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Rate Adjustment Based Congestion Control Protocols in Wireless Sensor Networks

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Abstract— Wireless sensor networks are mainly used for event detection having huge number of sensor nodes distributed geographically with one or more base stations. Event detection results into the congestion among sensors due to limited memory, limited processing power and shared transfer medium. Congestion leads to packet drop, power consumption and reduces reliability; hence congestion control is a necessity in wireless sensor networks. In this paper, firstly a description of the various aspects of congestion control in wireless sensor networks is presented. Then various existing congestion control transport layer protocols based on rate adjustment technique in wireless sensor networks are presented. Finally a comparative analysis of these protocols based on various parameters like congestion detection, congestion notification, rate adjustment, hop-by-hop/end-to-end, loss recovery, application type, traffic direction, evaluation parameters, bandwidth allocation, evaluation type, topology, packet size, number of sensors, buffer size, coverage area, simulation time, traffic load and simulation environment is presented.

Index Terms- Wireless Sensor Networks, Transport Layer Protocols, Congestion Control, Rate Adjustment, Event Detection.

1 INTRODUCTION

WIRELESS Sensor networks (WSNs) have achieved enormous popularity in past few years. In wireless sensor networks, thousands of autonomous sensor motes are installed in specific areas as per the requirement to gather the event data as shown in figure 1. Sensor motes sense the required information, do some preprocessing and forward it towards the one or more remote sink nodes. Without sink nodes, sensor nodes can either be source nodes or forwarder nodes. Sink nodes may also send queries to sensor nodes to get required data. So, the traffic direction in wireless sensor networks can be either upstream (in case of event detection) or downstream (in case of query control) [1]. After receiving data from sensor nodes, sink nodes aggregate the data and send it to the end user through internet. Sensor nodes are extremely small but expensive devices with limited capability to process, to store data, small communication range and having limited battery power [2]. Sensor nodes can be deployed in two ways: structured or unstructured according to the application [3]. In structured manner, all or some of the wireless sensor motes are deployed in predetermined way. On the other hand, in unstructured manner, all the sensor motes are deployed in random way. Topology of sensor networks can be either single hop based or multi hop based. In single hop topology, each sensor mote is one hop away from sink. In multi hop topology, sensor nodes are one or more hops away from base station. Wireless sensor networks are having great applications like environment monitoring [4], habitat monitoring [5], security surveillance, home automation, healthcare etc.

The rest of the paper is structured as follows: basics of congestion control are described in section 2. Various rate adjustment based congestion control transport layer protocols are presented in section 3. Comparative analysis based on various parameters is presented in section 4. Section 5 draws conclusion.

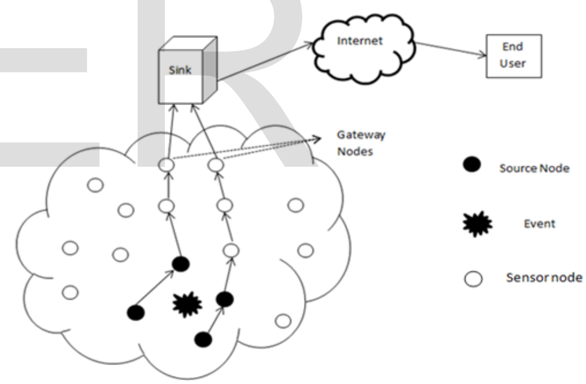

Fig. 1. Architecture of wireless sensor networks.

2 CONGESTION CONTROL

Congestion happens as the offered load exceeds the existing network capacity [6]. Congestion occurs in wireless sensor network due to the characteristics like event driven nature, dynamic changes of network topology, resource constrained nodes, shared medium, many-to-one communication [7]. Due to event driven nature of wireless sensor networks, when an event occurs, a great number of sensor nodes become active and large amount of traffic is sent towards the sink at the same time that results into channel contention and buffer overflows at intermediate nodes, hence congestion occurs. Dynamic changes of topology occurs due to certain reasons like sensor node failure, energy exhaustion, area changes and these changes result into certain route failures and lead to the congestion in other routes. Sensor motes are resource constrained in terms of limited storage capacity, limited processing power

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and limited battery power. Restricted processing power and limited memory causes the buffer overflow to occur even if network bandwidth is available. Due to limited energy, sensor nodes go into sleep mode that results into delay of processing when next time these nodes receive data. Shared medium causes packet collisions and delay in processing. Many-to-one communication nature of wireless sensor networks causes congestion among the sensor motes nearby sink node due to network convergence.

