A Survey of Transport Layer Protocols for Wireless Sensor Networks

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Abstract— **This paper describes the concept of wireless sensor networks which is an emerging class of networks that can be used to monitor real time situations. Existing transport layer protocols such as TCP and UDP are inappropriate for wireless sensor networks. So, there is a need of special protocols to provide reliability and congestion control for transport layer of wireless sensor networks. In this paper, we first describe the basics of wireless sensor networks. Then we elaborate the aspects of congestion control and reliability. Then we present various transport layer protocols which are specifically designed for sensor networks to provide both congestion control and reliability. Then a comparison of these protocols is given on the basis of various parameters like congestion detection, congestion notification, congestion avoidance, reliability level, reliability direction, loss recovery, loss notification, energy efficiency and simulation environment. At the end, we address certain open research issues of transport layer protocols in wireless sensor networks.**

Index Terms— **Congestion Control, Energy Efficiency, Reliability, Transport Layer, Wireless Sensor Networks.**

I. Introduction

Wireless Sensor Network [1] consists of one or more sinks and a number of sensor nodes distributed among the network. Wireless sensor network monitors some physical or environmental condition such as temperature, pressure, vibration, motion or sound etc. Wireless sensor networks often operate in remote areas with harsh conditions. The deployment of sensor nodes depends upon the type of application. The deployment is either random or pre planned. Since wireless sensor networks are deployed in inaccessible areas so they have the feature of self organization which means that wireless sensor networks operate without manual configuration. Sensor nodes are low power devices which consists of a small microcontroller, an RF transceiver, memory, and an energy source usually a battery or solar cell. Sensors nodes have one or more sensors to sense some particular environmental properties. Energy is the scarce resource for sensor nodes as it is not possible to charge the batteries because of either the inaccessible area they are deployed in or low cost hardware being used. Base station has good processing power and enough memory. The sensor nodes can be categorized as source nodes and intermediate nodes. Wireless sensor networks can be categorized as single hop and multi hop networks. In single hop networks every node is one hop away from the sink, while in multi hop networks there are intermediate nodes between sink and any given node. Wireless sensor networks can have two directions of data flow, one from source to sink and another from sink to source. The data flow from source to sink is called upstream data flow in which source nodes are the one that sense and collect the information from the environment they are deployed in and relay that information towards the intermediate nodes on the path to sink. Sink is responsible for data collection and relaying it to external networks which may be wired or wireless networks. The data flow from sink to source is called downstream data flow in which sink queries the network about some event and the nodes which are in the vicinity of the location of the occurrence of that event, responds to the query of sink. Wireless sensor networks are more flexible than wired networks as wireless sensor networks can accommodate the addition of sensor nodes, upgrades and expansion without any infrastructure changes. Moreover, for applications like rotating or moving objects, wired networks make monitoring impractical.

Wireless sensor networks can also be categorized as structured and unstructured [1]. Unstructured wireless sensor network contains dense collection of sensor nodes. Sensor nodes are deployed in ad-hoc manner. In unstructured wireless sensor network, maintenance is difficult because of dense deployment of sensor nodes. Structured wireless sensor network contains sensor nodes that are deployed in a pre-planned manner. Management cost is low and maintenance is easy for structured wireless sensor network because of less sensor nodes deployed. Depending upon whether sensor nodes have same capabilities, wireless sensor network can be categorized as homogenous and heterogeneous. In homogenous sensor network all nodes have same capabilities in terms of energy, processing power and memory. In heterogeneous sensor networks, some special sensor nodes are equipped with more processing and communicating capabilities. Wireless sensor network is an emerging class of networks which can be used to monitor an object, area or both [2]. Object monitoring involves structural monitoring, medical diagnostics, urban terrain mapping etc. Area monitoring involves military surveillance, environment surveillance, habitat monitoring etc. Both area and object monitoring involves disaster management, emergency response etc.

