A Cross-Layer Congestion Control Algorithm Based on Traffic Reallocation in Wireless Sensor Network

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Abstract: Congestion is an essential problem in Wireless Sensor Networks (WSNs). In this paper, we present a traffic allocation and reallocation algorithm based cross-layer. There are mainly two parts in this framework: Efficient COgestion Traffic Allocation (ECOTA), Efficient COgestion DEection and Mitigation (ECODEM). By measuring Round Time of Trip (RTT), current traffic and node minimum energy of all paths, some low energy consumptions and short delay paths will be selected to increase the success rate of data transmission. When the congestion happens to Sensor Network, the congested areas will be detected by methods of checking node buffer and cross-layer state, and then nodes can quickly recover from congested situations by diverting the traffic to the non-congested area. Simulation results show that the proposed algorithm compared with COTA+CODEM can improve the success rate of packet delivery, reduce the transmission delay of end to end and improve the overall performance of the network.

Key words: Congestion, cross-layer, traffic allocation, traffic reallocation, ECOTA, ECODEM.

1. Introduction

WSNs have become a popular technology applied in military, environmental and ecological monitoring. It also plays an indispensable role in earthquake monitoring and medical systems [1], [2]. Sensor nodes are deployed densely in a multi-hop communication manner. The dynamic changes of wireless link quality and topology as well as emergencies caused by malicious operations are likely to cause local or global network congestion.

Congestion can result in high transmission delay, data loss and low network throughput [3], [4]. Most serious situation is that the sink node cannot receive information from the source. Since sensor nodes often switch between sleeping and working mode, the network topology changes will cause dynamic changes of link and throughput. If the power of sensor nodes is low, computing and communication capabilities will also be limited. The congestion design detection and relief scheme can improve the Quality of Service (QoS) of network, so they have become a hot research.

To realize the reliability of transmission and improve the throughput, in this paper, we propose a traffic allocation and reallocation algorithm based cross-layer, which is named ECOTA+ECODEM.

This paper is organized as follows. Section 2 presents relative works. Section 3 provides a congestion avoidance and traffic allocation algorithm. Section 4 is mainly about congestion detection and mitigation algorithm. The simulation results based on different algorithms and compared with COTA+CODEM is shown in Section 5. Following this, a conclusion of this paper is given.

2. Relative Works

Congestion in WSNs can be divided into two types: one is the node level of congestion. It is common with traditional network congestion, in which the packet traffic sent exceeds the node's transmission capacity, resulting in data packet loss caused by buffer overflow and increasing of network queuing delay; the other is wireless link level congestion. Wireless channel is a shared resource, where, however, only one node can use the wireless channel among adjacent nodes on the same time. It will generate an access violation caused by link-level congestion, when a plurality of adjacent nodes compete for the use of the radio channel. Congestion will increase packet service time, reduce link utilization and network throughput.

As to congestion detection, literatures [5]-[8] exploited node internal data queue length to determine the congestion status of the network. The congestion is to happen, when the packet buffer length exceeds its upper limit threshold value. Some methods in the literature can solve some problems of congestion, but these also have drawbacks that they need to set the proper threshold value by artificial. If the threshold value were high, network resource would be wasted due to the congestion cannot be identified in time. Congestion can also be detected through channel sample testing. The radio channel will have a busy state, once the congestion occurs due to the competition of wireless link among nodes. In literature [9], a new method was designed for clustered networks to detect congestion. In this paper, traffic situation under real-time monitoring was calculated to determine whether congestion occurs in the cluster by cluster head and the probability of buffer overflow of nodes, but this method needed the support of the underlying communication protocol, as well as adding node energy consumption. Judging from the data packet receiving rate of sink nodes, we can also know whether network congestion is happening [5]. However, the application scene of this method is limited which only applies to periodic data network and has a long detection period.

In terms of congestion avoidance, the common methods are to control the data sending rate which is controlled by allocation rate or cache notice. Rate allocation mechanism is applied to network of relatively stable structure in which the data of sending and generating are strictly computed and allocated. Data generating rate of each node and sending rate of its child node are slower than the assigned transmission rate, thus the network throughput in each local region surpasses its network traffic. The congestion avoidance mechanism exploited lightweight cache management [10]. The sending node will receive the cache information from destination node and the sending node initiates to send data only when the destination node has enough space to cache received data. This method prevents the intermediate nodes on the path from congestion caused by insufficient cache. Paper [11] added features of node power conservation compared with [10]. IPD [12] detected congestion by the length of queue. The queue will increase when the internal queuing time is longer than the internal processing, and its length can calculate the cache occupancy. When congestion occurs, IPD first calculates the priority of packets, and discards certain packets to achieve the purpose of congestion analysis and control. WSNs are event-driven network. Congestion control is often incorporated into the routing algorithm, since the congestion has a bad influence on the reliability and load balance [13]-[15]. These algorithms not only judge the congestion based on caching factors that were neglected such as delay, node power, but also control the congestion at the expense of data accuracy.