Generally, congestion can be categorized as node level congestion and link level congestion in wireless sensor networks [6]. Node level congestion happens due to buffer overflow at particular sensor motes. Buffer overflow causes the packet drops and queuing delays. Packet drops affect the reliability and throughput of the application and results in retransmissions that waste the resources of sensor nodes. Link level congestion occurs as a result of channel interference and increases packet service time. Congestion can be persistent congestion and transient Congestion [8]. Persistent congestion occurs when source data generation rate is high and can be solved by dropping packet and using end-to-end acknowledgements. Transient congestion occurs due to channel interference and can be dealt by using backpressure mechanism.

Congestion control in wireless sensor networks can be done by using end-to-end approach or by using hop-by-hop approach [9]. In end-to-end approach, sink node detects the congestion and informs the source the node by explicit acknowledgement or in terms of time outs. Then the source node performs the necessary action like rate adjustment for congestion control. In hop-by-hop approach, midway nodes notice congestion, perform action and inform the upstream nodes. Energy consumption and packet drop is less in hop-by-hop mechanism and it deals with congestion in less time than end-to-end mechanism.

Congestion control phase can be divided into three parts: congestion detection, congestion notification and congestion mitigation [8].

Congestion detection: congestion detection part involves finding the occurrence of congestion and location at which congestion has occurred [10]. Various parameters like packet loss, queue length, channel load, channel busyness ratio, throughput measurement, packet service time, packet inter-arrival time, delay [8] are used for congestion detection. Mostly the single parameter is not enough to detect congestion, so a combination of them is used.

Congestion notification: After detecting the congestion, that node must send information to neighboring nodes about congestion to control it. Congestion notification can be either explicit or implicit [8]. In explicit way, separate control packets are used to notify congestion that takes extra overhead. In implicit way, the congestion information is included in header of normal data packets, and overhearing by downstream motes is used to get the information. Notification can be either single bit or detailed information about congestion [11]. Using single bit notification, additive increase multiplicative decrease (AIMD) rate adjustment [12] can be applied while using detailed information exact rate adjustment can be implemented.

Congestion Mitigation: after receiving the notification of congestion, node must take necessary actions to alleviate the congestion to avoid packet loss, wastage of energy and to increase reliability. Based on the application congestion is controlled either by rate adjustment or by resource control. In rate adjustment based method, rate of packet generation and forwarding rate is reduced. In resource control based method, alternate resources like non congested nodes are used to route the congested traffic. Other methods like mobile virtual sink [13], learning automata [14], and MAC layer enhancements are also used for congestion control [15].

3 Rate Adjustment Based Congestion Control Transport Layer Protocols

Transport layer protocols are used for the services such as reliability, packet loss recovery, congestion control, flow control, energy efficiency and heterogeneous application support [16]. This paper summarizes the various congestion control transport layer protocols that use rate adjustment method.

CODA: Congestion detection and avoidance [17] is energy efficient congestion control protocol that uses buffer length and channel load to detect congestion. To reduce energy consumption, channel load is measured only when a sensor mote has data to send. When congestion is detected, that sensor mote notifies its upstream motes through open loop hop by hop backpressure to decrease their rate. Sink sends acknowledgements (ACKs) through closed loop to source sensor motes to control their data generation rates. Due to combination of these mechanisms, CODA handles both persistent and transient congestion. Performance metrics used are average energy tax and average fidelity penalty.

CCF: Congestion control and fairness [18] is distributed and scalable protocol for many-to-one routing. CCF makes use of packet service time for congestion detection and controls congestion by measuring the available bandwidth and determining the size of subtrees and equally distributing the bandwidth into child motes. Fairness is achieved by using two methods: Probabilistic selection method and epoch based selection method. Probabilistic selection selects the backlogged node with maximum subtree size. In Epoch based selection, equal number of packets is forwarded from each downstream mote in one epoch.

Fusion [19] is congestion mitigation protocol that combines three mechanisms: hop-by-hop flow control, rate limiting source traffic and a prioritized medium access control. Buffer length is used to infer congestion and is indicated by setting congestion bit. When child node overhears a packet with congestion bit set, it forwards only one packet to signal downstream nodes and stops sending data to give priority to parent node. The fairness among near sink and distant nodes is achieved by using rate limiting mechanism. To give priority to congested sensors, prioritized MAC layer is used that reduces their backoff window size.

