AntMQoS: An Ant-based Multi-Constrained QoS Routing Protocol for Wireless Sensor Networks

Dilip Kumar, Tarunpreet Kaur

Abstract—**With the rapid development of microelectronics, wireless sensor networks (WSNs) have started to evolve into various applications that require complex operations, ranging from health care to multimedia transmission. However, successful deployment of resource-limited WSNs in such applications requires strict quality-of-service (QoS) constraints. This paper presents an ant-based multi-constrained QoS routing protocol (AntMQoS) for wireless sensor networks. It is a hierarchical routing protocol which takes independent routing decision to meet the application-specific QoS requirements (latency and reliability) of heterogeneous traffic generated by the source nodes. Simulation results reveal that AntMQoS performs better in terms of reliable data transmission, on-time data delivery, and energy efficiency to maximize the network lifetime..**

Index Terms— **Wireless sensor network (WSN); Quality-of-service (QoS); Ant colony optimization (ACO); End-to-end (E2E) delay; Residual energy; Routing protocol; Packet delivery ratio (PDR)**

I. Introduction

Wireless sensor network is a collection of small autonomous devices called sensor nodes deployed over geographical areas to monitor physical or environmental phenomena such as temperature, pressure, sound, vibrations, motion and seismic events at different locations. The construction of the sensor node mainly focuses on conserving energy, reducing cost and complexity, increasing flexibility, and providing robustness and fault tolerance [1].

The early research on WSN has mainly focused on monitoring applications, such as habitat and environmental monitoring, but with immense proliferation in micro-electromechanical systems (MEMS) along with large acceptance of wireless networking technologies have enabled widespread utilization of WSNs in different environments and for different purposes [2].

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The new applications domains of WSNs have received some denominations in the literature. Sensor networks composed of smart sensor nodes used for transmitting video, audio, still images and scalar data in real-time and non-real-time may be called wireless multimedia sensor networks (WMSNs). Sensor networks deployed inside factories or industries used to monitor or control an industrial process termed as industrial wireless sensor networks (IWSNs). Sensor network composed of biomedical sensor nodes used for fostering health care applications termed as wireless body area networks (WBANs) [3-4]. These application domains generate diverse traffic which requires QoS assurance in terms of delay, reliability, energy efficiency, bandwidth utilization, jitter and throughput [5]. QoS guarantees in WSNs are a difficult and more challenging task to achieve due to the heterogeneous sensor nodes and the various applications domains running over these networks have different constraints in their nature and requirements [6].

Routing protocols have the ability to facilitate application-specific QoS requirements under multiple constraints such as bandwidth, delay, packet loss, hop count, and energy [7]. In multi-constrained QoS routing determining an optimal route that satisfies the multiple constraints has been proven to be NP-complete [8], because the optimization of one metric leads to deprivation of another. So there is need of designing and developing routing protocols which can focus more and more on multiple metrics. An ACO algorithm is essentially a system based on agents which simulate the natural behavior of ants to solve the various optimization problems.

This paper revisits the issue of QoS in WSNs to propose a new multi-constrained routing protocol (AntMQoS) that uses ACO to meet the application-specific QoS requirements of heterogeneous traffic generated by the source nodes. AntMQoS is a hierarchical routing protocol which takes independent routing decision by relying on three QoS metrics associated with the link: residual energy, end-to-end delay and packet loss ratio. It distributes the diverse traffic over multiple paths by estimating the quality of the path in order to reduce congestion and improves the network lifetime.

The rest of the paper is organized as follows: Section 2 presents the related work. The proposed protocol is described in section 3. Section 4 describes the performance analysis of protocol through simulation. Finally, section 6 concludes the paper.

