

DPCC: Dynamic Predictive Congestion Control in Wireless Sensor Networks

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Abstract

Congestion occurs in wireless sensor networks (WSNs) when nodes are densely distributed, and/or the application produces high flow rate near the sink due to the convergent nature of upstream traffic. Congestion can lead to packet losses, delay, and energy waste due to a large number of packet drops and retransmissions. Therefore it is necessary to carry out congestion control which detects congestion precisely and regulates it fairly. To achieve this objective, a dynamic predictive congestion control (DPCC) algorithm is proposed in this paper. The DPCC can predict congestion in a node and will broadcast traffic on the entire network fairly and dynamically. Simulation results show that the proposed protocol is more efficient than previous ones.

Keywords: *Wireless Sensor Network, Congestion Control, Predictive, Fairness.*

1. Introduction

In the recent years, the rapid advances in micro-electro-mechanical systems, low power and highly integrated digital electronics, small scale energy supplies, tiny microprocessors, and low power radio technologies have created low power, low cost and multifunctional wireless sensor devices, which can observe and react to changes in physical phenomena of their environments. These sensor devices are equipped with a small battery, a tiny microprocessor, a radio transceiver, and a set of transducers that used to gathering information that report the changes in the environment of the sensor node. The emergence of these low cost and small size wireless sensor devices has motivated intensive research in the last decade addressing the potential of collaboration among sensors in data gathering and processing, which led to the creation of Wireless Sensor Networks (WSNs).

A typical WSN consists of a number of sensor devices that collaborate with each other to accomplish a common task (e.g. environment monitoring, target tracking, etc) and report the collected data through wireless interface to a

base station or sink node. The areas of applications of WSNs vary from civil, healthcare and environmental to military. Examples of applications include target tracking in battlefields [1], habitat monitoring [2], civil structure monitoring [3], forest fire detection [4], and factory maintenance [5].

However, with the specific consideration of the unique properties of sensor networks such limited power, stringent bandwidth, dynamic topology (due to nodes failures or even physical mobility), high network density and large scale deployments have caused many challenges in the design and management of sensor networks. These challenges have demanded energy awareness and robust protocol designs at all layers of the networking protocol stack [6].

The upstream traffic from sensor nodes to the sink is many-to-one multi-hop convergent. Fig. 1 shows many-to-one traffic pattern. The upstream traffic can be classified into four delivery models: event-based, continuous, query-based, and hybrid delivery. Due to the convergent nature of upstream traffic, congestion more probably appears in the upstream direction. Congestion that can leads to packet losses and increased transmission latency has direct impact on energy-efficiency and application QoS, and therefore must be efficiently controlled. Congestion control generally follows three steps: congestion detection, congestion notification, and rate-adjusting.

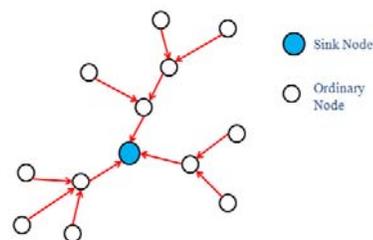


Fig. 1 Many-to-one traffic pattern in wireless sensor networks

In response to congestion, a rate adjustment mechanism must be designed and implemented properly in order to eliminate or avoid congestion. A number of different schemes were reported in the literature in last few years. A stop-and-start and hop-by-hop strategy is employed in [7]. In [8] and [11], an end-to-end and AIMD-like (Additive Increase Multiplicative Decrease) rate adjustment approach is employed. All of these mechanisms, however, aim at guaranteeing the simple fairness instead of the weighted fairness. A priority-based congestion control protocol (PCCP) is presented to achieve the weighted-fairness transmission for single-path routing WSNs in [14]. In this paper we introduce a priority-based rate adjustment algorithm called joint priority algorithm (JPA), which guarantees weighted fairness in multipath routing WSNs. In this scheme, intermediate nodes keep a record of the information on joint priorities (JP) of their neighbors. When congestion is detected, the sending rates of the upstream neighbors of the congested node are limited based on their joint priorities. In other words, upstream neighbors with important traffic will share more bandwidth than others when congestion occurs. Each data source, however, will send packets with its current equal rate when there is no congestion.

Two types of congestion could occur in WSNs [9] (As can be seen in Fig. 2). The first type is node-level congestion that is common in conventional networks. It is caused by buffer overflow in the node and can result in packet loss, and increased queuing delay. Packet loss in turn can lead to retransmission and therefore consumes additional energy. For WSNs where wireless channels are shared by several nodes using CSMA like (Carrier Sense Multiple Access) protocols, collisions could occur when multiple active sensor nodes try to seize the channel at the same time. This can be referred to as link level congestion. Link-level congestion increases packet service time, and decreases both link utilization and overall throughput, and wastes energy at the sensor nodes. Both node-level and link-level congestions have direct impact on energy-efficiency and QoS.