As to congestion relief, the common methods are to control the data rate. While the system detects the occur of congestion, intermediate nodes are reducing the data sending rate to inhibit the spread of congestion to downstream and noticing the congestion to upstream nodes. The upstream nodes can adjust data sending rate according to their own state or further forward the notification message. TADR [16] used the idle or unload nodes to alleviate congestion. The idle nodes around the congestion area are used to route data packet. TADR was designed to bypass network congestion through a mixed virtual potential field and reach their destination points. COTA [17] allocated traffic based on path heuristic information to avoid increasing load on hot spots. They have their own advantage, but duplicate nodes on the established paths and the data latency in the network are not considered, besides the possible traffic fluctuations in the allocation process.

Congestion avoidance, detection and mitigation strategies are proposed in this paper. According to the node energy consumption and transmission delay, in terms of congestion avoidance, a node traffic allocation method named Efficient COgestion Traffic Allocation (ECOTA) is proposed which allocates the traffic reasonably. In ECOTA, the delay fluctuation due to congestion is avoided during the allocation process. The ratio of buffer occupancy rate, the node receiving rate (RR) and cross-layer state are used to determine whether the network congestion occurs. The node buffer change (BC) can also be used to accurately predict congestion whether occurs or not in some certain extent. The traffic reallocation algorithm named Efficient COgestion DEection and Mitigation (ECODEM) based on congestion depth (CD) is proposed, which can assign the traffic to a non-congested area in case of network congestion while ensuring the transmission delay minimum and using the node energy rationally.

3. Congestion Avoidance and Traffic Allocation Algorithm

ECOTA based on COTA is proposed in this paper. The network latency is reduced on the basis of traffic allocation of paths. Paths create different nodes except the source and destination node in ECOTA. In multi-path routes, one node lying in different paths is most likely to cause congestion due to their own packet loss caused by buffer overflow. ECOTA can avoid network congestion caused by several bottleneck nodes using disjoint multipath as well.

Due to the own features of wireless network, channel failure happens sometimes in the data transmission. In view of this situation, the general solution is to use multiple paths to increase the reliability of data transmission. Assuming e is the channel failure rate, and the average number of hops from source to sink is h. To achieve the expected reliability r, the minimal number of paths N can be calculated with the following equation:

$$N = \frac{\log(1-r)}{\log(1-(1-e)^{k})}. \tag{1}$$

When the number of paths is less than N, some paths should share more tasks and repeat transporting data. When the number of paths is greater than N, the subsequent algorithm is used. N paths are selected from these paths in transmission to reasonably avoid congestion controlling the residual energy of nodes and decrease the latency in transmission.

In the early establishment of paths, Round Time of Trip (RTT) of path is calculated. RTT is used as the only external indication to achieve the goal of dynamic traffic allocation on the N paths. In order to prevent the flapping of traffic allocation due to the fluctuations of RTT, the following formula is used to adjust RTT.

$$\mathrm{RTT}_{p_i} = (1-\alpha)\mathrm{RTT}_{p_i}(t-1) + \alpha \mathrm{RTT}_{p_i}(t). \tag{2}$$

In order to control the allocated rate, every path is assigned with a weight t, and the allocated traffic M_{p_i} in recent t period for each path is calculated. Then,

$$W_{s,p_i}^{d} = \frac{\frac{1}{RTT_{p_i}}}{\sum_{p_i \in p_s^d} \frac{1}{RTT_{p_i}}} \times \frac{\frac{1}{M_{p_i}+1}}{\sum_{p_i \in p_s^d} \frac{1}{M_{p_i}+1}} \times \frac{E_{p_i}}{\sum_{p_i \in P_s^d} E_{p_i}}. \tag{3}$$

Here, E_{p_i} is the minimum node residual energy on the path.

