Hop-by-hop traffic-aware routing to congestion control in wireless sensor networks

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Abstract

One of the major challenges in wireless sensor networks (WSNs) research is to prevent traffic congestion without compromising with the energy of the sensor nodes. Network congestion leads to packet loss, throughput impairment, and energy waste. To address this issue in this paper, a distributed traffic-aware routing scheme with a capacity of adjusting the data transmission rate of nodes is proposed for multi-sink wireless sensor networks that effectively distribute traffic from the source to sink nodes. Our algorithm is designed through constructing a hybrid virtual gradient field using depth and normalized traffic loading to routing and providing a balance between optimal paths and possible congestion on routes toward those sinks. The simulation results indicate that the proposed solution can improve the utilization of network resources, reduce unnecessary packet retransmission, and significantly improve the performance of WSNs.

1. Introduction

Wireless sensor network (WSN) refers to a group of spatially dispersed and dedicated sensors for monitoring and recording the physical conditions of the environment and organizing the collected data at a central location. Example applications: environment monitoring, agricultural scenarios.

When large numbers of nodes become active and transmit data traffic, it leads to congestion. Congestion affects performance, throughput, packet retransmission and energy. In traditional centralized approach, data traffic from sensor nodes accumulates near one sink. This leads to ineffective energy consumption and packet delays. Usage of multiple sinks[1,2] is a solution. The key concept of proposed algorithm is to construct two independent gradient fields using depth and traffic loading, respectively. The depth is built using path finding algorithms.
The second factor addresses the traffic loading of neighbouring nodes that may become the next forwarder. Once the traffic loading exceeds a threshold, it means that there is congestion at a node in the path toward a specific sink; the packets would flow along other suboptimal paths.
Hybridising these gradients allows for dynamic routing. In other words, this method leads to a trade-off between the shortest paths and traffic at overloaded node.

2. Related works

Limited bandwidth causes frequent congestion in WSNs. Some of the studies which were meant to solve this issue have been discussed here.
Congestion detection and avoidance (CODA)[3]: CODA includes three elements – congestion detection based on receiving, open loop hop-by-hop back pressure, and closed loop multi-source rate adjustment. CODA controls the rate of flow of packets based on the additive-increase/ multiplicative-decrease (AIMD) algorithm. This technique is energy-efficient, but unreliable for accurate deliveries.

The event-to-sink reliable transport (ESRT) [4] protocol improved the reliability of event data transmission in wireless sensor networks. In this method, all sensor nodes monitor their internal buffers to find traffic congestion. The sink node periodically configures the source sending rate with broadcasts the congestion state to all sensor nodes.

Interference-aware fair rate control (IFRC) uses static queue thresholds to determine congestion level and operates congestion control by adjusting outgoing rates on each link based on AIMD scheme. It employs a tree rooted at each sink to route all data.

SPEED manages congestion by rerouting the incoming traffic around the hot spot. Another scheme is proposed to split the traffic from the source into multiple paths to achieve load balance and increase throughput.
To avoid additional costs of multi-path routing when the network is not congested, biased geographical routing (BGR) protocol is presented to reactively split traffic, when congestion is detected.
In gradient search, a node builds its own gradient field in response to neighbour nodes in the direction of a specific sink. Data traffic flows along the direction with the steepest gradient in order to reach the sink.
SGF is a gradient-based routing protocol to reach significant energy savings. The authors suggest a new gradient field for nodes without using routing tables. The values are updated on demand by data transmission with little overhead.

In addition to energy-aware, traffic control is also an important issue in WSNs. It means that the routing algorithm finds optimal routes by balancing congested areas and the shortest path. It is proved that this algorithm obtains significant improvement in end-to-end delay and jitter over any kinds of networks and traffic conditions with a few overheads.

Gradient based traffic-aware (GRATA) [5] routing utilizes the expected packet delay at one-hop neighbour and the number of hops to make routing decisions.

Contributions in this paper are as follows:

- Leading to multi-sink WSN applications with heavy traffic scenarios, in which a large amount of traffic may cause black spot on the paths to the sink.
- Using the number of hops from the local node to the sink, while current traffic information contains the queue length, the congestion degree and the average cumulative queue length construct the gradient field at each node.

- Adjusting the congestion window and data transmission rate of sender nodes in order to improve overall throughput.