Congestion control protocol efficiency depends on how much it can achieve the following performance objectives: (i) First, energy-efficiency requires to be improved in order to extend system lifetime. Therefore congestion control protocols need to avoid or reduce packet loss due to buffer overflow, and remain lower control overhead that will consume additional energy more or less. (ii) Second, fairness needs to be observed so that each node can achieve fair throughput. Fairness can be achieved through rate-adjustment and packet scheduling (otherwise referred to as queue management) at each sensor node. (iii) Furthermore, support of traditional quality of service (QoS)

metrics such as packet loss ratio and packet delay along with throughput may also be necessary.

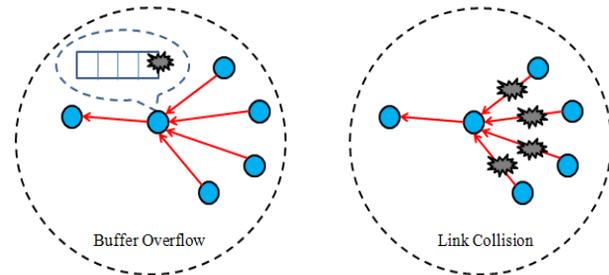


Fig. 2 Congestion in wireless sensor networks

The rest of the paper organized as follows: in section 2, we explain the related works. Section 3 describes the system models. Section 4 explores the DPCC protocol with details. Section 5 describes simulation parameters and result analysis. Final section is containing of conclusion and future works.

2. Related Works

There are several congestion control protocols [9]-[12] for sensor networks. They differ in the way that they detect congestion, broadcast congestion related information, and the way that they adjust traffic rate when congestion occurs. In this section, we review some of them and discuss their limitations.

Congestion detection and avoidance (CODA) [11] proposes an open-loop, hop-by-hop backpressure mechanism and a closed-loop, multi-source regulation mechanism in event-driven WSNs. Sensor nodes detect congestion by monitoring the channel utilization and buffer-occupancy level. In response to congestion, the congested sensor nodes send backpressure messages to their neighbors which may drop packets, reduce their sending rate and further propagate backpressure messages. If the sending rate of a source node is greater than the preset threshold, the source node must receive a continuous stream of ACKs from the base station in order to maintain that rate. By this means, the base station may limit the sending rate of a source node based on deciding how many ACKs to broadcast. CODA employs the AIMD (Additive Increase Multiplicative Decrease) coarse rate adjustment. It only guarantees simple fairness of the congestion control.

Event-to-sink reliable transport protocol (ESRT) [13] monitors the local buffer level in intermediate sensor nodes and sets a congestion notification bit in the packet when the buffer overflows. If a base station receives a packet whose congestion notification bit is set, it

broadcasts a control signal to inform all source nodes to reduce the sending rate according to certain proportion. ESRT limits sending rate of all source nodes when congestion occurs regardless of where the hot spot happens in WSNs. The best way is to regulate those source nodes that are responsible for this congestion.

Priority based congestion control protocol (PCCP) [14] defines a new variable, congestion degree as ratio of average packet service time over average packet inter-arrival time at each sensor node. Congestion degree is intended to reflect the current congestion level of each sensor node. Based on congestion degree, PCCP employs a hop-by-hop rate adjustment technique called priority-based rate adjustment (PRA) to adjust the scheduling rate and the source rate of each sensor node in a single-path routing WSN. In the tree-based network topology of single-path routing WSNs, a sensor node will only have one downstream neighbor, but it may have multiple upstream neighbors. The whole data flow generated by a source node will pass through the nodes and links along with the single routing path. Sensor nodes learn the number of upstream data sources in the sub tree roots and measure the maximum downstream forwarding rate. Finally, they calculate the per-source rate based on priority index of each source node.

In Fusion [15], congestion is detected in each sensor node based on measurement of queue length. The node that detects congestion sets a congestion notification (CN) bit in the header of each outgoing packet. Once the CN bit is set, neighboring nodes can overhear it and stop forwarding packets to the congested node so that it can drain the backlogged packets. This non-smooth rate adjustment could impair link utilization as well as fairness, although Fusion has a mechanism to limit the source traffic rate and a prioritized MAC algorithm to improve fairness.

