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Congestion Detection and Avoidance based Transport Layer Protocols for Wireless Sensor Networks

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Abstract:- Congestion can occur in wireless sensor networks when multiple sensor nodes try to transmit data. The sensor nodes closer to sink are more liable to congestion as they generally carry large upstream traffic. Congestion leads to higher packet loss, increased packet delay, less energy efficiency and poor throughput. Thus, congestion control is an important aspect that should be considered while designing transport layer protocols. In this paper, we first describe the basics of wireless sensor networks and their architecture. Then we elaborate the aspects of congestion control. Then we present various transport layer protocols which provide congestion control and then a comparison of these protocols is given on the basis of various parameters viz. congestion detection, congestion notification, congestion mitigation, hbh/e2e, fairness, energy efficiency, simulation/testbed, network topology, number of sensor nodes, buffer size, packet size, radio transmission range, coverage area, channel bit rate, initial transmission rate, simulation time, energy, fairness, latency, queue size, throughput, source rate, packet drop and fidelity . At the end, we present open research issues in congestion control protocols for wireless sensor networks.

Keywords:- Congestion Detection, Congestion Notification, Congestion Mitigation, Transport Layer, Wireless Sensor Networks.

I. INTRODUCTION

Wireless sensor network [1] is comprised of loads of sensor nodes with one or more sink nodes. The sensor nodes are capable of sensing any environmental or physical condition like vibration, temperature, pressure, motion, humidity or sound etc [2]. Sensor networks can be used for habitat monitoring [3], structural monitoring [4], environment surveillance [5], military surveillance or medical diagnostics etc. Sensor node consists of a small processor, memory, power unit, sensing devices, actuators and radio transceivers [6]. Sensor nodes generally use battery or solar power as power unit. Energy is a scarce resource in sensor networks. Sink has enough memory and good processing power. Apart from sink, sensor nodes can be categorized as source and intermediate nodes as shown in Fig. 1. Wireless sensor networks can be categorized as single hop and multi hop. In single hop sensor networks, every node is one hop away from the sink. In multi hop networks, there are intermediate nodes between source and sink. Wireless sensor networks can have two directions of data flow, upstream and downstream [7]. Upstream data flow is from source to sink in which source nodes sense and collect the data from the environment they are deployed in and relay the information to the intermediate nodes on the path to sink. Downstream data flow is from sink to source in which sink queries the network about some event and the nodes which receive the data related to that event respond to the query. Depending upon whether sensor nodes have similar capabilities, sensor networks can be categorized as homogenous and heterogeneous [8-9]. In homogenous sensor networks, every sensor node has same energy, memory and processing power. In heterogeneous sensor networks, some special sensor nodes have extra processing capability.

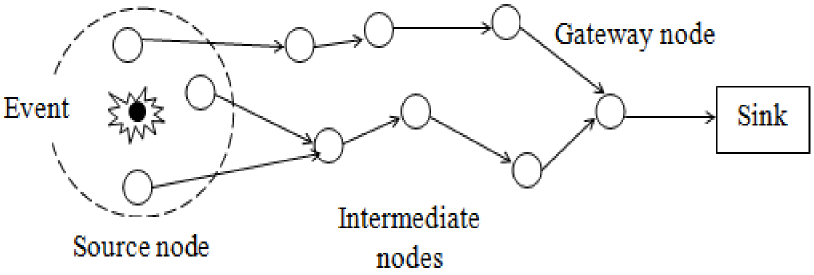

Fig. 1: Wireless Sensor Network

The protocol stack of wireless sensor network consists of five layers: physical layer, data link layer, network layer, transport layer and application layer as shown in Fig. 2 [10]. Physical layer provides facilities of modulation, transmission and receiving techniques. Data link layer provides services such as medium access, data transmission, flow control and error control. Network layer provides the facility of routing the data provided by the transport layer. Transport layer protocols provide services such as reliability, packet loss recovery, congestion control, flow control, energy efficiency and heterogeneous application support [11]. Application layer consists of various protocols which provide numerous sensor network services. The protocol stack for wireless sensor network can also be divided into three management planes across each layer [12]. The planes are task management, power management and connection management. The task management plane distributes tasks among sensor nodes to provide energy efficiency and increase network lifetime. The power management plane deals with the power level of sensor nodes for sensing, processing, transmission and reception of data. The connection management plane maintains the network connectivity in case of situations like topology changes and node deployment.

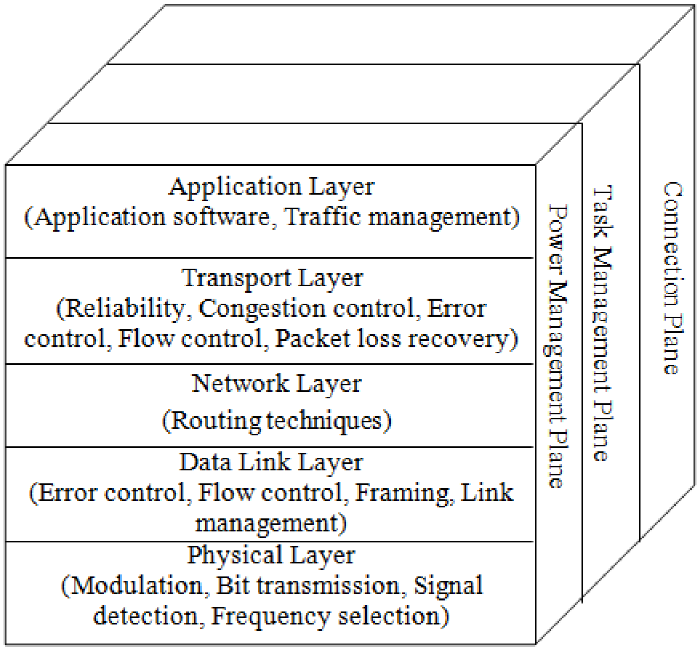
Application Layer
(Application software, Traffic management)
Transport Layer
(Reliability, Congestion control, Error control, Flow control, Packet loss recovery)
Network Layer
(Routing techniques)
Data Link Layer
(Error control, Flow control, Framing, Link management)
Physical Layer
(Modulation, Bit transmission, Signal detection, Frequency selection)
Power Management Plane
Task Management Plane
Connection Plane

Fig. 1: Wireless Sensor Network Architecture.

The rest of the paper is structured as follows: section II discusses basics of congestion control. A brief discussion of various congestion aware transport layer protocols is given in section III. In section IV, a comparison has been made on the basis of various parameters. Section V gives some open research issues related to congestion control protocols. At the end, section VI draws conclusions.

