A Cross-Layer Protocol Stack for Congestion Control in Wireless Sensor Networks

T. Yashashwini
Department of CSE Siddaganga Institute of Technology, Tumkur, Karnataka, India

R. Sumathi
Department of CSE Siddaganga Institute of Technology, Tumkur, Karnataka, India

ABSTRACT
As Wireless Sensor Networks are evolving in a wide range where high load demands dominate and affects the overall performance of the network, congestion remains a serious problem that has to be tackled effectively. Since the capacity of shared wireless medium is limited, channel contention and network congestion can be experienced during the operation of the network. In this paper, a new cross-layer protocol stack for congestion control is proposed that attempts to control network congestion during collisions. The proposed protocol stack aims to avoid buffer overflow at each node during high traffic density and thus reduce packet losses during transmission in order to achieve efficient communication in WSN. The simulation results show that the proposed cross-layer protocol efficiently mitigates packet losses and improves overall network throughput**.**

Keywords
Congestion control, Buffer Overflow, Collisions, Back-off time, Wireless Sensor Networks.

1. INTRODUCTION
Wireless Sensor Networks (WSNs) are wireless networks consisting of spatially distributed autonomous devices using sensors. It monitors physical or environmental conditions, such as temperature, sound, vibration, pressure, motion, or pollutants, at different locations [1] and are event-based systems that exploit the collective effort of densely deployed micro sensor nodes which continuously observe certain physical phenomenon. In general, the main objective of any WSN application is to reliably detect/estimate event features from the collective information provided by sensor nodes. Sensor nodes are low cost, light-weight, tiny devices with energy constraints. The sensor nodes are deployed frequently near the event sources and sinks in a redundant manner [2].

Congestion happens when the offered load is more than the available capacity of the network. Over the past few years, network congestion has been identified as a major problem in wired networks as well as ad-hoc wireless and sensor networks [3]. In wireless adhoc networks, congestion often increases the burst nature of data traffic resulting in large number of packet drops due to buffer overflow in the network layer and an increase in packet delivery latency [4], [5]. As most of the WSN applications are data gathering applications, the data gathered by a large number of sensors need to be delivered to a sink node through a multi-hop wireless network. Such networks often experience severe network congestion due to the limited buffer capacity of the sensor nodes and limited capacity of the shared wireless medium [3]. Congestion leads to a drop in the overall network throughput and energy waste in the highly energy constrained wireless sensor nodes [6]. If the sensor network is used for certain event detection applications, the loss of packets due to buffer overflow might also hamper the event detection reliability.

In the traditional layered architectures, the majority of the communication protocols are individually developed and optimized for different networking layers, i.e., transport, network, medium access control (MAC), and physical layers. Although these protocols achieve very high performance in terms of the metrics related to each of these individual layers, they are not jointly designed and optimized to maximize the overall network performance while minimizing the energy expenditure and overhead. Considering the scarce energy and processing resources of WSNs, joint design of networking layers, i.e., cross-layer design stands as the most promising alternative that has gained interest recently.

Most current research on congestion control focus mainly on the development and analysis of end-to-end control schemes by modifying existing schemes used in wired networks and adapting them to wireless domain [7]. Some other research focus on the development of new routing and Medium Access Control (MAC) protocols that aim at reducing congestion in the network [6], [7], [8].

Congestion in a network is characterised by buffer overflow, collisions and packet losses in the network. Based on the underlying medium access control (MAC) mechanism, after several unsuccessful transmission attempts, the packets are dropped at the sender node since buffer occupancy exceeds its limit.

Thus, we propose a new cross-layer protocol which can efficiently control the congestion by appropriately setting the back-off time based on the buffer occupancy at a node.

The remainder of the paper is organized as follows. Section 2 gives related work. Section 3 describes the definition. The protocol description is given in section 4. Section 5 and gives the simulation results and conclusion.

2. RELATED WORK
Cross-layer design in communication networks, especially in wireless networks, has attracted great attention recently in [9]. The recent work on WSN [10], [3] reveal that cross-layer integration and design techniques result in significant improvement in terms of energy conservation in WSN. There exists some research on the cross-layer interaction and design in developing new communication protocols [11].