II. Related Work

In recent years, many routing techniques have been proposed for multi-constrained QoS in WSN. Dorigo et al. [9] have adopted the idea and proposed an artificial algorithm based on the behavior of real ants in their colonies. While moving, ants deposit a chemical substance called pheromone, on the paths between the food sources and the nest. Thus, when other ants are searching for food, they can smell the pheromone deposited on their paths and they tend to choose a path marked by strong pheromone concentration. The ACO model was initially used to solve the travelling salesman problem (TSP). Since then, the model has been widely studied and improved.

Camilo et al. [10] proposed an improved version of ant-based routing protocol (EEABR) designed to extend the network lifetime by determining optimal routes in terms of energy consumption and distance. In Yang et al. [11] a multipath routing protocol is proposed, which extends the network lifetime by employing dynamic clustering and ant colony optimization mechanism. Cobo et al. [12] proposed an ant-based routing protocol (AntSensNet) which combines hierarchical structure with ACO-based routing to satisfy the QoS requirements of WMSNs. It utilizes a power efficient multipath video packet scheduling mechanism to reduce distortion in the video packet transmission.

Yu and Luo [13] presented an ant colony optimization based QoS routing algorithm (ACOWMSN) to maximize the network lifetime by utilizing delay, energy, bandwidth, and packet loss rate as QoS constraints to find minimum cost route from the source to the destination. Malik et al. [14] proposed an aco-based QoS-aware routing protocol (EAQHSeN) designed for heterogeneous WSNs to support both multimedia traffic and scalar data. EAQHSeN has the ability to achieve differentiated QoS requirements for control, multimedia, and scalar traffic by making the independent routing decision for each type of traffic.

Based on the above survey, it is observed that there are very few studies that consider the hierarchical structure to provide QoS support to diverse traffic classes generated by the sensor nodes. However, the major issue with flat ant-based routing protocol is scalability. This issue arises since each source node has to send ants to every other node in order to find multiple optimal routes towards the destination. As the number of sensor nodes increases, a number of ants generated by nodes would also increase and leads to congestion. Further, there are few protocols which only consider pheromone concentration for providing service differentiation to diverse traffic classes, which leads to the generation of large pheromone tables. There is a lack of studies which simultaneously consider heuristic factor and pheromone concentration factor to provide QoS support. Moreover, the routing protocols that support multi-constrained QoS are not energy efficient. Since energy efficiency is considered as the major constraint due to resource-limited WSN. Therefore, this protocol addresses these issues by combining hierarchical structure with ACO-based routing to satisfy the application-specific QoS requirements of heterogeneous traffic generated by the sensor nodes, while respecting the minimum energy consumption in order to maximize the network lifetime and scalability.

III. Ant-Based Multi-Constrained QoS Routing Protocol (AntMQoS)

AntMQoS is an ant-based multi-constrained QoS routing protocol designed for heterogeneous wireless sensor networks (HWSNs). It is a reactive routing protocol in which cluster heads (CHs) aggregate the heterogeneous traffic generated by the sensor nodes and takes independent routing decision based on the traffic requirements by determining multiple optimal routes between the CH and the sink node. This section describes the network model and ant-based multi-constrained QoS routing protocol for heterogeneous WSNs.

A. Network model

A WSN can be presented as connected and weighted graph $G = (V, E)$ here $V = \{v_i, v_j, ...v_n\}$ represents the set of nodes i.e. the CHs and the sink node in the network and $E = \{e_{ij}, e_{jk}, ...e_{xy}\}$ represents the set of bi-directional links between the CHs such that the nodes $v_i, v_j \in V$ and $i \neq j$.

Each node v_i in V maintains a pheromone table containing the pheromone value τ_{ij}^{s} of neighbor nodes which is required to reach the sink node s via neighbor v_j and hop count h_s, AntMQoS considers end-to-end delay, packet delivery ratio, and residual energy as QoS metrics for optimal path selection between CHs and the sink node.

B. Queuing model

AntMQoS is a hierarchical routing protocol in which CH organizes the data traffic generated by the sensor nodes into four different traffic classes based on the delay and reliability constraints and maintains the appropriate queue for each traffic class. A priority scheduler organizes the incoming packets according to their classes and priority. CHs distribute the diverse traffic over the multiple paths by estimating the quality of the path in order to reduce congestion and improve the network lifetime.

