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RESEARCH ARTICLE

Congestion-Aware Routing Scheme based on Traffic Information in Sensor Networks

Di Tang, Tongtong Li and Jian Ren*

Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824

ABSTRACT

In wireless sensor networks (WSNs), congestion introduces not only buffer overflow, but also transmission delay for message forwarding from the source node to the sink. In this paper, we propose a novel congestion-aware routing (CAW) scheme to reduce the packet end-to-end transmission delay while increasing network throughput. The proposed routing protocol is based on the geographic routing scheme. The relay node selection is determined by the sensor node location and the congestion condition in MAC layer of the local area. The proposed routing scheme utilizes the local area traffic information to select the next hop node so that the likelihood for traffic congestion and transmission delay can be minimized in the subsequent routing. The OPNET simulation results demonstrate that the proposed routing scheme can reduce the end-to-end packets transmission delay by 50% while increasing the network throughput for more than 2 times in our settings.

KEYWORDS

Congestion-aware; Routing protocol; MAC layer; Transmission delay; Cross layer design.

***Correspondence**

Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824

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1. INTRODUCTION

Wireless sensor networks (WSNs) consist of a large number of untethered and unattended sensor nodes. These nodes often have very limited and non-replenishable energy resources. The communication range and computational capability are both limited. Such networks are designed to collect information and transmit sensed data to one or more sink nodes. The information of the sensed data is critical for real-time processing and decision-making in both military and civilian applications, such as monitoring the forest fire and target locating. For these applications, end-to-end transmission delay is one of the most significant design issue for wireless sensor networks.

In WSNs, congestion not only increases the packet end-to-end transmission delay, but also decreases the packet delivery ratio, the network throughput and energy efficiency. In traditional networks, the existing research on congestion mainly focuses on the traffic control in both end-to-end and hop-by-hop communications. These algorithms are mainly applied in the transport layer or the Medium Access Control (MAC) layer. The goal is try to avoid congestion by limiting the transmission rate or reducing the traffic in the network. However, the aforementioned strategies are unsuitable for event-driven WSNs for the following two reasons. Firstly, reducing the source traffic may affect the validity of decision-making. For example, forest rangers cannot locate the real fire source when the traffic of source node is limited. Secondly, the traffic control strategies have negative impact on real-time processing. As an example, for congestion caused by burst traffic, when one or multiple burst events are sensed by a couple of sensor nodes simultaneously, the traffic control algorithm will postpone the transmission to reduce the congestion in the MAC layer. The delayed information may affect the correctness of real-time processing. How to reduce the packet end-to-end transmission delay remains one of the most important design issues for congestion control algorithms.

The existing routing algorithms mainly focus on the end-to-end communication delay. They generally assume that delay between two nodes is constant. However, when the number of sink nodes is low in the networks, the traffic close to the sink nodes will be much congested. As a result, the end-to-end transmission delay will increase due to congestion. In addition, the distributed routing protocols

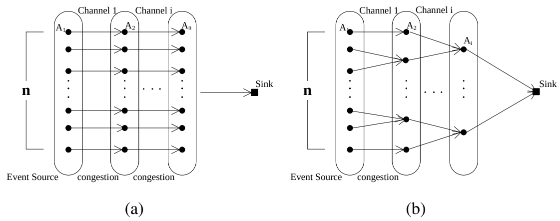

Figure 1. The link layer congestion: (a) General distributed routing algorithms that may lead to congestion in subsequent forwarding; (b) Illustration of the CAW routing algorithm

may introduce the congestion in MAC layer. In [1], the author has investigated the performance of CSMA/CA distributed coordination function comprehensively. It has demonstrated that the congestion condition would deteriorate significantly with increasing of the number of simultaneous transmissions. In a distributed routing protocol, the routing path is decided independently using a different routing strategy, such as geographic based routing protocols [2, 3]. Due to lack of cooperation, source nodes would select relay nodes independently to forward the messages in a limited area. As shown in Figure 1(a), the congestion occurs when the sensor nodes in the set of A_1 attempts to transmit messages simultaneously in the source area. Then, in the subsequent packet end-to-end transmission, MAC layer congestion cannot be avoided when these selected relay nodes try to forward the packets to the next hop simultaneously through channel i. Since all the packets are forwarded to one centralized sink in the network, congestion would occur hop-by-hop.