Hop-by-hop congestion control schemes using feedback mechanism have also been widely studied. If the paths experience congestion persistently, the hop-by-hop backpressure eventually reaches the source and allows it to throttle the transmission rate. The authors in [12] have mentioned that such hop-by-hop congestion control schemes react much faster than end-to-end schemes. However, such schemes might not be very suitable for multi-hop wireless networks since the backpressure needs to propagate through multiple hops through an already congested network before the source can throttle its transmission rate. Contention based Medium Access Control (MAC) protocols like 802.11 constitute one of the major sources of network congestion [3]. Use of such protocols in multi-hop wireless networks makes the network congestion even worse.

CCF (Congestion Control and Fairness) [13] uses packet service time to deduce the available service rate and therefore detects congestion in each intermediate sensor node. Congestion information, that is packet service time in CCF, is implicitly reported. CCF controls congestion in a hop-by-hop manner and each node uses exact rate adjustment based on its available service rate and child node number. CCF guarantees simple fairness. That means each node receives the same throughput. However the rate adjustment in CCF relies only on packet service time which could lead to low utilization when some sensor nodes do not have enough traffic or there is a significant packet error rate (PER).

In Fusion [4], congestion is detected in each sensor node based on measurement of queue length. The node that detects congestion sets a CN (congestion notification) bit in the header of each outgoing packet. Once the CN bit is set, neighboring nodes can overhear it and stop forwarding packets to the congested node so that it can drain the backlogged packets. This non-smooth rate adjustment could impair link utilization as well as fairness, although Fusion has a mechanism to limit the source traffic rate and a prioritized MAC algorithm to improve fairness. Siphon [14] also infers congestion based on queue length in intermediate nodes, but it uses traffic redirection to weaken congestion. There is no rate adjustment in Siphon.

In CADA [15], node's congestion level is measured by an aggregation of buffer occupancy and channel utilization. It actually counts the growing rate of buffer's occupancy and when a certain limit exceeds, node is considered congested. On the other hand if packet delivery ratio decreases drastically while the local channel loading reaches the maximum achievable channel utilization, it infers that there is channel congestion. For congestion mitigation CADA employs both resource control and rate control depending on the case. If congestion takes place in an intersection hotspot then resource control applies, while if congestion takes place in a convergence hotspot traffic control applies. Simulation results prove that CADA present better results concerning throughput, energy consumption, end to end delay and average per hop delay.

Adaptive Rate Control (ARC), [16], is an LIMD-like (linear increase and multiplicative decrease) algorithm. In ARC, if an intermediate node overhears that the packets it sent previously are successfully forwarded again by its parent node, it will increase its rate by a constant α. Otherwise it will multiply its rate by a factor β where $0 < \beta < 1$. ARC does not use explicit congestion detection or explicit congestion notification and therefore avoids use of control messages. However the coarse rate adjustment could result in tardy control and introduce packet loss.

Priority based Congestion Control Protocol (PCCP) [17], innovatively measures congestion degree as the ratio of packet inter-arrival time along over packet service time. PCCP still introduced node priority index to reflect the importance of each sensor node. Based on the introduced congestion degree and node priority index, PCCP utilizes a cross-layer optimization and imposes a hop-by-hop approach to control congestion.

In [18], an energy efficient congestion control scheme for sensor networks called Enhanced Congestion Detection and Avoidance is proposed which comprises of three mechanisms. First, the approach uses buffer and weighted buffer difference for congestion detection. Secondly, proposed a bottleneck-node-based source data sending rate control scheme and finally uses a flexible queue scheduler for packets transfer.

The ANAR [19] mechanism is another cross-layer optimization scheme, which combines transport-layer congestion control and network-layer routing protocol. The Cross-Layer Active Predictive Congestion Control (CL-APCC) scheme [20] for improving the performance of networks applies queuing theory to analyze data flows of a single-node according to its memory status, combined with the analysis of the average occupied memory size of local networks. In order to ensure the fairness and timeliness of the network, the IEEE 802.11 protocol is revised based on waiting time, the number of the node's neighbors and the original priority of data packets. The sending priority of the node is adjusted dynamically. DiffQ [21] provides practical adaptation and implementation of differential backlog that involves a cross-layer optimization of both congestion control and MAC scheduling in real multi-hop wireless networks. ACT (Adaptive Compression-based congestion control Technique) [22] is an adaptive compression scheme for packet reduction in case of congestion. The main problem of ACT is its high complexity.