II. CONGESTION CONTROL

Congestion is said to occur in sensor networks when the incoming traffic load becomes greater than the available network capacity [13]. The architectural characteristics of the node and network cause congestion [14]. The architectural characteristics of a node which may lead to congestion are limited memory, slow processor and limited energy of nodes. Sensor nodes have limited memory in the form of buffers. If incoming rate at a node is greater than its outgoing rate, node has to drop packets due to the insufficient capacity of buffers. Slow processors also cause congestion as queues may build up due to them even though there is sufficient network capacity. The limited energy of nodes causes them to go to sleep mode when they are not in the receiving or transmitting mode. The architectural characteristics of network which may lead to congestion are many to one nature, event driven nature, channel interference and reporting rate. Due to many to one nature of sensor networks, congestion is faced by the nodes near the sink as packets from the network converge there. Wireless sensor networks can have two kinds of flows: event driven or periodic [15]. Event driven flows may have fluctuating reporting rate while periodic flows have constant reporting rate. For both these flows, congestion occurs on increasing the reporting rate. In wireless sensor networks, channel contention occurs due to the shared communication channel. It may occur among the packets of same flow or flows passing through the same vicinity.

Congestion can be categorized as link level and node level congestion [16]. The buffer overflow of the sensor node causes node level congestion. It results in packet drops and queuing delays. Packet loss reduces throughput and reliability. It also degrades channel utilization and results in retransmissions which wastes limited energy of nodes. Link level congestion occurs when the wireless channel is shared by nodes using multiple access protocols. Link level congestion occurs when the channel is accessed by multiple sensor nodes at the same time which results in increased packet service time and reduced throughput and link utilization. Congestion can be transient or persistent [17]. In transient congestion, hotspots are created very close to sources. Localized and fast time scale mechanisms are effective to deal with transient congestion as they are capable of providing backpressure. In persistent congestion, hotspots occur closer to sinks. The localized backpressure and packet dropping techniques can be used to deal with persistent congestion.

Congestion can be controlled in two ways: end-to-end and hop-by-hop [18]. End-to-end mechanism relies on end nodes to detect congestion. It can perform exact rate adjustment at sources. It also simplifies the design at intermediate nodes. Here, congestion is indicated in case of time out or redundant acknowledgements. In hop-by-hop mechanism, congestion is detected by intermediate nodes. Hop-by-hop mechanism resolves congestion quickly. Packet loss and energy expenditure is less in hop-by-hop mechanism.

The congestion control mechanism can be divided into three phases: congestion detection, congestion notification and congestion avoidance [19].

A. Congestion Detection

Congestion detection checks the occurrence of congestion and the location of congestion occurrence. Congestion can be detected with the help of various parameters such as channel status, queue length, packet rate, packet service time, packet inter-arrival rate, packet delivery time and node delay etc [19]. Channel status describes how busy the channel is and if the sensed channel load crosses the threshold, it indicates congestion. Queue build up indicates that the packet incoming rate outmatches the packet outgoing rate. So in order to detect congestion, a threshold limit is set and if queue length crosses that threshold, it indicates congestion. Queue length is an effective measure of congestion detection with link layer acknowledgements enabled. Packet rate is defined as the rate at which sensor nodes receive or send packets. Packet service time is the time taken by a sensor node to process a packet. If packet service time becomes greater than the packet inter arrival time, queue builds up and leads to queuing delay. Packet delivery time gives the time taken by a packet to get to the buffer of next node from the buffer of preceding node [20]. It includes transmission time and reception time at the destination along with service time. Node delay signifies the delay a packet has to suffer at a node. If packet gets delayed than expected time, it indicates congestion.

B. Congestion Notification

Congestion notification can be classified as implicit and explicit [19]. The former one piggybacks the congestion information in either data packets or control packets like ACK, RTS or CTS. Overhearing of outgoing packets of downstream nodes can also be used here. The latter one uses special control packet for congestion notification. Explicit congestion notification is rarely used because of the limited sensor energy. The congestion information which is being sent can be a single bit or detailed information. In case of single bit notification, additive increase multiplicative decrease (AIMD) [21] can be used for rate adjustment, while in case of detailed notification; exact rate adjustment can be used. The congestion information can be send to sink, source or the parent node.

C. Congestion Avoidance

Congestion avoidance mitigates congestion in sensor networks. Congestion indicates that the present load is greater than that the network can handle. Thus to alleviate congestion, following schemes can be used: rate control, packet drop, traffic redirection, polite gossip policy and cross layer design optimization [14]. By decreasing the rate and dropping packets, network load is reduced which helps in decreasing the level of congestion. Exact rate adjustment and additive increase multiplicative decrease (AIMD) schemes can be used for rate control. In AIMD, rate is aggressively reduced in case of congestion and additively increased when there is no congestion. In exact rate adjustment scheme, rate adjustment takes place on the basis of the congestion information available from the neighbors. Packets can be dropped to mitigate congestion when buffer of congested node becomes full. The node can adopt the technique of not receiving further packets until the buffer occupancy falls below the threshold limit. In sensor networks, some data is more important than other. So to improve the technique of packet drop, packets can be labeled with priorities so that packet with less priority can be discarded in case of congestion. Traffic redirection redirects the traffic to uncongested paths. In case of congestion, the excess packets can be transmitted to sink through alternative paths. Virtual sinks [22] can also be used to redirect traffic. In polite gossip policy [23], each node broadcasts its metadata to its neighbors periodically. Cross layer interaction [24] between transport and underlying layers is an efficient way of congestion control. MAC layer provides channel status which can be incorporated in congestion control mechanisms.

Fig. 3 shows the working of congestion control protocols in transport layer. Firstly, source nodes sense the event and send packets to intermediate nodes. If intermediate node receives packet, it will check whether congestion has occurred. In case of no congestion the node forwards the packet. But if congestion has occurred, congestion notification step is performed and nodes are notified of congestion and rate adjustment mechanism is followed.

In order to evaluate transport layer protocols providing congestion control, several performance metrics have been proposed which are congestion degree, throughput, latency, energy tax, fairness, deadline miss ratio, average packet loss and fidelity penalty. Congestion degree is a metric for congestion detection which is given by the ratio of packet service time to packet inter-arrival time [25]. Throughput is given by the total number of packets that the sink node receives [26]. Latency is the time between the generation of a packet and its arrival at the destination [27]. Energy tax is given by all the packets dropped in the network divided by all the packets received by the sink node [17]. Fairness means fair allocation of bandwidth among sensor nodes [28]. Fairness allows equal number of packets to be sent to sink from each sensor node. Deadline miss ratio is given by the ratio of the number of packets that arrive at the sink node within deadline to the total number of packets that are sent towards the sink node [29]. Average packet loss is given by dividing all the packets dropped by total number of packets produced in the network. Fidelity penalty is given by the throughput calculated at the sink node with the protocol enabled divided by the throughput calculated at the sink node without enabling the protocol [17].