To solve this problem, we propose a CAW routing scheme to reduce the potential congestion in subsequent packet forwarding by monitoring the traffic in the MAC layer. In the proposed routing scheme, each sensor node selects the relay node based on two different routing strategies: the shortest path forwarding and the congestion-aware forwarding. In the shortest path forwarding, the relay node selection follows the geographic routing strategy [2] based on the geographic location. In the congestion-aware forwarding algorithm, each sensor node selects the relay node based on the channel competing results. When traffic congestion is not detected, then the shortest path routing algorithm will be used and congestion-aware transmission algorithm is used otherwise. The shortest path routing algorithm ensures an efficient end-to-end message transmission from the source node to the sink node. The congestion-aware forwarding can effectively reduce end-to-end message transmission delay and improve the system throughput by reducing traffic congestion.

The rest of this paper is organized as follows. In Section 2, the related work is reviewed. The system model is presented in Section 3. The proposed scheme is described in Section 4. Section 5 provides analysis on the end-to-end transmission delay through the multi-hop packet delivery. Section 6 provides simulation results and performance analysis on the proposed scheme. We conclude in Section 7.

2. RELATED WORK

Congestion control is a critical design issue in WSNs. In [4], the authors classifies congestion into two categories. One is defined as node-level congestion caused by buffer flow. And the other one is defined on link-level congestion caused by distributed MAC layer protocols. The distributed MAC protocols allow the sensor nodes to compete to obtain the opportunity to seize the channel which will introduce more collisions.

The existing research mainly focus on congestion caused by buffer overflow in node-level congestion. To reduce the congestion, these works utilize the traffic control as the major technique. In [5], the authors provided a comprehensive review on traffic congestion and proposed a scheme to avoid congestion based on congestion detection, hop-by-hop backpressure and multi-source regulation. The receiver monitors the traffic and the current buffer occupancy. The traffic information will be sent through backpressure messages to upstream neighbors to limit the packet sending rate. Furthermore, the multi-source regulation provides a congestion control in the end-to-end communication. In [6], the authors proposed a mechanism named Fusion based on three congestion mitigation techniques, including hop-by-hop flow control, limiting source rate, and prioritized medium access control. These three congestion techniques could mitigate the congestion by preventing the transmission to the congested nodes. Then, Chen and Yang [7] proposed a congestion-avoidance scheme based on light-weight buffer management. The basic idea of the scheme is based on the hop-by-hop flow control. It employed a $1/k$ buffer solution to prevent hidden terminals from causing traffic congestion.

Several MAC layer protocols [8–10] have been proposed to reduce the link-level congestion. In [9], the authors proposed a modified carrier sense multiple access protocol (CSMA) to improve the network performance. The protocol tried to reduce the cost of channel state checking, and then added a machine learning approach to predict the probability of a successful reception. In [10], the authors proposed a power back-off scheme to resolve collisions by limiting the transmission power. And the authors in [8] proposed an enhanced p-persistent CSMA. They proposed a method to calculate a proper p for CSMA based on the partial network topology information. However, these proposed algorithms mainly focus on modifying the current CSMA protocols in which the requirements and assumptions are not practical in WSNs.

Beside traffic control strategies, routing based congestion-avoidance protocols are also effective methods

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to reduce the congestion in networks. The main idea of these research is to reroute the packets to bypass the congestion area. SPEED [11] reduced the congestion by throttling or rerouting the traffic to detour the congestion area. The authors in [12] introduced some virtual sinks with a longer range multi-radio in WSNs. The authors assumed sensors can communicate with a long range communication radio to bypass the potential congestion area. In [4], the authors proposed a congestion control scheme by calculating the mean of the packet generation rate. LACAR routing scheme in [13] was designed to probabilistically avoid congestion by choosing lightly loaded nodes according to the location information. In [14], a traffic-aware dynamic routing algorithm was proposed to route the packets around the congestion area and scatter packets to light loaded relay nodes to alleviate buffer flow. These routing algorithms need topology information to decide the routing path which is not practical in WSNs.