SenTCP: Sensor transport control protocol [20] is hop-by-hop feedback congestion control mechanism. It makes use of average local packet service time and average local packet inert-arrival time to infer congestion. When congestion occurs, each midway sensor mote issues a response signal to its neighbors, which conveys the local congestion degree and the buffer occupancy ratio. Buffer occupancy ratio is ratio of backlogged packets over the total buffer capacity. Then nodes adjust their forwarding rate according to the feedback signals received from upstream nodes and decide whether to relay feedback signal or not.

IFRC: Interference aware fair rate control [21] is a rate allocation based protocol that makes use of average queue length to infer congestion. In IFRC, each node sends its average queue length and congestion indication bit in each packet. Overhearing is used by potential interferers to get the congestion information. Potential interferers of a node include its subtree, its neighbor's subtree, and its parent's neighbor's subtree. IFRC uses AIMD approach for fair and efficient rate allocation at each node. When queue length exceeds beyond threshold at a node, that node halves its own rate and sends congestion information to potential interferers. Then the data rate which is lowest among all the interferers of congested node is assigned to each node

CONSISE: Sink to sensors congestion control [22] provides explicit rate control approach for downstream (sink to sensors) flows. CONSISE divides nodes into two categories: a subset of nodes is defined as receivers that are concerned with messages and remaining nodes just act as forwarders. Congestion factors include reverse path traffic and broadcast storm from sink to sensors. Each node uses downstream channel conditions to maintain current forwarding rate and local conditions to set maximum forwarding rate. Sending rate of upstream nodes is determined by explicit feedback about sending rate of downstream nodes. Downstream nodes select a preferred upstream receiver that can send data at a higher rate while rest of the nodes reduces their data rate. This controls the downstream congestion from sensors to sink.

RCRT: Rate controlled reliable transport [23] provides the end-to-end explicit loss recovery. In RCRT, whole functionality of congestion detection and rate adjustment is placed in base stations. RCRT uses negative acknowledgements (NACK) based scheme to ensure end-to-end reliability. It considers that as long as network is able to repair packet losses around round trip time, network is not congested. High time to recover a lost packet than round trip time is used as congestion indication. RCRT uses AIMD rate adjustment; it adjusts the total aggregate rate of all the flows as perceived by the sink. Once congestion is detected, sink calculates the new allocation rates for all flows depending upon the loss rate and sends these rates as a separate packet to each source node or piggybacks them in NACK packet.

PHTCCP**:** Prioritized heterogeneous traffic-oriented congestion control protocol [24] provides efficient rate control for prioritized heterogeneous traffic. Feasible transmission rates of heterogeneous data are ensured by using inter-queue and intra-queue priorities. Packet service ratio in terms of average packet service rate and packet scheduling rate is used to infer congestion. When packet service ratio is lesser than one, it specifies both link level and node level collisions. When this ratio is equal to or greater than one, it indicates a decrease in level of congestion. Congestion information is sent along with data packets and scheduling rate is updated hop-by-hop.

CTCP: Collaborative transport control protocol [25-26] provides end-to-end reliability and congestion control. CTCP uses hop-by-hop acknowledgements and releases buffer immediately that increases the forwarding buffer capacity. In CTCP, base station determines the reliability level required by the application and is set during establishment of connection between source and base station. Two levels of reliability are used in CTCP. Reliability level 1 is used for applications having some redundant data or that can tolerate losses. Reliability level 2 uses double ACK's that provide high reliability and consume more energy. Congestion is detected based on buffer thresholds and uses explicit messages for notification and congestion control.

HCCP: Hybrid congestion control protocol [27] uses packet delivery rate and buffer length of each sensor mote to detect congestion. Each node calculates congestion index which is the difference of remaining buffer length and net flow size and exchanges congestion degree periodically with other nodes. Congestion occurs when the net flow size is greater than remaining buffer size and is controlled by adjusting data rates. The upstream nodes that may be congested in next time period is allocated more data rates.

UHCC: Upstream hop-by-hop congestion control [28] is a cross layer design protocol that provides both congestion control and priority based fairness. UHCC uses remaining buffer size and traffic rate at MAC layer of each senor mote to calculate congestion index. As congestion index reaches below zero, congestion is indicated. Rate adjustment is used to mitigate the congestion. Forwarding rate of a sensor mote and its child nodes is calculated based on their traffic priority and also considers whether node can become congested in next time interval. Traffic priority of a node is the sum of its source traffic priority and child nodes traffic priority. New data rates and congestion tendency are piggybacked to inform upstream and downstream motes implicitly.

