LCART: Lightweight Congestion Aware Reliable Transport Protocol for WSN Targeting Heterogeneous Traffic

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Abstract. This paper presents energy efficient transport layer protocol for heterogeneous WSN, named as LCART. LCART fuses the prevalent or reciprocal functionalities of Transport, MAC and Wireless-Physical layers in order to achieve energy efficiency and meeting QoS objectives of heterogeneous WSN. LCART intelligently provide congestion control by the simultaneous use of Packet Service Time (TPST), Packet Inter Arrival Time (TPIAT), Buffer Occupancy Level (m_i) and Channel Loading Threshold limits ($\lambda_{Threshold}$) constraints to formalize new source rate plan for avoiding congestion. LCART achieves packet level reliability by using explicit NACK and β parameter entirely being governed by the nature of the traffic. LCART has been tested for 24 mote ad-hoc topology and results reveal that it exhibit highest good throughput of 0.3112 Mbps, $<$ 80msec and $<$ 130 msec average End-to-End (E-2-E) packet latency for high and low prioritized packet information, 1.014% average percentage packet drop and overall exhibits energy efficient behavior (lowest per packet communication cost) in comparison to TCP-Westwood+ (TCP-WW+), TCPWestwood (TCP-WW), TCPNewReno and TCPReno.

Keywords. Performance, Design, Reliability, WSN, Transport Protocol, Cross-layer, IEEE802.11, MAC/Wireless-Physical, QoS, Latency

1 Introduction

The concept of using WSN for heterogeneous application scenarios[1] by just simple reconfiguration of the WSN motes has attracted the intention of the research community recently. This enables the WSN to address variety of applications ranging from environmental monitoring (scalar by nature) to military (scalar as well multimedia by nature) by involving multiple disciplines of control, signal processing and embedded computing[12,8,13,9]. The transport layer for heterogeneous WSN has gained fundamental importance for ensuring the data reliability

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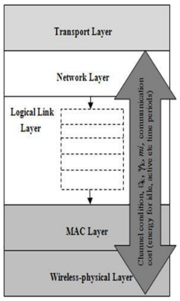
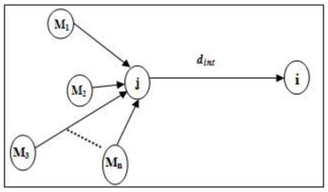
[1] throughout the paper this term represent the mixed traffic scenario including the multimedia information flow e.g. audio

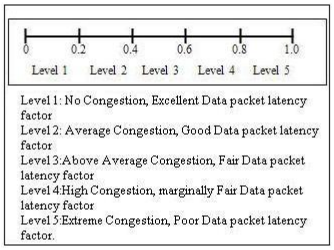
and congestion control feature[4] of the design [12,8]. In WSN, the transport layer protocol is responsible for reliably communicating the sensed information form source mote to sink [8,11]. Presently the transport layer protocols are designed either by targeting the protocol efficiency or to address the range of application scenarios[9,11] where the protocol efficiency is comprised. Keeping this fact in mind, the researchers recently has come up with a new dimension of hybrid transport layer protocol designing also called as "Cross-layering" [6] which inherent the flavors of energy efficiency and addressing the range of application scenarios. Majority of the transport protocols for heterogeneous WSN like RT^2[3], RCRT[7], CTCP[1], FLUSH[5], DST[2] etc provides packet level reliability in upstream direction and uses ACK, SACK and NACK for ensuring reliability. These protocols also use TPST, TPIAT, m_i and $\lambda_{Threshold}$ in discrete isolated fashion, not simultaneous, for explicit or implicit congestion notification within WSN. Except RT^2, which cross-layered the Transport layer functionality with the Routing layer, rest all does not utilize this approach for gaining network efficiency while complying with the stringent QoS objectives specific to heterogeneous WSN in an energy efficient manner. We have observed the dependency of transport layer over underlying MAC and Wireless-physical layers[10] and based on this we are envisaging a cross-layered approach for transport protocol named as 'LCART' which is energy efficient and addressing the range of application scenarios. The rest of the paper is organized as following. After the introduction the proposed transport layer protocol scheme LCART is described in Section 2 followed by Section 3 which describes the simulation setup and results. The discussion followed by the conclusions will be presented in the last section 4.