3. Method

Location and position of congestion	At the sensor nodes
Congestion Detection method	Gradient based model using depth and traffic loading
Congestion Notification method	Information in header hence implicit
Congestion Control method	Adjustment of rate of transmission, Congestion window control
Application Type Considered	Continuous
Control Pattern	Hop-by-Hop
Node Distribution	Random
Sink Location	Static; Multiple sinks
Homogeneous/Heterogeneous WSN	Homogenous
Loss Recovery	Yes
Priority	Yes
MAC	802.15.4 standard
Evaluation Type	NS2 simulator
Evaluation Parameters	Packet loss ratio, energy consumption, effect of weighted factors, data transmission rate
Data flow in WSN	Event driven
Generic/Cross Layer	Generic
Compared with	SPF, CODA, ESRT, GRATA
Features	Dynamic traffic aware routing
Classification Approach	Yes
Advantages	Explained below
Limitations	

Congestion Detection Method

In this section, we will be looking at the making of gradient-based routing model and traffic based routing model, and also integrating them together to make a dynamic routing decision taking model. We first describe the depth field for a gradient field, this is based on the shortest cost model. To reflect the traffic information in each of the neighbouring nodes we add an additional field into the gradient field. A node informs its neighbours about the distance cost from itself to sink and the possible congestion by monitoring the number of packets, the congestion degree and the average cumulative queue length.

Depth field:

To make each packet flow towards the sink we define the routing function Vid(v) as :

Vid(v) = Depth(v)

where depth(v) is the depth of node v with respect to the sink i. Depth(v) will become the length if the algorithm chooses the hop count as its routing metric .Depth(v) has some special properties due to the decentralized traffic pattern of wireless sensor networks. The depth difference between node v and its neighbouring nodes can only be -1,1,0 since the neighbouring node is described to be one hop away. Because of this decentralized property the depth field encourages the packet to flow directly to sink node through the shortest path.

The following theorem will show that the shortest path paradigm is loop-free.

Theorem: If field Vd (v1) is independent of time, shortest path routing is loop free.
Proof: This theorem is proved by contradiction. Assume that the field Vd (v1) monotonically decreases from source to sink and the steepest gradient searches for a neighbor with lowest gradient index. If there is a loop, then packets go in a circle of v1 → v2 → … → vn → v1. However, this closed loop cannot work, due to not meeting the condition Vd (v1) < Vd (v1), because the number of hops from a node to sinks is unchanged or time-invariant.

If there are more than one neighbouring node with the same gradient values then the node chooses the next forwarder in a random stochastic process.

Traffic loading potential field: The traffic factor is now taken into the gradient field after the depth field has been taken. It consists of two types of information one is the hop count and the other is the traffic loading. The traffic factor is expected to provide better routes and hence to improve the throughput in wireless sensor networks.
Normalized buffer size field, congestion degree and average cumulative queue length are defined to extract the loading of traffic in each node.

(i)Normalized buffer size field:

The node v sends a packet to node x only when node x has enough buffer size to store the packet sent by node v .That is why packets will not be dropped at the receiver as a result of buffer overflow. The queue length field at node v is defined as $V_q(v)=Q(v)$. The normalized buffer size at node v is defined by the function Q(v) as

Q(v)=(Number of packets in the queue buffer)/(Buffer size at node v)

Q(v) has value between [0,1], basing on this information the node will be forwarded towards the unloaded area.

(ii)Congestion degree: The node chooses its neighbouring node by looking at the queue length field, the one with the shortest queue length will be chosen as the next node. Most of the times congestion occurs because of the burst traffic, if the burst occurs at node v then it may have low queue length but it cannot be chosen as the next destination as many packets will enter node v because of the buffer around node v and hence the low queue length cannot distinguish this problem. So, the congestion degree field is being defined so that the problem can be resolved.

Congestion degree is used to indicate the changing tendency of a buffer queue over a period of time. Function $V_c(v)$ is used to denote the normalized congestion degree at node v as

$$V_c(v)=(T_s/T_a)$$

where Ta is the time interval between arrival of the two adjacent data packets at MAC layer and T_s is the average processing time of data packets at local node. If $V_c(v)>1$ then it's an indication that congestion may possibly happen at this node in the near future and hence it's not a proper choice .

