DELAY-AWARE ROUTING PROTOCOL FOR TIME-CRITICAL WIRELESS SENSOR NETWORKS

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ABSTRACT

In this paper, we propose a distributed traffic-balancing routing protocol for large-scale wireless sensor networks to distribute traffic from sources to sinks effectively by utilizing the number of hops and the current queue size at one- and two-hop next neighbors to make routing decisions. Specifically, each node has a gradient field deciding a neighbor node to reach a sink. The gradient index of each node contains the distance cost from a source to a respective sink and traffic information from neighbor nodes. The presented algorithm considers the traffic of surrounding neighbors before forwarding packets to any sink using gradient search for routing in balance between optimal paths and possible congestion on the routes towards those sinks. This method leads to a trade-off between shortest paths and packet delay which is caused by congestion at overloaded nodes. Simulation results show that the proposed scheme effectively reduces the overall packet delay and improves throughput ratio with heavy traffic.

Keywords: *routing protocols; wireless sensor networks; congestion control; network throughput; packet delay.*

1. INTRODUCTION

In large-scale networks, a large number of nodes become active and transmit data traffic toward sinks. This may cause congestion areas [1], [2]. Congestion increases packet delay and decreases network lifetime due to retransmission. The traditional centralized approach in which data traffic from sensor nodes gathers toward a unique sink [3]–[5] is not efficient in terms of energy consumption or packet delays and even impossible due to limited network capacity. Therefore, the use of multiple sinks is proposed as a feasible scheme for such problems [6]–[9].

In event-driven sensor networks such as detection and monitoring applications, nodes normally operate under low or idle load state, when events occur they suddenly become active and lead a part of the network to overload state causing congestion areas [10], [11]. Many studies have been investigated to solve routing in wireless sensor networks (WSNs) based on gradient search [6], [12]–[14]. A node builds its own gradient field in response to neighbor nodes towards a specific sink. Data traffic then flows along a direction with the steepest gradient to reach a sink. The cost model can take in terms of hop count from a sink to node, physical distance, energy consumption or cumulative delay depending on objectives of routing such as network lifetime, packet delay or throughput [6].

Based on the observation about gradient search schemes, this study proposes a traffic-balancing routing algorithm for large-scale WSNs to route packets around congestion areas made by other paths towards sinks. The main concept of our algorithm is to construct a gradient field using three factors: number of hops, number of packets at one-hop neighbor and the minimum number of packets at two-hop neighbor corresponding to a previous node. The number of hops (distance cost) is normally built as in gradient-based routing protocols which find the shortest paths for packets. The second and third factors address the queue length at neighbor nodes that may become the next forwarder. Once the queue length, changing with network traffic, exceeds a threshold, it means congestion at a node towards a specific sink. One node asks surrounding nodes to increase (decrease) its gradient field so that packets could flow along other paths. This method leads to a trade-off between shortest paths and packet delay which is caused by congestion at overloaded nodes.

The rest of this paper is organized as follows. In Section II, we build the system model in which the total gradient field is built and how to combine the local and global cost model in our proposed scheme. In Section III, we describe the implementation of the proposed algorithm. Simulation results and performance evaluation are presented in Section IV. We conclude the paper in Section V.

2. SYSTEM MODEL

2.1 Distance Cost Model

A node defines a scalar field, called the node’s height [15] by advertising packets. This is a common method to provide the basic routing function in several routing algorithms, referring to the well-known SPF algorithm (Shortest Path First) [16]. A packet is forwarded on the link with the steepest gradient to the next node. Each node x maintains distance cost with respect to each sink i^*(in a multi-sink scenario),

$$\nabla_i^d(x) = hop\_count_i. \qquad (1)$$

With hop count, each node discovers a list of parents, siblings and children in respect to a sink from neighbors, whose hop count is respectively lower, equal and one unit bigger on the path toward a specific sink. A node maintains a table with those relative nodes for each sink. In light traffic, a node should choose routes with the lowest distance to sink in order to ensure energy consumption and end-to-end delay. However, since a large number of nodes become active and send data to sinks simultaneously, this causes congestion areas leading to packet delays or loss.