In WSNs, all the packets will be forwarded to one or more centralized sink nodes. The likelihood of the link layer congestion will increase in the area closer to the sink. As shown in Figure 1(a), congestion increases in the physical channel through the hop-by-hop delivery. The existing congestion control strategies mainly focus on limiting transmission rate and reducing the traffic without considering the potential congestion in the subsequent transmission. These methods may not reduce end-to-end transmission delay in the subsequent transmission. In this paper, we propose a congestion-aware (CAW) routing protocol to reduce the link-level congestion. The main idea of the proposed routing algorithm is to utilize the channel competing results to reduce the number of potential relay nodes in each hop. As shown in Figure 1(b), CAW reduces the number of potential concurrent transmissions and therefore, the traffic congestion. Through monitoring the traffic information, each node reselects its next hop relay node when traffic congestion occurs.

3. SYSTEM MODEL AND ASSUMPTIONS

We will describe our system model and the assumptions in this section.

3.1. The System Model

We assume that the WSNs are composed of a large number of sensor nodes and a sink node. The sensor nodes are randomly deployed throughout the sensor domain. The sink node is the only destination for all sensor nodes to forward messages through a multi-hop routing strategy. The information of the sink node is made public. We also assume that each sensor node knows its relative location in the sensor domain and has knowledge of its immediate adjacent neighboring nodes. The information about the relative location of the sensor domain may be broadcasted in the network for routing information updating [15]. Each sensor node is able to monitor the local traffic information. It can obtain information of the transmitted packets through monitoring the physical channel within its communication range.

3.2. MAC Layer Protocol

Carrier sense multiple access with collision avoidance (CSMA/CA) is one of standard medium access control protocols in WSNs. In CSMA/CA mechanism, the exponential backoff scheme is employed as the major backoff scheme. Each node starts to monitor the physical channel once it has packet to transmit. Before each attempt of transmission, the tag node with packet to transmit keeps monitoring the channel for a period of Distributed Inter Frame Spacing (DIFS). If the channel is sensed busy, the tag node defers its transmission until the channel is idle for DIFS. Then the station generate a random backoff interval before transmitting. The time following an idle DIFS is divided into slots, and each slot is equal to σ which is depended on the physical layer.

In each stage of backoff, the backoff window will be uniformly chosen in the range $(0, w-1)$. The value of w will be initially set equal to CW_{min} and doubled after a failure of transmission up to $CW_{max} = 2^m CW_{min}$. The value of w will be equal to $2^i CW_{min}$ after the ith transmission attempt. The stage between the ith transmission attempt and the $(i+1)$th attempt is called as the ith stage. Once the packet is successfully transmitted by the tag node, the value of w will set equal to the initial value.

The backoff time counter decreases until the channel is idle, and stops counting when the channel is busy for a successful transmission or collision. Once the channel is sensed idle, the counter will be reactivated. When the counter reaches zero, the tag node transmits its packet through the channel. There will be a period of Short Inter-frame Spacing (SIFS) before the receiver sends back an acknowledgement (ACK) to the tag node.

The four-way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS) mechanism, is also utilized in the MAC layer as an access mechanism. This mechanism can increase the system performance by solving the hidden node problem.

4. THE PROPOSED ROUTING SCHEME

We now describe the proposed routing scheme. The algorithm consists of two strategies for routing path selection: the shortest path forwarding based on geographical information, and the congestion-aware forwarding based on physical channel competing results.

4.1. Overview of the Proposed Routing Scheme

In CAW, we assume that each node maintains the relative locations of its immediate adjacent neighboring nodes. Each node selects the relay node based on the shortest path forwarding and congestion-aware forwarding. Firstly, the source node A composes a candidate set for the relay node selection. The candidate set includes its all immediate adjacent neighboring nodes that are closer to the sink node than itself. We denoted this set as $\mathcal{N}_A$. In the shortest path forwarding, the node A selects the node B that is closest to the sink node as the relay node when it has packets to forward when no traffic congestion is detected. Otherwise, A selects a relay node based on the congestion-aware forwarding scheme. If node A fails to access the channel, it will monitor the physical channel to obtain the channel competing results. Assume that A's neighboring node C has successfully accessed the channel and forwarded its packet to its relay node D. Then if $D \in \mathcal{N}_A$, node A selects D as its relay node in the congestion-aware forwarding.

In the shortest path forwarding, each sensor node independently selects the relay node according to the relative location which might increase the number of relay nodes. The number of potential transmissions may increase with the number of relay nodes in a local area. The number of the forwarding nodes may increase traffic congestion for the subsequent packet delivery [1]. The results may also introduce more transmission collision and significantly prolong the congestion delay. Our proposed CAW scheme enables the sensor nodes to utilize the traffic condition and channel competing results to reselect relay nodes in a congestion area. In this way, we can reduce the number of concurrent transmission in the subsequent forwarding by decreasing the number of relay nodes. While decreasing end-to-end transmission delay, the CAW routing strategy can also increase the network throughput at the same time.