(iii)Average cumulative queue length: This field shows the landscape of congestion towards the sink. Awareness packet (AP) is used by each node to attach its buffer size and broadcasts it in order to update its neighbouring routing tables. The receiving node compares the APs received from all the nodes and selects the one with lowest potential field and then calculates the average cumulative queue length towards the sink using the equation mentioned below

$$V^i_a(v)= \sum_0^n(Q(v))/(n)$$

where $\sum_0^n Q(v)$ is the cumulative queue length from node v in the direction to sink i, and n is the number of hops in the best path to reach sink i. The traffic loading gradient field at node v is expressed as:

$$V_T^i(v)= \alpha_1 Vq(v)+ \alpha_2 Vc(v)+ \alpha_3 V_a^i(a)$$

where α_1, α_2, α_3 are 3 are the weighted factors and independently control the degree of influence of three fields on routing decision ($\alpha_1+\alpha_2+\alpha_3=1$). Vq(v) denotes the normalized queue length at node v, Vc(v) represents the congestion degree at node v, and $V_a^i(a)$ is the average cumulative queue length in response to sink i at node v.

Congestion Control Method

Traffic-balancing routing cost model: When a node has a packet to send to its adjacent nodes, it calculates the gradient field of its neighbours using the following equation:

$$V^i(v)=V_d^i(v)+ \beta V_T^i(v)$$

Where β is the weighted factor of the traffic cost and $V_d^i(v)$ is the depth gradient field with hop number in response to sink i .The traffic loading factor $V_T^i(v)$ is defined as

$$V_T^i(v)=\{ V_T^i(v)/1\} \text{ if } \{V_T^i(v)<1/\text{otherwise}\}$$

The value of β indicates the weight of the traffic loading factor and it also indicates when the traffic-aware method starts to drive the packet out of the congested areas and scatter them in the unloaded areas. The theorem below defines the boundary of β .

Theorem : When β is chosen to satisfy: $\beta < \min\{ \Delta V_d^n(2)\}$ then the new gradient field Vi (n) at node n does not bring a packet backward to neighbour n + 2 from an interesting sink. Here, $\Delta V_d^n(2) =|V_d(n+2)-V_d(n)|$ is the difference between node n and its two-hop neighbours in hop number (distance).

Proof: Assume that the field Vd(.) monotonically decreases from source to sink. A similar argument could be used for a monotonically increasing field Vd(.). From the above equation, we know that $|V^i_d(n+2)-V^i_d(n)| > \beta$. The method of choosing $V_T^i(.) \in [0,1]$ yields in $\beta > \beta$ (

$V_T^i(n)$- $V_T^i(n+2)$) .Combining above two inequalities one obtains: $V^i_d(n+2)+\beta V_T^i(n+2)>V^i_d(n)+\beta V_T^i(n)$ or $V^i(n+2)>V^i(n)$.

The lower bound of β is decided by the theorem given below.

Theorem: The traffic cost takes effect on the total gradient V^i only when: $\Delta V^i_n(1)\leq\beta$. Here, $V_d^n(1) =|V_d(n+1)-V_d(n)|$. Similar to Theorem 2, this equation denotes the difference of hop numbers between node n and its one-hop neighbours.
Proof: The theorem is proven by contradiction with a monotonically decreasing function Vd(.). A similar argument could be used for a monotonically increasing field Vd(.). Assume that there is a point where $\Delta V^i_n(1) > \beta$. With the same argument as in previous Theorem, we have Vi (n + 1) > Vi (n). That means that routes with new Vd(.) behave like those of Vd(.), and the adding traffic factor has no impact at this point. Therefore, the total gradient value is affected by the traffic cost only when the equation in the theorem obtains.

Congestion window control: The traffic in WSNs has a centrality nature, because of which bypassing the intermediate local hotspots is tough because the hotspots would again appear at the sink if the scattered packets approach the sink from different directions. To avoid this problem a solution has been proposed which is hop-by-hop congestion control scheme, which controls the congestion by adjusting the data transmission rate and channel access priority and by sharing the MAC layer channel info of the downstream node with the transport layer of upstream node.

The network communication performance metrics such as energy saving, transmission fairness, and network throughput could be affected because of the rate adjusting strategy. After receiving the AP signals from the downstream node, the upstream node should consider its own congestion condition and adjust the size of the local channel and data transmission.