FACC: Fairness-aware congestion control protocol [29] implements congestion control and allocates fair bandwidth to all the source flows. In FACC, forwarder sensor motes are divided into near-source motes and near-sink motes. Near-source sensor motes preserve a per-flow state and allocate an almost fair rate to each downstream node. On the other hand, near-sink sensor motes do not need to preserve per-flow state and use a lightweight probabilistic dropping technique based on queue length and hit frequency**.** The near-sink mote sends a warning message to the near-source motes when a packet is dropped. Then the near-source mote calculates and allocates the almost fair rate to each passing flow. Finally, the near-source mote sends a control message to respected source mote containing updated sending rate using AIMD scheme. Channel busyness ratio is used as congestion indicator.

ECODA: Enhanced congestion detection and avoidance for multiple classes of traffic [30] operates at network and MAC layer. It uses two buffer thresholds and weighted buffer difference of nodes for congestion detection. Each packet is assigned a dynamic priority based on delay, number of hops and its static priority. When buffer level exceeds certain threshold, low priority packets are dropped instead of tail dropping. Local generated traffic and route-through traffic are assigned to different queues to achieve fairness. One packet is sent from local generated traffic and next from route through traffic of each source in round robin manner. From each source, high priority packets are sent first. Transient and persistent congestion both are handled by ECODA effectively. Transient congestion is dealt by using implicit hop-by-hop backpressure. Bottleneck node detection and source rate control is used for persistent congestion control.

IRCRT: Improved rate controlled reliable transport protocol (IRCRT) [31] works according to RCRT [23] with improved rate adjustment. Congestion is detected on the basis of time to recover from packet losses. It improves the channel utilization by eliminating the nodes that are in OFF state during rate computations by the sink node. Secondly, during congestion, sending rate of congested nodes is decreased more than that of steady nodes.

CADA: Congestion avoidance, detection and alleviation in wireless sensor networks protocol [32] works in both proactive and reactive manner for congestion control. In proactive manner, it tries to reduce the source traffic by carefully selecting the representative nodes as the subset of nodes to send the event information. Then congestion is detected by monitoring buffer occupancy periodically and measuring channel load when node has data to send. CADA uses both traffic control and resource control for congestion avoidance. When congestion occurs due to intersection hotspot, then congestion is avoided by redirecting traffic to bypass the hotspot. When convergence hotspot is there, then congestion is controlled by using AIMD like rate reduction.

HCCC: A hop-by-hop cross layer congestion control [33] uses the MAC layer channel information for congestion control. Buffer occupancy ratio and congestion index of a mote is used to detect congestion. Congestion degree of a node is the ratio of inter-arrival time and average processing time of a packet. Congestion information is sent to upstream nodes by using RTS/CTS frames. These feedback signals are generated before and after data packet transmission. Then upstream node performs the feedback signal processing and local congestion processing to determine its own data transmission rate. Data forwarding rate adjustment and channel access priority at MAC layer is used to deal with congestion. Channel access priority depends on the contention window size which in turn affects the transmission rate.

DPCC: Dynamic priority based congestion control [34] uses the exact rate adjustment mechanism on the basis of dynamic priority index to mitigate congestion. Congestion index as the ratio of average packet scheduling rate over average packet service rate is used to reflect the congestion level at each sensor mote. When congestion index is more than 1, it indicates packets will be queued up and information is piggybacked into data packets. DPCC divides the traffic into three categories: urgent, quick and normal and each type of traffic is having own queue at each node. As the congestion reaches beyond threshold, traffic of motes near the sink is prioritized to have good performance.

PCCP: Priority-based congestion control protocol for controlling upstream congestion in wireless sensor network [35] works for both single path and multi path routing. It creates a priority table based on importance of each source mote and shares this table with all the necessary motes within the network. It controls the congestion by using priority table and congestion degree which is the ratio of packet inter-arrival time over packet service time. Congestion is mitigated by using multipath hop-by-hop rate adjustment based on priority index.

Congestion Control Based on Reliable Transmission in Wireless Sensor Networks [36] provides the priority based congestion control mechanism for reliable transmission of emergency information. Three different priority queues: High, Median and Low are used at each node for different types of data. It detects the congestion based on queue length and queue variation rate. Positive queue variation rate indicates that congestion can occur at the next time period and negative value indicates that congestion is mitigated. If queue variation rate is more than threshold value, means there is probability of congestion then normal rate adjustment is applied. If queue length continuously increases fast, means probability of congestion is higher at next moment then emergent rate adjustment is applied.