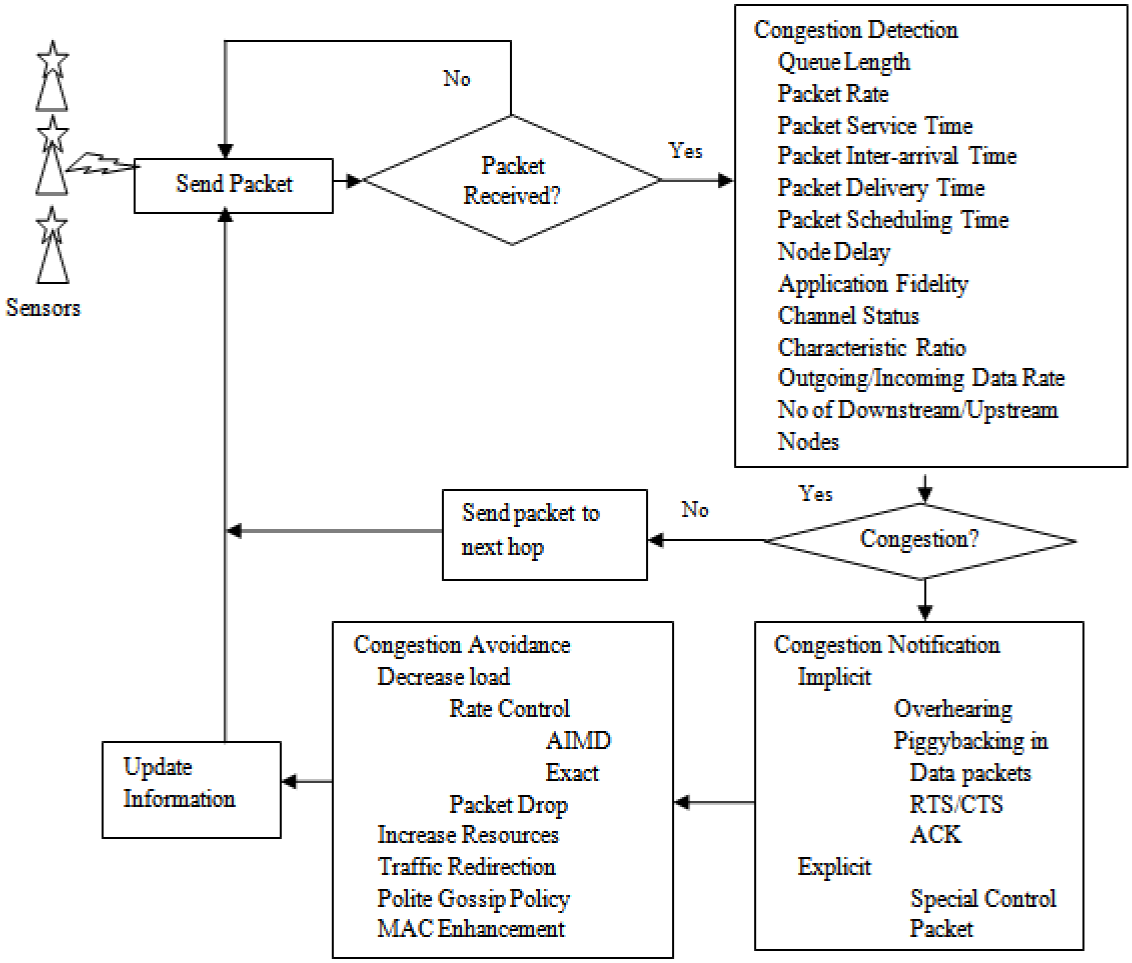

Fig. 3: Congestion control flow chart.

III. TRANSPORT LAYER PROTOCOLS

Transport layer protocols provide services such as reliability, congestion control, flow control, energy efficiency and packet recovery. In this paper we summarize the protocols which provide congestion control.

ARC: Adaptive Rate Control [30] provides efficient medium access control without any use of explicit control packets. In a multi hop network, it also provides fair allocation of bandwidth to the sensor nodes. For congestion detection, it uses whether a node can successfully inject the packet into the network. The packet becomes a part of the route through traffic if it is successfully injected in the network. It is a signal to the children of that node to increase the data generation rate. But if the packet is not successfully injected by the parent, it signals that network is blocked and hence the node reduces its rate of data origination. Thus ARC uses AIMD approach to mitigate congestion. It uses back off period as a phase shift effect to the application periodicity so that synchronization among the periodic traffic streams can be broken.

RAP [29] is a real time communication protocol which provides two types of services: event and query. to ensure fairness, the packets which originate farther from the sink are assigned high priority than the ones that are originated closer to the sink node. RAP provides velocity monotonic scheduling (VMS) to reduce deadline miss ratio. It gives support for both distance and deadline aware scheduling. Deadline aware means priority of packet is related to its deadline while distance aware means priority of the packet is related to its distance. The greater the distance, the higher the priority is and similarly the shorter the deadline, the higher the priority is.

CODA Congestion Detection and Avoidance [17] is an energy efficient congestion control protocol. It uses buffer occupancy and channel status for congestion detection. If buffer occupancy crosses the threshold, it samples the channel to detect congestion. It can handle both transient and persistent congestion. Open loop hop-by-hop backpressure is used to handle transient congestion. In open loop, when congestion is perceived, all the neighboring nodes receive a suppression message to decrease their sending rates. Closed loop multi source regulation is used to handle persistent congestion. In closed loop, sink sends a stream of ACKs to control the transmission rate of sources if congestion is detected. CODA provides a mechanism of implicit priority and maintains acceptable fidelity.

CCF Congestion Control and Fairness [28] provides hop-by-hop congestion control and fair delivery of packets to sink node. It makes use of packet service time at MAC layer to infer congestion. Each node calculates a per node packet rate by dividing the data rate and subtree size. This rate is piggybacked in the header of data packets and propagated downstream by making use of the broadcast nature of the sensor network. Thus no additional control packets are required. CCF uses packet queues and subtree size of every child to provide fairness. CCF provides fairness using epoch based proportional selection or probabilistic selection of sensor nodes for their data transfer. CCF can work with any routing and MAC protocol. It is scalable as it needs to maintain per node state only.