2 PROPOSED TRANSPORT PROTOCOL: LCART

The concept of proposed LCART for heterogeneous WSN is shown in the Fig. 1. The LCART is comprised of Congestion Control, Packet Reliability and Data prioritization modules for heterogeneous application support. LCART looks after the system throughput, motes energy budget, E-2-E data packet latency and data packet drop by having two control loops running concurrently. E-2-E sink enabled feedback control loop monitors the E-2-E data packet latency and the control loop triggers the source motes to readjust their transmission rates thereby minimizing the number of data packets actually suffering from an unwanted queue delay caused by congestion. Whereas the Local Intermediate buffer mote enabled feedback loop monitors the TPIAT, TPST, channel conditions in its vicinity and local 'm_i'. It informs sink mote about these statistics which is helpful in computing the new source rate plan according to the monitored statistics. This efficiently exploits the network resources while minimizing the inter-hop packet delay and its drop caused by collisions, bad channel conditions and congestion. Other than this it is also responsible for the rapid data packet retrieval, in an H-b-H fashion, during the events of data packet loss caused by either condition discussed above. The detailed explanation of the proposed scheme is outlined in the following subsections below:







Level 1: No Congestion, Excellent Data packet latency factor
Level 2: Average Congestion, Good Data packet latency factor
Level 3:Above Average Congestion, Fair Data packet latency factor
Level 4:High Congestion, marginally Fair Data packet latency factor
Level 5:Extreme Congestion, Poor Data packet latency factor.

Fig. 1: The Cross-layered Approach Fig. 2: Mote scenario separated by 'd_{int}'
Fig. 3: Different levels of congestion

2.1 Congestion Control

The purpose of this module is to effectively control the congestion in order to minimize the packet drop due to congestion and to achieve optimum system throughput. When the network starts for the first time LCART computes the initial sending rate plan for different sources with the help of 3 control packets transmitted in upstream towards sink. After knowing TPST, TPIAT values (as it dictates the time gap between the successive packet transmissions) and the channel threshold limit '$\lambda_{Threshold}$' the sink computes the initial source transmission rate 'x_0' in terms of packets per second (pps) and is given by

$$x_0 = min(T_{PST},\, T_{PIAT},\, \lambda_{Threshold}) \tag{1}$$

Load Threshold limit Computing Load threshold limit in terms of bits per second (bps) at any mote would be essential for avoiding the congestion to happen within network. Consider the scenario as shown in Fig. 2 with two motes 'i' and 'j' separated by 'd_{int}' distance a part from each other with 'n' neighboring motes to mote 'j'. Assume the load being generated by source mote 'j' is 'λ_{jj}', packet size is in bytes and source transmission rate is in '*pps*' then λ_{jj} would be:

$$\lambda_{jj} = \frac{rate\, in\, pps * 512 * 8}{10^6}(Mbps) \tag{2}$$

For the mote 'j' if it is sensing and relaying child mote's load, then the total effective load shared by it is:

$$\lambda_{ej} = \lambda_{jj} + \sum \lambda_{kj} \;\; \forall \;\; k \epsilon H \tag{3}$$

where H is the set of child motes and 'λ_{ej}' is the effective load shared by a mote with sensing feature, the effective load for the case of relay mote having no sensing feature is given by:

$$\lambda'_{ej} = \sum \lambda_{kj} \;\; \forall \;\; k \epsilon H \tag{4}$$

Now let us define 'p' as the probability of successful delivery of data packets to the next possible hop, and 'q' as probability of failure ($q = 1 - p$). So the data packets passed to mote 'i' by mote 'j' will be $p.\lambda_{ej}$i.e.

$$\lambda_{ji} = p.(\lambda_{ej} = \lambda_{jj} + \sum \lambda_{kj} \;\; \forall \;\; k \epsilon H) \tag{5}$$