HRTC: A hybrid algorithm for congestion control in wireless sensor networks [37] is a dynamic scheme combining two most important techniques of congestion control that is: traffic control and resource control. When congestion is detected, nodes send hop-by-hop backpressure signals to suppress transmission rate and along with it checks whether resource control can be applied. If it can, it applies resource control and stops sending backpressure signals. Otherwise source node decreases data rate and sets a bit in header that rate adjustment has been applied. In future if resource control can be applied, again a backpressure message is sent to inform source node to send full data rate. Thus, hybrid approach takes advantage of both traffic control and resource control.

IACC: Interference aware congestion control protocol for wireless sensor networks [38] deals with inter-path and intra-path congestion and provides interference aware scheduling scheme. IACC considers the sensor network as undirected graph. Firstly, it estimates the capacities of all links and forwards them to the sink. Then a schedule is constructed such that each node transmits at appropriate time and at appropriate rate. Schedule construction involves rate distributions and slots assignments. Rate is allocated to each node based on number of source nodes underneath subtree of that node. Slots assignment is used to avoid collisions such that non-interfering links can transmit data simultaneously.

Probabilistic approach for predictive congestion control in wireless sensor networks [39] measures the congestion level by using buffer occupancy and adaptive threshold value on the buffer capacity of each node. After detection of congestion, feedback signals are sent to upstream nodes that control their rate either by using rate regulation or split protocol is used by receiver node to control transmission rate. To avoid packet drops due to fading channel, back-off interval are adjusted on the basis of channel quality. Capacity of channel is estimated by using Rayleigh distribution.

4 Comparative Analysis of Protocols

Table 1 presents the comparison of various protocols based on parameters like congestion detection, notification, rate adjustment method, hop-by-hop/end-to-end, loss recovery.

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TABLE 1: COMPARISON OF VARIOUS RATE ADJUSTMENT BASED CONGESTION CONTROL TRANSPORT LAYER PROTOCOLS

Protocol	Congestion Detection	Notification	Rate Adjustment Method	H-by-H/E-to-E	Loss Recovery
CODA[17] Wan et al. (2003)	Buffer occupancy, channel load	Explicit	End to End AIMD rate control	E-to-E	No
CCF[18] Ee et al. (2004)	Packet service time, Queue length	Information in header	Exact rate control	H-by-H	Yes
Fusion[19] Hull et al. (2004)	Queue length	Bit in header	Rate limiting and prioritized MAC, stop sending packets.	H-by-H	No
SenTCP[20] Wang et al. (2005)	Queue length, Packet service time, Packet inter-arrival time	Feedback signal	Rate control	H-by-H	No
IFRC[21] Rangwala et al. (2006)	Average queue length	Information in header	AIMD rate control	H-by-H	No
CONSISE[22] Vedantham et al. (2007)	Wireless channel load	Implicit	Periodic rate control	H-by-H	Yes
RCRT [23] Paek et al. (2007)	Time to repair losses	Explicit signals from sink	Additive increase and multiplicative decrease based on loss rate	E-to-E	Yes
PHTCCP[24] Monowar et al. (2008)	Packet service ratio	Information in header	Dynamic rate adjustment	H-by-H	No
CTCP[25] Giancoli et al. (2008)	Transmission error loss, Queue occupancy	Start and stop signals	Rate adjustment	H-by-H	Yes
HCCP[27] Sheu et al. (2008)	Queue length, Net flow size	Information in header	Rate control	H-by-H	No
UHCC[28] Wang et al. (2009)	Remaining buffer size, Traffic rate at MAC layer	Information in header	Rate adjustment based on priority	H-by-H	No
FACC[29] Yin et al. (2009)	Buffer occupancy and hit frequency	Warning and control message	Packets drop or fair bandwidth allocation	H-by-H	No
ECODA[30] Tao et al. (2010)	Dual buffer threshold, Weighted buffer difference	Information in header	Delay based rate control	H-by-H	No
IRCRT[31] Akbari et al. (2010)	Time to recover packet losses	Explicit message	Rate adjustment based on congested and non congested nodes	E-to-E	Yes
CADA[32] Fang et al. (2010)	Buffer occupancy Channel utilization	Implicit	Resource control, Rate adjustment	H-by-H	No
HCCC[33] Wu et al. (2011)	Packet interarrival time, Packet service time, Queue occupancy	Feedback signal	AIMD rate control, Channel access priority adjustment	H-by-H	No
DPCC[34] Lin et al. (2011)	Packet scheduling rate, Packet service rate	Information in header	Exact rate adjustment based on dynamic priority	H-by-H	No
PCCP [35] Patil et al. (2012)	Ratio of packet inter-arrival time over packet service time	Information in header	Rate adjustment based on priority index	H-by-H	No
Cong. Ctrl. Based on Rel. Trans.[36] Hua et al. (2014)	Queue length, Queue variation rate	-	Exact rate adjustment	H-by-H	No

