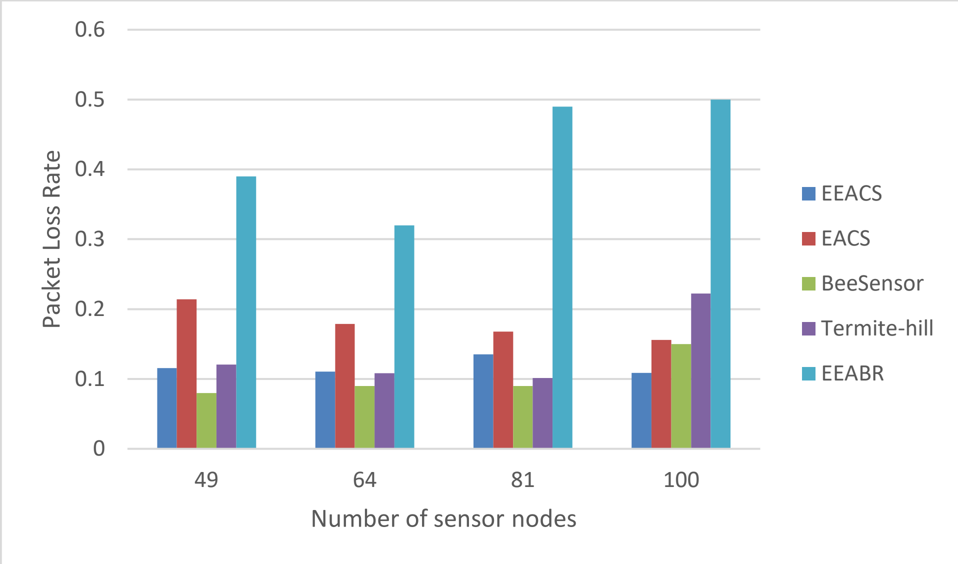

Figure 3. Packet loss rate of different routing algorithms by using different number of sensor nodes

Latency which is the time taken to send a packet from source node to destination node is one of the criteria to measure how well the algorithm can reduce the congestion problem. Figure 4 depicts the comparison of the latency between EEACS, EACS, BeeSensor, EEABR and Termite-hill. As can be seen, Termite-hill has the highest latency while EEACS has the lowest latency among all. This is expected because EEACS minimizes the search and submission time by referring to the information stored in the routing table. EEACS will select the node with the highest pheromone value and residual energy from the routing table. From these experiments, it can be concluded that even though BeeSensor achieved the second highest success rate, it still needs improvement in terms of time taken to submit the packets. On the other hand, since Termite-hill does not consider the exploration of potential sensor nodes, the next termite will mostly choose the previous optimal sensor nodes without exploring the other potential sensor nodes. This situation leads to the congestion problem during packet submission.

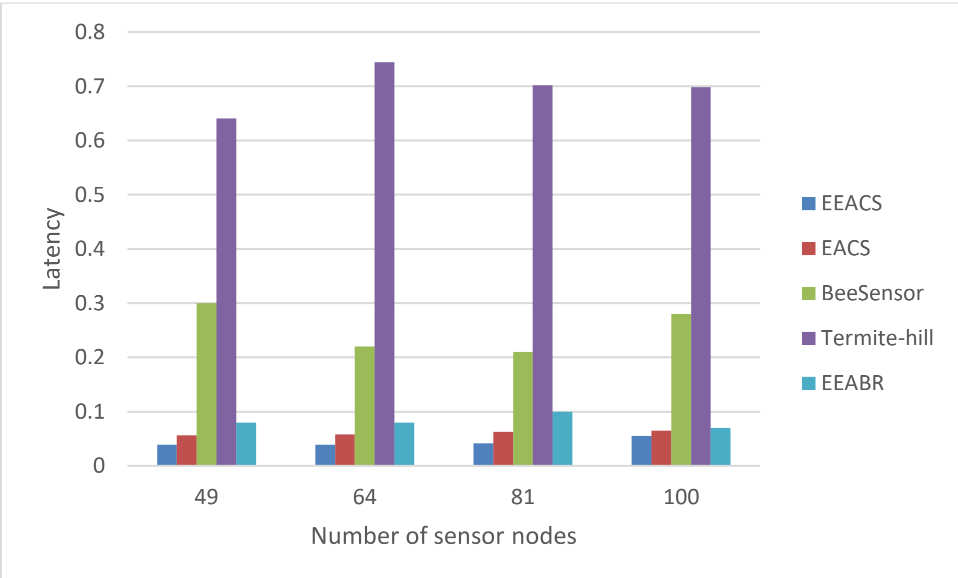

Figure 4. Latency of different routing algorithms by using different number of sensor nodes

