An Ant-Based Routing Algorithm to Achieve the Lifetime Bound for Target Tracking Sensor Networks

Peng Zeng and Haibin Yu
Shenyang Institute of Automation Chinese Academy of Sciences
{zp,,yhb}@sia.cn

***Abstract*- We consider the maximum lifetime routing problem for target tracking sensor network. The goal is to find the optimal routing to not only maximize the lifetime of the network but also provide real-time data transmission services. We first propose a novel model to formally define the lifetime of target tracking sensor network by establishing the relationship between individual sensors and the whole sensor network. In this model, we derive the key factor in routing that determines the lifetime bound. Then, considering this factor, we discuss the implementation of an ant-based routing algorithm. Preliminary result demonstrates the appealing performance of our proposed scheme.**

I. Introduction

Target tracking is one of the most important applications of the wireless sensor network, which is delay sensitive and needs the information to be transmitted to a central controller reliably within a certain deadline. However, a wireless sensor network is resource constrained and poses many challenges while designing an efficient routing protocol for deadline-driven traffic. Due to the limited battery power of the sensor nodes, it is extremely important that the routing be energy efficient, which aims at increasing the network lifetime. Besides limited energy, delay in routing is another factor which hinders the goal of transferring time critical information reliably across the network.

To expose what factors have the most impact on longevity of network and consequently how the optimal routing algorithm is designed, mathematical models providing upper bounds on the lifetime of sensor networks have been developed [1], [2]. However, to the best of our knowledge, none of these approaches has explicitly considered the real-time requirements in their models. As a result, most QoS routing algorithms for sensor networks like [3], [4] are designed without knowledge of what factors determine the lifetime of such network for time critical applications.

In this paper, we first propose a novel model to formally define the lifetime of target tracking sensor network that explicitly considers the end-to-end delay constraint, from which we can see the key factors that determine the lifetime. Then, with the reference of this model, we suggest an ant based routing algorithm to achieve the bound.

II. A Mathematical Model Of The Energy Consumption Of Routings

A. Assumptions on the Sensor Network

To model the lifetime of target tracking sensor networks, we make the following assumptions:

1) A static network of N homogeneous sensor nodes and a base station node distributed over a big area R with uniform density ρ .

2) The sensor network works with an event-driven model. The sensor nodes that detect the target send their readings to the base in a multi-hop fashion. Each node generates one data packet per time unit. We call it a round.

3) The target behavior is modeled by a spatial probability distribution function $f(x,y)$. The target is circularly observable with a radius of observation equal to d_s . So, in each round, n_s nodes can detect a target, $n_s = \pi \cdot d_s^2 \cdot \rho$.

4) The delay per hop is the same along a path that packets take through the network (denoted $HopDelay$). So the end-to-end delay constraints (denoted Γ) can be mapped to the bounds on path length as $MaxLen = \frac{\Gamma}{HopDelay}$.

5) Each sensor node has a battery with finite energy E , whereas the base station has an unlimited amount of energy available to it. All nodes transmit at the same constant power. So all nodes have the same radio transmission range h , the same energy consumption r for receiving one packet and the same energy consumption t for transmitting one packet.

B. Modeling Energy Consumption during One Round

For each round t , $1 \le t \le T$, every data source sends a packet of length k to the base station. Formally, a routing is a vector $y = \left(y_i^t\right)_{1\le t\le T}$,where y_i^t represents the total number of packets that are sent by intermediate node i during the t th round. Observe that we can think of the routing y as being a sequence $y = \left(y^1,\ldots,y^T\right)$, where y^t is the routing used during the t th round. The only restriction we place on routings is that they should satisfy the end-to-end delay constraints. So, not all of the intermediate nodes between data sources and the base station are eligible to participate in routing. We call the nodes that can construct a routing shorter than $MaxLen$ the "eligible nodes"

Based on the radio transmission range, we partition the set of all sensor nodes V into subsets $S_0, S_1, \ldots, S_n$, satisfying $V = S_0 \cup S_1 \cup \ldots \cup S_n$, $S_i \cap S_j = \phi$ for all $i \neq j$ and no S_i is empty. S_i is the set of nodes that can be reached from the base station node B in i hops ($S_0 = \{B\}$), but not less than i hops. We call S_i the sphere of radius i around B. $s_i = |S_i|$ is the total number of the sensor nodes in S_i. We further introduce balls of radius i denoted B_i, with $B_i = S_0 \cup \ldots \cup S_i$, and cirques outside B_i denoted O_i, with $O_i = V - B_i$.