The weight of each path is calculated. At last, the assigned rate of each path is presented as follows.

$$\lambda_{s,p_i}^{d} = \frac{W_{s,p_i}^{d}}{\sum\limits_{p_i \in P_s^d} W_{s,p_i}^{d}} \times N \times R. \tag{4}$$

Here, N is the allocated number of paths, R is the data sending rate of data source and the number of overall paths is m. The complexity of algorithm is $O(N)$. The pseudocode of ECOTA is written as follows.

Algorithm: ECOTA

1. Begin
2. For k=1 to m
3. Get RTT_{p_i} and E_{pi}
4. End For
5. Choose N paths of largest value $W_{s,pi}^{d}$
6. Allocate traffic to N paths $\lambda_{s,pi}^{d} = \frac{W_{s,pi}^{d}}{\sum\limits_{pi \in p_s^d} W_{s,pi}^{d}} \times N \times R$
7. End

4. Congestion Detection and Mitigation Algorithm

In wireless sensor networks, the most common methods of detecting congestion are to judge whether the buffer occupancy (BO) rate exceeds a certain threshold value. If the occupancy rate of the node exceeds the threshold, the threshold as the basis of congestion detection does not necessarily reflect the real situation. Another popular way is to compute the congestion level (CL) which is the ratio of node packet receiving rate and sending rate. The bigger value of CL means that the congestion is more serious. In the case of high congestion, the congestion level might be small when the remaining space of buffer is small and packet loss occurs. The cross-lay factor is also an effective way to detect congestion. An enhanced congestion detection algorithm based on CODEM [17] combined with the above three techniques was proposed in this paper. CODEM uses a static determination method which uses only several fixed threshold to determine whether the congestion occurs. In ECODEM, we will use a gradient way to detect congestion.

The node situation in the next moment can be predicted by BC. If it is predicted that congestion occurs in the next moment, the node will be sending which rate written as $\rho \times \lambda_{s,p_i}^{d}$ $(0 \le \rho \le 1)$. The detailed procedure is as follows.

Rule 1. If $\mathrm{BO} < \alpha_1$, the node receives feedback messages from upstream nodes and $\mathrm{BC} > \gamma$, the sending rate is set to $\rho \times \lambda_{s,pi}^{d}$.

Rule 2. If $\mathrm{BO} > \alpha_1$, the congestion bit is set. The congestion node sends back pressure message to control the packet sending rate of upstream nodes.

Rule 3. If $\mathrm{BO} > \alpha_2$, the node begins to discard packets.

Rule 4. If node receives congestion message from upstream and $\mathrm{CL} > \beta$, it is the same as Rule 2.

Rule 5. If $\mathrm{BO} > \alpha_1, \mathrm{CL} < \beta$ and $\mathrm{BC} < \gamma$, the congestion is relieved. The node sending rate is set to $\lambda_{s,p_i}^{d} \times \mu$.

Rule 6. If $\mathrm{BO} < \alpha_1$ and $\mathrm{CL} < \beta$, the congestion is eliminated and the congestion bit is set to 0.

If there is a congestion situation in the network, the traffic should be reassigned and the unused paths should be used as much as possible while reducing the traffic. In ECOTA, the paths are established with no duplicate nodes. In ECODEM, the traffic reallocation problem is solved since the path is uncrossed. The main idea of ECODEM is first to transfer the traffic in the congested area to other non-congested area in the premise of no-cross paths. Next, the location of congestion is determined by calculating CD. In the final reallocation process, two factors of node residual energy and delay are used to calculate the reallocation ratio, and the algorithm complexity is $O(N)$. The specific algorithm of ECODEM is as follows.

Algorithm: ECODEM

1. Begin
2. For k=1 to N
3. Get CD value of the K path according to the reverse pressure
4. End For
5. If the number of unused paths is more or equal to the number of congested paths, transfer the traffic to unused paths
6. End if
7. If the number of unused paths is less than the number of congested paths
8. For the congested paths $W_{s,p_i}^d = \dfrac{\frac{1}{RTT_{p_i}}}{\sum_{p_i \in P_s^d} \frac{1}{RTT_{p_i}}} \times \dfrac{\frac{1}{M_{p_i}+1}}{\sum_{p_i \in P_s^d} \frac{1}{M_{p_i}+1}} \times \dfrac{E_{p_i}}{\sum_{p_i \in P_s^d} E_{p_i}} \times CD_{s,p_i}^d \times \theta$
9. The reallocated traffic is $\lambda_{s,pi}^d = \dfrac{W_{s,pi}^d}{\sum_{pi \in p_s^d} W_{s,pi}^d} \times N \times R$
10. End

5. Simulation Results

To validate the performance of the proposed scheme, simulate experiments under the NS2 simulator in two methods including COTA + CODEM and ECOTA + ECODEM, are executed. After the experiment, the performance of these three mechanisms in term of packet delivery rate, end to end delay and throughput will become items of analyzing and comparing.