II. Congestion Control

Congestion is said to occur in sensor networks when the incoming traffic load becomes greater than the available network capacity [3]. The congestion control mechanism can be divided into three phases: congestion detection, congestion notification and congestion avoidance [4]. 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 [4]. 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. 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.

Congestion notification can be classified as implicit and explicit. 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) [5] can be used for rate adjustment, while in the case of detailed notification, exact rate adjustment can be used. The congestion information can be send to sink, source or the parent node.

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. 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 [6] can also be used to redirect traffic. In polite gossip policy [7], each node broadcasts its metadata to its neighbors periodically. Cross layer interaction [8] 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.

Congestion can be controlled in two ways: end-to-end and hop-by-hop. 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.

III. Reliability

Reliability refers to the successful delivery of each segment that the source nodes generate to the final destination. Reliability level can be categorized in packet reliability, event reliability and destination reliability. Packet reliability means every packet generated from source is delivered successfully to the destination node. Event reliability in wireless sensor network refers to successfully detection of the event. Destination reliability refers to all the packets should be delivered successfully to a particular node or to a group of nodes.

The loss recovery refers to recovery of packets with retransmission. The loss recovery can be performed in two ways: end-to-end loss recovery and hop-by-hop loss recovery. In end-to-end recovery method, only the source node caches the data and it is the duty of the sink node to detect any kind of loss and then send request to source node for retransmission of the lost packet. In hop-by-hop recovery method, all intermediate nodes cache the data and detect losses and send requests for retransmission.

Transport layer protocols implement different mechanisms for loss detection and notification. Positive acknowledgements are used when all data packets generated from source nodes are received correctly at destination node. Negative acknowledgements are used if data packet is not received or if packet received incorrectly. The receiver sends selective acknowledgement, it informs the sender that all the packets are received in order using one control packet. In explicit acknowledgement, after receiving a packet, node explicitly notifies the sink that packet is received correctly. In implicit acknowledgement, when a node send some packet to other node and after sometime node hears that neighbor node forwards that packet to other nodes then node assumes that packet was received correctly.

Figure 1 shows the working of a transport layer protocols in wireless sensor networks. Firstly, source nodes sense the event and send packets to intermediate nodes. If intermediate node receives packet, it stores it in the cache otherwise loss recovery mechanism is used to recover the data. Nodes that receive data generate a positive acknowledgement and send it to source node. If received data is not in sequence, it means data is lost so the node generates negative acknowledgement and sends it to source node and requests for retransmission of data. Otherwise if data is received properly congestion is checked, 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.

IV. Transport Layer Protocols

Existing transport layer protocols such as TCP (Transmission control Protocol) and UDP (User Datagram Protocol) work very well for wired networks but they have many critical issues in wireless sensor world. TCP has poor performance in wireless environment in terms of both energy efficiency and throughput. TCP provides end-to-end reliability which conserves more energy at every hop. Congestion control in TCP is end-to-end which takes more time to alleviate as compared to hop-by-hop congestion control so it is unsuitable for wireless sensor networks. UDP does not provide reliability which is often needed for many sensor applications. Also it does not provide congestion control and flow control that can lead to packet loss and unnecessary energy consumption. Thus UDP is also inappropriate for wireless sensor network. So, there is a need of special protocols to provide reliability and congestion control for transport layer of wireless sensor networks.

PSFQ [9] (Pump Slowly Fetch Quickly) is a hop-by-hop downstream transport protocol. In this protocol firstly user node slowly inject messages into network and if there is any packet loss occurs then it uses aggressive hop by hop error recovery. As it uses hop-by-hop loss recovery so all intermediate nodes buffer data in their cache and forwards packet with proper schedule. PSFQ uses the concept of loss aggregation in which when any loss occurs it combine all the message losses into one single fetch operation. It also uses a report operation which gives data delivery information to users. PSFQ has several limitations such as PSFQ forward messages in sequence means any node does not forward packets until it does not receive all the packets so it increases the latency. PSFQ uses hop-by-hop loss recovery in which all intermediate nodes cache the data so there is need of more cache spaces.