C. Route Discovery

In AntMQoS, each CH maintains two tables: neighbor table and pheromone table which contains routing information about the neighbors. When the CH wants to communicate to the sink node S, it generates forward ant (FAnt) to search an optimal path for appropriate traffic class of the packet. The CH either broadcasts or unicasts the FAnt based on the routing information stored in neighbor and pheromone table. On its way to the sink node, the FAnt maintains the records of the intermediate nodes. The packet format of FAnt is shown in Fig. 2.

The packet type field indicates that it is a FAnt. The H field indicates the path length. The TTL (time to live) field indicates the number of hops that ant can pass for its CH source. TTL value decreases at each hop and when it

Packet type	H	TTL	Seq No	S_id	D_id	D_{max}	E_{min}	SR_{min}

Fig. 1. Forward ant packet format

becomes 0, the FAnt is discarded. The Sequence number (Seq. No.) is the number of FAnt. S_id indicates the previous node ip address and D_id indicates the next node ip address. D_{max} is the maximum queuing delay, E_{min} is the residual energy of minimum energy node and SR_{min} is the minimum success rate of each traffic class.

When the intermediate node receives the FAnt packet, it updates the S_id, D_id, D_{max}, E_{min}, SR_{min} fields of the FAnt packet. Based on the routing information of QoS requirements of each traffic class, the intermediate node either broadcasts or unicasts the FAnt packet. If the appropriate route towards the sink node is available, then the node makes the probabilistic decision for selecting the next hop node according to the following equation

$$P_{ij}^{k} = \begin{cases} \dfrac{(\tau_{ij}^{k})^{\alpha}(\eta_{ij}^{k})^{\beta}}{\sum_{s\in N_i^d}(\tau_{ij}^{k})(\eta_{ij}^{k})^{\beta}} \end{cases} \quad (1)$$

where P_{ij}^{k} is the probability of selecting the next node j or traffic class k. τ_{ij}^{k} denotes the pheromone value for node j and η_{ij}^{k} denotes the heuristic factor of node j for traffic class k. N_i^d is the set of neighbor nodes of i, α, β are the control parameters for pheromone and heuristic respectively.

The heuristic factor in equation (1) considers three QoS constraints: E2E delay $(E2E\_D_{i,j}^{k})$ residual energy (RE_j^k) and packet loss ratio (PLR_j^k) to select the appropriate next hop node j for particular traffic class. For path $P = (v_a, v_b, ...S)$ from CH v_a to the sink node S its QoS metrics are computed as follows:

1) E2E Delay: The E2E delay associated between two CH nodes can be evaluated from three parameters: the propagation delay d_{prop} which depends on the distance between the nodes, the transmission delay d_{tx} is the time between the first bit sent and last bit received by the destination node and the queuing delay d_{queue} is the amount of the time has to wait in the queue

$$D_{i,j} = d_{prop} + d_{tx} + d_{queue} \quad (2)$$

The E2E delay between node i and j for traffic class k is defined as

$$E2E\_D_{i.j}^{k} = \frac{\sum_{p=1}^{p_x}\Delta t_{i,j}^{p}}{p_x} \quad (3)$$

where p_x is the total number of packets generated by the source node i, $\Delta t_{i,j}^{p}$ is the time of packet p transmitted from node i to j along the route.

2) Residual energy: The residual energy of neighboring nodes of node i influences the chance of sensor node j, $j \in V$ as the next-forwarder node. The total energy consumption of node j is given by

$$E(t) = E_r + E_{cpu} + E_t \quad (4)$$

The residual energy of node j for traffic class k is defined as

$$RE_j^k = E_i - \sum_{p=1}^{p_x} E^p(t) \quad (5)$$

where E_i denotes the initial energy of node j, E_r denotes the energy consumption for receiving data packets, E_t denotes the energy consumption for transmitting packets , E_{cpu} is the energy consumption in computation and sensing, and p_x is the total number of packets transmitted or received by the node j.