Fusion [31] is a congestion control protocol which consists of three techniques: flow control, rate limiting and prioritized medium access control (MAC). Fusion uses queue occupancy to detect congestion. Local congestion is signaled via backpressure which decreases packet loss and useless transmission of packets which are headed to be dropped at downstream nodes. When congestion is detected, a child can send only one packet to its parent. Parent generally has more traffic to transmit than child. So to provide access to parent, Fusion proposes a prioritized MAC layer technique. Prioritized MAC layer avoids buffer drops by giving priority to backlogged nodes for shared medium access. The problem of unfairness towards the sources whose packets have to move over multiple hops is resolved using source rate limiting.

Trickle [23] is a sensor network protocol which provides code propagation. Polite gossip policy is used for code metadata exchange with nearby neighboring nodes. Trickle exchanges code metadata instead of actual code. Code metadata is sent periodically but if nodes hear new metadata they reduce their broadcast period so that updates can be send quickly. If nodes hear same data from their neighbors, they suppress their own broadcast. Trickle does not flood the network; instead it just sends a trickle of data so that nodes can stay up-to-date. All messages are sent to local broadcast address. Trickle broadcast results in two possibilities: either a recipient detects the need of an update or every node is already up-to-date. This broadcast takes place because an updated node hears that some node has older code or an out-of-date node hears that some node has new code.

Siphon [22] provides congestion control. and handles funneling effect. Funneling effect means where generated events move quickly towards the sink nodes. Siphon uses queue length to detect congestion. But despite rate control, it employs traffic redirection for congestion control. Virtual sinks are used to provide traffic redirection. They are used to cut down the load of loaded sensor nodes. They redirect the load from overloaded physical sensors to virtual sinks. Siphon has the stargate implementation of virtual sinks. Siphon consists of two radios: one with long range and another with short range. Events are siphoned to physical sinks using radios with long range. The radio with short range interacts with sensor field at the siphon points.

SenTCP Sensor Transport Control Protocol [32] provides congestion control for upstream traffic. It makes use of buffer occupancy and congestion degree to detect congestion. Upon congestion detection, intermediate nodes issue feedback signal, which consists of local buffer occupancy and congestion degree. Source node and intermediate nodes demands for transmission rate adjustment upon receiving the feedback signal and then they will decide whether they should relay the feedback signal backward. If they need to relay the feedback signal, they should update the information carried in the feedback signal using their own congestion information. Congestion is regulated quickly by hop-by-hop feedback control and packet drops are reduced which in turn leads to energy efficiency and increased throughput.

PCCP Priority based Congestion Control [15] is congestion control protocol based on node priorities. Nodes are assigned priority on the basis of their location or function. It deals with two types of congestion: link and node level. PCCP detects congestion using packet inter-arrival time and packet service time. It enables cross layer optimization. PCCP embarks congestion information in data packet header. PCCP uses status information of parent to perform exact rate adjustment. PCCP realizes priority based fairness. It provides different priorities to routed and generated traffic. In PCCP, the node having high priority will get high bandwidth. When there is low congestion, PCCP has a drawback of increasing the source transmission rates without considering their node priority. PCCP mitigates only local congestion without considering the fact that congestion may happen in the next time interval.

IFRC Interference aware Fair Rate Control [33] is a rate allocation protocol. It makes use of queue length for congestion detection. It uses two thresholds to infer congestion. It communicates the congestion information via overhearing. IFRC uses AIMD scheme to adjust outgoing rate to control congestion at each link. IFRC assigns the data rate which is lowest among the interfering neighbors of the congested node. The potential interferes of a node includes, its neighbors, neighbors of its parent and neighbors of its parent’s parent. IFRC circulates congestion information and data rate among the neighbors to ensure fairness. IFRC reduces packet drops by reducing the throughput. The scheme of collecting rate information from neighbors increases processing overhead and energy consumption.

LWBM Light Weight Buffer Management [34] is a buffer based congestion avoidance technique. It prevents the buffer of intermediate nodes from overflowing with the data packets of intermediate nodes. It provides fairness in buffer access. It performs load balancing over various paths to multiple sinks. It uses buffer status to infer congestion. Each node propagates its buffer status to its neighboring nodes using piggybacking. In LWBM, a node sends data only when receiving node’s buffer is not full. Thus, it adjusts the sensor node’s transmission rate to approximate optimal values and avoids congestion. It implements congestion control in various MAC techniques like TDMA with fixed interval and CSMA with implicit ACK enabled.

TARA Topology Aware Resource Adaptation [35] makes use of resource control to alleviate congestion. That is, in case of congestion, it enables more nodes to become active to increase the capacity. TARA uses buffer occupancy and channel loading to infer congestion. It makes use of two nodes to alleviate congestion, distributor and merger node. It establishes a detour path from the distributor to the merger. Hotspots occur between the alternative path and the original path. The traffic from the hotspot is distributed by the distributor and the two flows are merged by the merger. The network stops the use of alternative path when congestion is alleviated. TARA is a topology aware, energy efficient and distributed protocol. It makes use of capacity analysis model to determine the required topology.

CAF Congestion Avoidance and Fairness [36] controls congestion using topology information. It uses buffer occupancy of downstream nodes to detect congestion. CAF provides efficient load balancing and fairness by monitoring buffer occupancy. CAF calculates characteristic ratio using the count of downstream and upstream nodes. CAF makes use of this information for rate adjustment of upstream nodes. CAF uses adaptive rate adjustment where a node transmits a packet only when it is sure that the next node can hold the packet in its buffer otherwise the node keeps the packets and fills its own queue. In case of transient congestion a rippling effect is produced from the congestion spot towards upstream direction. In case of severe congestion, downstream nodes fill their buffers and thus refrain from sending packets which results in source transmission rate reduction.

HCCP Hybrid Congestion Control Protocol [37] exists between network layer and MAC layer. It is called hybrid as it considers both packet delivery rate and buffer size of nodes. It calculates congestion degree to detect congestion. Congestion degree is calculated using buffer size, incoming data rate and outgoing data rate. If congestion degree is greater than zero, it indicates buffer is in light state and there will be no congestion in the next time interval. If congestion degree is less than zero, buffer of the node is in heavy state and there is a possibility of congestion in the next time interval. The congested sensor node advertises its congestion degree to its neighbors by broadcasting a suppression message. It adjusts the rate of upstream neighboring nodes to provide congestion control.