So the time taken by a mote 'j' to transfer 'λ_{ej}' to mote 'i' is simply $1/p$, so the associated delay due to channel accessing is $T_{ch} = \frac{1}{p}$. This gives the number of channel slots required to send the entire data from mote 'j' to mote 'i'. If 'T_{pkt}' is defined as the one operating cycle then $\rho.T_{pkt}$will be termed as the mote's operating duty period, the time for which a mote is in active condition (during Tx, Rx and idle listening). So the mote's OFF time 'T_{OFF}' is given by:

$$T_{OFF} = (1-\rho).T_{pkt} \tag{6}$$

So for mote 'j' with transmission error 'e_j' and 'λ_{ej}' being an effective load the transmission would be:

$$T_{tx} = (1+e_j)(p.(\lambda_{ej} = \lambda_{jj} + \textstyle\sum \lambda_{kj} \ \forall \ k \epsilon H)) * T_{pkt} \tag{7}$$

$$T_{rx} = (\textstyle\sum \lambda_{kj} \ \forall \ k \epsilon H) * T_{pkt} \tag{8}$$

and so the idle listening is

$$T_{\Lambda} = \rho.T_{pkt} - (T_{rx} + T_{tx}) \tag{9}$$

$$T_{\Lambda} = [\rho - [(\textstyle\sum \lambda_{kj} \ \forall \ k \epsilon H) + (1+e_j)(p.(\lambda_{jj} + \displaystyle\sum \lambda_{kj} \ \forall \ k \epsilon H))] * T_{pkt}] \tag{10}$$

So the T_{OFF} will be:

$$T_{OFF} = T_{pkt} - (T_{rx} + T_{tx} + T_{\Lambda}) \tag{11}$$

$$T_{OFF} = T_{pkt} - ((\textstyle\sum \lambda_{kj} \ \forall \ k \epsilon H) * T_{pkt} + (1+e_j)(p.(\lambda_{jj} + \textstyle\sum \lambda_{kj} \ \forall \ k \epsilon H))* \\ T_{pkt} + [\rho - [(\displaystyle\sum \lambda_{kj} \forall \ k \epsilon H) + (1+e_j)(p.(\lambda_{jj} + \displaystyle\sum \lambda_{kj} \forall \ k \epsilon H))] * T_{pkt}]) \tag{12}$$

Now we can avoid the congestion by limiting the mote's effective load to some threshold value i.e.

$$\lambda_e \, or \, \lambda_e^{'} \leq \lambda_{Threshold} \tag{13}$$

Now we are going to find this threshold and for this we set $T_{\Lambda} \geq 0$ and substitute $(\sum \lambda_{kj} \ \forall \ k \epsilon H)$ by $\lambda_{Threshold}$we will get:

$$\lambda_{Threshold} \leq \tfrac{[\rho - p.(1+e_j).\lambda_{jj}]}{[(1+e_j).p+1]} \tag{14}$$

New Rate Computation *'It is defined as the optimal source transmission rate value computed based on the instantaneous network statistics including TPST, TPIAT, channel loading and* m_i*'.* Now we will discuss the optimal solution for updating mote's transmission rate, being triggered by the sink for easing the congestion within the network while simultaneously supporting the data reliability. The solution is based on the Robust Kalman estimator (*Predictor and Corrector Estimator*) with the intention to have minimal processing over head and to gain significant network efficiency. Consider a network plan having 'N' motes distributed in space with 'n' neighboring motes to any particular mote within network.

Time Update: Time update helps in estimating (at current discrete time interval k) the source transmission rate and error covariance based on the a priori statistics of TPST, TPIAT and 'm_i'.

Let $T_{PST}(i,j)$, $T_{PIAT}(i,j)$, $m_i(i,j)$ represents the TPST of the 'i^{th}' mote, TPIAT between the two motes and memory occupancy level of the 'i^{th}' mote which is feedback to the 'j^{th}' mote at $k+1$ interval.