3) Packet loss ratio: Packet loss rate can be assessed by the ratio between the numbers of packets lost to the total number of packets transmitted by the source node. A high value can indicate a congestion problem, bad channel quality caused by fading and interference. The packet loss ratio metrics for traffic class k is expressed as follows

$$PLR_j^k = 1 - SR_j^k \quad (6)$$

Based on these QoS metrics, the heuristic factor can be computed as follows

$$\eta_{i,j}^{k} = \frac{(RE_{ij}^{k})^{\beta_1}}{(E2E\_D_{ij}^{k})^{\beta_3}(PLR_{ij}^{k})^{\beta_2}} \quad (7)$$

where β_1, β_2, and β_3 are the constants which indicates the importance of each QoS metrics for the selection of the next hop node. Higher value of β_1 increases the probability of choosing a node with more residual energy from the neighboring node of i. Higher value of β_2 increases the probability of selecting a node with minimum packet loss ratio. β_3 is a parameter that controls the selection of the next-hop node based on their E2E delay.

When the FAnt reaches the sink node, it has the maximum delay associated with route Dmax, the minimum residual energy of the route Emin , and the minimum success rate SRmin supported by route. This information is evaluated by the sink node in order to check the quality of the path for each QoS metrics according to the application requirements. The backward ant (BAnt) is generated corresponding only to the FAnt which meets the application requirements. If the route does not satisfy the application requirements, then the FAnt is discarded.

The BAnt contains the information corresponding to the FAnt and travels along the same path traversed by the FAnt and updates the pheromone value on the intermediate nodes until it reached the sink node. The amount of pheromone on each path is determined by using two pheromone update rules given below.

1) The local pheromone update rule: Local pheromone update is performed by all the ants after each construction step. Every ant applies the pheromone only to the last edge traversed. Moreover, expressions (8) and (9) are used to update the quality of pheromone on the path between node i and j time t.

$$\triangle\tau_{i,j}^{k}(t+1)=(1-\rho)\tau_{i.j}^{k}(t)+\rho\triangle\tau_{i.j}^{k}(t+1) \quad (8)$$

$$\triangle\tau_{i,j}^{k}(t+1)=[N-S_{F}^{m}(t)]^{-1}[h_{count}]^{-1} \quad (9)$$

where ρ refers to the pheromone evaporating rate $(\rho\in(0,1])$, $\tau_{i,j}^{k}$ is the pheromone increment on the path (i,j) for traffic class k in the current round. N is number of sensor nodes with energy greater than the threshold energy, S_{F}^{m} represents the total number of sensor nodes that ant m visited as it traverses from the source node to the destination node at time t. h_{count} represents the number of hops from the sink node. Equation (9) builds a better pheromone distribution near the sink node and will encourage remote CHs to find better path.

2) The global pheromone update rule: The global update rule adds pheromone to the completed path of all paths traversed. The best path traversed indicates the optimal path. The global update rule is determined as follows

$$\triangle\tau_{i,j}^{k}(t+1)=(1-\gamma)\tau_{g}^{k}(t) \quad (10)$$

$$\triangle\tau_{g}^{k}(t)=\alpha_{1}(D)+\alpha_{2}(E)+\alpha_{3}(SR) \quad (11)$$

$$D=\max D_{j}^{k} \quad (12)$$

$$E=\min RE_{j}^{k} \quad (13)$$

$$SR=\min SR_{j}^{k} \quad (14)$$

where γ refers to the pheromone evaporating rate $(p\in(0.1)]$, τ_{g}^{k} is the global pheromone increment on the path (i,j) in the current round. α_1,α_2, and α_3 are the weight factors assigned to the delay, residual energy and success rate, respectively and their values depend upon the QoS requirements.

