ACO-Inspired Energy-Aware Routing Algorithm for Wireless Sensor Networks

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***Abstract*—Multi-hop networks such as WSN attract an intensive attention as an emerging technology which plays an important role for practical IoT applications. These multi-hop networks generally consist of mobile and small terminals with limited network and terminal resources which makes the networks vulnerable to various network status changes. Moreover, the limited terminal resource, especially their limited battery capacity, is one of the most important issues to be addressed for a prolonging lifetime of the networks. For realizing efficient communications in such networks, a bunch of works has already been done especially in routing and transmission technologies. However, conventional works in the routing field still suffer from an issue called energy hole problem, which is generally caused by unbalanced communication loads due to the difficulty of adaptive route management. To address the issues, this paper proposes a novel routing algorithm, which utilizes ACO-inspired routing based on the residual energy of terminals. The performance evaluation reveals its potentials of the balanced energy consumption as well as the network work performances.**

I. INTRODUCTION

Wireless sensor network (WSN) generally consists of terminals which have the capability of environmental sensing and communication. Terminals in WSN transmit the sensed information to a sink, which plays a role of information collection and processing, by direct or multi-hop transmission. WSN is thought to be a promising technology for wide-range observation and requires a bunch of sensors for the sensing and relaying the information. Terminals in WSN are driven by batteries with limited capacity because continuous powering to terminals in the network is nearly impossible. Moreover, WSN assumes long-term operation and smaller batteries are preferred due to the manufacturing and deploying costs. In addition, the cost of replacing the batteries significantly increases when terminals are deployed in the environment which operators cannot access the terminals easily such as deep forests and under water. Therefore, prolonging the lifetime of WSN with limited battery capacity is an important issue to operates the network as long as possible and thus efficient routing and communication technologies are imperative for the objective.

For prolonging the lifetime of WSN, there are a bunch of routing methods with various approaches have been studied such as [1]–[3]. Although the methods improves the efficiency in a certain degree, there is a drawback in the scalability to the increase of physical network domain because they require central management for information processing and terminals with particular capability. To address the drawback, autonomous and distributed mechanisms inspired by the behaviours of living organisms such as insects are proposed [4]–[7]. They were proposed to solve various problems with autonomous and distributed optimization procedure by imitating the behaviour of the living organisms usually do in a real environment. In this paper, we adopt the concept of ACO (Ant colony optimization) [4]–[6] for an energy-aware routing. In the proposed routing, ACO is utilized not to optimize route, but to dynamically select routes according to the residual energy of terminal using the transition statuses for the optimization process of ACO.

II. RELATED WORK

A. Energy-Aware Routing Protocols for WSN

Paper [1] introduces an asymmetric communication for energy saving which utilizes the fact that sinks are generally operated by external power supplies. Thus, sinks have a capability of long-range transmission compared with terminals operated by batteries. Therefore, terminals with energy constraints adopt multi-hop communication with shorter-range communication to send information to sinks and sinks directly send information to terminals with long-range communication. In other words, terminals operated by battery require less energy consumption compared with the required energy in sinks. However, sink placement greatly affects the energy saving ability because the sum of path lengths from terminals to sinks determines required energy consumption.

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The routing method introduced in paper [2] utilizes several topologies according to the network characteristics for the reduction of energy consumption. The method adaptively utilizes star-shaped, tree-shaped, chain-shaped, and cluster-shaped topologies. In the star-shaped topology, sinks become the centre of the star and other terminals utilize direct transmission to the sinks for reducing the required energy to receive, process, and aggregate the sensed data. The tree-shaped topology will be applied to suppress the required energy for transmission by using multi-hop transmission. In the chain-shaped topology, the method establishes a single route that travels every terminal once and optimizes the route length to be minimized for improving reliability. In the cluster-shaped topology, the method divides networks into clusters that have 2-hop neighbours at maximum as the conventional clustering in WNS does. Then, the cluster head aggregates received information and sends it to sinks to suppress the total amount of send and receive data and transmission distance. However, environment changes due to join and leave of terminals or other factors enforces the method to re-calculate the optimal topology and the cost increment in proportion to network size becomes an inevitable issue.