Let $x_i[k]$ represents the current data transmission rate (pps) of the mote 'j' at interval 'k'. The mote 'j' may relay or generate the data information and is given by equation given in section Load Threshold Limit ($Eq14$). Then its estimated rate for interval $k+1$ is given by

$$x_{k+1} = [C_k - A_k].x_k + B_k.U_k.x_k + G_k.w_k \tag{15}$$

where, $x_k \epsilon R^n$, $U_k \epsilon R^y$and $w_k$is the process noise having mean $\overline{w_k}$=0 and covariance $\overline{w_k . w_k}^T$and is written symbolically as w_k $(0, Q)$ and over bars denotes the expected value. A_k is $n \times 1$ congestion matrix governed by the intermediate mote memory congestion/memory occupancy level at any interval k and is given by:

$$A_k = \begin{bmatrix} m_i(i, j_1) \\ m_i(i, j_2) \\ . \\ . \\ m_i(i, j_n) \end{bmatrix}, B_k = G_k = \begin{bmatrix} 1\,0\,.\,.\,0 \\ 0\,1\,.\,.\,0 \\ .\,.\,.\,.\,. \\ .\,.\,.\,.\,. \\ 0\,0\,.\,.\,1 \end{bmatrix}, C_k = \begin{bmatrix} 1 \\ 1 \\ . \\ . \\ 1 \end{bmatrix} \text{ and}$$

U_k is $n \times 1$ control matrix and is given by $U_k = \begin{bmatrix} U_k(i, j_1) \\ U_k(i, j_2) \\ . \\ . \\ U_k(i, j_n) \end{bmatrix}$

where by considering the case for mote 'i' and 'j'

$$U_k(i, j) = \epsilon_k(i, j) + \gamma_k(i, j) \tag{16}$$

where, $\epsilon_k(i, j)$ is the error between the estimated value of the TPST of mote 'i', 'T'_{PST}', at mote 'j' and actually observed packet service time at the 'i^{th}' mote (will be informed to mote 'j' at interval $k+1$) and is given by:

$$\epsilon_k(i, j) = T'_{PST} - T_{PST} \tag{17}$$

and $\gamma_k(i, j)$ is the error between the estimated value of the TPIAT at mote 'j' and actually observed TPIAT at the mote 'i' and is given by:

$$\gamma_k(i, j) = T'_{PIAT}(i, j) - T_{PIAT}(i, j) \tag{18}$$

Now let us define 'x_0' as the initial source and intermediates mote rate calculated as in section 2.1 ($Eq\,1$). So the procedure is repeated several times under random scenarios and the initial estimated sending rate value for every mote (including, source, relay or intermediate buffer motes) would be taken by averaging the previous historical values, i.e.

$$\hat{x}_0 = \overline{x}_0 \tag{19}$$

and likewise the error covariance for sending rate would be:

$$P_0 = P_{x_0} = (x_0 - \overline{x}_0)(x_0 - \overline{x}_0)^T \tag{20}$$

So incorporating the system dynamics the *Time Update* equation for error covariance would be:

$$P^-_{k+1} = A_k P_k A^T_k + G_k Q_k G^T_k \tag{21}$$

and the estimation for the transmission rate would be:

$$\hat{x}_{k+1} = [C_k - A_k]\hat{x}_k + B_k U_k \hat{x}_k \tag{22}$$

Similarly for sink, the incoming data or actual output of the system is given by:

$$z_k = H_k x_k + v_k \tag{23}$$

where,

$z_k \epsilon R^t$, G_k and H_k are simple scaling matrix and,

$v_k \epsilon R^t$is the measurement noise (if any). Here we are assuming it to zero.

Measurement Update: Measurement update helps in (feedback to time update in $k+1$ interval) correcting the source transmission rate and error covariance by taking into account the effect of measurement 'z_k'. So the *Measurement Updates* for error covariance and estimated rate value by taking the effect of measurement 'z_k' would be:

$$P_{k+1} = [(P^{-}_{k+1})^{-1} + H^{T}_{k+1} R^{-1}_{k+1} H_{k+1}]^{-1} \tag{24}$$

$$\hat{x}_{k+1} = \hat{x}^{-}_{k+1} + P_{k+1} H^{T}_{k+1} R^{-1}_{k+1} (z_{k+1} - H_{k+1} \hat{x}^{-}_{k+1}) \tag{25}$$

We can represent this estimation and correction of new sending rate value that incorporates the effect of congestion (by having a knowledge of T_{PST}, T_{PIAT}, ϵ_k, γ_k, m_i) as shown in Fig. 4.

Once the sink computes the rate for every source it will then inform the new transmission rate to every source (in form of rate control packet in downstream fashion). The source upon receiving the new rate plan will start sending the new packets with this newly defined transmission rate value.