Adaptive Rate Control (ARC), [12], is an LIMD-like (linear increase and multiplicative decrease) algorithm. In ARC, if an intermediate node overhears that the packets it sent previously are successfully forwarded again by its parent node, it will increase its rate by a constant α . Otherwise it will multiply its rate by a factor β where $0 < \beta < 1$. ARC does not use explicit congestion detection or explicit congestion notification and therefore avoids use of control messages. However the coarse rate adjustment could result in tardy control and introduce packet loss.

CCF (Congestion Control and Fairness) [9] uses packet service time to deduce the available service rate and therefore detects congestion in each intermediate sensor node. Congestion information, that is packet service time in CCF, is implicitly reported. CCF controls congestion in a hop-by-hop manner and each node uses exact rate

adjustment based on its available service rate and child node number. CCF guarantees simple fairness. That means each node receives the same throughput. However the rate adjustment in CCF relies only on packet service time which could lead to low utilization when some sensor nodes do not have enough traffic or there is a significant packet error rate (PER).

Those existing congestion control protocols for WSNs have limitations. For example, they only guarantee simple fairness, which means that the sink receives the same throughput from all nodes. However, sensor nodes may have different priority or importance due to either their functions or the location at which they are deployed.

3. System Models

This section describes network and node models, as shown in Figs. 3 and 4, respectively.

3.1 Network Model

This paper addresses upstream congestion control for a WSN that supports single-path routing. The network model to be investigated in this work is depicted in Fig. 3, where sensor nodes are supposed to generate continuous data and form many-to-one convergent traffic in the upstream direction. CSMA/CA MAC protocol is implemented in MAC layer. Each sensor node could have two types of traffic: source and transit. The source traffic is locally generated at each sensor node, while the transit traffic is from other nodes. As shown in Fig. 3, node 1 is a source node and only has source traffic, while nodes 2, 3, 4, 5, 6 and 7 are source nodes as well as intermediate nodes because they have source traffic as well as transit traffic. Each node could have two types of neighbor nodes: backward and forward. For example, the backward node of node 3 is node 1, because its data can be sent by node 3 and forward nodes of node 3 are nodes 5, 6 and 7. In this paper, $f(i)$ is the set of forward nodes of i and $b(i)$ is set of backward nodes of i . For example, in Fig.3, $b(3)$ is equal $\{1\}$ and $f(3)$ is equal $\{5, 6, 7\}$.

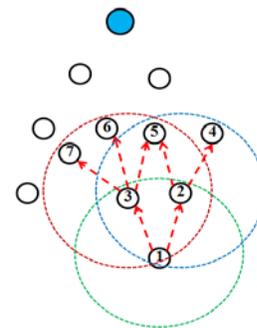


Fig. 3 General network model

3.2 Node Model

Node model of the investigated wireless sensor network is presented in Fig. 4. The source traffic of node i is generated with source traffic rate (r_s^i) by itself locally. The transit traffic of node i is received with transit traffic rate (r_{tr}^i) from its child nodes through MAC layer of node i . Both r_s^i and r_{tr}^i are converged through network layer to MAC layer as total input rate of node i (r_{in}^i). Traffic packets could be queued if r_{in}^i ($r_{in}^i = r_s^i + r_{tr}^i$) exceeds packet forwarding rate (r_f^i) at MAC layer. Congestion could take place in node i if r_{in}^i is larger than r_f^i continuously, when the buffer of node i could be filled up quickly and finally overflow. This congestion can be controlled by reducing r_{tr}^i in the DPCC protocol.

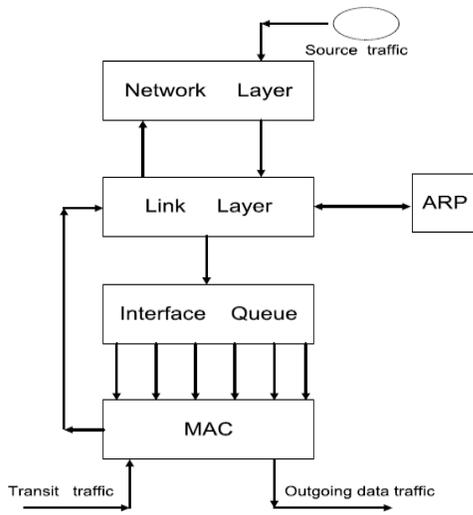


Fig. 4 General node model

4. DPCC Protocol

The DPCC protocol tries to increase throughput and reduce packet loss while guaranteeing distributed priority-based fairness with lower control overhead. The congestion control scheme of sensor node i is shown in Fig. 5. DPCC protocol consists of three components: backward and forward nodes selection (BFS), predictive congestion detection (PCD) and dynamic priority-based rate adjustment (DPRA), which are introduced with responsibility for precise congestion discovery and weighted fair congestion control.