PHTCCP Prioritized Heterogeneous Traffic-oriented Congestion Control Protocol [38] provides proficient rate control for prioritized heterogeneous data. To ensure feasible transmission rates of heterogeneous data, it uses inter queue and intra queue priorities. Sink nodes assign priorities to each type of sensed data. Packet service ratio is employed to detect congestion which is given by dividing packet service rate and packet scheduling rate. When this ratio is greater than or equal to one, it reflects decrease in the level of congestion. When this ratio is less than one, it reflects link level congestion as packets will be queued up. Packet service ratio is capable of indicting both link and node level congestion. PHTCCP makes use of hop-by-hop rate control. It guarantees that heterogeneous data reaches the sink at required rates. It also ensures efficient utilization of link capacity.

MCCP Multievent Congestion Control Protocol [20] supports three types of event reporting: general, fair and prioritized. Sink node selects the suitable reporting mode. Buffer size and packet delivery time are used to infer congestion. The packet delivery time of a node exceeding the same of its previous node results in buffer overflows and hence causes congestion. It assigns priorities to source traffic and transit traffic. It divides queue length of a sensor node in three categories: low, optimal and high. MCCP tries to keep the queue length in optimal range. For any other range, sensor nodes will adjust the reporting rates of its previous nodes through slot time. In MCCP, sensor nodes calculate slot length on the basis of network conditions. MCCP reduces packet drops and increases system throughput.

UHCC Upstream Hop-by-hop Congestion Control protocol [39] provides upstream congestion control and priority based fairness. UHCC is a cross layer protocol as it calculates congestion index with the help of traffic rate and unoccupied buffer size at MAC layer. If congestion index is less than zero, it indicates buffer overflow, otherwise it indicates that buffer has space to hold the traffic. Rate Adjustment component calculates new rates for child nodes and source traffic with its source traffic priority. It piggybacks the new rate information in packets to inform the child nodes and parent nodes. It uses rate adjustment for congestion mitigation. While adjusting the rate, it considers whether the node can become congested in the next time interval.

FACC Fairness Aware Congestion Control [40] provides both congestion control and fair bandwidth allocation for each data flow. It uses packet drop at sink to detect congestion. On the basis of location of nodes, FACC divides nodes into two classes: nodes which are closer to sink and nodes which are closer to source. Nodes closer to source nodes maintain state of each flow. Nodes closer to sink node drop packets on the basis of some probabilistic method. Hit frequency and buffer occupancy are used to decide about packet drops. In case of packet loss, nodes closer to sink send a warning message to the nodes closer to source nodes. These nodes transmit control message to source nodes which in turn perform transmission rates adjustment considering the status of channel and present transmission rates.

CADA Congestion Avoidance, Detection and Alleviation [41] provides high data transmission quality in case of congestion. Firstly it tries to prevent congestion by selecting a small number of nodes from the event area and suppressing their data rates. When congestion becomes inevitable due to traffic mergence, it uses buffer occupancy and channel utilization to detect congestion. It can alleviate congestion in two ways: resource control and traffic control. Resource control tries to alleviate congestion by exploiting available network resources. Traffic control alleviates congestion by rate adjustment of source and intermediate nodes. Each node has a record of the state information of the incoming traffic. Resource control can mitigate congestion in an intersection hotspot. Traffic control can mitigate congestion in a convergence hotspot.

ECODA Enhanced Congestion Detection and Avoidance [42] uses both MAC layer and Network layer information. It uses weighted buffer difference and two buffer thresholds to infer congestion. It estimates channel status. It has a flexible packet scheduler which can dynamically schedule next packet to send. ECODA handles both transient and persistent congestion differently. It makes use of hop-by-hop backpressure mechanism to handle transient congestion. It uses a source transmission rate control scheme based on bottleneck node and multipath load balancing to handle persistent congestion. Thus it can find out bottleneck nodes and adjust the source sending rates accordingly. ECODA assigns two priorities to every packet: static and dynamic. If queue is nearly full, it does not use tail dropping; instead it drops low priority packets. ECODA provides fairness by scanning the queue for routed traffic from end to top.

DPCC Dynamic Priority based Congestion Control [43] exploits dynamic priority to represent significance of packets. When wireless multimedia sensor network is highly congested, the traffic of nodes near the sink is prioritized to maintain a good throughput. DPCC defines three types of traffic: normal, quick and urgent. It has three queues one for each type of traffic. It also has a classifier which can classify the traffic and put them into relevant queues. It uses congestion index to infer congestion which is given by dividing packet scheduling rate and packet service rate. When congestion index is less than one, it indicates no congestion. When congestion index is greater than one, it indicates congestion as packets will be queued up. Congestion information is embarked on data packets. It uses dynamic priority based rate adjustment.

HCCC Hop-by-hop Cross layer Congestion Control [44] uses MAC layer information to infer congestion. It uses buffer occupancy ratio and congestion degree for congestion detection. Congestion degree is given by dividing packet inter-arrival time and packet service time. It informs upstream neighbors by making use of RTS and CTS frames. HCCC generates and transmits feedback signals before transmitting data packets. It regulates channel access priority and data transmission rate to control congestion. Data transmission rate depends upon channel access priority which in turn depends upon the size of contention window. Thus it uses contention window size to adjust transmission rate.

FBCC Feedback Congestion Control [45] is a congestion control protocol. It also ensures fairness. It is designed using linear discrete time control theory. Lyapunov-Krasovskii scheme is used to prove the stability of this method. It infers congestion using queue occupancy. Queue occupancy is calculated using incoming and outgoing traffic rate. In case of congestion, the parent node is informed. The parent node adjusts data transmission rate and transmits the packet to another child node. FBCC requires that sum of children traffic should not exceed the parent traffic. FBCC increases throughput, energy efficiency, quality of service and network efficiency.

HTAP Hierarchical Tree Alternative Path [26] mitigates congestion by forming dynamic alternative paths to sinks. The topology control scheme of HTAP provides the primary connectivity in the sensor network. The tree formation scheme comes up with all the routes from source to sink. HTAP uses queue occupancy to detect congestion. It uses the outgoing to incoming data rate to start the creation of alternative paths. These alternative paths consist of nodes which are not present in the original path. When congestion occurs in the network, it reroutes the excess traffic to sink through alternative paths. The powerless nodes are taken care by informing the neighbors of the situation and paths are updated by removing the power extinct node from them.

