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Taxonomy of Congestion Control Protocols in Wireless Sensor Networks

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Abstract— Congestion control in wireless sensor networks is an appealing area to networking researchers since a decade. Recent advancement in wireless communications enabled the development of low-cost, low power, small size sensor networks. As we continue to expand the applications of these networks, we would need to ensure that the applications are not affected by congestion in network. Thus, congestion control is one of the major issue that has to be considered while designing any transport protocol for Wireless Sensor Networks. In this paper, we highlight various issues of congestion control in Wireless Sensor Networks and then provide a review of existing protocols for detecting and controlling congestion. Finally, several performance metrics used for measuring congestion are assessed and the state-of-the-art comparative analysis for Wireless Sensor Networks is put forth with our own Congestion Control Preference (CCP) parameter to select best protocol in the available category.

Keywords— Congestion control, wireless sensor networks, CCP, centralized congestion control, distributed congestion control

I. INTRODUCTION

Wireless sensor network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental condition. WSNs have scarce resources like limited communication bandwidth, small memory, low processing power, etc.

Congestion control has been an active area of networking research for several decades. Since, congestion control in wireless networks is different from wired ones; it has to be dealt differently. Basically, congestion control comes into picture when improper allocation of resources is done. This means congestion control deals with allocating the network resources such that the network operates at an acceptable performance level even when the demand exceeds. These network resources include link bandwidth, buffer space (memory), and processing capacity at intermediate nodes. In order to achieve this, congestion control system must properly monitor the state of the network. If we fail to do this, then the network, will not be able to work effectively. When some network element is congested, it processes traffic very slowly and hence packets are lost. Hence, users won't receive expected packets (or conformation of delivery) in the time and the system begins to resubmit packets and new packets cause further congestion. Such situation is called congestive collapse [9].

Congestion is intended to occur in wireless sensor networks, when the offered traffic load exceeds the available capacity of sensor nodes. In most wireless applications, every sensor node will send the event it has sensed to a sink node (or base station). This operation makes the sensors closer to the sink, resulting in congestion as indirectly, they tend to act as sink for all previous nodes. Congestion may cause packet loss, lower network throughput and sensor energy waste which leads to increase in latency.

The traditional protocols for controlling congestion cannot be applied for WSNs because of following reasons [11]:

- The traffic in traditional network is disordered because the data flows across each other, while it is centripetal in WSN.
- In wired domain, the bottleneck of congestion occurring is the changing links while with WSN it is the sink or the nodes close to sink.

The main focus of this paper is congestion control techniques for wireless sensor networks. To understand what could cause the congestion in network and how congestion can affect it, we could consider an example: With the introduction and development of Wireless Multimedia Sensor Networks (WMSNs), the upstream traffic can have high bit rate. Such high speed upstream traffic may cause congestion [13]. Further, congestion are of two types: Node level and link level. Node level congestion is caused due to buffer overflow in the node. Whereas interference, contention and bit error causes link level congestion. Congestion leads to packet loss which in turn leads to additional energy consumption and lesser reliability.

Transport protocols are intended to alleviate congestion. Therefore, there are several issues to consider when designing a transport control protocol for Wireless Sensor Networks. We would be considering the following issues as part of this paper [10]:

- Guarantee reliability
- Energy efficiency

Further in this paper we will study how various protocols use different mechanisms to cope up with these challenges.

The remainder of the paper is organized as follows: We first briefly present the schemes which enhance the congestion control performance in the wireless sensor networks. After that we describe the schemes in detail. This will be concluded with a survey of analysed techniques using the congestion control preference formula as per Eq. (1).

II. RELATED WORK

In the literature many congestion control protocols have been developed and proposed with varied design objectives. And hence existing work can be categorized into three groups: transport protocols, centralized congestion control scheme and distributed congestion control scheme [8]. Among these, two categories namely centralized and distributed congestion control schemes are discussed below:

A. Centralized congestion control Scheme

The Transport layer protocols in which congestion control schemes are implemented at the base station or sink fall under this category. Such protocols are: Flush [1], RCRT [3] and STCP [6].