Figure 5 shows a comparison of energy efficiency between EEACS, EACS, EEABR, BeeSensor, and Termite-hill calculated based on the formula by [20]. This formula measures the energy efficiency based on the total energy used to submit 1000 bits of data to destination node where lower energy efficiency is better than higher energy efficiency. Based on the figure, it clearly shows that EEACS has the lowest energy efficiency while Termite-hill has the highest energy efficiency in all scenarios. These results are expected because EEACS can reduce the energy consumption of each sensor node by fairly distributing packets among potential sensor nodes. Exploitation of optimal sensor nodes from previously constructed routing paths and exploration of new potential sensor nodes is balanced effectively to better preserve the energy consumption in the system. In contrast, Termite-hill, which consumes the most energy during packet submission and has low packet received value, achieved the highest energy efficiency among others, and eventually leads to the least network lifetime.

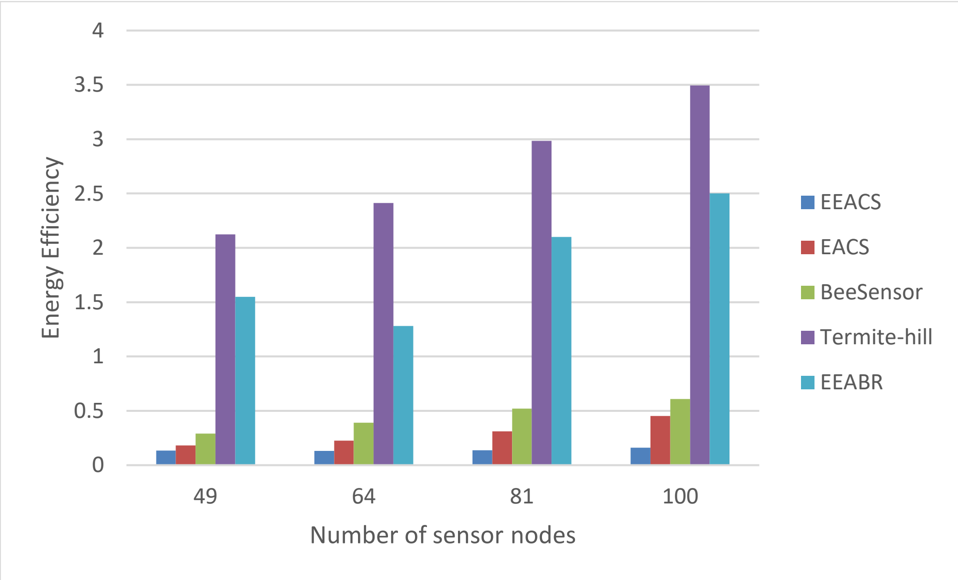

Figure 5. Energy efficiency of different routing algorithms by using different number of sensor nodes

The summary of performance for all algorithms is shown in Table 2. Based on the table, EEACS achieved the best performance as compared with EACS, BeeSensor, Termite-hill and EEABR in large network size and eventually lead to a more balanced energy level of sensor nodes.

Table 2. Comparison of the routing algorithms when routing packets using 100 sensor nodes

Routing Algorithm	Success Rate	Packet Loss Rate	Latency	Energy Efficiency
EEACS	**0.89**	**0.11**	**0.06**	**0.16**
EACS	0.84	0.16	0.07	0.45
BeeSensor	0.85	0.15	0.28	0.61
Termite-hill	0.78	0.22	0.70	3.50
EEABR	0.5	0.5	0.07	2.5

5. Conclusion

EEACS algorithm that consists of state transition rule, local pheromone update, and global pheromone update achieved the best overall performance especially in large network size as compared to EACS, BeeSensor, Termite-hill, and EEABR in terms of success rate, latency and energy efficiency. The state transition rule that considers the pheromone value and sensor nodes remaining energy plays vital role during the node selection process. In addition, the local pheromone update is able to reduce the hotspot problem by encouraging exploration of other potential paths, while the global pheromone update is used to encourage exploitation of optimal path by depositing more pheromone to the path. EEACS algorithm is expected to improve sensor nodes utilization by distributing packets to several potential optimal paths and eventually can increase the network lifetime. For future works, packet priority aspects will be considered to improve the packet routing in WSN as the real environment may have various types of sensor nodes that carry different kind of data packet.

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