Optimized LEACH-C [3] also adopts cluster-based routing that estimates required energy consumption according to the geographical location of terminals and the number of cluster members on sinks. Optimized LEACH-C utilizes the estimated energy consumption to generate an initial solution and utilize the simulated annealing to generate heuristic solutions. Then, the solution is notified to each terminal and clusters will be assigned for terminals entirely. However, sinks in optimized LEACH-C must play roles of information collection, calculation for clustering, and notification of the results which exponentially increase the operational costs.

B. Ant-Colony Optimization

As the solutions for the issues described in II-A, network-wide optimization which is accomplished by autonomous and distributed state prehension and decision done by an individual terminal so-called divide-and-conquer method is considered desirable. As an example of such an optimization, there is a strategy called swarm intelligence which is inspired by the group behaviour of insects and the simple individual behaviour of them optimize objectives entirely. There are a bunch of methods that applies the optimization for network management modelling terminal behaviours as a portion of swarms.

ACO (Ant Colony Optimization) inspired by the feeding behaviours of ants is proposed as the one particular application [4]–[6]. ACO generally utilizes the agents called “ant” that secretes “pheromone” to the travelled route as an evaluation value of the route for adaptive and continuous route update. Therefore, applying ACO to the environment such as WSN, which the communication condition changes in a short time and mutual state prehension by terminals is difficult, exerts itself to achieve effective performance.

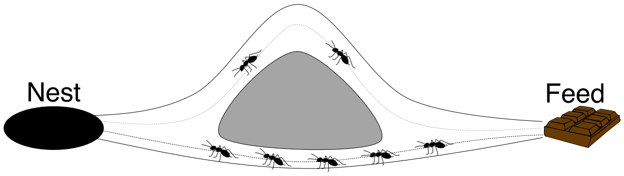

Fig. 1. The principle of ACO routing.

ACO has an ability to discover the shortest route without an effort of centralized management by utilizing the behaviours of ant and the pheromone secretion as described previously. Thus, ACO is applied to various combinatorial problems such as TSP (Traveling Salesman Problem). An ant in the feeding behaviour detects pheromones on grounds and follows them towards feeds and then traces back to the nest with the feeds secreting pheromones. As the secreted pheromones volatilize at a constant pace, more pheromones remain in shorter routes compared with longer routes. A route with more pheromones attracts more ants and the pheromone secretions in neighbouring regions of the shortest route becomes active, that is, ants tend to select the shortest route as time elapses as shown in Fig.1.

Paper [5], [6] proposed the basic ACO model called Ant System (AS). Here, we would explain the AS with TSP which is the particular application to combinatorial problems. In the application, each ant is treated as m agents and placed in n cities, and creates a route based on the rule that each agent visits each city only once and decide next city to be visited according to the pheromone level. The following Eq.(1) calculates the probability that agent k in city i on cycle t travels city j in the next cycle.

$$p_{ij}^{k}(t) = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}\,[\eta_{ij}]^{\beta}}{\displaystyle\sum_{s \in J_k(i)} [\tau_{is}(t)]^{\alpha}\,[\eta_{is}]^{\beta}} & j \in J_k(i) \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where $\tau_{ij}(t)$ represents the pheromone level between city i and j on cycle t, η_{ij} represents the invert of route length between city i and j, $J_k(i)$ represents set of visitable cities of agent k in city i, and α, β are the constant.

After the agent finishes its travel of visiting every cities and creation of the route, AS calculates the pheromone level to be secreted to the travelled route with the following Eq.(2).

$$\Delta\tau_{ij}^{k} = \begin{cases} \dfrac{1}{C_k} & (i,j) \in T_k \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

where τ_{ij}^{k} represents the pheromone level to be secreted between city i and j and C_k represents the length of route T_k that agent k created. Then, AS applies the calculated pheromone level to the route and update the residual pheromone level using Eq.(3).

$$\tau_{ij}(t+1) = \rho\tau_{ij}(t) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \tag{3}$$

where ρ represents volatile coefficient, that is, AS volatilizes a certain pheromone level from the remaining pheromones and adds secreted pheromones by agents. AS continuously repeats this procedure until it discovers the optimal solution.