LABP Learning Automata Based Protocol [46] provides congestion control. It assigns priorities to source and transit traffic. It calculates congestion degree to infer congestion. Congestion degree is given by dividing packet service time and packet arrival time. If congestion degree is greater than one, it indicates congestion. Wireless channel’s broadcast nature is used by the congested node to inform neighbors of its state. Intermediate nodes interact with the environment and adjust the rate on the basis of buffer occupancy. Every node has learning automata which takes the decisions. It trains itself using the past behavior. Here an action is selected and rate is adjusted based upon the response of the environment.

IV. COMPARATIVE ANALYSIS OF PROTOCOLS

In section III, we furnished a brief discussion of congestion aware transport layer protocols. Their major features are summarized in Table 1. In Table 1, comparison has been made on these protocols using different parameters like congestion detection, congestion notification and congestion avoidance, hbh/e2e, fairness, energy efficiency.

Table 1: Comparison of various congestion aware transport layer protocols for wireless sensor networks.

Protocol	Congestion Detection	Congestion Notification	Congestion Mitigation	HbH/ E2E	Fairness	Energy Efficiency
ARC(Woo et al., 2001)	**The event of successful transmission of packets**	**Implicit**	**AIMD rate control**	**HbH**	**Fair**	**Yes**
RAP(Lu et al., 2002)	**-**	**-**	**MAC enhancement, packet dropping**	**E2E**	**Fair**	**-**
CODA(Wan et al., 2003)	**Queue length, channel status**	**Explicit**	**AIMD rate control**	**E2E**	**Fair**	**Yes**
CCF(Ee et al., 2004)	**Packet service time**	**Implicit**	**Exact rate control**	**HbH**	**Fair**	**Yes**
Fusion(Hull et al., 2004)	**Queue length**	**Implicit**	**Stop and start rate control**	**HbH**	**Priority based**	**No**
Trickle(Levis et al., 2004)	**-**	**-**	**Polite gossip technique**	**HbH**	**-**	**No**
Siphon(Wan et al., 2005)	**Queue length, application fidelity**	**-**	**Traffic redirection via virtual sinks**	**HbH**	**-**	**Yes**
SenTCP(Hu et al., 2005)	**Queue length, packet service time, packet inter-arrival time**	**Explicit**	**Rate control**	**HbH**	**Fair**	**Yes**

PCCP(Wang et al., 2006)	**Packet inter-arrival time, packet service time**	**Implicit**	**Exact rate control**	**HbH**	**Priority based**	**Yes**
IFRC(Rangwala et al., 2006)	**Queue length**	**Implicit**	**AIMD rate control**	**HbH**	**Fair**	**No**
LWBM(Chen et al., 2006)	**Queue length**	**Implicit**	**Rate control to near optimal value**	**HbH**	**-**	**Yes**
TARA(Kang et al., 2007)	**Queue length, channel status**	**Implicit**	**Dynamically enabling backup nodes**	**E2E**	**-**	**No**
CAF(Ahmad et al., 2008)	**Queue length, characteristic ratio**	**Implicit**	**Adaptive rate control**	**HbH**	**Fair**	**Yes**
HCCP(Sheu et al., 2008)	**Queue length, incoming data rate, outgoing data rate**	**Implicit**	**Rate control**	**HbH**	**-**	**No**
PHTCCP(Monowar et al., 2008)	**Packet service ratio**	**Implicit**	**Rate adjustment**	**HbH**	**Priority based**	**Yes**
MCCP(Hussain et al., 2009)	**Packet delivery ratio, queue length**	**-**	**Schedule based rate control**	**HbH**	**Both**	**Yes**
UHCC(Wang et al., 2009)	**Queue length, traffic rate at MAC layer**	**Implicit**	**Rate control**	**HbH**	**Priority based**	**-**
FACC(et al., 2009)	**Packet drop at sink node**	**Explicit**	**Rate control**	**HbH**	**Fair**	**Yes**
CADA(Fang et al., 2010)	**Queue length, channel status**	**Implicit**	**Resource control, rate adjustment**	**HbH**	**-**	**Yes**
ECODA(Tao et al., 2010)	**Dual buffer threshold, weighted buffer difference**	**Implicit**	**Rate control**	**HbH**	**Fair**	**Yes**
DPCC(Lin et al., 2011)	**Packet scheduling rate, packet service rate**	**Implicit**	**Exact rate control**	**HbH**	**Priority based**	**No**
HCCC(Wu et al., 2011)	**Packet inter-arrival time, Packet service time, queue length**	**Explicit**	**AIMD rate control, channel access priority adjustment**	**HbH**	**Fair**	**Yes**
FBCC (Li et al., 2012)	**Queue length**	**Implicit**	**Traffic redirection**	**HbH**	**Fair**	**No**
HTAP(Sergiou et al., 2013)	**Queue length, out/in data rate**	**Implicit**	**Alternative path (Traffic redirection)**	**HbH**	**-**	**No**
LABP(Hashemzehi et al., 2013)	**Packet service time, packet inter-arrival time**	**Implicit**	**Learning automata based rate control**	**HbH**	**-**	**Yes**

Different techniques have been adopted by different protocols for congestion detection. Combination of parameters like queue length, packet rate, channel status, node delay, packet service time, packet drop, packet delivery time, characteristic ratio, packet scheduling rate, incoming to outgoing rate, count of downstream to upstream nodes, and packet inter-arrival time are used for congestion detection. Fusion, IFRC, FBCC and LWBM detect congestion on the basis of queue length only. CODA uses both queue length and channel status to infer congestion. ARC infers congestion using the event if packets are successfully forwarded. CCF makes use of packet service time for congestion detection. Siphon detects congestion using queue length, application fidelity and channel status. SenTCP detects congestion using queue length and congestion degree. TARA and CADA use buffer occupancy and channel load. Protocols such as PCCP, DPCC, PHTCCP, UHCC and HCCC use cross layer information to infer congestion. PCCP and LABP infer congestion using packet inter-arrival and packet service time. PHTCCP makes use of packet service and scheduling rate. MCCP uses packet delivery time and buffer size. UHCC uses traffic rate at MAC layer and unoccupied buffer size to infer congestion. FACC uses packet drop at sink to detect congestion. CAF uses buffer occupancy and characteristic ratio. ECODA infers congestion via weighted buffer difference and dual buffer threshold. DPCC uses the ratio of packet scheduling rate to packet service rate to detect congestion. HCCC uses packet service time, buffer occupancy ratio and packet inter-arrival time. HCCP and HTAP detect congestion using queue length and ratio of outgoing rate to incoming rate.

Congestion can be notified in two ways: implicit or explicit. Most of the protocols notify congestion in implicit manner. ARC notifies congestion by overhearing of successful transmission or not by the parent node.