For most of recently developed sensors, the transmission range is at least twice the sensing range [5]. So, it is most likely the sensors that detect the target are all located in the same sphere. Further we do not consider data aggregation in our model. This means the sensing data is transmitted unchanged to the base. Below, we analysis the energy consumption of sensor nodes in spheres S_i in three cases:

1) The target has the probability P_{O_i} to be in O_i, $P_{O_i} = \iint_{O_i} f(x,y)dxdy$. When the target is in O_i, the eligible nodes in spheres S_i are responsible for relaying packets from spheres S_{i+1} to the base station. We calculate the energy consumption for the node in S_i in this case as:

$$m_{O_i} = \frac{P_{O_i} \cdot n_s}{n_i} \cdot (r + t) \tag{1}$$

where n_i is the number of eligible nodes of S_i. According to the end-to-end delay constraints, the distance between data sources and the eligible nodes in S_i should be less than $MaxLen - i$. The value of n_i is calculated by statistic method as described in [6].

2) The target has the probability P_{S_i} to be in S_i, $P_{S_i} = \iint_{S_i} f(x,y)dxdy$. When the target is in S_i, sensor nodes that detect the target act as data sources and send packets to S_{i-1}. The energy consumption in this case is,

$$m_{S_i} = \frac{P_{S_i} \cdot n_s}{s_i} \cdot t \tag{2}$$

3) The target has the probability $P_{B_{i-1}}$ to be in B_{i-1}, $P_{B_{i-1}} = \iint_{B_{i-1}} f(x,y)dxdy$. When the target is in B_{i-1}, there is no energy consumption for the nodes in spheres S_i

We integrate the energy consumption of the above three cases, and define the energy consumption model for the node in S_i during one round as,

$$m_i = m_{O_i} + m_{S_i} \tag{3}$$

C. Bounding Network Lifetime

In this paper, lifetime is defined as cumulative time of network working while satisfying the quality of tracking requirement (end-to-end delay constraint). Based on the energy consumption model of each sphere, the lifetime bound is calculated as:

$$LB = \frac{E}{\max\{m_1, m_2, \ldots, m_n\}} \tag{4}$$

where $\max\{m_1, m_2, \ldots m_n\}$ is the most energy consumption of all nodes during one round. We call the sphere with $\max\{m_1, m_2, \ldots m_n\}$ the bottleneck sphere. When all eligible nodes in the bottleneck sphere failed resulted from the deplete of energy, the sensing data outside this sphere will not reach the base on time, which causes quality failure.

D. Discussion

In delay bounded routing, the data delivery capability of an intermediate node is measured by not only the residual energy level but also the distance from the node to the base. In the above model, we classify the nodes in the network by their data delivery capability and bound the network lifetime by the longevity of eligible nodes in bottleneck sphere. The model exposes that the criteria for choosing eligible nodes to participate in routing is decisive in maximizing the lifetime, and the best routing algorithm can do is to balance the traffic evenly between the eligible nodes in the bottleneck sphere. But, none exist QoS routing algorithm has considered this factor and make the traffic planning from the global view. Bellow, we propose an ant-based routing algorithm to achieve this bound. The Ant System - positive feedback, distributed computation, and constructive greediness – has the potential to reach the global or "near-global" optimum.

III. AN ANT-BASED ROUTING ALGORITHM

Informally, our ant-based routing algorithm can be described as follows:

- When a sensor node detects the target, it begins data transmission. A forward ant is launched from this source node toward the base station.
- Each forward ant searches for the destination by selecting the next hop node according to the link probability distribution. Initially all the links have equal probability.
- While moving forward, each forward ant remembers the list of nodes it has visited and tries to avoid traversing the same node.

- Once a forward ant finds the destination, a backward ant is created, which moves back along the links that the forward ant had traversed.

- During the backward travel, the pheromone is distributed to each node in the path.

- In the next data transmission, the link probability distribution of each intermediate node will be updated according to the pheromone.

A. Pheromone Maintenance

The pheromone in this algorithm is used as a way to record the traffic load in each path on global behavior. The pheromone effects make the forward ant avoid to choose the path with heavy traffic load and balance the energy consumption across the whole network.

Initially the pheromone at each node is set to a constant value. During each backward travel, the backward ant is piggybacked with the length of the path in terms of number of hops (denoted by Hop) and the residual energy level of the path (denoted by E_{all}), The pheromone τ_i of each intermediate node i in the path is updated by the backward ant as follow:

$$\tau_i = \tau_i + \frac{E_{all}}{Hop} \tag{5}$$

where E_{all}/Hop is the residual energy unit to reflect the traffic load of the path.