AS enables ACO-based routing with simple procedures of individual terminals to find the optimal route without using centralized network management. In addition, data will be travelled with the optimal route generally improves the reliability and thus make the energy consumption per packet lower. Although the mechanism finds and utilizes efficient route in terms of network performance, a concentration of traffic load to specific routes may be a cause of early-leave of terminals due to exhaustion of batteries.

III. AERO: ACO-INSPIRED ENERGY-AWARE ROUTING

A. Overview and Operation Principle

In the following sections, we propose ACO-inspired energy-aware routing named AERO based on the residual energy of terminals for an adaptive and dynamic routing. The significant characteristic of AERO is that the agent ant behaviour tries not to find the optimal solution, but to semi-optimal solutions. This is to prevent routes with the sufficient pheromone level from utilizing continuously until the terminals on the routes exhaust their batteries, that is, AERO positively utilizes the transient state of ACO to improve the route diversity.

AERO introduces three types of control packet imitating ant to apply ACO into routing, namely forward ant (F-ANT), backward ant (B-ANT), and data ant (D-ANT). In addition, AERO does not secrete pheromones into links between terminals as the conventional ACO does, but into terminals. The secreted and residual pheromone levels are notified to neighbouring terminal with periodical hello message exchanges as the conventional routing protocols do. The following describes the brief routing procedure of AERO with Fig.2–4.

In AERO, a source terminal first sends F-ANTs towards the desired destination with the same way as the conventional routing protocols do as shown in Fig.2. The F-ANTs sent by the source terminal travel with various routes and the F-ANTs stores the terminal ID and the residual energy of each intermediate terminal during the travel. The destination terminal that receives the F-ANTs waits for other F-ANTs the predetermined duration to collect multiple route information.

After the predetermined wait time elapses, the destination terminal that received multiple F-ANTs evaluates each route using the stored information in the F-ANTs. Note that, the detailed evaluation procedure will be explained in III-B. The destination terminal generates B-ANTs that contains obtained route information and its evaluation value after the evaluation procedure completes. Then, the B-ANTs starts their travel by tracing back the route that F-ANTs travelled and the B-ANTs secrete pheromones to the intermediate terminals on the route during the travel. This procedure is recursively done until the B-ANTs reach the source terminal. Note that, the source terminal also waits for other B-ANTs the predetermined duration to receive multiple B-ANTs as same to the case of F-ANT.

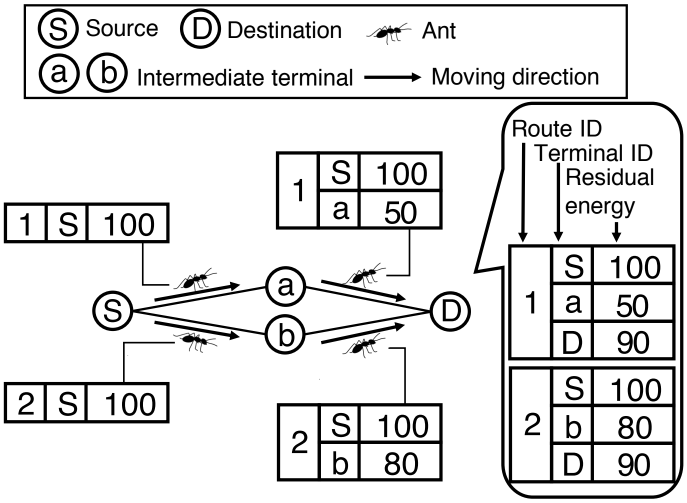

Fig. 2. Forward ant.