Fusion uses backpressure to notify congestion. Congestion information is piggybacked in the header of forwarded packets for CCF, PCCP, IFRC, LWBM, PHTCCP, UHCC, HCCP, CAF, DPCC, FBCC and LABP protocols. CADA piggybacks congestion information in ACK frame. Only CODA, HCCC and FACC use explicit congestion notification. In CODA, upstream neighbors are notified via a backpressure message. HCCC makes use of RTS and CTS frames for congestion notification.

Mostly transport layer protocols use AIMD or exact rate adjustment to avoid congestion. Both ARC and CODA use AIMD. The difference is that ARC performs hop-by-hop rate adjustment while CODA performs end-to-end rate adjustment. RAP uses MAC enhancements and packet dropping. CCF, PCCP and DPCC use exact rate adjustment. Fusion uses stop and start rate adjustment. Trickle uses polite gossip policy. Siphon uses traffic redirection via virtual sinks. LWBM uses rate adjustment to near optimal value. TARA dynamically enables backup nodes to handle congestion. CAF uses adaptive rate adjustment. PHTCCP and FACC use hop-by-hop rate adjustment. MCCP adjusts rate of its previous hops through slot adjustment. SenTCP, UHCC, HCCP and HCCC use rate adjustment. CADA uses both resource control and rate control. ECODA uses bottleneck node base source sending rate control. HCCC also uses channel access priority adjustment. FBCC and HTAP use traffic redirection. LABP uses learning automata based rate adjustment.

Congestion can be controlled in two ways: end-to-end or hop-by-hop. Only RAP, CODA and TARA protocols employ end-to-end mechanism for congestion control. Rest of the protocols employs hop-by-hop congestion control mechanism.

Some protocols provide energy efficiency; some provide fair bandwidth allocation, while others provide both energy efficiency and fairness. Protocols which support fair bandwidth allocation are ARC, RAP, CODA, CCF, SenTCP, HCCC, ECODA, FACC and CAF. ECODA provides flexible weighted fairness. Some protocols provide priority based fairness. These protocols are Fusion, PCCP, PHTCCP, UHCC and DPCC. PCCP and UHCC assign priorities to nodes. PHTCCP handles prioritized heterogeneous traffic. DPCC uses dynamic priority to represent significance of the packet. In case of congestion DPCC prioritizes the traffic of nodes near the sink. Protocols such as ARC, CODA, CCF, Siphon, PCCP, LWBM, CAF, PHTCCP, FACC and HCCC are energy efficient.

Table 2 compares these protocols on the basis of simulation/testbed, network topology, number of sensor nodes, buffer size, packet size, radio transmission range, coverage area, channel bit rate, initial transmission rate and simulation time. Transport layer protocols can be implemented in simulator, testbed or both. Table 2 shows which protocols are implemented in simulator and which protocols are implemented in testbed. RAP is simulated in GloMoSim simulator [47]. The protocols which are simulated in ns-2 [48] are: CODA, Siphon, TARA, PHTCCP, MCCP, DPCC, HCCC, HCCP, FACC, CADA and ECODA. Trickle and IFRC are implemented in TinyOS [49]. Siphon and Fusion are implemented on Mica2 motes. CODA and CCF are implemented on testbed using Berkeley motes. HTAP is implemented in Prowler simulator [50] while LABP is implemented in OPNET simulator [51]. Most of these protocols have either adhoc or grid topology. Some protocols have tree or linear topology. ARC, IFRC, MCCP, UHCC, ECODA, DPCC and LABP have tree topology. RAP, Trickle, Siphon, CAF and HTAP have grid topology. SenTCP has linear topology. Rest of the protocols has adhoc topology. The following Table 2 gives the rest of the parameters.

Table 2: Comparison of congestion aware transport layer protocols on the basis of simulation parameters.

Protocol	Simulation /testbed	Network topology	No of sensor nodes	Buffer size (pkts)	Packet size (bytes)	Radio tx range (metres)	Coverage area (metre^2)	Channel bit rate (bps)	Initial tx rate (pkts/s)	Simulation time (seconds)
ARC	Simulation	Tree	12	-	30	-	-	-	5	1800
RAP	Simulation	Grid	100	-	32-160	30.5	136 × 136	50 K	-	-
CODA	Both	Ad-hoc	30	-	64	40	-	-	-	30
CCF	Both	Ad-hoc	116	10	30	-	-	19.2 K	0.5	50000
Fusion	Testbed	Ad-hoc	55	-	36	-	1493	38.4 K	0.25	-
Trickle	Testbed	Grid	19	-	36	-	160 × 40 inch^2	-	40	-
Siphon	Both	Grid	48	-	-	40, 250	-	2 M	1	1800
SenTCP	Simulation	Linear	20	200	250	-	-	-	-	90
IFRC	Testbed	Tree	40	64	32	-	1125	250 K	0.02	4200
LWBM	Simulation	Ad-hoc	500	12	30	100-200	1000 × 1000	512 K	10	200
TARA	Simulation	Ad-hoc	81	10	100	-	160 × 160	2 M	1	-

CAF	**Simulation**	**Grid**	**100**	**15**	**30**	**250**	**400 × 400**	**-**	**10**	**180**
HCCP	**Simulation**	**Ad-hoc**	**500**	**32**	**40**	**100**	**1000 × 1000**	**512 K**	**4**	**200**
PHTCCP	**Simulation**	**Ad-hoc**	**100**	**10**	**29,33,41, 64**	**30**	**100 × 100**	**32 K**	**4**	**60**
MCCP	**Simulation**	**Tree**	**21**	**50**	**36**	**20**	**100 × 100**	**-**	**-**	**-**
UHCC	**Simulation**	**Tree**	**10**	**10-100**	**1**	**-**	**-**	**1 M**	**-**	**400**
FACC	**Simulation**	**Ad-hoc**	**51**	**-**	**1000**	**-**	**1000 × 1000**	**-**	**-**	**150**
CADA	**Simulation**	**Ad-hoc**	**2000**	**10**	**30**	**100**	**500 × 500**	**2 M**	**-**	**-**
ECODA	**Simulation**	**Tree**	**35**	**20**	**36**	**70**	**1000 × 1000**	**-**	**-**	**250**
DPCC	**Simulation**	**Tree**	**90**	**8**	**32**	**50**	**-**	**-**	**1**	**6000**
HCCC	**Simulation**	**Ad-hoc**	**100**	**500**	**200**	**30**	**100 × 100**	**2 M**	**5**	**400**
FBCC	**Simulation**	**-**	**-**	**120**	**-**	**-**	**-**	**-**	**-**	**3.5**
HTAP	**Simulation**	**Ad-hoc, Grid**	**100**	**512 K**	**1**	**-**	**500 × 500**	**250 K**	**-**	**-**