Although the existing schemes [23-26] play important roles in improving performance of WSNs, designing an effective congestion control scheme is still a challenging issue in WSNs.

3. DEFINITIONS

Buffer capacity B_{cap}: It gives the maximum number of packets that a node can buffer.

Backoff-time $t_{back\text{-}off}$: It is the amount of time that a node should wait to transmit its next frame during the collision and its default value is 51.2µs.

Buffer Count B_{cnt}: It is a counter to the buffer and it can be incremented or decremented when inserting or retrieving data from the buffer respectively.

Buffer fill B_{fill}: This gives the percentage of buffer filled and it is given by,

$$B_{fill} (\%) = (B_{cnt} / B_{cap})*100$$

4. PROPOSED CROSS-LAYER PROTOCOL STACK

The traditional protocol stack is as shown in fig1.a. In this stack, the collisions at MAC layer will affect the transmission. During collisions, the channel is in busy condition and hence the back-off time is set to find an idle channel. The data is stored in the buffer until the MAC layer senses the media. In the traditional architectures, it is observed that the back-off time is set without having the knowledge of buffer status. If medium is not sensed in a minimal back-off time, there are more chances of packet losses due to buffer overflow.

In order to overcome this situation, a cross-layer design approach is proposed and it is defined as, "the breaking of OSI hierarchical layers in communication networks". The cross-layer architecture includes merging of layers, creation of new interfaces, or providing additional interdependencies between any two layers as shown in fig1.b.

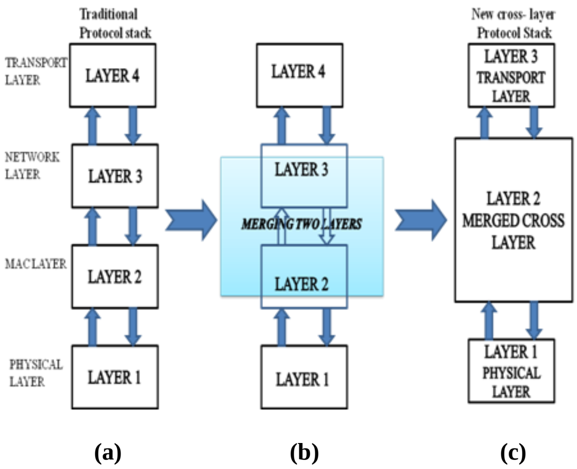

Fig 1: Proposed Cross-layer Protocol Stack.

The proposed cross layer protocol stack is as shown in fig1.c. In this stack, the network layer and MAC layer functionalities are merged to form a single merged cross layer. The merged cross-layer monitors the buffer status and as well as finds the collision free media. In the proposed stack, the back-off time is set based on the buffer status information.

The proposed merged cross-layer protocol composed of two main modules: (1) Buffer monitoring logic and (2) Transceiver logic as shown in fig 2.

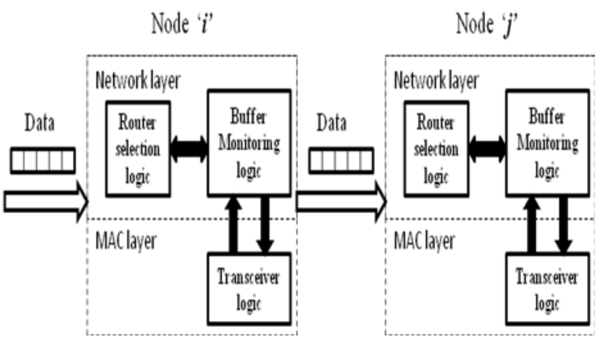

Fig 2: Logical Interaction between two merged cross-layers.