Following are the conditions which will decide the severity of congestion:

Condition 1. For any source mote the following condition must be satisfied for the updated estimated rate value:

$$\lambda_e \, or \, \lambda^{'}_e = \frac{rate\, in\, pps *512*8}{10^6}(Mbps) \leq \lambda_{Threshold} \tag{26}$$

Condition 2. The buffer occupancy index scale as shown in Fig. 3 will define the severity of the congestion within heterogeneous WSN

Condition 3. TPST Vs TPIAT: If TPST $>$ TPIAT then it may lead to queue build up and packets will have to suffer from unwanted long queue delay. This condition allows the receiving mote to inform the sender to reduce its transmission rate. However, if TPST $<$ TPIAT then for this case the mote may likely to ask the sending mote to increase its transmission rate.

Condition 4. Load Threshold limit: To avoid congestion the mote should balance the load it is actually putting on the channel and is being governed by $\lambda_{Threshold}$ limit as deduced in the Section 2.1.1.

In this section we have outlined the theoretical foundation for the congestion control. In the next section we will now give the theoretical understanding for the packet reliability.

2.2 Packet Reliability

For multimedia traffic scenario, the packet based reliability is being dictated by the application specific QoS 'β' parameter. The purpose of this module is to ensure the packet level reliability for both data packets (upstream) and control packets (downstream). It will take channel conditions, E-2-E TTL, traffic class, packet priority and NACK as input and will decide the necessary reliability measures for that particular information that includes packet storage and packet retrieval. Functionally this module comprised of Packet Storage and Packet Retrieval using NACK sub-modules.

Packet Storage Upon packet reception Packet Storage module will retrieve the received packet's type (NACK, Data or Rate packet), priority, nature of traffic class and packet's E-2-E TTL. It will then take necessary measures to define the maximum allowable store time ($\frac{20*RTT}{\beta}\, msec$) for that packet within the buffer based on its nature (‘β’ parameter). This module will also compute the ‘m_i’ for finding the congestion index and new transmission rate plan. It also couples its functionality with active queue scheduling feature of the packet scheduler (will be discussed in section 2.3.1) for necessary memory scheduling.

Packet Retrieval using NACK The LCART uses the explicit NACK control signaling (triggered by lower layer information), as shown in the Fig. 5, at the transport level for Packet Retrieval from the immediate or subsequent buffer motes. The NACK packet informs this module about the packet ID, source from which this packet originates and sequence number ‘s’ for missing packet retrieval. Also this module together with the Packet Scheduler (as will be discussed in section 2.3.1) will take necessary measure for its orderly sending.

2.3 Data Prioritization for Heterogeneous Traffic Support

The purpose of this module is to take care of the heterogeneous traffic flows from various source ID’s ‘i’, that occur simultaneously in any reference time frame. It will rank and scheduled the packet transmission, having sequence number ‘s’, by taking into account the packet priority ‘b’, weighting co-efficients ‘$W^i_{b,s}$’ and E-2-E packet TTL information. It not only helps in scheduled transmissions of the packets but also help in combating challenges posed by the application specific stringent QoS requirements. This module is further comprised of Packet Scheduler and Packet Transmission sub-modules.

Packet Scheduler This module interacts with the congestion control and reliability modules in order to facilitate the network that fulfills the criteria of minimum congestion and high reliability assurance. It will interact with the reliability module to serve the following functionalities:

1. Order the stored packets based on its priority and E-2-E TTL information,
2. Based on available ‘$\lambda_{Threshold}$’ and weighting co-efficients information it will assign the channel bandwidth to heterogeneous traffic flows,
3. Active queue scheduling, flushes buffer (i.e. delete the packets from memory which are assumed to be delivered or passed the maximum allowable time limit for storage being governed by the information specific weighting co-efficients and ‘β’ parameter), and
4. Reliability module will request Packet Scheduler to find the packet as in NACK.