Kim et al. has proposed Flush [1] which is designed as a reliable, bulk transport protocol for wireless sensor networks and assumes that only one flow is active for a given sink at a time.

The authors Paek and Govindan, has put forward RCRT[3], a rate-controlled reliable transport protocol for sensor networks in which sensor readings are transmitted from one or more sensors (sources) to a base station (or sink).

Iyer et al. has proposed STCP [6] (Sensor Transmission Control Protocol) as a generic and flexible transport layer protocol that offers both end-to-end reliability and congestion control mechanism. The majority of functionality is realized at base station.

B. Distributed congestion control scheme

What follows are the protocols that are categorized under this congestion control scheme.

Hull et al. has proposed a congestion control scheme that detects congestion based on queue length and channel sampling. Fusion [4] combines three mechanisms for controlling congestion: hop-by-hop flow control, rate limiting source traffic and prioritized MAC.

CODA [5] (Congestion Detection and Avoidance) is an energy efficient congestion control scheme proposed by Wan et al., that detects congestion based on buffer occupancy and channel load. It comprises of three mechanisms: Receiver based Congestion Detection, open loop hop-by-hop backpressure and closed loop multisource regulation.

Giancoli et al. proposed CTCP [7] (Collaborative Transport Control Protocol) as a reliable and energy efficient congestion control transport layer protocol that adapts itself to different applications through a two level mechanism of reliability variation. It is termed as collaborative because all nodes detect and act on congestion control.

In the next section we will see how these protocols help in controlling congestion through different mechanisms.

III. CONGESTION CONTROL IN WSN

As discussed earlier, congestion could be link level or node level. Congestion increases latency and also degrades link utilization which in turn has an impact on energy efficiency. Hence it is necessary to control congestion efficiently. As stated in section I, an upstream traffic in WMSNs causes congestion; let us see how various protocols with different mechanisms can help control congestion. Three mechanisms that help to achieve this are: congestion recognition, congestion notification and rate adjustment [10].

Congestion recognition - Congestion recognition deals with detecting congestion with the help of some commonly used mechanisms. They can be queue occupancy [3], [9], [12], time to recover loss [5] or channel sampling [4].

Congestion notification - Upon congestion recognition, transport protocols need to disseminate the congestion information from the congested node to sensor node. The way of disseminating information is categorized into implicit congestion notification and explicit congestion notification. The former approach piggybacks congestion information in the data packets. The later makes use of special control messages to notify the involved sensor nodes of congestion like suppression messages used in [5].

Rate adjustment - When congestion indication is received by the sensor node rate adjustment can be implemented by additive increase multiplicative decrease (AIMD) as in [3].

A. Protocols for congestion control

Flush [1] is a receiver-initiated transport protocol for moving bulk data across a multi-hop, wireless sensor network. It follows a centralized congestion control scheme. Flush works with the assumption that only one flow is active for a given sink at a time. It uses a pipelined transmission scheme. It provides end-to-end reliability, reduces transfer time, and adapts to time-varying network conditions. This is accomplished using end-to-end acknowledgments, implicit snooping of control information, and a rate-control algorithm that operates at each hop along a flow. Flush achieves its goal of reliability, using end-to-end reliability protocol. In this the sink keeps track of all received packets. It sends the selective (NACK) requests repeatedly to the source for missing packets until it receives all packets successfully.

Second goal of Flush is to minimize transfer time. But sending packets as quickly as possible poses problems. So, it dynamically estimates the sending rates that will maximize the pipeline utilization. This dynamic rate control algorithm follows two basic rules:

Rule 1: A node should only transmit when its successor is free from interference.

Rule 2: A node's sending rate cannot exceed the sending rate of its successor.