4.1 Buffer monitoring logic

The main function of buffer monitoring logic is to maintain the buffer status information of nodes which is participating in transmission. The overall procedure of buffer monitoring logic is given in Algorithm 1.

Whenever collisions occurs, the transceiver logic will send a collision message (collision message includes information about collisions and requests to send a value K in order to set its back-off time) to buffer monitoring logic. Whenever a request comes from transceiver logic, based on the number of collisions and buffer occupancy the suitable 'K' value is calculated by buffer monitoring logic and the corresponding 'K' value is sent to the transceiver logic. This procedure is repeated whenever request comes from the transceiver logic.

Algorithm 1: Buffer Monitoring Logic

Step 1: **Start**
Step 2: Initialize counter=0 when buffer is empty.
Step 3: Start counter, increment or decrement counter by 1when inserting or deleting data from buffer
Step 4: ***if*** MAC layer sends a request ***then***
Step 5: calculate B_{fill} as,
B_{fill} (%)= (B_{cnt}/ B_{cap})*100
Step 6: check the value of B_{fill} in 4 ranges
Range 1: ***if*** 0<B_{fill}<25%
Set K=4;
Send K value to transceiver logic
end if;
Range 2: ***if*** 25%<B_{fill}<50%
Set K=3;
Send K value to transceiver logic
end if;
Range 3: ***if*** 50%<B_{fill}<75%
Set K=2;
Send K value to transceiver logic
end if;
Range 4: ***if*** 75%<B_{fill}<100%
Set K=1;
Send K value to transceiver logic
end if;
Step 7: ***if*** B_{fill} = B_{cap} ***then***
Set K=0;
Send K value to transceiver logic, then send feedback signal as stop sending the further packets to sender nodes.
end if;
Step 8: end if;
Step 9: ***else*** goto step 2;
Step 10: **end**.

4.2 Transceiver logic

The main function of transceiver logic is to set back-off time during collisions. The overall transceiver logic procedure is given as flowchart in fig.3. Here 'N' refers to the number of re-transmission attempts and 'R' refers to the random integer used to set random back-off time at each node during collision and it ranges between 1 and 2^K.

The procedure of transceiver logic is as follows: when a transmitter wants to send a frame, it senses the medium to transmit, if the medium is found idle it transmits the frame after an inter frame time space (i.e., 9.6µs). If collision exists during transmission, the transceiver logic sends the collision message to buffer monitoring logic, upon receiving the collision message, the merged cross-layer triggers the buffer monitoring algorithm and it sends the corresponding K value to transceiver logic.

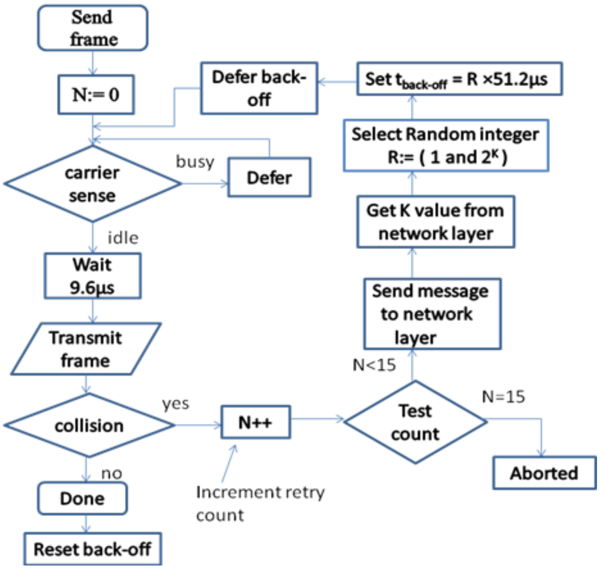

Fig 3: Transceiver logic

After receiving the K value, the transceiver logic calculates the back-off time. Once the back-off time is elapsed, the medium is sensed to find if it is idle or not, if the medium is found idle then node transmits its frame and resets the back-off to its initial value. If the medium is busy, then the same procedure is followed to set new back-off time. The transceiver logic restricts the number of retransmission attempts to 16 counts. After this number of attempts, the transmitter gives up transmission and discards the frame.
The main function of both buffer monitoring and transceiver logic is to avoid buffer overflow during collisions and to avoid packet losses during transmission and thus attempts to mitigate congestion. Since the back-off time is depending on the value K, the back-off time is set such that, the merged cross-layer has to sense the medium in a faster rate to avoid buffer overflow.