Condition 5. For overall network, the multimedia communication shares 60% bandwidth while rest 40% bandwidth is assigned for scalar information exchange including both critical and less-critical by nature. Empirically the following normalized bandwidth share values are selected:

1. For multimedia flow $b = 1$, and $W^i_{b,s} = 0.6$,
2. For critical scalar information $b = 2$ and $W^i_{b,s} = 0.25$, and

3. For scalar less-critical information, $b = 3$ and $W^i_{b,s} = 0.15$.

Condition 6. Empirically the maximum effective rate for multimedia and other scalar motes comes to be:

1. Multimedia: $W^i_{b,s} * \lambda_{Threshold} = 0.6 * \lambda_{Threshold}$,
2. Scalar critical: $W^i_{b,s} * \lambda_{Threshold} = 0.25 * \lambda_{Threshold}$, and
3. Scalar less critical:$W^i_{b,s} * \lambda_{Threshold} = 0.15 * \lambda_{Threshold}$

Condition 7. Likewise if the parent mote and child motes are all intermediate motes then the link will be shared maximally by the child intermediate mote having highest branch priority i.e.

$$\sum P_h = P_l \quad \forall\, h \epsilon H \tag{27}$$

where,

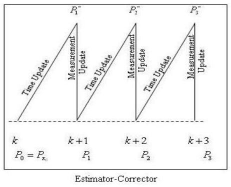
P_l= effective priority of the intermediate mote 'l',

$\sum P_h = \sum W^i_{b,s}$ $\forall\, h \epsilon H$, $b \epsilon S$, $s \epsilon E$, $i \epsilon D$ is the effective sum of all motes (source, intermediate etc) priorities that are attached to the intermediate mote 'l' can also be computed by the sum of priorities of data that a particular mote is keeping/handling.

Packet Transmission This module will transmit packet in an order defined by the Packet Scheduler.

Table 1. Network Parameters

Parameter	Values
Frequency (Hz)	914e+6
RX & CS Threshold (W)	3.6252e-10 W & 1.559e-11
Ifqlen	50 packets
Mote Initial & Idle power (W)	100 & 712e-6
Mote Rx & Tx power (W)	35.28e-3 & 31.32e-3
Mote Sleep power (W)	0.001
Data Packet Size	512Bytes
β	$0 < \beta < 1$
ρ	1
v_k	0
e_j	1%



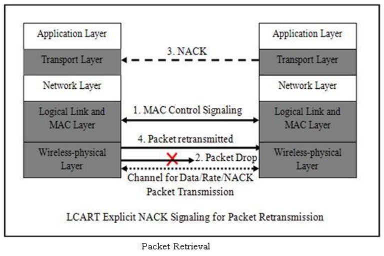


Fig. 4: Estimator Corrector for Rate Adjustment
Fig. 5: Packet Retrieval for LCART

3 SIMULATION SETUP AND RESULTS

NS-2 has been used for evaluating the LCART in a multi-hop scenario[2] as shown in Fig. 6, comprising of 24 motes spaced randomly at an average distance of around 100 meters (m) apart from each other and covering a region of $1000m \times 1000m$. Motes $0-9$ are considered as basic source or leaf motes while motes 11–23 are intermediate motes (may or may not have sensing feature) and mote 10 acts as Sink. The source motes 1, 4 and 7 are considered to be multimedia by nature while source motes 3, 5, 6 and 0, 2, 8, 9 are scalar-critical and scalar less-critical by nature. For this network we extensively evaluated LCART for the case of total good throughput of the system, average E-2-E data packet latency, network energy consumption and the average packet drop. In this simulation setup we focused more on results from practical perspective and for this we have used the following parameters listed in the Table 1. The simulation also incorporates the effect of errors introduced by channel interference (addition of uniform errors both at transmission and reception side independently). The performance of the LCART is evaluated against TCP-WW+, TCP-WW, TCPNewReno and TCPReno.