4.1 Backward and Forward Nodes Selection

The node i selects a forward node for itself according to received rate adjustment values from $f(i)$. The node i selects the one as a forward node which received rate

value from it is max. Then node i send notification to selected forward node. For increasing the throughput, the other forward nodes of node i which is not selected as a forward node of this node adjust the new rates for their other backward nodes.

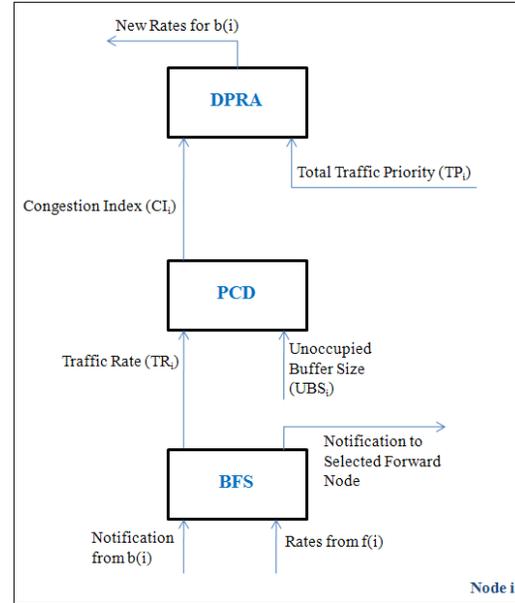


Fig. 5 Congestion control scheme in node i

4.2 Predictive Congestion Detection

Congestion index (CI_i) reflecting the current congestion level at each sensor node i is determined on its unoccupied buffer size (UBS_i) and traffic rate (TR_i) at MAC layer as follows:

$$CI_i = UBS_i - TR_i \quad (1)$$

$$UBS_i = MBS_i - OBS_i \quad (2)$$

$$TR_i = (r_s^i + \sum_{j \in b(i)} r_{ji} - \sum_{k \in f(i)} r_{ik}) \times T \quad (3)$$

Here, MBS_i and OBS_i are defined as the maximal buffer size and current queue length of node i . r_{ji} and r_{ik} denote the average upstream input traffic rate from node j to i and downstream output traffic rate from node i to k , respectively.

On the other hand, r_{ji} and r_{ik} are updated periodically at each time interval T as follows:

$$r_l^{new} = [(1 - \omega) \times r_l^{old}] + \left[\omega \times \frac{n_T}{T} \right], \forall l = i, ji, ik \quad (4)$$

Here, n_T denotes number of the new arriving packets during the time period T , and ω is a constant satisfying $0 < \omega < 1$.

If $CI_i < 0$, it means that congestion may occur in the node i with this traffic rate. In this state, DPRA component must adjust the traffic rates of backward nodes to avoid congestion.

4.3 Dynamic Priority-based Rate Adjustment

Total traffic priority (TP_i) in each sensor node i is calculated as follows:

$$TP_i = \sum_{j \in b(i)} TP_j + SP_i \quad (5)$$

Here, SP_i and TP_j are defined as local source traffic priority of node i and total traffic priority of node j which is the member of $b(i)$, respectively. Traffic priority ratio of node i (TPR_i) and its backward nodes (TPR_{ji} , $j \in b(i)$) in one hop are obtained as follows:

$$TPR_i = \frac{SP_i}{TP_i} \quad (6)$$

$$TPR_{ji} = \frac{TP_j}{TP_i} \quad (7)$$

According to Eq. (6) and Eq. (7), source traffic rate of node i and each transit traffic rate of this node can be allocated with the traffic priority as follows:

$$r_{s_new}^i = TPR_i \times CI_i \times \frac{1}{T} \quad (8)$$

$$r_{ji_new} = TPR_{ji} \times CI_i \times \frac{1}{T} \quad (9)$$

5. Performance Evaluation

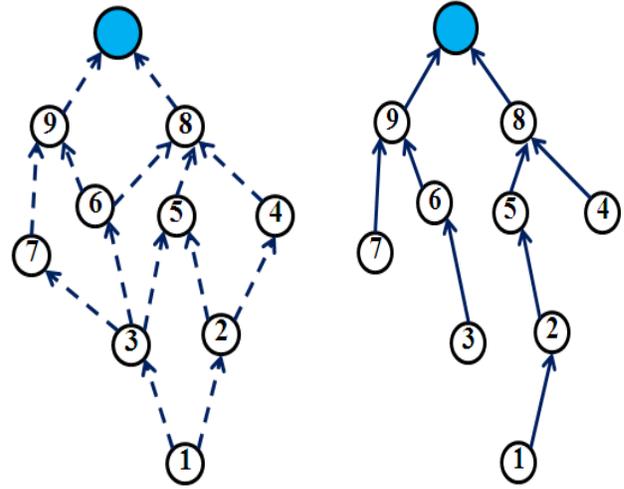
In this section, performances of the DPCC protocol are shown by simulation. The scenario is similar to Fig. 6 (a), where 9 nodes send traffic packets to the sink with different SP and form many-to-one upstream traffic. The network stack of each node consists of IEEE 802.11 MAC layer. Simulation parameters are listed in Table 1.