IV. Performance Analysis

In this section, the performance of the proposed AntMQoS protocol is evaluated and compared against that of AODV and EEABR [14] protocols. The proposed protocol is simulated in NS2 simulator of version 2.35 with the following simulation environment as shown in Table 1.

We report the following performance metrics for evaluating the performance of proposed protocol.

TABLE I
Simulation Environment

Parameter	Value
Network area	200 x 200 m^2
Number of nodes	20 – 160
MAC layer (IEEE standard)	IEEE 802.11
Antenna type	Antenna/OmniAntenna
Physical type	Phy/WirelessPhy
Channel type	Channel/WirelessChannel
Packet size	120 Bytes
Frequency	2.4 GHz
Max communication range	50 m
Energy model	EnergyModel
Data transmission rate	250 kbps
Initial energy	30 J

A. Energy Consumption

The results for energy consumption of proposed protocol is shown in Fig. 2. The results obtained show that proposed AntMQoS protocol has better performance as compared with EEABR, and AODV protocols. This is because AntMQoS reduces the flooding of ants for locating the sink node in the network by adopting the hierarchical structure for data transmission in which traffic is distributed among the CHs without propagating the entire network. Thus a number of control routing overheads are lesser than as compared to EEABR, which consequently reduces the energy consumption of AntMQoS and hence improves the network lifetime.

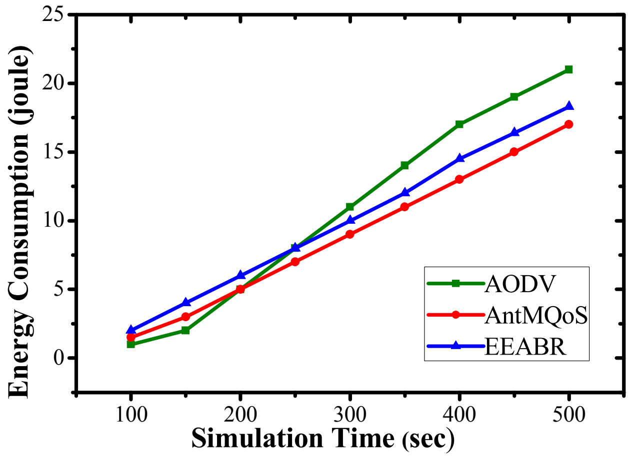

Fig. 2. Energy consumption of AntMQoS, EEABR, and AODV

B. End-to-end Delay

The results for end-to-end delay of proposed protocol are depicted in Fig 3. The results obtained show that the average delay associated with data packets of diverse traffic class in AntMQoS is lower than those of EEABR and AODV. Since it is a multipath routing protocol, it would immediately recover the path failure by forwarding the data packet over another path without introducing any delay. Moreover, the congestion control mechanism at CH in AntMQoS efficiently reduces the queuing delay by releasing less pheromone concentration at congested CH. Thus, multipath routing as well as congestion mechanism of AntMQoS reduces the E2E delay as compared to EEABR and AODV.

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Algorithm of Proposed Protocol
Input:
(1) The neighbor table: A table containing information of neighborhood nodes.
(2) Pheromone table: A table containing pheromone values associated with these neighbors.
Initial pheromone for all nodes = 0
Output:
Update table with all values required to transmit data.
Pheromone values of selected nodes.
Steps:
1. Nodes send data packets to CH
   While CH receives data packets **do**
      Aggregate data packets from all nodes
   End while
2. Source CH node sends FAnts
   If routing information towards the sink node is available
      Unicast FAnt to next CH node according to routing information
   Else
      Broadcast FAnt
   End If
3. Intermediate node receives FAnt
   If routing information is available
      Determine nest hop node with probability P using Eq. 1
   Else
      Broadcast FAnt
   End If
4. FAnt reaches destination
   If D_{max}, E_{min} and SR_{min} meets the application requirements
      Construct BAnt and calculate local and global pheromone contribution to BAnt
   Else
      Discard BAnt
   End If
   While intermediate CH nodes receives BAnt **do**
      Compute local pheromone to be released by BAnt using Eq. 8
      Compute global pheromone to be released by BAnt using Eq. 10
      Save pheromone information and unicast BAnt
   End while
5. When the source CH node receives BAnt
   While data packet **do**
      If data packet = delay intolerant
         Select next hop CH node using Eq. 9 by considering control parameter β_3 only
      Else If data packet = loss intolerant
         Select next hop CH node using Eq. 9 by considering control parameter β_2 only
      Else
         Select next hop CH node using Eq.9 by considering all control parameters β_3, β_2 and β_1
      End If
   End while