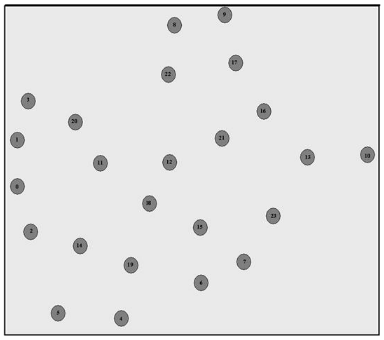


Fig. 6: Network topology

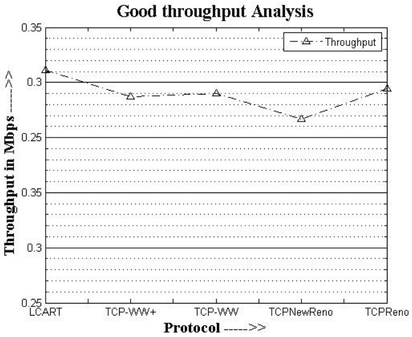


Fig. 7: Good throughput Comparison

Good Throughput comparison for LCART with other transport layer protocols is shown in Fig. 7. As we can see from the graph LCART exhibits highest good throughput of 0.3112 Mbps in comparison to TCP-WW+ whose good throughput is 0.2874 Mbps, TCP-WW (0.2902 Mbps) , TCPNewReno and TCP Reno (0.2668 and 0.2941 Mbps). TCP-WW+ and TCP-WW, also called the sender-side variants of TCP-NR, relies on mining of the ACK control signaling for setting the congestion control parameters like slow-start threshold limit and congestion window which are then used in estimating the source transmission rate values. As mining of ACK stream involves the close monitoring of per packet ACK beside the actual data flow, includes the E-2-E latency for data packet with

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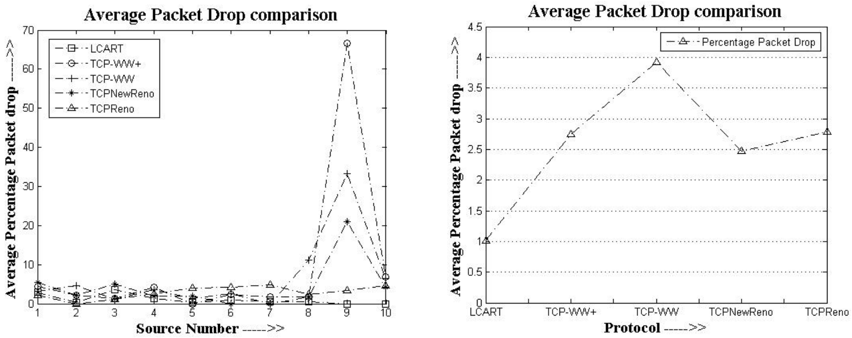
[2] We have used Ad-hoc On-Demand Distance Vector (AODV) and IEEE802.11 as Routing agent and underlying MAC/Wireless-Physical layer standards.

an addition of the ACK reception latency (which is variable) at the source side, thus would increase the time gap between the successive transmission and hence results in drop of system good throughput. Whereas the main reason for this good behavior exhibited by LCART comes from the protocol efficiency gain from the cross-layer design which not only best utilizes the network resources for finding the optimal source transmission rates but also helps in quick retrieval of lost packet information. This optimal source transmission rate value, which is based on feeding the real time monitored statistics to Kalman based predictor-corrector estimator, prevents the unwanted events of packet drop and source transmission rate reduction, thus results in high system good throughput.

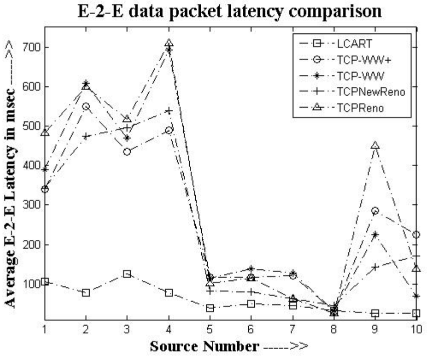
Fig. 8 (a) and 8 (b) shows the *Average Packet Drop* comparison of LCART against various transport layer protocols. From the packet drop behavior exhibited by various sources as shown in Fig. 8 (a) for various transport layer protocols it is evident that among all protocols only LCART guarantee the successful delivery of high and low priority packet information. It also evident from Fig. 8 (b) that LCART exhibits only 1.0137% (of the total communication) packet drop in comparison to 2.7394%, 3.9133% for TCP-WW+ and TCP-WW and 2.47%, 2.8% subsequently for TCPNewReno and TCPReno. The TCP-WW+ and TCP-WW avoids packet drops by the use of an additive increase/adaptive decrease (AIMD) paradigm to enhance the classic AIMD algorithm. It, upon experiencing a packet loss, performs E-2-E bandwidth estimation (at the sender side) for future packet transmissions. As this sender based dynamic phenomenon of rate adjustment is entirely based on received ACK monitored statistics and could possibly result in enormous packet drop before the new bandwidth estimation has taken place and that is why their average percentage data packet drop for the entire communication is higher. The reason, the LCART shows lowest packet drop in comparison to others is because of its transport layer dependency on lower MAC and Wireless-Physical layers which actually feedback's the transport layer about the channel conditions and the severity of the congestion in the neighborhood that result in packet drop. Another primary reason of this low drop is its stochastically tuned reliability component ('β' parameter) which is based on the nature of the traffic, defines the time of storage at local intermediate buffer motes.