5. SIMULATION RESULTS

We analyse the performance of the proposed cross-layer protocol using the Qualnet simulator. The proposed cross-layer protocol is compared to Fusion [4]. Fusion exploits three techniques to mitigate congestion: hop-by-hop flow control, rate limiting source traffic when transit traffic is present i.e., rate control, and a prioritized MAC protocol. Fusion is briefly explained in section 2 of this paper. The main difference between Fusion and the proposed cross-layer protocol is the fact that Fusion uses a prioritized MAC protocol in which the randomized back-off time is set without the knowledge of buffer status... Fusion mainly focuses on combining the above mentioned three techniques together to mitigate congestion. On the other hand the proposed cross-layer protocol combines both buffer monitoring logic and Transceiver logic to mitigate congestion.

5.1 Simulation parameters

The simulation parameters are set as follows. 100 sensor nodes (including source and sink nodes) are randomly deployed in a square region of 100m×100m. The nodes communication radius is 30m. The routing protocol used is DSR (Dynamic Source Routing). The initial energy of sensor nodes is 0.1J. The total buffer size is 512Kbytes. The simulation parameters are listed in the below table.

Simulation parameters	Value
Communication range	30m
Data rate	2Kbps
Transmission power	2dbm
Buffer size	512 bytes
Packet size	100 bytes
Initial energy	0.1J

5.2 Performance metrics

The following performance metrics are considered for performance analysis:

Reliability: The reliability of a network is defined as the ratio of total packets sent to the total packets received at sink node.

Buffer overflows: The memory limitations of the sensor nodes necessitate limited sized buffers to be used. This metric gives the percentage of total packets lost due to buffer overflow.

Energy efficiency: It is the most important metric in WSNs which determines the amount of energy consumed at each node.

5.3 Results

Fig.4 depicts the impact of traffic density on network reliability with respect to different buffer sizes. Increase in traffic density will have a negative impact on reliability of the network. As network load increases, the number of packets to be transmitted also increases and leads to the increase in data traffic at each node. Increase in traffic density leads to more number of packet losses.

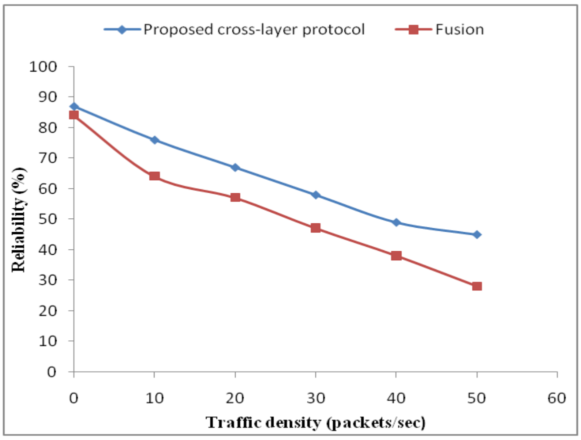

Fig 4: Reliability of a network and Traffic density at each node

It is observed that the proposed cross-layer protocol presents better performance than Fusion. The fact that in the proposed scheme, the network traffic is distributed to other nodes in terms of feedback mechanism and the buffer monitoring logic avoids buffer overflow at each node during collisions.

In fig.5, the impact of traffic density on buffer overflows is illustrated. Buffer overflows occur when incoming data packets is more than the outgoing data packets. Here high buffer overflows indicates more number of packets lost and vice-versa. As traffic density increases more number of packets in the queue also increases and hence leads to buffer overflow. The proposed scheme mainly aims to avoid buffer overflow and hence as shown in fig.5, the buffer overflows is higher in Fusion as compared to the proposed scheme.