In the simulation, the parameters are set as follows. 50 sensor nodes are randomly distributed in a square region of $1000m \times 1000m$. The nodes' communication radius is 250m. The data transmission rate is 1Mb/s and the initial energy of sensor nodes is 1J.

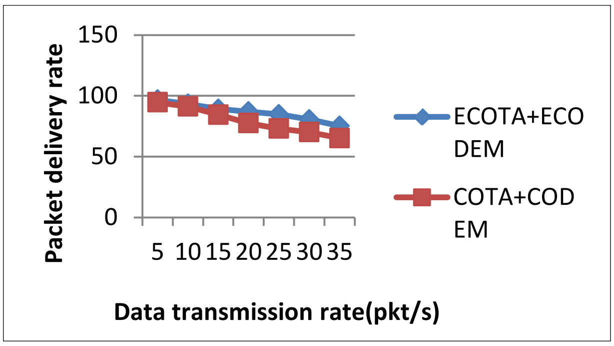

Fig. 1. Packet delivery rate.

Fig. 1 depicts packet delivery rate associated with the two congestion control schemes. It indicates that the packet delivery with ECOTA+ECODEM is higher than COTA+CODEM. The performance of ECOTA+ECODEM supers the other one especially clear when the data rate is up to 15 packets per second.

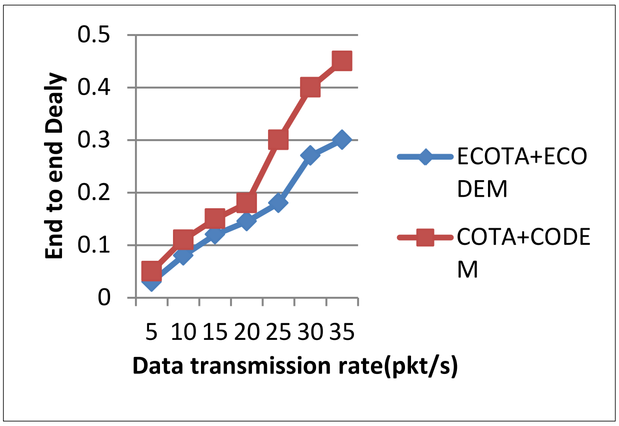

Fig. 2. End to end delay.

Fig. 2 compares end to end delay for the two schemes. As the network load increase, the end to end delay becomes high. The two schemes perform likely until the data transmission rate are 20 packets per second. Then the superiority of ECOTA+ECODEM is explicit since the end to end delay is reduced by 10 percent. The packet queuing time decreases significantly and the user experience is enhanced.

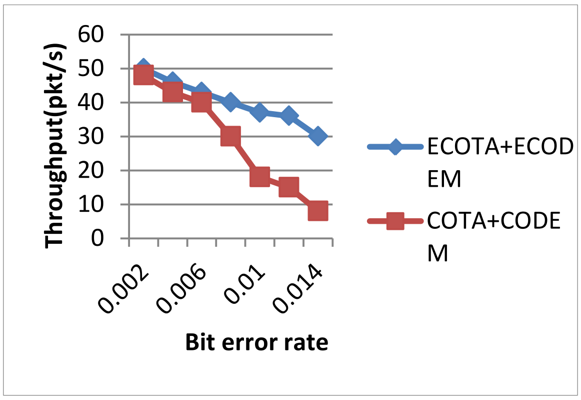

Fig. 3. Throughput.

Fig. 3 shows the network throughput for the two schemes. The results show that the throughput with ECOTA+ECODEM is much higher than the other scheme, especially when the bit error rate becomes larger and the data fluctuation is less.

6. Conclusions

In this paper, an enhanced algorithm scheme (ECOTA + ECODEM) has been proposed to realize the goal of congestion avoidance, detection and mitigation. The traffic is reallocated after the energy and delay of other paths to recover the network from congestion quickly. A method for predicting congestion is also proposed to analyze quickly that whether there is congestion in the network. Simulation results show that the proposed algorithm improves the performance about 10%. It can improve the packet delivery rate and throughput while reducing the end to end delay. Above all show that the network is improved.

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