HRTC[37] Sergio et al. (2014)	-	Explicit message	Rate adjustment and resource control	H-by-H	No
IACC[38] Kafi et al. (2014)	Dynamic link Interference , capacity	-	Rate distribution, Slot assignment	-	No
Prob. App. For pre. Cong. Ctrl.[39] Uthra et al. (2014)	Buffer occupancy, Adaptive threshold value on buffer capacity	Explicit Message	Rate regulation and Split protocol	H-by-H	No

Congestion detection is done by using combination of parameters like packet service time, packet inter-arrival time, channel load, buffer occupancy, time to recover lost packets, dual buffer thresholds etc. CODA and CADA makes use of both buffer occupancy and channel load to infer congestion. Fusion and IFRC infer congestion on the basis of queue length only. CCF makes uses of packet service time along with queue occupancy for congestion detection. Combination of queue length and congestion degree in terms of packet inter-arrival time and packet service time is used by SenTCP and HCCC to infer congestion. DPCC, PHTCCP, UHCC and HCCC protocols use cross layer information for congestion detection. RCRT and IRCRT use high time to recover the lost packets as indication of congestion. DPCC and PHTCCP infer congestion by using packet scheduling rate and packet service rate. CTCP detects congestion by using transmission error loss and queue occupancy. HCCP uses queue length and net flow size as difference of incoming and outgoing flows for congestion detection. Traffic rate at MAC Layer and remaining buffer size infers congestion in UHCC. ECODA detects congestion by using weighted buffer difference and dual buffer threshold. PCCP makes use of packet service and packet inter-arrival time to infer congestion. IACC detects congestion on the basis of dynamic link interference and capacity of each link.

Congestion notification can be either explicit or implicit. Mostly implicit mechanism is preferred over explicit mechanism. In all CCF, Fusion, IFRC, CONSISE, PHTCCP, HCCP, UHCC, ECODA, DPCC, PCCP congestion information is sent implicitly in header of data packets. CODA, SenTCP, RCRT, CTCP, FACC, IRCRT, HCCC, HRTC use explicit signals for congestion indication. CODA sends backpressure messages to its upstream neighbors. In RCRT, explicit signals are sent from sink. CTCP uses START and STOP signals for congestion indication. FACC uses warning and control messages for congestion information.

Different protocols use different methods for rate adjustment like AIMD rate control, priority based rate control, exact rate control, periodic rate control etc. CODA performs end-to-end AIMD rate adjustment. Fusion uses prioritized MAC layer and start and stop sending packets for rate control. CCF, DPCC and PCCP use exact rate adjustment. RCRT uses the loss rate to perform additive increase and multiplicative decrease. ECODA performs the rate adjustment based on maximum delay of path.

Congestion control is done either hop-by-hop or end-to-end. End-to-End method is used by only CODA, RCRT and IRCRT. Rest all protocols use hop-by-hop mechanism. Lost packets recovery is provided by CCF, CONSISE, RCRT, CTCP, IRCRT protocols.

Table 2 presents a comparison based on type of application, traffic direction, evaluation parameters used to evaluate protocol, bandwidth allocation, existing protocols with which that protocol is compared. Different protocols are used for different type of applications like periodic, continuous, event, or hybrid of all these. CODA can be used for continuous, periodic and event type traffic also. IFRC, CTCP, HCCP, FACC, HCCC, PCCP and IACC are applicable to continuous traffic form source nodes. ECODA and UHCC are used for periodic traffic flows. CADA is used for event type traffic flows. HRTC, RCRT and IRCRT are applicable to all types of flows.

Traffic direction in wireless sensor networks is either upstream or downstream. All the compared protocols work for upstream traffic direction except CONSISE work for downstream traffic direction. Protocols are evaluated by using various different parameters like energy tax, fidelity penalty, fairness, number of retransmissions, packet latency, packet loss ratio, throughput, delay, queue length etc. Energy consumption is used by CODA, PHTCCP, FACC, HCCC and DPCC. Fairness is used by CCF, Fusion, RCRT, UHCC, FACC, ECODA and PCCP. Throughput is used by IFRC, RCRT, PHTCCP, UHCC, FACC, ECODA, HCCC, PCCP, HRTC and IACC. Latency is used by Fusion, CONSISE, ECODA and DPCC. Packet loss is used by SenTCP, PHTCCP, HCCP, UHCC, FACC and HCCC [40].