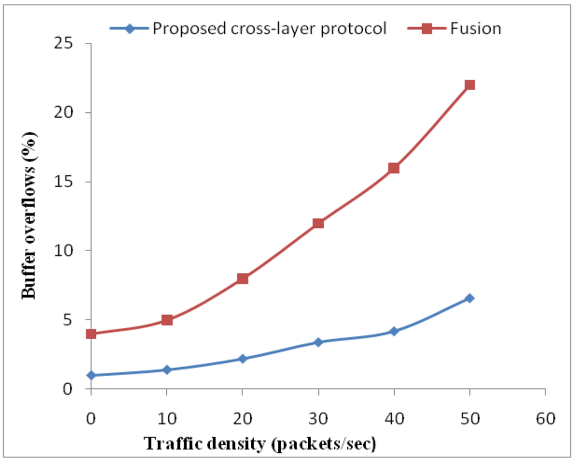

Fig 5: Buffer overflows with respect to Traffic densities.

The average energy consumption at each node due to the increase in traffic density is shown in fig.6.Energy is an important factor in WSN's since overall network performance is based on energy level at each node. As traffic density increases, the packets that has to be transmitting also increases. The node has to consume some amount of energy during each packet transmission and hence increase in data packets will lead to the consumption of more energy. In the proposed scheme the network traffic is distributed among all nodes by using feedback mechanism and by using the feedback mechanism, the amount of energy consumed at each node can be reduced. Fig.6 depicts that the proposed scheme is more energy efficient as compared to Fusion.

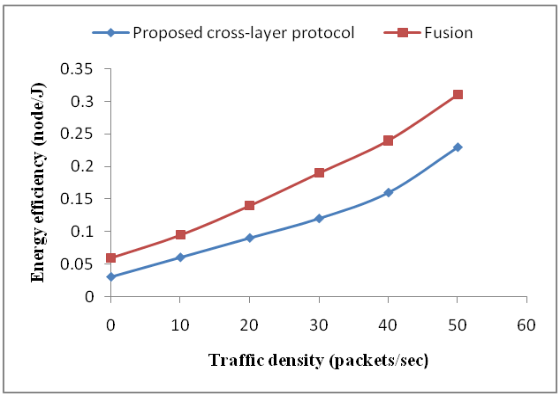

Fig 6: Average energy consumption per node and Traffic density

6. CONCLUSION

In this paper, a new cross-layer congestion control protocol stack is presented that aims to mitigating packet drops due to buffer overflow. The simulation results show that the proposed protocol is also energy efficient and even with increase in traffic density, the performance of the network achieves high reliability with less packet drops due to buffer overflows.

7. REFERENCES

[1] K. Romer and F. Mattern, "The design space of wireless sensor networks," *IEEE Wireless Communications*, vol. 11, no. 6, pp. 54–61, December 2004.

[2] S. Toumpis and L. Tassiulas, "Optimal deployment of large wireless sensor networks," *IEEE Transactions on Information Theory*, vol. 52, no. 7, pp. 2935–2953, 2006.

[3] M. C. Vuran, V. C. Gungor, and O. B. Akan, "On the Interdependency of congestion and Contention in Wireless Sensor Networks," presented at *ICST SenMetrics '05*, San Diego, CA, 2005.

[4] B. Hull, K. Jamieson, and H. Balakrishnan, "Mitigating Congestion in Wireless Sensor Networks," in *ACM SenSys 2004*. Baltimore, MD, 2004.

[5] I. Demirkol, C. Ersoy, and F. Alagoz, "MAC Protocols for Wireless Sensor Networks: A Survey," in *IEEE Communications Magazine*, 2005.

[6] C. Song, S. Hamid, and N. Guevara, "Improving performance of MAC layer by using congestion control/avoidance methods in wireless network," in *Proceedings of the 2001 ACM symposiumon Applied computing*. Las Vegas, Nevada, United States: ACM Press, 2001.

[7] E. J. Anderson and T. E. Anderson, "On the stability of adaptive routing in the presence of congestion control," in *IEEE INFOCOM*. San Fransisco, CA, 2003.

[8] I. Glauche, W. Krause, R. Sollacher, and M. Greiner, "Distributive routing and congestion control in wireless multihop ad hoc communication networks," *Physica A*, pp. 677 - 701, 2004.