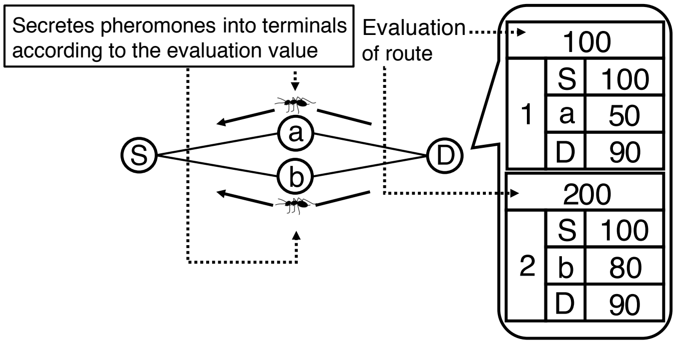

Fig. 3. Backward ant.

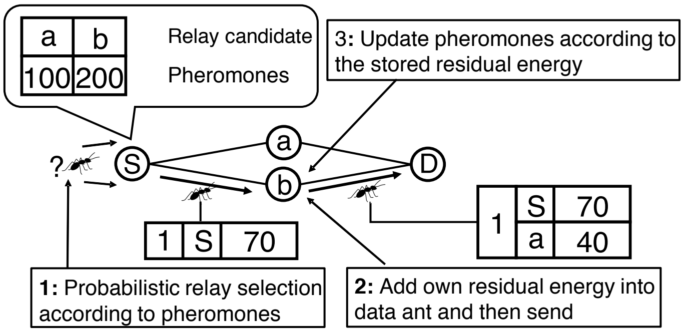

Fig. 4. Data ant.

After the arrival of B-ANTs at the source terminal, it starts forwarding procedure for data encapsulated by D-ANT. Senders of D-ANT, namely source and intermediate terminals, selects the next hop terminal probabilistically according to the pheromone level on the candidate receivers. Once the sender determines the receiver, it records own residual energy to the D-ANT and the D-ANT travels to the receiver. The detailed receiver selection procedure will be explained in III-C. The receiver that the D-ANT reach then updates own pheromones according to the stored information in the D-ANT as the procedure described in III-B. By repeating the above procedure recursively, AERO updates the pheromones on intermediate terminals and the data encapsulated by the D-ANTs will reach the destination terminal.

B. Route Evaluation and Pheromone Update

A pheromone level on each terminals is calculated by two evaluation values that are calculated by a destination terminal with the collected route information and stored terminal information in D-ANT. We would describe the evaluation values as $H_{A,i}$ and $H_{B,i}$ in the following. Note that, the pheromone level in AERO will always be a positive value and AERO assigns the upper and lower limits of the level.

(a) Evaluations on destination terminals

As described in III-A, destination terminals calculate the evaluation values for each route using the information obtained by F-ANTs. In this procedure, AERO first calculates the average residual energy $E_{sd,i}$ of each terminal in route i whose source and destination terminal is s and d by the following Eq.(4).

$$E_{sd,i} = \frac{\sum\limits_{j \in n_{sd,i}} e_{ij}}{|n_{sd,i}|} \tag{4}$$

where e_{ij} represents the residual energy of terminal j on route i, $n_{sd,i}$ represents the set of terminals in route i. Then, the destination terminal calculates the average residual energy of whole routes using the result of Eq.(4) by Eq.(5).

$$E_{sd} = \frac{\sum\limits_{i \in r_{sd}} E_{sd,i}}{|r_{sd}|} \tag{5}$$

where r_{sd} represents the route set obtained by F-ANTs. Follow by the calculations, the destination terminal calculates the evaluation value $H_{A,i}$ using the following Eq.(6).

$$H_{A,i} = (1-\beta)\,\frac{E_{sd,i}}{E_{sd,\max}} + \beta \left(\frac{\sum\limits_{j \in n_{sd}, e_{ij} \leq E_{sd}} (e_{ij} - E_{sd})}{|e_{i,\mathrm{low}}|\, E_{sd}} + 1 \right) \tag{6}$$

where $E_{sd,\max}$ represents the maximum average residual energy in the route set r_{sd}, $e_{i,\mathrm{low}}$ represents the number of terminals in route i whose residual energy is lower than E_{sd}, and β is a constant.