CODA [10] (Congestion Detection and Avoidance) is an energy efficient and upstream congestion control protocol. CODA comprises of three mechanisms, receiver-based congestion detection, open loop hop-by-hop backpressure, closed-loop end-to-end multi-source regulation. It uses buffer occupancy and channel sampling to detect congestion. It assumes that event occurrence is the source of congestion not wireless links or interference. It handles both persistent and transient congestions. CODA performs rate adjustment through traditional TCP-like AIMD (Additive Increase Multiplicative Decrease) mechanism and thus often leads to the occurrence of packet loss. However it does not offer reliability control feature and offers only unidirectional control in forward direction from source to sink. CODA requires signaling messages. In open loop, when congestion is detected, a backpressure message is sent to all neighbors in order to reduce their rate or drop packets. In closed-loop, if a node transmits data at a greater rate than the one preconfigured, it will receive a continuous stream of ACK’s from the sink in order to trim the rate.

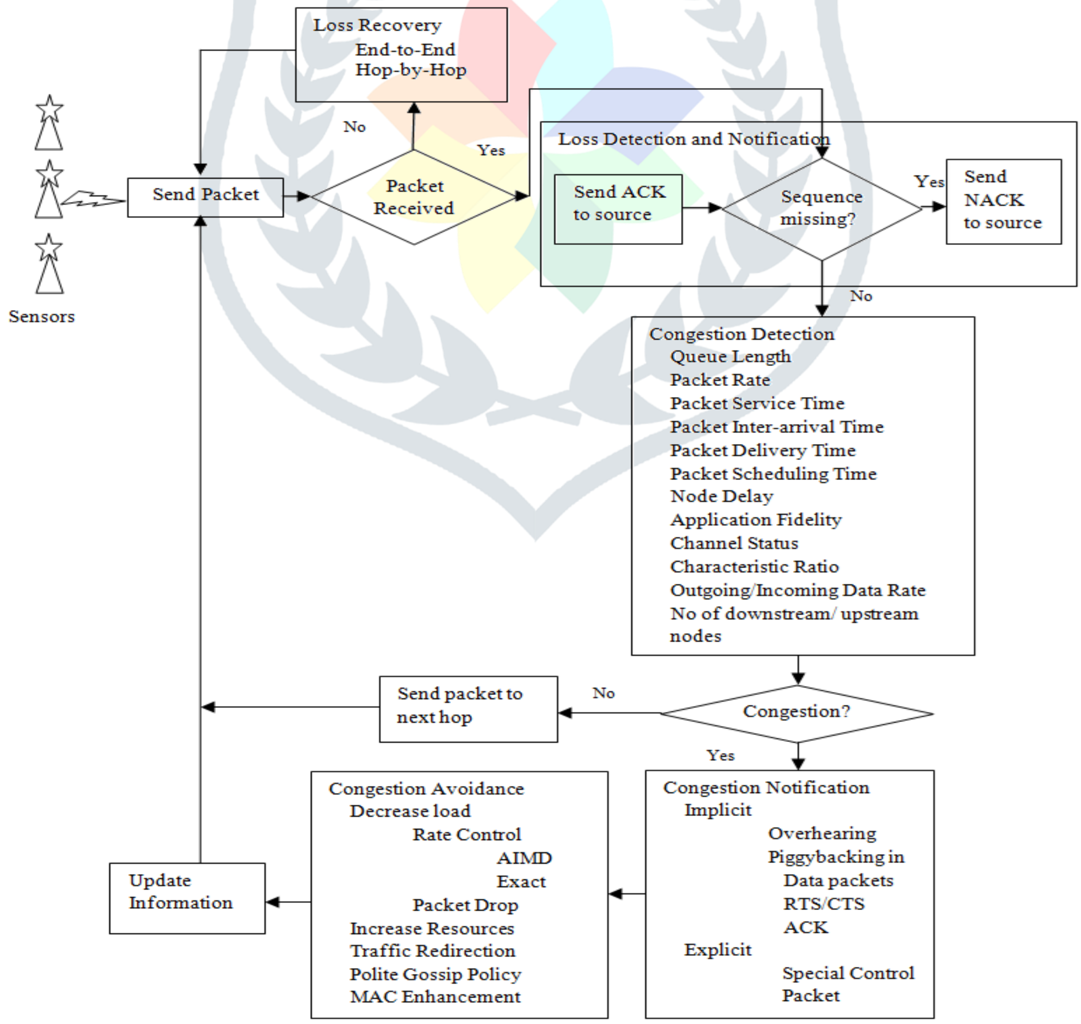

Figure 1 A flow chart of Transport Layer Protocol

ESRT [11] (Event to Sink Reliable Transport protocol) provides upstream event reliability, energy efficieny and congestion control. The base station implements the algorithm to take the decision that the event is detected reliabily or not. It provides reliability for applications not for every packet. In ESRT reliability is classified as observed reliability and desired reliability. The observed reliability r_i is the number of data packets that are received at sink node in decision interval i. The desired reliability R is the number of data packets required which ensures the event detection reliabily. If event to sink reliability is lower than required then it increase the reporting frequency to get the required reliability or if event to sink reliability is greater than required, then reporting frequency is decreases to avoid the congestion and it saves energy consumption. ESRT has several limitations such as it does not guarantee reliable delivery of every packet, it only gurantees reliable detection of individual event to sink node. In wireless sensor network multiple events occur at same time so there is difficulty in adjusting the reporting frequency.