Table 1: Simulation parameters

Parameters	Value
Data rate	1 Mbps
Buffer size	20 packets
Number of sensors	9
Initial energy	2J
Time interval T	1 sec
ω	0.2
Simulation time	80 sec
Data packet size	512 bits

Performance comparisons of the DPCC with PCCP protocol on throughput and fairness are provided as follows.

The network model in this scenario is assumed similar to Fig. 6 (b) for PCCP protocol.



a) Network model in DPCC b) Network model in PCCP

Fig. 6 Network model in this scenario

5.1 Normalized Throughput

We study the impact of changing the source traffic rate on throughput. We change the traffic rate at the each source node from 5 to 40 packets/sec. We assume that priority of all nodes is same in this evaluation.

Normalized network throughputs of DPCC and PCCP are shown in Fig. 7.

As it can be seen, proposed protocol has performance better than MCMP in network throughput especially when that traffic rate at the source node is increased.

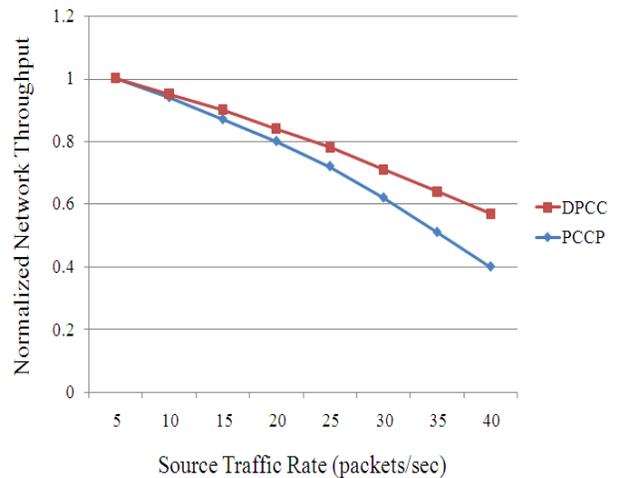


Fig. 7 Normalized network throughput

5.2 Priority-based Fairness

In this case, we use the same topology as in Fig. 6, but the nodes will be configured with different source traffic priority index (SP_i) as follows: node 4 with source traffic priority index 3, node 5 with source traffic priority index of 2 and all other nodes with source traffic priority index of 1.

It is assumed that node 5 only remains active in the time interval [20 sec, 60 sec] and node 6 only remains active in the time interval [30 sec, 50 sec] and generate traffic packets based on source traffic priority SP_5 , SP_6 .

By the Fig. 8 it can be seen that priority-based fairness has been achieved.

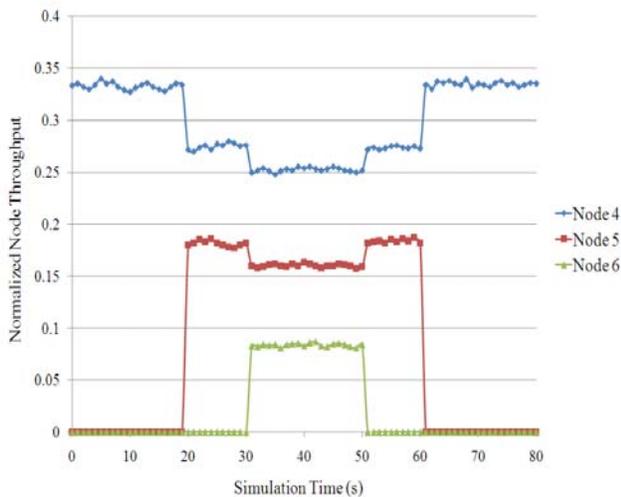


Fig. 8 Normalized node throughput in DPCC

6. Conclusion

In this paper, we propose a dynamic predictive congestion control (DPCC) algorithm. The DPCC can predict congestion in the node and will broadcast traffic on the entire network fairly and dynamically. Simulation results show that the proposed protocol is more efficient than previous algorithms especially in network throughput evaluation.

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