2.2 Queue Length Field

This paper considers collision areas on the way of buffer monitoring. A node s sends a packet to another sensor x (neighbor of s) only when x has enough buffer space to store the packet from s. The proposed idea avoids packets dropped at the receiver due to buffer overflow. The value of buffer length field at a node is the average queue length by samples over a small time interval Δt_q to ensure for the stability of routing metric. An advertising packet (ADV) is generated after a minimum update time to inform neighbor nodes about congestion. A node can detect congestion areas in 2-hop away by routing technique using 2-hop information.

The function Q(x) denotes the normalized buffer length at node x as defined by Eq. (2)

$$Q(x)=\frac{(\text{Number of packets in the buffer})}{(\text{Buffer capacity})}. \qquad (2)$$

The value of Q(x) is in the range of [0,1] which denotes traffic information. Buffer-based method is to indicate possible congestion at the destination node [10].

2.3 Traffic-balancing Routing Cost Model

In this approach, a node chooses one of its neighbor nodes to become the next forwarder considering buffer size at 1-hop neighbor (x) and the next 1-hop neighbor of x with minimum buffer size $(x*)$. This means that a node takes into account on both 1-hop neighbor and 2-hop neighbor which can become the next possible forwarder after x.

In several previous studies, the authors use 1-hop information into the cost model to find the next forwarder [9], [13]. However, the limited local information packets cannot avoid the heavy congested region. Otherwise, a node exploits information to several hops away; it then obtains a greater knowledge for spreading traffic to a broad region. However, this approach takes a significant amount of overhead. Thus, a node needs a balance between locality while network still gets information to send packets over the least congested areas. By taking two-hop information into account, packets are spread to directions to avoid heavily congested areas while the increasing overhead is not significant.

Once a node has a packet (s) to send towards a sink, it calculates and compares the gradient field for each of its neighbors $x\ (x \in nbr(s))$ in response to each sink i following Eq. (3)

$$\nabla_i(s,x) = (1-\alpha)\nabla_i^d(x) + \alpha\nabla_i^c(x) + \beta\nabla_i^c(x^*) \quad (3)$$

where α, β are the weighted factors of traffic costs and $\nabla_i^d(x)$ is the gradient field with the number of hops. $\nabla_i^c(x)$ and $\nabla_i^c(x*)$ denote traffic cost at 1-hop and 2-hop neighbor, respectively. We choose the buffer size at the next neighbors as the possible packet delay of node x to forward a packet of node s toward a sink i.

Our scheme regards to α as a primary factor which significantly affects the routing decision. Then, β is used to evaluate the traffic condition at 2-hop neighbor which can potentially impact on the network performance if the respective previous neighbor is chosen. The following theorem presents the boundary of α and β. It considers the shortest path neighbors as backbone routes to define the limitation for those factors. Each node dynamically calculates a gradient value following Eq. (3) with respect to each neighbor based on the traffic condition at the node with the shortest distance to sink (parents $-p \in nbr(s)$) and other neighbors (siblings $-m \in nbr(s)$, children $-l \in nbr(s)$).

Theorem 1. A node with distance $\nabla_i^d(s) = d$from a specific sink will forward packets to its siblings $\nabla_i^d(m) = d$ instead of parents $\nabla_i^d(p) = d - 1$ based on shortest path routing if the weighted factor α that satisfies

$$\alpha \geq \frac{1}{1 + Q(p) - Q(m) + \frac{\beta}{\alpha}[Q(p^*) - Q(m^*)]}. \quad (4)$$