RCRT [3] is a reliable transport protocol that uses end-to-end explicit loss recovery. But congestion detection and rate adaptation are placed at sink (base station) that offers two important advantages: efficiency and flexibility. The design of a multipoint-to-point reliable transport layer protocol is guided by six goals: (1) reliability of end-to-end data transmission by each source to base station. This is a requisite for applications that are loss-intolerant. Such high rate applications include networked imaging, structural health monitoring and acoustic source localization. (2) The second goal is to preserve network efficiency by avoiding congestion collapse. In congestion collapse, sources are sending data faster than the network can transport them to the base station. Consequently, no useful work is done by the network, since packets are repeatedly lost and continually retransmitted. (3) This goal involves explicit support to multiple concurrent applications in RCRT. (4) The fourth goal is flexibility which is offered by allowing different applications to choose different capacity allocation policies. A capacity allocation policy determines how the overall network capacity is apportioned among the different sources. (5)The protocol functionality is isolated from sensors. This goal is motivated by the constraints of the current generation of sensor. (6) The last goal requires the RCRT be robust to routing dynamics and to nodes entering and leaving the system [3]. RCRT basically has three logical components: Congestion Detection, Rate Adaptation and Rate Allocation.

End-to-end Reliability - This is achieved using end-to-end negative acknowledgments. NACK-based end-to-end loss recovery scheme implemented in RCRT guarantees 100\% reliable data delivery. The sink maintains a list of missing packets per flow to detect packet loss. And then requests for the same. The sink also maintains a list of out-of-order packets for each flow to provide in-order delivery of data packets to the application.

Congestion Detection - This component makes decision whether network is congested or not. The congestion detection mechanism is based on the intuition that the network is uncongested as long as end-to-end losses are repaired quickly enough. It uses time to recover loss as a congestion indicator.

Rate Adaptation - RCRT responds to congestion by adapting the transmission rates by AIMD approach. While it uses AIMD, it adapts the total aggregate rate of all the flows as observed by the sink, rather than the rate of a single flow.

Rate Allocation - After the calculation of total rate R(t) by the rate adaptation mechanism, the role of rate allocation component is to implement the capacity allocation policy P_j associated with its sink. The authors have put forth three different policies for the current prototype of RCRT viz., demand-proportional, demand-limited and fair.

STCP [6] - Congestion detection and avoidance is an important aspect in sensor networks. The random early detection (RED) mechanism proposes that an intermediate node drop a packet when it experiences congestion. Hence the source is notified by NACK. STCP adopts a method in which intermediate nodes monitor the load experienced and explicitly notify the end nodes by setting a binary congestion bit in the packets; but with some modification. Each STCP data packet has a congestion notification bit in its header. Every sensor node maintains two thresholds in its buffer: t_{lower} and t_{higher}. When the buffer reaches t_{lower}, the congestion bit is set with a certain probability. When the buffer reaches t_{higher}, the node will set the congestion notification bit in every packet it forwards. When this packet is received at the base station; it informs the source of the congested path by setting the congestion bit in the acknowledgement packet. After receiving the congestion notification, the source may either slow down the transmission rate or route the packets along different path.

Fusion [4] - Fusion, a congestion control scheme has three techniques: hop-by-hop flow control, rate limiting and a prioritized MAC.

Hop-by-hop flow control has two components: congestion detection and congestion mitigation. Congestion can be detected by queue occupancy and channel sampling. One of the easiest way to detect congestion is to monitor a sensor's queue size: if the fraction of space available in the output queue falls below a high water mark α (authors have assumed, $\alpha = 0.25$), the congestion bit of outgoing packets is set; otherwise the congestion bit is cleared. CODA [5] has put forth a different way of detecting congestion. The state of the channel is sampled at a fixed interval. Then depending on the number of times the channel is busy, it will calculate a utilization factor. If this value rises above a certain level, the congestion bit is set otherwise, it is cleared. Congestion mitigation means throttling transmissions to prevent queues at their next-hop node from overflowing. When a sensor receives a packet from its parent with the congestion bit set, it allows its parent to drain its queue by halting the data flow. Hence, the hop-by-hop flow control will not allow the sensor node to send data when the receiver's buffer is full.

The rate limiting scheme is appraised as follows. It is assumed that all sensors offer the same traffic load. N is the total number of unique sources routing through the parent. The N is estimated by the sensor node. Then each sensor's sending rate is regulated by a token bucket scheme. A sensor accumulates one token every time it hears its parent forward N packets, up to a maximum number of tokens. The sensor is allowed to send only when its token count is above zero, and each send costs one token. This approach rate-limits the sensor to send at the same rate of each of its descendants.