Bandwidth is allocated based on priority in Fusion, PHTCCP, UHCC, PCCP and DPCC. Heterogeneous prioritized traffic is handled by PHTCCP. DPCC allocates dynamic priority to packets to indicate their importance. DPCC prioritizes the traffic of nodes near the sink in case of congestion. Fair bandwidth allocation is done in rest of protocols.

TABLE 2: COMPARISON OF PROTOCOLS BASED ON EVALUATION PARAMETERS

Protocol	Application type	Traffic direction	Evaluation parameters	Band-width Allocation	Results comparison with existing protocol
CODA[17] Wan et al. (2003)	Periodic or continuous event	Upstream	Energy tax, Fidelity penalty	Fair	-
CCF[18] Ee et al. (2004)	Event	Upstream	Fairness, Number of retransmission per packet	Fair	-
Fusion[19] Hull et al. (2004)	Hybrid	Upstream	Network efficiency, Aggregate sink received throughput, Node imbalance, Packet latency, Network fairness	Priority Based	-
SenTCP[20] Wang et al.(2005)	Periodic, Event	Upstream	Throughput, Packet loss ratio	Fair	TCP
IFRC[21] Rangwala et al. (2006)	Continuous	Upstream	Per flow goodput, Queue length, Rate adaptation	Fair	-
CONSISE[22] Vedantham et al.(2007)	Information from sink to sensors	Down-stream	Latency, Number of retransmissions	Fair	-
RCRT [23] Paek et al.(2007)	All flows	Upstream	Fairness, Packet reception , Goodput	Fair	IFRC[21]
PHTCCP[24] Monowar et al. (2008)	Periodic, Event	Upstream	Queue length, System throughput, Energy efficiency, Packet drop rate	Priority based	CCF[18]
CTCP[25] Giancoli et al. (2008)	Continuous	Upstream	Average delivery rate, Energy consumption	Fair	-
HCCP[27] Sheu et al. (2008)	Continuous	Upstream	Packet drop rate, Control overhead, Total source rate,	Fair	Rate based scheme AFA[41],Buffer based scheme [42]
UHCC[28] Wang et al. (2009)	Periodic	Upstream	Throughput, Fairness, Packet loss ratio	Priority based	PCCP [43], CCF[18]
FACC[29] Yin et al. (2009)	Continuous	Upstream	Packet drop rate, Throughput, Energy consumption, Fairness	Fair	-
ECODA[30] Tao et al.(2010)	Periodic	Upstream	Throughput, Weighted fairness, End-to-End Packet delays,	Fair	CODA[17]
IRCRT [31] Akbari et al.(2010)	All flows	Upstream	Total send and received packets, average delivery ratio	Fair	RCRT[23]
CADA [32] Fang et al.(2010)	Event	Upstream	Throughput, End-to-End delivery ratio, Energy consumption, Per hop delay	Fair	TARA [44
HCCC[33] Wu et al. (2011)	Continuous	Upstream	Packet loss ratio, Average source data rate, Throughput, Energy efficiency	Fair	CODA[17], ESRT[45], FUSION[19]
DPCC[34] Lin et al. (2011)	Event, periodic	Upstream	Energy efficiency, Loss probability, Latency	Dynamic Priority based	CCF[18], PRCSDCC[46]
PCCP [35] Patil et al.(2012)	Continuous, Event	Upstream	Fairness, Packet loss ratio, Packet delay, Throughput	Priority based	-
Cong. Ctrl. Based on Rel. Trans.[36] Hua et al.(2014)	Periodic and emergent	Upstream	Throughput, Delay, Packet loss rate	-	-
HRTC[37] Sergio et al. (2014)	All types	Upstream	Throughput	Fair	-
IACC[38] Kafi et al. (2014)	Continuous	Upstream	Packet reception ratio, Number of retransmissions, Average throughput	Fair	-
Prob. App. For pre. Cong. Ctrl.[39] Uthra et al.(2014)	Continuous	Upstream	Throughput, Buffer occupancy, Source rate	Fair	DPCC[47], ADCC[48]

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TABLE 3: COMPARISON OF RATE ADJUSTMENT BASED CONGESTION CONTROL TRANSPORT LAYER PROTOCOLS BASED ON SIMULATION PARAMETERS