In addition, the proposed CAW routing scheme can reduce the energy consumption introduced by congestion.

Instead of keeping trying to transmit the packets in a congested area and consuming more energy, CAW can reduce the congestion by decreasing the number of contending nodes. As a result, the number of transmission attempts for each node also be reduced. The proposed CAW can also balance the energy consumption in congestion area. Since the channel competing results should be uniformly distributed in the available forwarding nodes, the forwarding nodes may take turns to be selected for message forwarding. As shown in Figure 2, the black nodes might be selected as the forwarding nodes for the current message forward. However, the gray nodes can provide more options for relay nodes selection when burst events occur.

4.2. Congestion-Aware (CAW) Routing Algorithm

Based on the previous description, we summarize the proposed CAW routing scheme in Algorithm 1.

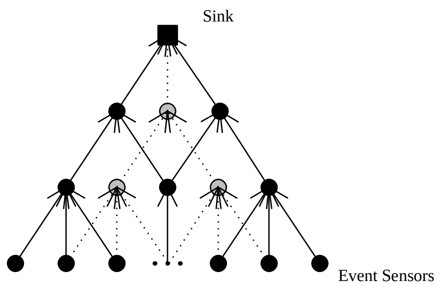

Figure 2. Dynamic tree formation

Algorithm 1 Node A derives the next hop routing node based on the MAC layer congestion condition