The first member of Eq.(6) gets closer to 1 when the residual energy of terminals composing route i is high. The second member of Eq.(6) gets closer to 1 when the variance of residual energy of terminals in route i is small. The calculated evaluation value $H_{A,i}$ will be stored in B-ANTs and the intermediate terminals that the B-ANTs travels update their pheromones by adding the evaluation value to the current pheromone level.

(b) Pheromone update with data ant

D-ANTs records the residual energy of travelled terminals and intermediate terminals update their pheromones using the evaluation value calculated by the stored information. The evaluation value for D-ANTs $H_{B,j}$ for intermediate terminal j will be calculated by the following Eq.(7).

$$H_{B,j} = \frac{e_j - E_{sj}}{E_{sj}} \tag{7}$$

where E_{sj} represents the average residual energy of intermediate terminals between source terminal s and the terminal j which the D-ANT currently stays. The evaluation value $H_{B,j}$ becomes a positive value when the residual energy of current terminals is larger than the average residual energy, and becomes a negative value when lower. Afterward, the terminal adds $H_{B,j}$ to own pheromone to increase or decrease the pheromone level.

C. Route Selection

The route selection of AERO is done by the probabilistic way based on the pheromone level on each terminal. Each terminal first confirms the set of candidate intermediate terminals for sending data towards the destination terminal before D-ANTs travel to other terminals. If there is only one candidate terminal in the set, the D-ANTs just start their travel towards the terminal. If there are multiple candidates, sender terminal m calculates the probability that the D-ANTs travel towards the next intermediate terminal n using the following Eq.(8).

$$Q_{mn} = \frac{P_n}{\sum\limits_{i \in N_m^d} p_i} \tag{8}$$

where Q_{mn} represents the probability that terminal m selects terminal n as the next hop terminal, P_n represents the pheromone level in terminal n, and N_m^d represents the set of candidate intermediate terminals to F-ANTs towards the destination terminal d from terminal m. By the above probabilistic intermediate terminal selection, AERO assigns a higher priority to the terminal with a larger pheromone level and data encapsulated by D-ANTs travel towards the destination terminal.

IV. PERFORMANCE EVALUATION

A. Simulation Setup

We conducted computer simulations to evaluate the effectiveness of AERO to the conventional routings with the network simulator QualNet [8]. In the simulations, we adopt AODV [9], Optimized LEACH-C [3], and AS [5], [6] as the routing to be compared. In the simulations, we adopt two scenarios to evaluate the performance from the viewpoint of communication qualities and network lifetime. The first scenario evaluates the network performance by changing terminal densities that greatly affect the routing results. The second scenario evaluates the network lifetime by observing the number of active terminals over time. The simulation

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Routing methods	AODV, Optimized LEACH-C, AS
Simulation duration	1,000 seconds
Simulation area	1,000m × 1,000m
The number of terminals	100 – 400
Wireless medium	IEEE 802.11b
Bandwidth	11Mbps
Communication radius	100 m
Terminal Placement	Random
The number of sessions	50 sessions
Source terminals	Randomly chosen
Packet generation interval	100 ms
Packet size	1,000 Bytes
Battery capacity	18,000 mAs
Power consumption for sending	840 mAs
Power Consumption for receiving	800 mAs

detail can be found in the following paragraphs. The common parameters for the simulations are shown in TABLE I.

In the simulations, terminals are randomly placed in the region of 1,000 m square area and communicate each other using IEEE 802.11b with the radius of 150 m at maximum. Source terminals and the number of packets to be transmitted are randomly chosen, and every packet is transmitted every 100 ms with the size of 1,000 Byte. Note that, the average number of transmitted packets throughout the simulations was 23,385 packets. There are two sinks in the simulations and each source terminal sends data towards one or two sinks randomly.