STCP [12] (Sensor Transmission Control Protocol) is an end-to-end upstream transport protocol. It provides controllable variable reliability and congestion control. For event driven flows it uses ACK based end-to-end-retransmission in which positive acknowledgement is send to source node when packet is received at sink node after receiving acknowledgement, node deleted that packet from its buffer. NACK based end-to-end retransmission is used for continuous flows in which base station sets a timer, if it does not received packet until timer expires it sends negative acknowledgement to source node. In STCP sensor nodes uses a session initiation packet which helps in making the association of source node with sink node. When base station receives the session initiation packet, it sends ACK to sensor nodes which inform the source nodes that the connection is established and after getting ACK sensor nodes starts transmitting the data to sink node. In STCP sensor nodes always wait for ACK so it causes long latency in large scale of multi hop wireless sensor network.

PORT [13] (Price Oriented Reliable Transport) is an upstream reliable transport protocol which provides reliability, congestion control and energy efficiency. PORT uses node prices which are defined as the total number of attempt transmission in between sensor node and sink node. To ensure energy efficiency it uses two schemes. In first scheme, sink node sends feedback of the exact reporting rate of each source node and also sends its energy consumption. In second scheme source nodes send feedback to sink nodeabout congestion.It is an optimal routing scheme, because of congestion it increase the nodes cost. PORT makes three assumptions: first, source nodes would keep reporting data for a long period of time based on interest, second, sink node has the knowledge about the sources of data from where it originates and third, sink node is aware about the information of that carries a data packet.

SenTCP [14] is an open loop hop-by-hop congestion control protocol for upstream traffic flow. SenTCP calculates the congestion degree in every intermediate sensor node by using average local packet service time and average local packet inter-arrival time and buffer occupancy. In case of congestion, each intermediate sensor node issues a feedback signal to its neighbors, which carries the local congestion degree and the buffer occupancy ratio. Buffer occupancy ratio is the ratio of backlogged packets over the total buffer size. The intermediate sensor nodes and source sensor node need to adjust their sending rate after receiving feedback signal from upstream neighbouring nodes. Then they will decide whether or not they should relay the feedback signal backward continuously. If needing to relay it, they should update the information carried in the feedback signal using their local congestion information. This use of hop-by-hop feedback control regulates the congestion quickly and reduces packet dropping, which in turn conserves energy and increases the throughput.