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Node A determines the candidate set for the next hop node selection by choosing all its neighboring nodes that are closer to the sink node than itself. Denoted the set as N_A.
Selects node B in the set N_A that is closest to the sink node as the next hop node based on its relative location.
if the packet fails to be delivered to the next hop node, then
    Node A monitors the channel from the MAC layer to obtain the information of the packet that can be successfully transmitted.
    Suppose C is the node that successfully transmits the packet to its relay node D.
    if the destination node D is in the set N_A then
        Node A reselects node D as the next hop node.
    end if
end if
```

5. THE ANALYSIS ON CONGESTION IN END-TO-END TRANSMISSION

The proposed CAW algorithm mainly focuses on solving the congestion problem caused by the burst events. Firstly, we will give the analysis on the congestion in one hop. In the one hop domain, the sensor nodes may keep collecting data and forward the data to the sink nodes during occurrences of the burst events. Secondly, we will further analyze the end-to-end transmission delay from the source node to the sink node through the multi-hop packet delivery.

5.1. One Hop Congestion Analysis

Definition 1 (End-to-end transmission delay)
The end-to-end transmission delay is defined as average time duration from the time the packet is generated at bottom of the MAC queue of the source node until the sink node receives the packet successfully through the multi-hop delivery.

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Definition 2 (Contending delay)
The contending delay is defined as the average time duration from the time the packet is at the top of the MAC queue to the ACK that the packet is received by the transmitting node in the one hop domain.

The propagation delay is a constant based on the physical layer settings. In our analysis, it is included in the contending delay as defined in Definition 2. The CSMA/CA adopts the exponential backoff scheme to minimize the collision probability. In [1] and [16], the authors have studied the collision probability and saturation throughput for Distributed Coordinate Function (DCF) mechanism which is one of mechanisms in CSMA/CA. We shall follow the definitions and analysis results to derive the mean access delay that a single packet is successfully transmitted to its destination in the one hop area. Suppose that the packet is successfully transmitted in the jth transmission attempt. In [16], the authors derived the average delay per stage as follows:

$$E[D_j] = T_s + j \cdot T_c + E[slot]\Sigma_{i=0}^{j}(\frac{W_i - 1}{2}), \quad (1)$$

$$E[slot] = (1 - P_{tr})\sigma + P_{tr}P_sT_s + P_{tr}(1 - P_s)T_c. \quad (2)$$

where $\frac{W_i-1}{2}$ is the average number of slot times that the station defers in the stages, T_c is the time duration the channel is busy for sensing a collision and jT_c is the time duration that the packet waits for collisions until it reaches the jth stage, T_s is the time duration that the packet is transmitted successfully in the jth stage, and $E[slot]$ is the average time that a station defers in a slot. σ is the period of an empty unit slot. T_s is the time duration when the tag node monitor a successful transmission. P_{tr} is the probability that at least one station other than the tag node transmit in the a random chosen slot which is defined different from [1], since the analysis mainly focuses on the transmission delay for a given tag node. Let P_{tr} denote the probability that the tag node can successfully monitor transmission and collision in the channel. Then it is calculated as follows:

$$P_{tr} = 1 - (1 - \tau)^{n-1}, \quad (3)$$

where n is the number of contending sensor nodes within the one hop range and τ is the probability that the node transmits a packet in a randomly chosen slot time.

Let P_s be the probability that the tag station can monitor a successful transmission when at least one node other than tag node transmits. It can be derived as:

$$P_s = \frac{(n-1)\tau(1-\tau)^{n-2}}{P_{tr}}. \quad (4)$$

In [1], the probability τ was derived based on a Markov model as follows:

$$\tau = \frac{2 \cdot (1 - 2p) \cdot (1 - p)^{m+1}}{W \cdot (1 - (2p)^{m+1})(1 - p) + (1 - 2p)(1 - p^{m+1})}, \quad (5)$$

where p is the conditional probability that each packet meets a collision at each transmission attempt regardless of the number of retransmissions suffered in one hop. The p can be calculated as follow:

$$p = 1 - (1 - \tau)^{n-1}. \quad (6)$$

Combining equation (5) and equation (6), the probabilities τ and p can be solved by numerical methods. Since p is the function of n, we denote $p(n)$ instead of p in following analysis.