(a) Evaluation for terminal density

In this simulation, we evaluate the impact of terminal density to communication performance by successful delivery rate and end-to-end delay. The successful delivery rate is calculated by dividing the number of received packets by the number of packets generated in terminals. The end-to-end delay indicates the time gap between the initiation time of packet transmission and the time that the destination sink receives the packet.

(b) Evaluation for network lifetime

In this simulation, we evaluate the number of active terminals every 25 seconds to show the efficiency of each routing method. In the evaluation, we defined the active terminal as the terminal with the battery capacity of 40% of the initial capacity. We conducted the simulation with 100 and 200 terminals to evaluate the performance in a tough environment for the routing methods since the available route diversity is limited to a certain degree.

B. Simulation Result

(a) Evaluation for terminal density

Fig.5 and Fig.6 show the results for the communication performances. In the results, we exclude abnormal results caused by unclosed sessions. Moreover, we also exclude the values of top and bottom 5% as the outlier in the calculation of the end-to-end delay.

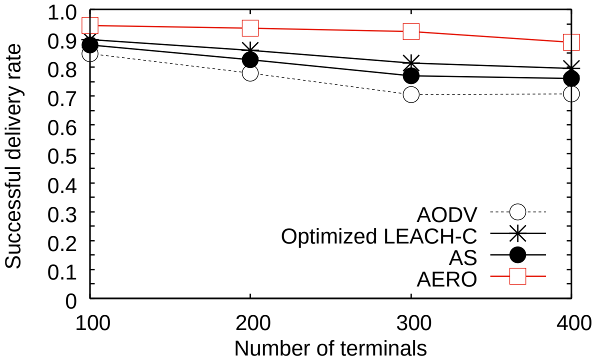

Fig. 5. Successful delivery rate.

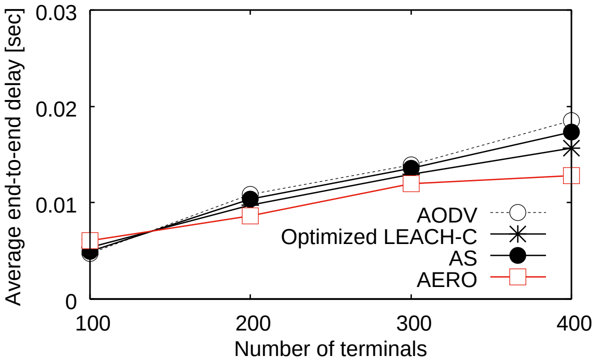

Fig. 6. Average end-to-end delay.

Fig.5 shows the result of successful delivery rate. The result depicts that the proposed method, AERO, could achieve the successful delivery rate of nearly 90% independent from terminal density. This is due mainly to the adaptive and dynamic route management of AERO which effectively suppresses unnecessary route re-establishment by avoiding the leave of terminals caused by the exhaustion of batteries. The conventional AODV decreases its reliability since the routing procedure is basically aimed to establish a single end-to-end route from a source terminal to the destination terminal based on a route length. Moreover, the route length only takes hop counts into a consideration and other metrics such as residual energies and reliability are not the metrics for evaluating route qualities. Thus, the route established by AODV could not achieve better route quality except for the route length. Optimized LEACH-C could achieve better routing performance due to its complex and centralized comprehensive route management since it can comprehend the entire network states and derive entirely optimal solutions. The pure AS could achieved a certain degree of improvement compared with AODV since AS can take other metrics into account as the pheromone level. However, the improvement is limited because the pure AS does not do its optimization once the optimal solutions found and further optimization will be suspended until another route request comes.