Algorithm: data transmission rate & channel congestion window size
Input: Local buffer occupancy ratio (Br), upstream nodes' buffer occupancy ratio attached in AP signal (B′ r), the congestion degree of the current node (Cd), the congestion degree of upstream node attached in AP signal (C′ d), ϕ is the adjustable factor that can control the degree of influence of two fields on data transmission rate.
Result: data transmission changing rate (ΔR), data transmission rate (R)
- Initialize node information;
- Compare (Br with B′ r) and (Cd with C′ d)

- **Case1**: if (Br >B′ r && Cd> C′ d) then ΔR = ϕ (Br -B′ r) + (1-ϕ) (Cd - C′ d), R=R+ ΔR;

//ΔR will be a positive value

- **Case2**: if (Br >B′ r && Cd< C′ d) then ΔR = ϕ (Br -B′ r) + (1-ϕ) (Cd - C′ d), R=R+ ΔR;
// ΔR value will be a trade-off between buffer occupancy ratio and congestion degree

- **Case3**: If (Br <B′ r && Cd< C′ d) then ΔR = ϕ (Br -B′ r) + (1-ϕ) (Cd- C′ d), R=R+ ΔR;
// ΔR will be a negative value

- **Case4**: if (Br <B′ r && Cd> C′ d) then ΔR = ϕ (Br -B′ r) + (1-ϕ) (Cd - C′ d), R=R+ ΔR;

// ∆R value will be a trade-off between buffer occupancy ratio and congestion degree

where R is the local node's data transmission rate. Rmax is the maximum data transmission rate of local node during the period of time from the moment it responds to congestion feedback signal to present and ∆R is the data transmission changing rate that is determined with buffer occupancy ratio and congestion degree value. And Br be the buffer occupancy ratio of the current node and B'r be the buffer occupancy ratio of upstream node, which can be attached to AP signal.

Performance evaluation and comparison with other methods

Performance of the proposed scheme is assessed with 4 other congestion control schemes, SPF(Shortest Path First), CODA[10], ESRT[11] and GRATA with respect to the following factors:

i) Packet Loss Ratio

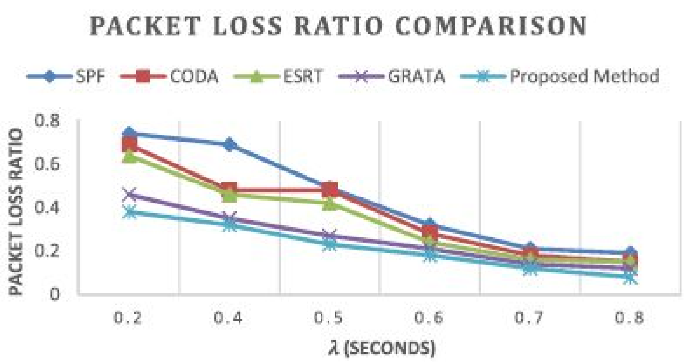

Figure 1 Average packet loss ratio versus different values of packet inter arrival times.

After comparing tests with all the methods, it is seen that the proposed scheme relatively has lower packet compression ratio. This is because of the ability to predict network congestion landscape and adjust data transmission rate in high traffic situations.

ii) Energy consumption

The proportion between the total taken energy at all nodes to send or transmit all packets and total bits in data packets which are received at the sink is called the medium energy consumption per bit and this is being evaluated.

Table 2 Average energy consumption per bit

Algorithm	λ (s)					
	0.2	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
SPF	0.74	0.69	0.49	0.32	0.21	0.19
CODA	0.69	0.48	0.48	0.28	0.18	0.15
ESRT	0.64	0.46	0.42	0.24	0.16	0.15
GRATA	0.51	0.39	0.33	0.21	0.14	0.1
Proposed	0.40	0.32	0.23	0.18	0.12	0.08

The proposed method consumes much lesser energy. This is mainly because it can reroute the paths and pass them to non congested areas. Also, the proposed method has the ability to adjust packet transmission rate.

Even considering the aspect of end-to-end packet delay, the method works better in comparison to other schemes, especially when data transmission is high. This is attributed to the fact that the gradient based scheme tries to prevent forwarding packets to immediate neighbours with high number of packets in the buffer. It also tries to balance network traffic and adjust data transmission rate between two nodes.

iii) Impact of weighted factors on network performance

In our scheme, one hop queue length is considered to be a more important factor than congestion degree and cumulative length. Thus $\alpha 1$ is always greater than or equal to the total of $\alpha 2$ and $\alpha 3$ in simulation.