[9] S. Shakkottai, T. S. Rappaport and P. C. Karlsson, Cross layer design for wireless networks, *IEEE Communications Magazine*, April 2003.

[10] L. van Hoesel, T. Nieberg, J. Wu, and P. J. M. Havinga, "Prolonging the lifetime of wireless sensor networks by cross-layer interaction," *IEEE Wireless Communications*, vol. 11, no. 6, pp. 78 - 86, Dec. 2004.

[11] T. Melodia, M. C. Vuran, D. Pompili, "The State of the Art in Crosslayer Design for Wireless Sensor Networks," *to appear in Springer Lecture Notes in Computer Science (LNCS)*, 2006.

[12] Y. Yi and S. Shakkottai, "Hop-by-hop Congestion Control over a Wireless Multi-hop Network," *IEEE/ACM Transaction on* Networking, 2006.

[13] C.-T. Ee and R. Bajcsy, "Congestion control and fairness for many-to-one routing in sensor networks," in *Proc. ACM Sensys*, Nov. 2004.

[14] C.-Y. Wan, S. B. Eisenman, A. T. Campbell, and J. Crowcroft, "Siphon: Overload traffic management using multi-radio virtual sinks in sensor networks," in *Proc. ACM SenSys*, Nov. 2005.

[15] W.-w. Fang, J.-m. Chen, L. Shu, T.-s. Chu, and D.-p. Qian, "Congestion avoidance, detection and alleviation in wireless sensor networks," *Journal of Zhejiang*

University - Science C, vol. 11, pp. 63–73, 2010, 10.1631/jzus.C0910204.

[16] A. Woo and D. C. Culler, "A transmission control scheme for media access in sensor networks," in *Proc. ACM Mobicom*, July 2004.

[17] C. Wang, B. Li and K. Sohraby, "Upstream Congestion Control in Wireless Sensor Networks through Cross-layer Optimization," *IEEE Journal on Selected Areas in Communications,* vo.25, no.4, pp.786-795, 2007.

[18] Liqiang Tao and Fengqi Yu, "ECODA: Enhanced Congestion Detection and Avoidance for Multiple Class of Traffic in Sensor Networks", Proceedings of the 15th Asia-Pacific Conference on Communications (APCC 2009), pp. 726-730, 2009

[19] Yu-Pin Hsu and Kai-Ten Feng, "Cross-Layer Routing for Congestion Control in Wireless Sensor Networks," *Radio and Wireless Symposium*, p.783-786, 2008.

[20] J. Wan, X. Xu, R. Feng and Y. Wu, "Cross-Layer Active Predictive Congestion Control Protocol for Wireless Sensor Networks," *Sensors 2009*, vol.9, no.10, pp.8278- 8310, 2009.

[21] A. Warrier, S. Janakiraman, S. Ha and I. Rhee, "DiffQ: Practical Differential Backlog Congestion Control for Wireless Networks," *INFOCOM,* pp.19-25, 2009.

[22] Joa-Hyoung Lee and In-Bum Jung, "Adaptive-Compression Based Congestion Control Technique for Wireless Sensor Networks,"*Sensors 2010*, vol.10, no.4, pp.2919-2945, 2010.

[23] Wei-wei Fang, Ji-ming Chen, Lei Shu, Tian-shu Chu and De-peiQian, "Congestion avoidance, detection and alleviation in wireless sensor networks," *J. Zhejiang Univ*, vol.11, no.1, pp.63-73, 2010.

[24] N. Sengottaiyan and R. Somasundaram, "A Modified Routing Algorithm for Reducing Congestion in Wireless Sensor Networks," *Eur. J. Sci. Res*, vol.35, no.4, pp.529- 536, 2009.

[25] P. Reena and L. Jacob, "A Cross Layer Design for Congestion Control in UWB Based Wireless Sensor Networks," *Int. J. Sens. Netw,* vol.5, no.4, pp.223-235, 2009.

[26] Jian-JunLeiand Gu-In Kwon, "Reliable Data Transmission Based on Erasure-resilient Code in Wireless Sensor Networks", *KSII Transactions on Internet and Information Systems*, vol.4, no.1, pp.62-77, 2010.