In this paper, we mainly focus on the analysis of the mechanism of RTS/CTS. The analysis procedure can also be applied in the base CSMA/CA mechanism. According to the backoff mechanism, the time duration of T_s and T_c can be expressed by following equations based on RTS/CTS:

$$\begin{array}{c} T_s = RTS + SIFS + \delta + CTS + SIFS + \\ \delta + PHY_{head} + MAC_{head} + L + SIFS + \\ \delta + ACK + DIFS + \delta \end{array}, \quad (7)$$

$$T_c = DIFS + RTS + SIFS + CTS, \quad (8)$$

where RTS, CTS, PHY_{head}, MAC_{head} and L are the transmission delay for the RTS, CTS, physical layer header, MAC layer header and the data payload respectively, and δ is the propagation delay.

Furthermore, the contending delay $C_i[D]$ in ith hop delivery can be calculated by

$$C_i[D] = \Sigma_{j=0}^{m} E[D_j] \cdot P_j. \quad (9)$$

where P_j is the probability of a successful transmission in jth stage, and can be calculated as follows:

$$P_j = \frac{(1-p)p^j}{1 - p^{m+1}}. \quad (10)$$

The average number of transmission attempts for a successful transmission can be derived as follows:

$$E[N_i] = \Sigma_{j=0}^{m} P_j \cdot j. \quad (11)$$

5.2. Multi-hop Congestion Analysis

In this section, we will further analyze the congestion in multi-hop networks and evaluate the performance of the proposed CAW. Suppose the sensor node can directly communicate with the the sensor node within its communication range. We suppose the burst event only occurs in a local domain. And they can be detected by sensors within the sensing range. Suppose the burst event is located at the center of the domain D, and the radius of domain D is the sensing range of sensor nodes. Then the burst event can be detected by the sensors in the domain D. The sensors at the center of domain will encounter a serious congestion. The sensor node A can directly communicate with the sensor nodes in the domain of D.

In fact, the number of sensor nodes competing for the channel access is $\lambda \cdot S(D)$, where λ is the density of sensor nodes and $S(D)$ is the area of D. In the subsequent packet delivery, the number of contending nodes may vary depend on the topology and the area of burst events. The probability that there is at least one collision in the multi-hop delivery can be derived as:

$$P_h = 1 - \Sigma_{i=1}^{h}(1 - p(n_i)), \quad (12)$$

where h denotes the hop distance from the source node to the sink node and n_i is the number of contending nodes in the ith hop.

In the ith hop transmission, the average transmission delay is calculated according to equation 9. Then the end-to-end transmission delay through the delivery from the source node to the sink node can be calculated using the following equation:

$$E[D] = \Sigma_{i=1}^{h} C_i[D]. \quad (13)$$

In addition, the energy consumed of sensor nodes is largely focused on the message transmitting and receiving. The number of transmission attempts is one of important issues for energy consumption. In fact, the number of transmission attempts is depended on the number of contending nodes. Based on the aforementioned results, the average number of transmission attempts for a successful transmission from the source node to the sink node in the multi-layer network can be computed as follows:

$$\mathcal{N} = \Sigma_{i=1}^{h} N_i, \quad (14)$$

where N_i is the average number of transmission attempts in the ith hop.

5.3. Numerical Results Analysis

In this section, we will give numerical results based on the theoretical analysis. Since the number of contending nodes depends on the topology and area of events, we consider two extreme cases for the multi-hop network: the worst case and the ideal case.

We divide the network into multi layers as shown in Figure 1. There is only one burst event in the network. The number of source nodes is determined by the density and the sensing range of the sensor nodes. In the worst case, the number of the contending nodes remains the same as the number of source nodes, that is $\lambda \cdot S(D)$. The packet confronts congestion hop-by-hop from the source node to the sink node. In the ideal case, the number of contending nodes in the source area cannot be reduced since the number of source nodes cannot be reduced. However, a ideal routing algorithm, the source nodes selects only one relay node in the next layer. Therefore, the number of contending nodes is minimal. Ideally, the number of contending nodes in subsequent forwarding can be reduced to three, includes the previous hop relay node, the current relay node, and the next hop relay node. In addition, in the last hop of the delivery, there are only two contending nodes in the communication range. The end-to-end transmission delay in the worst case and ideal case can be calculated using equation (13).