Proof: Consider a node with distanced hops from a specific sink and its neighbor nodes, the gradient fields at the node s in response to each of the siblings (m) and parents (p) are

$$\nabla_i(s,m) = (1-\alpha)d + \alpha Q(m) + \beta Q(m^*), \quad (5)$$

$$\nabla_i(s,p) = (1-\alpha)(d-1) + \alpha Q(p) + \beta Q(p^*) \quad (6)$$

In order to select one neighbor node on a suboptimal path to become a next forwarder, a node must satisfy the following condition:

$$\nabla_i(s,m) < \nabla_i(s,p) \quad (7)$$

by substituting Eq. (5) and Eq. (6) into Eq. (7), we obtain

$$\alpha \geq \frac{1}{1 + Q(p) - Q(m) + \frac{\beta}{\alpha}[Q(p^*) - Q(m^*)]}. \quad (8)$$

A packet should flow onto longer paths to avoid the congested area or overloaded nodes. By observing from Eq. (8), we see that the weighted factor α dynamically depends on the difference in traffic load ΔQ and $\Delta Q*$ (given $\Delta Q, \Delta Q* \in [0:1]$) between a sibling and a node lying on the shortest path to the sink, where

$$\Delta Q = Q(p) - Q(m),\ \Delta Q^* = Q(p^*) - Q(m^*). \quad (9)$$

For the simple case, we assign $\beta = 0.3\alpha$, it means that the proposed algorithm considers 1-hop traffic information as a more important parameter. Eq. (8) becomes

$$\alpha \geq \frac{1}{1 + \Delta Q + 0.3(\Delta Q^*)} \quad (10)$$

Generally, we choose the minimum value of α, then

$$\alpha = \frac{1}{1 + \Delta Q + 0.3(\Delta Q^*)}. \quad (11)$$

3. BUILDING THE ROUTING ALGORITHM

3.1 Distributing of Traffic Information

Traffic information is interchanged between sensor nodes through advertising packets. Each node including sinks periodically broadcasts an ADV packet to all neighbors after a predefined period of time. This time is set in a trade-off between the effects of updated information and network resource. Assume that all sensor nodes have the same queue capacity. Each ADV packet contains the hop count to reach a specific sink and the queue length field which is constructed in the previous section.

At first, each node builds by itself the distance and traffic cost fields, respectively on the gradient table G for all neighbors in response to sinks, initializing all fields to infinite. Since an ADV packet arrives, a node checks if the sink and source address have occurred in table G or not. At the first time, the table is null, the node will add these addresses and consider them as parent following that sink address. Conversely, it uses distance cost to classify source nodes into lists of parents, siblings or children corresponding to a specific sink. In addition, queue length field from ADV packet is updated into traffic cost fields on G with each neighbor. The node then employs new updated information to broadcast for its neighbors through ADV packets in period of time to update.

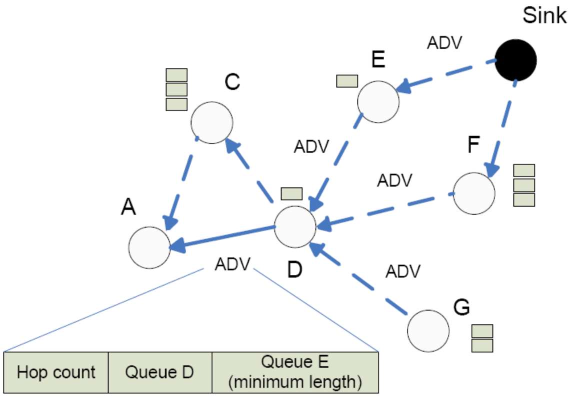


Fig. 1. Illustration of updating ADV packet.

3.2 Data Forwarding

After executing Algorithm 1 to process ADV packets, each node has information about its neighbor including distance cost to a specific sink and information about queue length as well. The node firstly checks the table of surrounding nodes, and calculates gradient fields in response to each of neighbors (except for the children and the node forwarding the packet for current node) using Eq. 3. It needs to note that the neighbor nodes with full buffer length will be removed from competition to become the next forwarder in order to reduce packet drop ratio.