C. *Packet Delivery Ratio*

The results for packet delivery ratio (PDR) of AntMQoS protocol is depicted in Fig. 4. The results obtained show that AntMQoS and EEABR exhibit similar increasing trends with minimum delivery ratio during the initial period of simulation. This is because of lack of sufficient information to find the appropriate routes at the beginning and when the ants have gathered much information the algorithm starts converges. Due to hierarchical approach, AntMQoS generates less amount of control traffic and does neither expand energy nor route packets on non-optimal paths. This is the reason that PDR in the case of proposed protocol is better than EEABR and AODV.

V. CONCLUSION

This paper proposes an ant-based multi-constrained QoS routing protocol (AntMQoS) for heterogeneous wireless sensor networks in which traffic is classified based on the delay and reliability constraints. The proposed protocol takes independent routing decision to meet the application-specific QoS requirements of the diverse traffic classes. Moreover, the protocol provides congestion control at cluster head by taking into account the amount of data of each traffic class currently processed by the cluster head and thus reduces the queuing delay of the appropriate traffic class. Simulation results reveal that the proposed protocol performs better in terms of energy efficiency, end-to-end delay, and packet delivery ratio as compared to EEABR and AODV routing protocol.

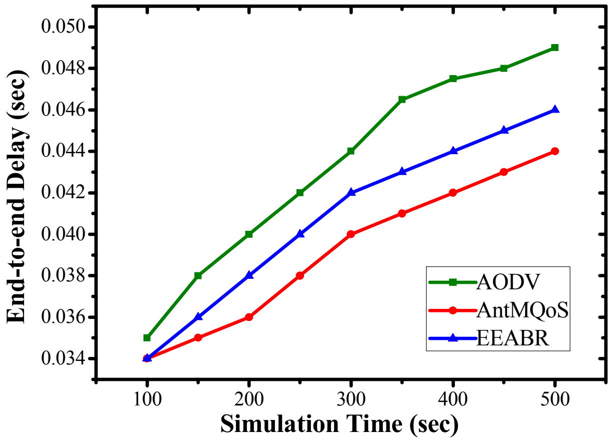

Fig. 3 End-to-end Delay of AntMQoS, EEABR, and AODV

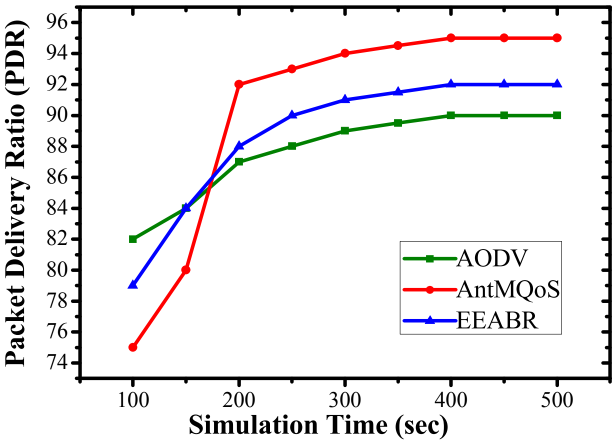

Fig. 4 Packet Delivery Ratio of AntMQoS, EEABR, and AODV

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