Table 3 compares these protocols on the basis of performance metrics used by these protocols. The performance metrics shown in Table 3 are: energy, fairness, latency, queue size, throughput, source rate, packet drop and fidelity. ARC, CODA, Fusion, Siphon, SenTCP, LWBM, TARA, CAF, PHTCCP, MCCP, CADA, DPCC, HCCC and HTAP use energy metric. Fairness metric is used by ARC, CCF, Fusion, PCCP, UHCC and FACC. PHTCCP, CADA, ECODA, DPCC and HTAP use latency metric. Queue size is used by PCCP, IFRC, CAF and FBCC. Throughput is used by CCF, PCCP, IFRC, CAF, PHTCCP, MCCP, UHCC, FACC, CADA, ECODA, HCCC and HTAP. Source rate is used by CCF, LWBM, HCCP and CADA. Packet drop is used by SenTCP, IFRC, LWBM, HCCP, PHTCCP, UHCC, FACC, DPCC, HCCC, FBCC and LABP. Fidelity is used by CODA, Siphon, TARA and CADA. RAP uses deadline miss ratio. Fusion makes use of node imbalance. Trickle uses redundancy and total transmissions per interval.

Table 3: Performance metrics used by congestion aware transport layer protocols in Wireless sensor networks.

Protocol	Energy	Fairness	Latency	Queue size	Throughput	Source rate	Packet drop	Fidelity
ARC	✓	✓	✗	✗	✗	✗	✗	✗
CODA	✓	✗	✗	✗	✗	✗	✗	✓
CCF	✗	✓	✗	✗	✓	✓	✗	✗
Fusion	✓	✓	✗	✗	✗	✗	✗	✗
Siphon	✓	✗	✗	✗	✗	✗	✗	✓
SenTCP	✓	✗	✗	✗	✗	✗	✓	✗
PCCP	✗	✓	✗	✓	✓	✗	✗	✗
IFRC	✗	✗	✗	✓	✓	✗	✓	✗
LWBM	✓	✗	✗	✗	✗	✓	✓	✗
TARA	✓	✗	✗	✗	✗	✗	✗	✓
CAF	✓	✗	✗	✓	✓	✗	✗	✗
HCCP	✗	✗	✗	✗	✗	✓	✓	✗
PHTCCP	✓	✗	✓	✗	✓	✗	✓	✗
MCCP	✓	✗	✗	✗	✓	✗	✗	✗
UHCC	✗	✓	✗	✗	✓	✗	✓	✗
FACC	✗	✓	✗	✗	✓	✗	✓	✗
CADA	✓	✗	✓	✗	✓	✗	✗	✓
ECODA	✗	✗	✓	✗	✓	✗	✗	✗
DPCC	✓	✗	✓	✗	✗	✗	✓	✗
HCCC	✓	✗	✗	✗	✓	✓	✓	✗
FBCC	✗	✗	✗	✓	✗	✗	✓	✗
HTAP	✓	✗	✓	✗	✓	✗	✗	✗

V. OPEN RESEARCH ISSUES IN CONGESTION CONTROL PROTOCOLS

The main features of transport layer protocols are reliability, congestion control, packet loss recovery, heterogeneous application support, energy efficiency and fairness. Reliability means successful delivery of packets to the destination nodes. Protocols like PSFQ, STCP, ESRT [52] etc provide reliability. Packet loss recovery mechanism is needed in case of packet loss. Packets can be recovered in two modes: end-to-end and hop-by-hop. With the help of modern motes having multiple sensors, heterogeneous applications can be supported in one sensor network. Thus transport layer protocols should make use of multi-purpose motes in wireless sensor network.

1. The protocols studied in section III and IV provide only congestion control. Mostly protocols focusing on congestion control reduce reliability. As reliability is an important aspect so some wireless sensor network applications require both reliability and congestion control.
2. The protocols studied in section III and IV do not provide packet recovery mechanism [53]. Packet recovery mechanism is needed because packets are susceptible to loss in wireless sensor networks due to several reasons such as node failure, route failure and congestion etc.
3. Some applications require mechanisms to control congestion in both upstream and downstream directions while most of these protocols except CODA provide congestion control in upstream direction only. Thus there is a need of transport layer protocols which offer congestion control in both upstream and downstream directions.
4. Congestion control protocols resolve congestion using end-to-end or hop-by-hop mechanism. There are no protocols which uses both mechanisms at the same time except CODA. But CODA simply uses both of these techniques. It has no mechanism to integrate these two techniques for optimization. Thus there is a need of protocols which integrates both these techniques for optimized results.
5. Transport layer can get useful information from network layer and MAC layer which can optimize the process of congestion control. Few protocols like PCCP, PHTCCP, UHCC, HCCC and DPCC use cross layer information from MAC layer for congestion detection and rate adjustment. The process of congestion detection will be optimized if transport layer protocols use cross layer information from both Network and MAC layer such as routing algorithm can inform transport layer protocol about route failure and thus transport layer can identify that route failure is the reason for packet loss not congestion.
6. Congestion control protocols support either event data or continuous data. But there is a need of protocols which can support both event driven and continuous flows. Only PHTCCP protocol provides support for heterogeneous traffic. Some wireless sensor network applications require support for heterogeneous data. So there is a need of proficient congestion control protocols which can handle diverse data within a single sensor node.
7. The use of AIMD for rate control gives biased results such as in CODA. The sensor nodes closer to sink gets higher sending rates as compared to the nodes deeper in the network. This causes the sink to receive an uneven number of packets from the sensor nodes. Thus exact rate adjustment should be used for rate control.

VI. CONCLUSION

This article has surveyed several congestion aware transport layer protocols for wireless sensor networks. Firstly, we described the concept of sensor networks and their architecture. Secondly, we described the aspects of congestion control in wireless senor networks. Then we provided the summary of existing transport layer protocols which provide congestion control. These congestion control protocols try to increase the network lifetime. Then we presented a comparative analysis of these protocols using parameters like congestion detection, congestion notification, congestion avoidance, simulation/testbed, network topology, number of sensor nodes, buffer size, packet size, radio transmission range, coverage area, channel bit rate, initial transmission rate, simulation time and performance metrics used by these protocols. Finally we presented some open research issues for congestion aware transport layer protocols in wireless sensor networks.

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