The third technique is a prioritized MAC layer that gives a congested node more priority over non-congested node to access the shared medium.

CODA [5] - As discussed in previous section, CODA consists of three mechanisms: Congestion detection, Open-loop, hop-by-hop backpressure and Closed-loop, multi-source regulation. Congestion detection - CODA keeps track of current channel load and buffer occupancy to detect congestion. If any of them exceeds a certain threshold value; the network is said to be congested.

Open-loop, hop-by-hop backpressure - In this mechanism, when a congestion is detected, a backpressure message is propagated to downstream nodes. Upon reception of such a backpressure message the node will throttle its transmission rate and will also decide whether to further propagate this message or not depending on its local network condition.

Closed-loop, multi-source regulation - In this mechanism, the source may regulate itself when it finds that its event rate is less than some fraction of the maximum theoretical throughput of the channel. But if source rate is high, closed-loop congestion control is triggered. At this point a source requires constant feedback from the sink to maintain its rate. As long as the reception of ACKs at sources continues smoothly they can maintain their event rates. But if they fail to receive ACKs sources are forced to reduce their rates.

CTCP [7] – Many times packet loss in sensor networks is due to transmission errors and not the network congestion. And the result of such misconception is the unnecessary rate reduction. Hence, it becomes important to implement a control congestion mechanism that considers the difference between a transmission error packet loss and the buffer overflow. In this proposal, all nodes participate to control congestion. This is done using signalling of messages. The node will broadcast STOP message to its neighbours if its buffer reaches the threshold T. And would resume the sending of packets to it by broadcasting START message to its neighbours. CTCP defines two reliability levels to accomplish energy efficiency.

IV. COMPARATIVE ANALYSIS

From the above reviewed transport layer protocols for congestion control in wireless sensor networks a comparative analysis with few performance measures is presented in the Table I. Different strategies used for controlling congestion and various performance measures used; the techniques are compared based on: how congestion is recognized, how congestion is notified to neighbour nodes or source node, what mechanisms are used to mitigate congestion, the type of control mechanisms used, how is bandwidth allocated and at last how energy efficient is the protocol. The Table II shows some advantages and limitations of various studied congestion control protocols.

TABLE I
COMPARISON OF VARIOUS CONGESTION CONTROL TECHNIQUES FOR WSN

Category	**Protocols**	**Reliability Level**	**Reliability Direction**	**Congestion Recognition**	**Congestion Notification**	**Congestion Avoidance**	**Type of Congestion control mechanisms**	**Bandwidth allocation**	**Energy Efficiency**
CENTRALIZED	Flush[1]	Packet	Upstream	Queue Occupancy OR Link interference	Implicit	Rate Adjustment	Rate-Based scheme	-	No
	RCRT[3]	Packet	Upstream	Time to recover loss	Implicit	Rate Adjustment (AIMD)	Rate-Based scheme	-	No
	STCP[6]	Packet	Upstream	Queue occupancy / length	Implicit	Rate Adjustment, Traffic reduce	Rate-Based scheme	Fair	Yes
DISTRIBUTED	Fusion[4]	Packet	-	Queue length and channel sampling	Implicit	Hop-by-hop flow control, rate limiting	Rate-Based scheme	Priority Based	No
	CODA[5]	-	Upstream	Buffer occupancy and channel load	Hop-b-hop backpressure	End-to-End rate adjustment	Rate-Based scheme	Fair	Yes
	CTCP[7]	Packet	Upstream	Queue occupancy, Transmission error loss	Explicit	Rate Adjustment	Buffer-Based scheme	-	Yes

Every transport layer protocol should support reliability, congestion control and energy efficiency.

A. Reliability

Reliability in wireless sensor networks [3, 5, 9, 12] is achieved by packet reliability or event reliability. Packet reliability is concerned with successful delivery of every packet to appropriate destination whereas, event reliability refers to the successful detection of events. Most of the protocols described here are concerned on packet reliability.

Reliability direction is categorized [2] into upstream reliability or downstream reliability. The former refers to communication between the sensor nodes and sink node. Later is concerned with communication between the sink node and sensor node. All protocols in our study provides upstream reliability.