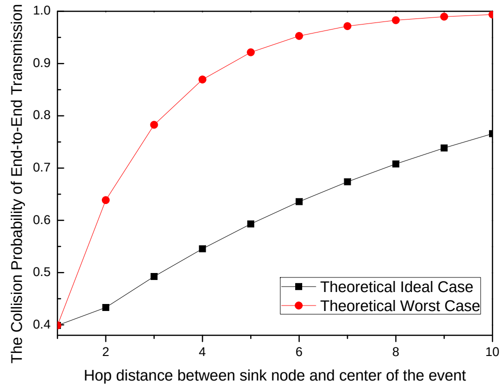

Figure 3. The end-to-end collision probability in multi hops. There are 20 contending nodes in the source node.

In Figure 3, it shows the end-to-end collision probability for a particular packet that experiences at least one collision from the source node to the sink node in both the ideal case and the worst case. It shows that in the ideal case, a properly designed routing algorithm can reduce the number of contending nodes in subsequent transmission, therefore, it can effectively decrease the end-to-end collision probability.

Then we give the numerical results on both end-to-end transmission delay and the number of retransmission. The results are present in Figure 5 and Figure 4. The parameters in the numerical results are listed in Table I.

Table I. Numerical Results Parameters Setting

Physical header	40 bits
MAC header	48 bits
RTS	40 bits
CTS	48 bits
Payload	250 bits
Channel bit rate	250k bit/s
Propagation delay, δ	1 μs
Slot time, σ	20 μs
SIFS	20 μs
DIFS	50 μs
Minimum CW, W	32
Number of CW size, m	5

6. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

In this section, we provide theoretical evaluate and simulation result to demonstrate performance of the proposed

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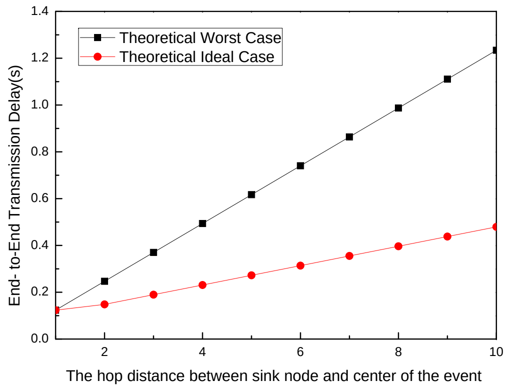

Figure 4. The end-to-end transmission delay in multi hops. There are 20 contending nodes in the source node.

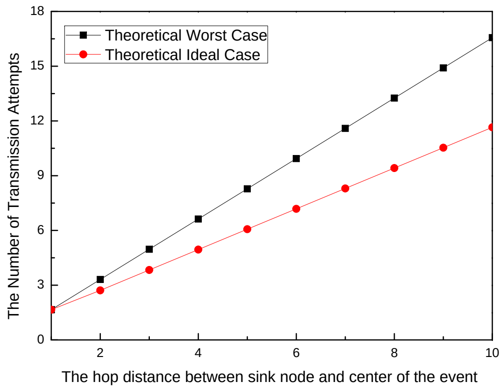

Figure 5. The end-to-end collision probability in multi hops. There are 20 contending nodes in the source area.

CAW routing scheme. Since congestion increases the transmission delay and decreases packet receiving rate, we will mainly focus on the end-to-end transmission delay and the network throughput.

6.1. Performance Metrics

We will define two metrics to quantitatively evaluate the network performance.

6.1.1. End-to-End Packet Transmission Delay (Δ)

The end-to-end transmission delay is composed by processing delay, transmission delay, propagation delay and congestion delay. In the simulation, the end-to-end transmission delay is defined by the following equation:

$$\Delta = \frac{\sum_{i \in \mathcal{I}} (T_{r_i} - T_{s_i})}{|\mathcal{I}|},$$

where $\mathcal{I}$ is the set of packets received, T_{s_i} is the time the packet is being sent out, T_{r_i} is the time the packet is being received, and $|\mathcal{I}|$ is the cardinality of the set $\mathcal{I}$.

6.1.2. Network Throughput ($\mathfrak{T}$)

Network throughput is another important metric to evaluate the routing scheme performance. Let $\mathfrak{T}$ be the normalized system throughput, then $\mathfrak{T}$ can be defined as follows:

$$\mathfrak{T} = \frac{B}{T},$$

where B is the total number of bits being delivered, and T is the total time consumption.

In the next subsection, our simulation results demonstrates that our proposed CAW routing scheme can achieve performance close to the ideal scenario.

6.2. Simulation Setup

The proposed CAW routing scheme is designed to reduce the link-level congestion. To show the performance of CAW routing protocol, we conduct simulations with different event source locations.

The sensing range is different from the communication range. Each sensor is able to sense the event within the sensing range. The number of the sensor nodes that sensed the burst events is determined by the topology and the sensing range. The actual number of contending nodes are less than or equal to the number of source nodes due to the difference between communication range and sensing range. The detailed simulation configurations are summarized in Table II, and two different simulation scenarios are described in Table III and Table IV.

Table II. Simulation Parameters Setting

Area Size	$100m \times 100m$
Deployment Type	Random
Network Architecture	Homogeneous sensor nodes with one sink node
Number of Nodes	600
Sink Coordinate	(90,90)
Communication Range	10m

6.3. Simulation Results

We conduct simulations using OPNET in different scenarios to show the performance of the proposed routing scheme. The results will be compared with a representative geographic based routing protocol. We

Table III. Simulation Scenario 1

Application Type	Event-driven
Event Location	(80,80); (70,70); (60,60); (50,50); (40,40); (30,30); (20,20)
Event Sensing Range	10m
Number of Source Nodes	18; 21; 18; 22; 16; 21; 18

Table IV. Simulation Scenario 2

Application Type	Event-driven
Event Location	(20,20)
Event Sensing Range	2m; 4m; 6m; 8m;10m 12m; 14m; 16m;18m 20m;
Number of Source Nodes	2; 7; 16; 18; 27; 39; 49; 64 ; 76;

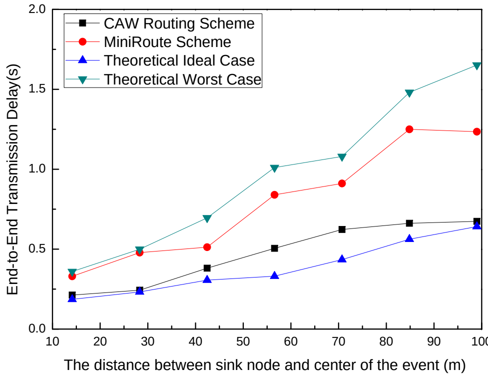