Protocol	Evaluation type	Topology	No. of sensors	Packet size (byte)	Coverage area(m^2)	Buffer size (packet)	Sim. Time (seconds)	Traffic load	Sim. Env./ Testbed
CODA[17] Wan et al. (2003)	Simulation and Testbed both	Random	30	64	-	-	30	-	NS-2
CCF[18] Ee et al. (2004)	Simulation and Testbed both	Random	116	30	-	10	50000	1pkt/ sec	-
Fusion[19] Hull et al. (2004)	Testbed	Random	55	36	16076 sq feet	8	-	0.25 to 4pkts/ sec	Motelab
SenTCP[20] Wang et al.(2005)	Simulation	Linear	20	250	-	200	90	-	-
IFRC[21] Rangwala et al. (2006)	Testbed	Tree	40	32	1125	64	4200	0.02 pkt/sec	-
CONSISE[22] Vedantham et al.(2007)	Simulation	Random	400	1024	600×600	-	-	-	NS-2
RCRT [23] Paek et al.(2007)	Testbed	Tree	40	64	1125	-	1800-3600	1.2 pkts/ sec	TinyOS based TestBed
PHTCCP[24] Monowar et al. (2008)	Simulation	Random	100	29,33, 41,64	100×100	10	60	4-16 pkts/ sec	NS-2
CTCP[25] Giancoli et al. (2008)	Simulation	Random	25	27	50×50	-	1000	1/50pkts/sec	TOSSIM
HCCP[27] Sheu et al. (2008)	Simulation	Random	500	40	1000×1000	32	200	4 pkts/ sec	NS-2
UHCC[28] Wang et al. (2009)	Simulation	Tree	10	128	-	10-100	400	-	-
FACC[29] Yin et al. (2009)	Simulation	Random	51	1000	1000×1000	-	150	-	NS-2
ECODA[30]	Simulation	Tree	35	36	1000×1000	20	250	-	NS-2
IRCRT [31] Akbari et al.(2010)	Simulation	Tree	18	-	-	100	300	-	NS-2
CADA[32] Fang et al.(2010)	Simulation	Random	2000	30	500×500	10	-	2Mbits /sec	NS-2
HCCC[33] Wu et al. (2011)	Simulation	Random	100	200	100×100	500	400	5 pkts/ sec	NS-2
DPCC[34] Lin et al. (2011)	Simulation	Tree	90	32	-	8 for each type of queue	6000	1-10 pkts/sec	NS-2
PCCP [35] Patil et al.(2012)	Simulation	-	-	-	-	-	-	-	NS-2
Cong. Ctrl. Based on Rel. Trans.[36] Hua et al.(2014)	Simulation	Tree	-	-	-	-	100	-	C based software
HRTC[37] Sergio et al. (2014)	Simulation	Uniform	30	128	100×100	512KB	1800	-	Prowler
IACC[38] Kafi et al. (2014)	Simulation	Random	256	29	-	-	-	-	TOSSIM

Prob. App. For pre. Cong. Ctrl.[39] Uthra et al.(2014)	Simulation	Tree	-	512	-	32	50	5 kb/sec	-

Table 3 presents a comparison based on evaluation type, topology used, number of sensors buffer size, packet size, coverage area, traffic load, simulation time and simulation environment used.

Transport layer protocols can be evaluated by using simulation, testbed or both. Different simulation environment is used by various protocols like NS-2 [49], TOSSIM, and Prowler etc. Protocols simulated in NS-2 are CODA, CONSISE, PHTCCP, HCCP, FACC, ECODA, IRCRT, CADA, HCC, DPCC and PCCP. IFRC, CTCP and IACC are implemented in TinyOS [50]. HRTC is implemented in Prowler [51] simulator.

Topology of nodes used by various protocols can be randomly distributed, tree structured or linear. ECODA, UHCC, RCRT, IFRC and IRCRT use tree topology. SenTCP has linear topology. In HRTC, nodes are uniformly deployed. In rest of the protocols, nodes are randomly distributed. Packet size, buffer size, coverage area, traffic load, simulation time parameters vary from protocol to protocol.

5 Conclusion

This paper presents a survey of various rate adjustment based congestion control transport layer protocols in wireless sensor networks. Firstly, this paper describes the basics of sensor network and their architecture. Secondly, basics of congestion control in wireless sensor network are presented. Thirdly, a brief introduction of various rate adjustment based congestion control transport layer protocols is provided. Finally, a comparative analysis of these protocol based on parameters like congestion detection, notification, rate adjustment method, hop-by-hop/end-to-end, loss recovery, type of application, traffic direction, evaluation parameters , bandwidth allocation, evaluation type, topology used, number of sensors, coverage area, buffer size, packet size, simulation time, traffic load, simulation environment used is presented.

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