B. Congestion control

Congestion control comprises of three mechanisms: congestion recognition, congestion notification and congestion avoidance.

Buffer occupancy [2] is one of the parameter used for detecting congestion. Buffer occupancy refers to the occupied buffer memory against the total available memory. CODA [5] uses this parameter to detect congestion. The protocols such as Flush [1], STCP [6] and CTCP [7] monitors queue occupancy for detecting congestion. Furthermore, RCRT [3] detects congestion based on the time required to recover from loss.

Upon congestion recognition, the congestion notification information has to be conveyed from congested nodes to their neighbours. This can be done in two ways: implicitly or explicitly. In implicit congestion notification, the congestion information is piggybacked in normal packets. On the other hand, in explicit congestion notification, the congestion information is sent by an explicit control message [7]. CTCP [7] uses this kind of notification. In Flush [1], RCRT [3], STCP [6] and Fusion [4] congestion is notified implicitly. CODA [5] uses hop-by-hop backpressure for notifying congestion.

Several protocols accomplish congestion control by different mechanisms. The basic classification can be [12]: Rate-based or buffer-based. The basic idea of the rate-based scheme is for a forwarding node to estimate the number of flows coming from each upstream neighbour and assign transmission rate based on fairness once congestion is detected. All protocols except CTCP [7] are based on this scheme. In buffer-based scheme a sensor will send a packet to its downstream neighbour only if the downstream neighbour's buffer has space to accommodate the packet.

C. Bandwidth allocation

Sensor nodes are scattered in a geographical area. Due to the many-to-one convergent nature of upstream traffic, it is difficult for sensor nodes that are far away from the sink to transmit data. Therefore, transport protocols need to allocate bandwidth fairly among all sensor nodes so that the sink can obtain a fair amount of data from all the sensor nodes. STCP [6] and CODA [5] allocates fair bandwidth. On the other hand, Fusion [4] allocates bandwidth based on priority.

D. Energy efficiency

Energy can be effectively utilized if packet losses are reduced. Thus, transport layer protocols should possibly avoid packet loss.

A comparative survey of different protocols using predicted values of Energy Efficiency and Reliability based on theoretical understanding of protocols is given in Table II and III. The preference value for congestion control protocol can be given by,

$$CCP \alpha EE*R \quad (1)$$

where, CCP is Congestion Control Preference that is proportional to the product of EE and R, R denotes reliability in terms of packet delivery rate and EE is Energy efficiency.

Table II and III shows the preference values of centralized and distributed protocols respectively which is calculated by predicted values of R and EE. These predicted values range from 1 to 5 whereas for CCP it ranges from 1 to 10. Here, in both the cases highest value indicates the best whereas lowest indicates the worst.

TABLE II

CCP EVALUATION W.R.T. CENTRALIZED PROTOCOLS

Protocol	**Predicted Value of R**	**Predicted value of EE**	**CCP**
Flush	4	2	8
RCRT	5	2	10
STCP	3	3	9

TABLE II

CCP EVALUATION W.R.T. DISTRIBUTED PROTOCOLS

Protocol	**Predicted Value of R**	**Predicted value of EE**	**CCP**
Fusion	4	2	8
CTCP	3	2	6
CODA	2	5	10

Based on the CCP values from Table I and II, we can conclude that RCRT is preferred over Flush and STCP for centralized category of protocols. Similarly, CODA is preferred over CTCP and Fusion for distributed protocols. Further, a graphical representation with respect to centralized and distributed protocols is given in Fig. 1 and Fig. 2 respectively.