IFRC [15] (Interference aware Fair Rate Control) is a distributed rate allocation scheme that uses queue size to detect congestion, shares the congestion state through overhearing, and converges to fair and efficient rates for each node. It proposes interference aware congestion control mechanism. IFRC uses local congestion detection based on the monitoring of the buffer occupancy. In IFRC the sensor node allocates and controls the data rate of its upstream and interfering neighbor nodes. IFRC considers all the links which create interference. For many-to-one data delivery, a set of potential interferers of a node include its neighbors, neighbors of its parent and as well as neighbors of its parent's parent. IFRC utilizes two thresholds for inferring congestion at the sensor node. When congestion is detected IFRC reduces the data rate to half. When congestion is alleviated, IFRC increases the data rate additively. The rate adaptation of the source nodes in IFRC is based on AIMD scheme. IFRC circulates the congestion and data rate state among the neighbors to ensure the fairness for data delivery. The IFRC's goal is to assign the data rate which is lowest among the interfering neighbors of the congested node.

PHTCCP [16] (Prioritized Heterogeneous Traffic-Oriented Congestion Control) provides efficient rate control for prioritized heterogeneous data. It uses intra-queue and inter-queue priorities for ensuring feasible transmission rates of heterogeneous data. Sink nodes assign priorities for each type of sensed data. Congestion level at each node is reflected by packet service ratio. It is the ratio of average packet service rate and packet scheduling rate. When this ratio is equal to 1, packet scheduling rate is equal to average packet service rate. When this ratio is greater than 1, packet scheduling rate is less than average packet service rate. Both of these cases reflect the decrease in the level of congestion. When this ratio is less than 1, it causes queuing up of packets. It also indicates link level congestion. Thus packet service ratio is an effective measure of detecting both link and node level congestions. PHTCCP guarantees efficient link utilization by using dynamic transmission rate adjustment. PHTCCP uses hop-by-hop rate adjustment which ensures that heterogeneous data reach the base station at their required rates. The output rate of a node is controlled by adjusting scheduling rate.

E^2SRT [17] (Enhanced Event to Sink Reliable Transport) is a modified version of ESRT which provides reliability, congestion control and energy efficiency. ESRT has a problem called 'over demanding' event reliability problem. This protocol solves this problem. It works same as that of ESRT, it checks the event to sink reliability. If it is greater than desired reliability it decreases transmission rate of packets to avoid congestion and minimizes the energy consumption. And if the event to sink reliability is lower than that desired reliability, it increases the transmission rate of packets to get the desired reliability. E^2SRT has good performance in terms of latency, throughput and loss rate as compared to ESRT.

ECODA [18] (Enhanced Congestion Detection and Avoidance) uses dual buffer thresholds and weighted buffer difference for congestion detection. It has a flexible queue scheduler for packet scheduling. It can dynamically select next packet to send. It uses a bottleneck-node-based source sending rate control scheme. ECODA dynamically estimates channel loading with an implicit manner and optimizes channel utilization. ECODA differentiates transient congestion and persistent congestion. For transient congestion, hop-by-hop implicit backpressure manner is used. For persistent congestion, bottleneck node based source sending rate control and multi-path loading balancing are proposed. Using this method, bottleneck nodes can be identified and source sending rate can be dynamically adjusted. Every packet has two kinds of priorities: static priority and dynamic priority. If queue is nearly full, it drops low priority packet rather than high priority packet. It does not use tail dropping. To ensure fairness, the algorithm scans the route-through traffic queue from head to tail. One packet from one source is sent from route-through traffic queue, and then a local generated packet is sent.