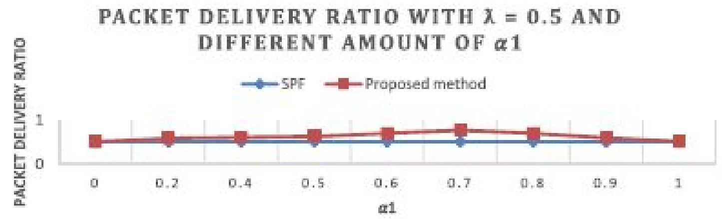

Figure 4 Packet delivery ratio with different amount of α_1.

In the above figure, with the traffic sending rate = 0.5s and through a range of $\alpha 1$, and other factors = 0 ($\alpha 2$ = $\alpha 3$ = 0), we see that with a small $\alpha 1$, it is difficult to have a high buffer threshold. On the other hand, with large $\alpha 1$, incoming packet is only prevented from using the shortest path even though the current buffer at parent node is small.

After various simulations, it is seen that high performance of the proposed system is obtained at $\alpha 1$=0.7, $\alpha 2$=0.2 and $\alpha 3$=0.1. The trade-off between one-hop and other traffic information (congestion degree and cumulative length) is to be considered. On an average, with the above factors, the packet delivery ratio of the scheme will be over 0.82 which is considerably greater than the other systems.

iv) Effects of data transmission rate

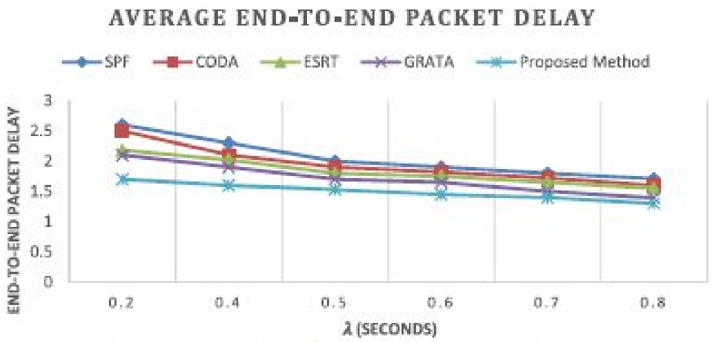

Figure 6 Shows the influence of transmission rate adjustment in the average end-to-end delay.

The graph indicates that congestion control with data transmission rate outperforms the others. This is because of its ability to decrease or increase data transmission rate in congested or non-congested places. When we consider this factor, automatically energy consumption and average end-to-end delay also improve.

Advantages:

- Adjustment of data transmission is very effective in high traffic situations
- Gradient based scheme allows us to avoid forwarding of packets to nodes which have high number of packets in the buffer.
- Ability to reroute and change rates of transmission allows better energy consumption and average end-to-end delay is better.

4.Conclusions

- In this paper, we proposed a hop-by-hop gradient-based routing scheme to evenly distribute traffic in WSNs with non-equivalent sink.
- The key concept herein is to utilize the number of hops and the current traffic loading of neighbors to make routing decisions.
- The proposed scheme reduces the number of packet retransmissions and packets dropped by preventing nodes with overloaded buffers from joining in routing calculation.
- Simulation results indicate that our proposed scheme *improves network performance* such as end-to-end packet delay, packet delivery ratio, and average energy consumption in comparison to other routing schemes including SPF, CODA, ESRT, and GRATA.
- To address practical concerns, the proposed routing algorithm can be *easily implemented* on existing devices without major changes.

Limitations

The limitation of the new method is that the values of traffic factors (α , β , and ϕ) are *chosen based on simulation experiments*.

Moreover, overhead is a common drawback of proposed algorithms.

The proposed scheme needs information about the number of hops and queue information supported from AP. Therefore, a part of network resource is used for sending/receiving this kind of broadcast information.

Improvements

In future work, we plan to build an analytical model to find the optimal value for these weighted factors. Moreover, some WSNs are application oriented, and different applications have different requirements. To conform to this diversity, an open framework is needed to consider other factors as well. We suggest that a general framework could be extended to optimize various other metrics through constructing other utilization fields and introducing additional mechanisms for performance enhancement.

For example, we can extend our method to support priority-based applications simultaneously through introducing an enhanced mechanism. The packets from different applications can be assigned to different weights carried in the packet header and in the queue. The packet with light weight is well cached with the idle nodes, and higher priority packet with heavy weight travels along shorter paths to approach the sink as soon as possible. These may be possible subjects of future work in this direction.

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