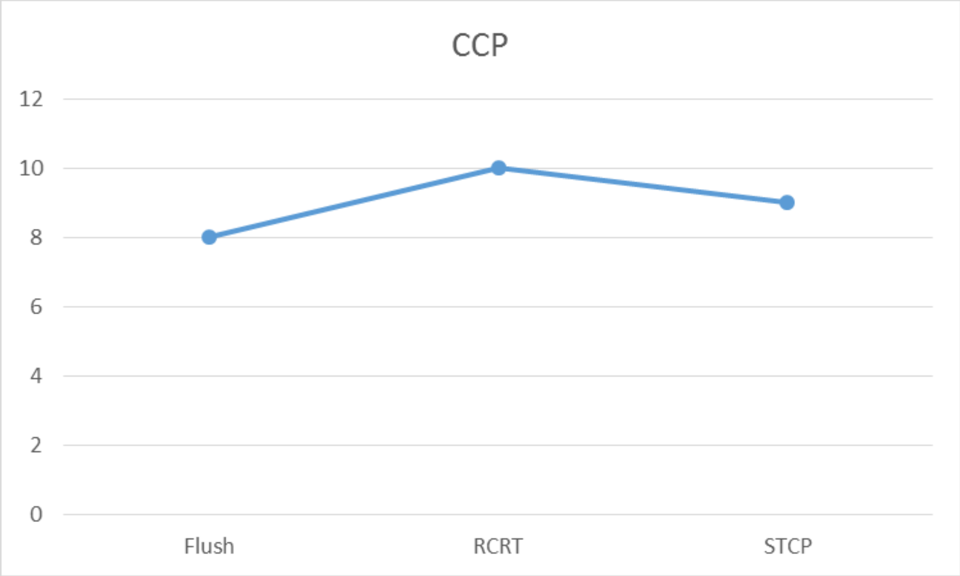

Fig. 1 Preference Analysis of Centralized Protocols

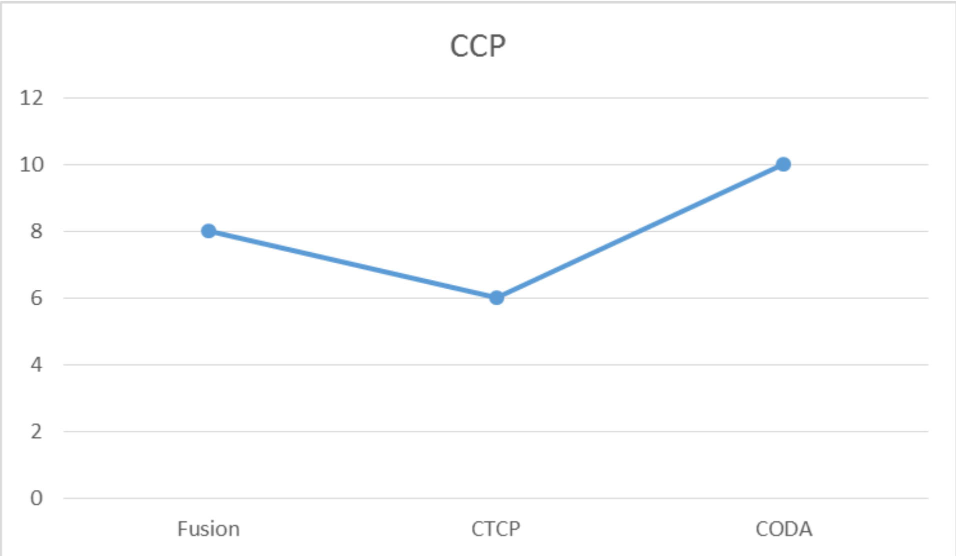

Fig. 2 Preference Analysis of Distributed Protocols

Need of protocol for any application may vary with the nature of applications. In context of this centralized protocols may prove good for some applications whereas distributed for others. For example, in case of critical applications like military or tidal sensors distributed protocols are better. And for non-critical applications like pollution sensors or sensors used internally by industries, centralized protocols are preferred.

V. CONCLUSION

This study, gives a comprehensive assessment of various congestion control proposals for WSNs. In this study, we also assessed various performance metrics that are used for measuring congestion; and an analytical comparison was put forth. Our parameter CCP plays a vital role in selecting the best protocol among two categories viz. centralized and distributed for WSNs. The congestion control techniques discussed in this paper have made a remarkable effort to come up with solutions in order to alleviate congestion in wireless sensor networks from different aspects and situations. Although these congestion control techniques prove to be useful, we still have many challenges that need to be solved in wireless sensor network as far as congestion control is concerned.

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