Fig.6 shows the result of the end-to-end delay for each routing method. The result shows that each protocol gradually increases the delay as the density increases. The reason for the increase due mainly to the increase of entire traffic in the

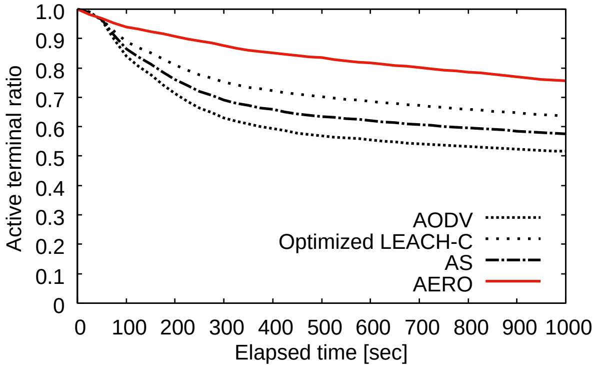

Fig. 7. Active terminal ratio (100 terminals).

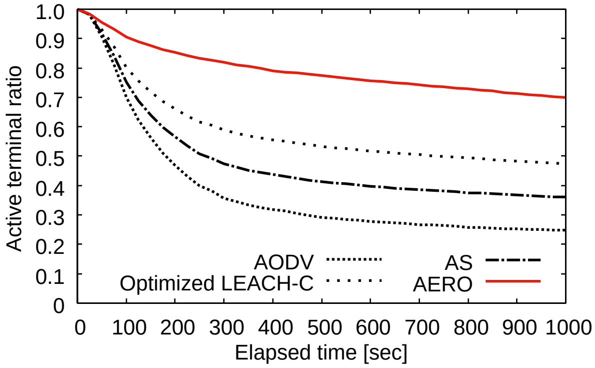

Fig. 8. Active terminal ratio (200 terminals).

networks, which will be a cause of queuing delay increase and interferes transmission of other terminals. Although the delay increase is inevitable for the reason, AERO could suppress the degradation with its adaptive route management and decrease the delay comparing to the other methods. In other words, the probabilistic intermediate terminal selection by D-ANTs could efficiently select the intermediate terminals with less traffic load. On the other hand, the other single route-based routing methods degrade the performance compared with AERO since their routing procedures only show the advantage on the route establishment.

(b) Evaluation for network lifetime

Fig.7 and Fig.8 show the transition of the active terminal ratio versus elapsed time. The result shows that AERO could reasonably reduce the number of inactive terminals compared with the other routing methods. Moreover, the decrease of the number in AERO seems to be linear, whereas the decrease of the other methods seems to be an inverse proportion or exponential. The main reason for the difference can be explained by the routing strategy that AERO takes the principle of dynamic and adaptive intermediate selection, whereas the others take one-time optimization principle in the establishment procedure. Another characteristic trend can be found when the simulation time elapses, that is, the decrease rate of the number in the conventional routing methods becomes gentle. This can be explained by the intermediate terminal selection of the methods since the methods try to utilize the optimal terminals for end-to-end routes and such terminals must transmit more packets than other terminals. Thus, the optimal terminals exhaust their batteries and become inactive sooner than the other non-optimal terminals. After the rapid exhaustion phase, the methods must select the rest of terminals as intermediate terminals and the selection procedure might autonomously balance traffic loads.

Summary of the simulations

Through the simulations conducted above, we confirmed that the proposed AERO can extend the network lifetime with reasonable networks performances. The major contribution of the improvement mainly derived from its adaptive and dynamic route and intermediate terminal selection principle, which utilizes transient state of ant-colony optimization. Moreover, the unique characteristic that AERO secretes pheromones not to links, but to terminals enables the adaptive and dynamic intermediate terminal selection.

V. CONCLUSION

This paper proposed ACO-inspired routing named AERO for WSN to balance traffic loads by utilizing the transient behaviours of the optimization. The performance evaluation reveals that the proposed AERO can achieve improved routing efficiency maintaining routing performances compared with other existing routing methods. In other words, AERO requires less transmission to send the same amount of data and improves energetic efficiency.

Although the improvement by AERO contributes to prolong the lifetime of WSN, there still be a room for improvement since AERO currently does not take into account terminal statuses such as awake and sleep mode. Moreover, refining the calculation procedure of the evaluation values and performance evaluations with realistic models can also be issues to be addressed.

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