B. Link Probability Distribution Management

At periodic time intervals, each node exchanges beacon message that includes the geographic location and the pheromone at the node with its neighboring nodes and constructs a neighbor table. According to the neighbor table, each node establishes its link probability distribution P as follow:

- n: number of neighbor nodes;
- X_i, Y_i: co-ordinates of the neighbor node i;
- X_2, Y_2: co-ordinates of the destination node;
- D_i: distance from the neighbor node i to the final destination, $D_i = \sqrt{(X_2 - X_i)^2 + (Y_2 - Y_i)^2}$;
- τ_i: pheromone at the neighbor node i;
- α, β: static coefficients;

$$P_i = \frac{(\tau_i)^\alpha / (D_i)^\beta}{\sum_{j=1}^{n} (\tau_i)^\alpha / (D_i)^\beta} \tag{6}$$

IV. Performance Evaluation

According to (1)-(4), LB is determined by the parameters as n_s, n_i, s_i, P_{O_i}, P_{s_i}, in which n_i correlates with hop bound $MaxLen$, network density ρ and radio transmission range h; n_s correlates with network density ρ and sensing range d; s_i correlates with network density ρ and radio transmission range h; P_{O_i}, P_{s_i} correlate with radio transmission range h and spatial probability distribution function $f(x,y)$. In this section, we fix h, d, $f(x,y)$ and vary the value of $MaxLen$ from 4 to 8 hops in increments of 1 hop.

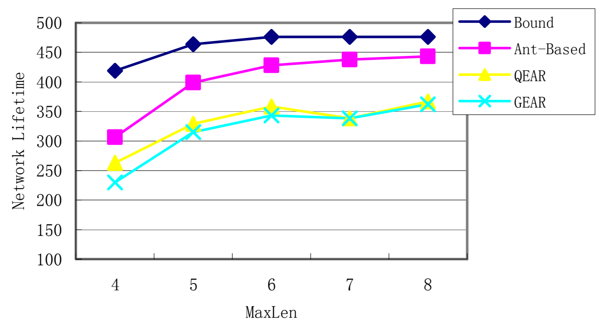

Figure 1: Network lifetime comparison of three algorithms

In Fig. 1 we show the simulation results for a sensor network with 900 nodes uniformly distributed across a 300m*300m plane. The resulting bounds increase with the increases of $MaxLen$, and reach the maximum value at $MaxLen = 6$. As expected, sphere 1 is the bottleneck sphere for all $MaxLen$, for it has the least node number and the heaviest work load. When $MaxLen \geq 6$, All nodes in sphere 1 are eligible nodes. We also compare the network lifetime achieved by our ant-based routing algorithm and two other recently proposed QoS routing algorithms, one is Geographic and Energy Aware Routing (GEAR) [3] which builds routes depending on both geographic and energy factor, the other is the QoS and Energy Aware Routing (QEAR) [4] which is based on GEAR and further balances node energy utilization by adaptively changes the transmission range. We can see the network lifetime in our ant-based routing quickly converges to the bound, which is significant higher than that of GEAR and QEAR.

References

[1] A. Giridhar, P. R. Kumar, Maximizing the Functional Lifetime of Sensor Networks. In Proc. IPSN 2005.

[2] Sha Kewei, Shi Weisong. Modeling the Lifetime of Wireless Sensor Networks. Sensor Letters, 2005, 3(2):126-135.

[3] Yan Yu, Ramesh Govindan, Deborah Estrin. Geographical and Energy Aware Routing: A Recursive Data Dissemination Protocol for Wireless Sensor Networks. UCLA/CSD-TR-01-0023, 2001.

[4] K. Akkaya and M. Younis, Energy-Aware and QoS Routing in Wireless Sensor Networks, in the Springer Cluster Computing Journal, Vol. 8 pp. 179-188, 2005.

[5] H. Zhang and J. C. Hou. Maintaining sensing coverage and connectivity in large sensor networks. In International Workshop on Theoretical and Algorithmic Aspects of Sensor, Ad hoc Wireless and Peer-to-Peer Networks, Feb. 2004

[6] P. Zeng, CZ. Zang, HB. Yu, Bounding the lifetime of Target Tracking Sensor Networks, Technical Report of SIA, 2005.