The node then forwards packets toward the neighbor with the smallest value of $\nabla_i(s,x)$. In special cases, if there are more than one node with the same minimum gradient value, the next forwarder is chosen from a random trial.

4. SIMULATION AND EVALUATION

4.1 Simulation Setup

In this simulation, we build a random topology in a $200m$x$200m$ area with 250 homogeneous sensor nodes and 4 sinks placed inside the grid, where the radio transmission range is up to $15m$ with consideration an effective coverage area for sensor nodes. The IEEE 802.15.4 standard is used as the MAC and physical layer. Where the radio frequency is set to worldwide bands 2450 MHz and radio data rate is set at 250 kbps.

Algorithm 1: Updating gradient table G with each of sinks

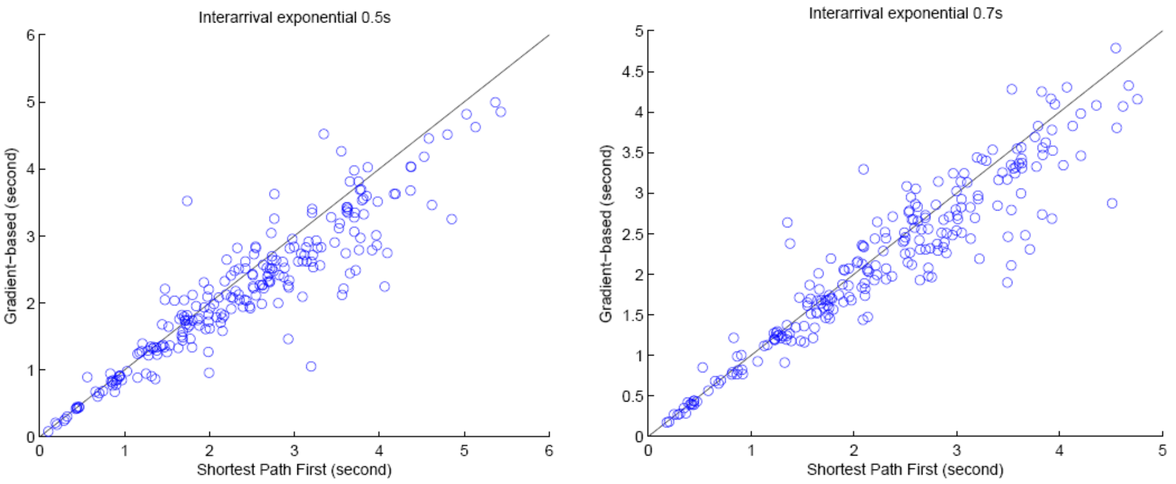
```
Hop-Count = $\nabla_i^d(x)$;
1-hop Traffic-Info = $\nabla_i^c(x)$;
2-hop Traffic-Info = $\nabla_i^c(x*)$;
if ($G = \oslash$) then
    Add new neighbor as Parent to table $G$ including
    Hop-Count, 1 & 2-hop Traffic-Info;
else
    if Hop-Count < value on the table G then
        Set Node Height is Hop-Count and the neighbor
        to be a Parent;
    end
    else if Hop-Count = value on the table G then
        Keep current Node Height and the neighbor to be
        a Sibling;
    end
    else
        Keep current Node Height and the neighbor to be
        a Child ;

    Update table $G$ with new value $\nabla_i^c(x), \nabla_i^c(x*)$;
end
Update new minimum Hop-Count and Traffic Info for
sending ADV packet;
```

Each node maintains traffic information at its neighbors by advertising packets periodically and relies on data forwarding procedure to forward packets over optimal paths toward one of the sinks. The application layer creates advertising packets with a length of 6 bytes and the data packet is set to 30 bytes. As regarded, the threshold ΔQ allows a sibling node to join into the competition as a candidate for next forwarder. The different queue length threshold between the parents and siblings at 1&2 hop neighbors is chosen with $\Delta Q = 0.4$ and $\Delta Q * = 0.1$. The weighted factors thus will be $\alpha = 0.7$ and $\beta = 0.2$.