HTAP [19] (Hierarchical Tree Alternative Path) is a resource control algorithm that attempts to mitigate congestion in wireless sensor networks by creating dynamic alternative paths to the sink. HTAP algorithm introduces a novel adaptive method for inferring congestion in the network. This adaptive method uses buffer occupancy as a first indication of congestion occurrence and then it employs the ratio of out/in data rate in order to trigger the alternative path creation. When congestion appears in the network the HTAP scheme transmits the excess packets to the sink through alternative routes, employing nodes which are not in the initial path from the source to the sink. HTAP consists of 4 schemes: topology control, hierarchical tree creation, alterative path creation and handling of powerless nodes. HTAP's successful and efficient functionality relies on a topology control scheme that creates the initial connectivity in the network and on a hierarchical tree scheme which discovers all possible upstream routes from the sources to the sinks when an event occurs. The topology control scheme is based on a variation of the local minimum spanning tree algorithm.

The following table 1 presents a comparison of above explained protocols on the basis of various parameters which are congestion detection, congestion notification, congestion avoidance, reliability level, reliability direction, loss recovery, loss notification, energy efficiency and simulation environment.

Table 1 A comparison of Transport Layer Protocols

Protocol	Congestion Detection	Congestion Notification	Congestion Avoidance	Reliability Level	Reliability Direction	Loss Recovery	Loss Notification	Energy Efficient	Simulation Environment
PSFQ	-	-	-	Packet	Downstream	Hop-by-hop	NACK	No	NS2,Testbed
CODA	Queue Length, channel status	Explicit	AIMD rate Adjustment	-	-	-	-	Yes	NS2,Testbed
ESRT	Queue Length	Implicit	Rate Adjustment	Event	Upstream	Event to Sink	-	Yes	NS2 Simulator
STCP	Queue Length	Explicit	Rate Adjustment, Traffic Redirection	Packet	Upstream	End-to-End	eACK, NACK	Yes	TOSSIM
PORT	Node Price	Implicit	Rate Adjustment, Traffic Redirection	Event	Upstream	-	-	Yes	NS2 Simulator
SenTCP	Queue length packet service time, packet inter-arrival time	Explicit	Rate Adjustment	-	-	-	-	Yes	Simulation
IFRC	Queue Length	Implicit	Rate Adjustment	-	-	-	-	No	Testbed
PHTCCP	Packet Service Ratio	Implicit	Rate Adjustment	-	-	-	-	Yes	Simulation
E^2SRT	Queue Length	Implicit	Rate Adjustment	Event	Upstream	Event to Sink	-	Yes	NS2 Simulator
ECODA	Dual buffer threshold, weighted buffer difference	Implicit	Rate Adjustment	-	-	-	-	No	Simulation
HTAP	Queue length out/in data rate	Implicit	Traffic Redirection	-	-	-	-	Yes	Simulation

V. Research Issues in Transport Layer Protocols

Some wireless sensor network 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. 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. 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. 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. There is a need of transport laye protocols which can provide faireness among the variety of sensor nodes that are from different distance to sink nodes. Only a few rotocols have support for fairness such as CCF [20]. To Gurantee successful data delivery,transport layer protocls should use loss recovery mechanisms which are energy efficient and more effective. As sensor nodes have small storage space so the protocol should have low storage requirments. Packet drop causes unnecessary retransmissions which consumes lot of energy so transport layer protocol should have a mechanism to avoid packet drop. Also the transport layer protocols should use the concept of node priority, it provides better QoS.

VI. Conclusion

This article has surveyed several transport layer protocols for both congestion control and reliability in wireless sensor networks. Firstly, we described the concept of sensor networks. Secondly, we described the aspects of congestion control and reliability in wireless sensor networks. Then we provided the summary of existing transport layer protocols which provide either congestion control or reliability or both. Then we presented a comparative analysis of these protocols using parameters like congestion detection, congestion notification, congestion avoidance, reliability level, reliability direction, loss recovery, loss notification, energy efficiency and simulation environment. Finally we presented some open research issues for transport layer protocols in wireless sensor networks.

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