Figure 6. Average packets end-to-end transmission delay with varying burst event location

denote the proposed routing protocol as CAW and the geographic based routing as $MinRoute$ in the following simulation results.

6.3.1. Source Event Location

In Figure 6, we compare the average packets end-to-end transmission delay between the two routing protocols that have the burst event located in different places, as detailed in Table I and Table III. In the simulation, the number of source nodes depends on the topology. We also compare the simulation results with the numerical results. The numerical results on ideal case and the worst case are computed based on the topology in the simulation.

Figure 6 shows that the $MinRoute$, as a distributed routing algorithm, experiences more congestion due to more potential concurrent transmissions through hop-by-hop delivery. Its end-to-end transmission delay is more close to the worst case. On the contrary, the end-to-end transmission delay in CAW is more close to the ideal case. It also shows that CAW can effectively decrease the end-to-end transmission delay by reducing the number of contending nodes in the subsequent packet delivery. With the increasing of distance from the event source to the sink, the CAW has a much shorter end-to-end transmission delay than the $MinRoute$.

6.3.2. Sensing Range

For a given nodes density, extending the event sensing range can increase the number of source nodes. However, the number of contending nodes in event source area not only depends on the number of source nodes but also on the communication range. The number of contending nodes in the source area is determined by the sensing range and nodes density if the sensing range is less than the communication range. If the sensing range is larger or equal to the communication range, the number of contending nodes in the source area is equal to $\lambda \cdot S(D)$. However, in the multi-hop delivery, the number of contending nodes in the subsequent forwarding can be affected by the the number of source nodes since all the packets are sent to the only sink node in the wireless sensor network. Therefore, increasing sensing range leads to more link-level congestion for packets forwarding other than in the source event area.

We conduct simulations for a fix event center to verify impact of sensing range on the performance of CAW routing scheme. The settings of the simulations are detailed in Table IV. In Figure 7 and Figure 8, the source event center is located at $(80, 80)$ and the sensing range increases from $2m$ to $20m$. The number of source nodes increases with the increment of the sensing range that is detailed in Table IV. In Figure 7, we compare the end-to-end transmission delays between the CAW and the $MiniRoute$. We have similar results as in Figure 6. In addition, the end-to-end transmission delay is almost the same when the number of source nodes is two for both routing algorithm. The gap of the end-to-end transmission delays between the two compared routing schemes increases with the number of source nodes. It is equal to the number of contending nodes before the sensing range reaches $10m$. Furthermore, the end-to-end transmission delay of $MiniRoute$ increases rapidly when the event sensing range is larger than the communication range $10m$. It shows that the $MiniRoute$ introduces much more congestion after the turning point. Since the $MiniRoute$ is initially designed as a distributed routing algorithm, the sensor node selects relay node dependently. The only sink node in the network makes the traffic more and more concentrated as the packets approach the sink node. On the contrary, the end-to-end transmission delay in CAW only increases linearly. The Figure 7 shows that the proposed CAW has a stable performance. It can effectively alleviate the congestion in the subsequent hop delivery. The simulation results on end-to-end throughput is shown in Figure 8. It compare the results when the sensing range is larger than the communication range.

7. CONCLUSIONS

In this paper, we present a congestion-aware (CAW) routing scheme for WSNs to reduce the link layer congestion. CAW routing utilizes the MAC layer traffic information to select routing path. The simulation results show that our proposed CAW routing scheme can reduce the end-to-end packet transmission delay by more than

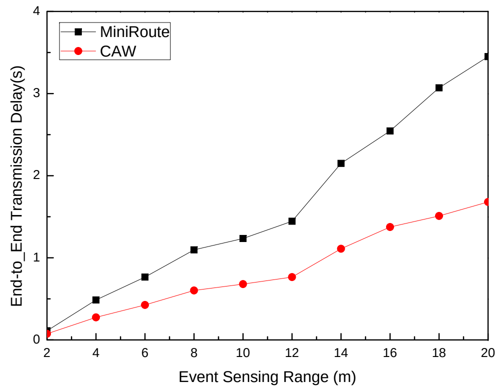

Figure 7. Average packet end-to-end transmission delay with varying event sensing range

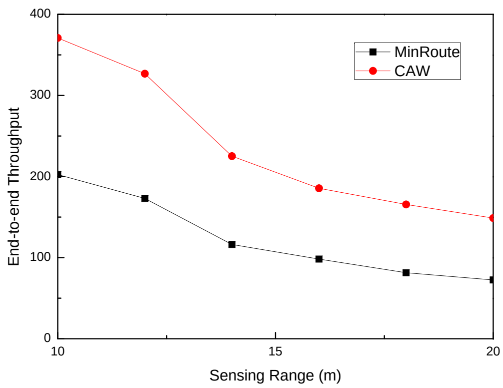

Figure 8. Network throughput with varying event sensing range

50% while increasing the network throughput for more than 2 times in our settings.

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