4.2 Numerical Results

Simulation results obtained from the proposed scheme are compared with the SPF routing algorithm to show improvement in overall packet delay with much various traffic rates.

1) *Poisson Distribution Traffic:* In this scenario, traffic is generated following the exponential distribution with mean outcome is set to $\alpha = 0.5s, 0.7s$ to show the various interarrival time for packets based on the Poisson distribution. This traffic generation model is more similar to traffic of real applications such as packet data networks. At a higher data rate, the number of an incoming packet at a node increases, leading to higher buffer length and therefore increasing the end-to-end packet delay for packets (Fig. 2). We observe that the proposed scheme outperforms SPF significantly as the sending rate increases because the gradient-based routing attempts to prevent forwarding packets from next neighbors with a high number of packets in buffer and balance network traffic as much as possible.



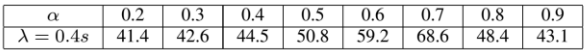
(a) Interarrival $\lambda = 0.5s$.

(b) Interarrival $\lambda = 0.7s$.

Fig. 2. *Averaged end to end delay in case of incoming traffic with exponential distribution* $\lambda = 0.5s, 0.7s$ *with 250 scatter plots for 250 sensor nodes. With higher load, gradient-based routing significantly obtains improvement in comparing to SPF.*

2) *Effect of weighted factors on network performance:* Firstly, the influence of α is presented in Table I under traffic sending rate $\lambda = 0.4s$ through a range of α. The $(\nabla Q *) / \nabla Q$ ratio is still 0.25. In case of SPF, α is 0 (40.9%). With a too large α, it means that incoming packet will prevent from the shortest path even though the current buffer at parent node is still small (0.1-0.2). This increases the end to end packet delay without improvement of traffic throughput. On the other hand, a too small α, it is difficult to obtain a high buffer threshold at the parent node. Therefore, the proposed scheme does not perform significantly more than SPF.

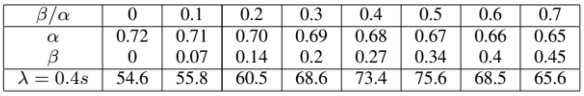
TABLE I
THROUGHPUT RATIO WITH VARIOUS VALUES OF α (%)



α	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$\lambda = 0.4s$	41.4	42.6	44.5	50.8	59.2	68.6	48.4	43.1

Secondly, we evaluate the impact of β on the network performance, which is shown in Table II. The traffic rate at each source is $\lambda = 0.4s$ as in previous cases. However, ∇Q and $\nabla *$ are assigned to 0.4 and 0.1, respectively, and the ratio between α, β is modified to examine the effects of the second traffic factor in the proposed routing scheme. Since network traffic is low, the packet loss rate is small. It increases with increasing the traffic load. Choosing a large β/α ratio, which $\beta$is nearly equal or greater than α is makes the routing scheme become inefficient because of the current traffic state at next neighbor (1-hop) reduces the effects on overall network performance.

TABLE II
THROUGHPUT RATIO WITH VARIOUS VALUES OF β (%)



β/α	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
α β	0.72 0	0.71 0.07	0.70 0.14	0.69 0.2	0.68 0.27	0.67 0.34	0.66 0.4	0.65 0.45
$\lambda = 0.4s$	54.6	55.8	60.5	68.6	73.4	75.6	68.5	65.6

5. CONCLUSIONS

In this paper, we present a routing protocol based on gradient search to improve overall packet delay in large-scale wireless sensor networks. The key concept is to utilize the number of hops and the current queue size at one- and two-hop next neighbors to make routing decisions. Simulation results show improvement in end-to-end packet delay in comparison with SPF scheme. In addition, the proposed algorithm reduces the number of packet retransmissions and packet drops by preventing nodes with the overloaded buffer joining into routing calculation.

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