Fig. 9 shows the *Average E-2-E Data Packet Latency* comparison for various transport layer protocols and the significance of this comparison highlights the use of LCART for WSN targeting heterogeneous traffic simultaneously. From the comparison it is obvious that the LCART outperforms all by exhibiting the least E-2-E data packet latency for every source. LCART exhibits < 80 msec E-2-E latency behavior for multimedia packet information and < 130 msec E-2-E latency for other, scalar-critical and less critical, packet information. TCPReno exhibits worst behavior among all for the high priority information, where as TCP-WW+ shows better response in comparison to TCP-WW, TCPNewReno and TCPReno. For the packet information coming from sources that uses TCP-WW+ and TCP-WW as transport agents actually suffers from a large variable delay. On average the TCP-WW+ and TCP-WW exhibits > 450 msec for high



(a) Average Packet dropped by sources (b) Average Packet Drop comparison
Fig. 8: Packet Drop comparison for LCART

priority sources 2, 4 and > 100 msec for high priority source 5 where as similar behavior is being exhibited by TCPNewReno and TCPReno respectively. The reason for this efficient behavior exhibited by the LCART is its fine congestion and reliability control whilst the use of cross-layering the common functionalities of transport and lower layers which keeps E-2-E packet latency to a minimum value. As the rate adjustment is based on Kalman based predictor-corrector estimator which takes lower layer information as input, therefore this control feedback phenomenon helps in achieving the optimal source transmission rate values which will keep network uncongested most of the time thus minimizing the E-2-E packet latency and packet drop rate caused by congestion thus resulting in energy efficient design. This optimality also ensures E-2-E data packet latency QoS objective of the multimedia application (e.g. for audio application it should be ≤ 150 msec[3]).



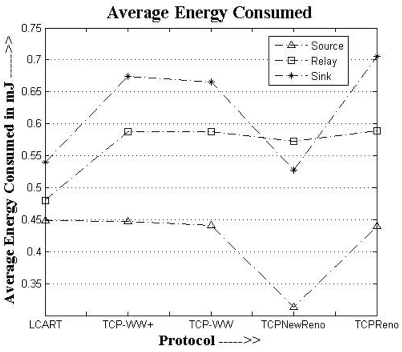


Fig. 9: Average E-2-E Packet Latency Comparison Fig. 10: Average per Packet Energy Consumed Comparison

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[3] http://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.114-200305-I!!PDF-E&type=items

Fig. 10 shows the *Per Packet Energy Consumption* (in mili Joules, mJ) comparison of LCART with other transport layer protocols. From the Fig. 10 it is obvious that the per packet energy consumed by LCART source motes is approximately 0.45mJ for the entire communication which is high (because of high throughput) in comparison to TCP-WW+, TCP-WW, TCPNewReno and TCPReno which consume per packet energy of 0.4475 mJ, 0.4410 mJ, 0.3126 mJ and 0.4394 mJ respectively. The reason why the TCP-WW+ and TCP-WW offers high per packet energy cost is being justified by its control channel probing (mining of ACK control signaling for bandwidth estimation for future transmissions). Also it is noticeable that the TCPNewReno has lowest throughput, source transmission rate is low in comparison to other protocols, and for that the source motes that uses TCPNewReno consumes less per packet energy which is approximately 0.3126 mJ for the entire communication.

Similarly the per packet energy consumed by the relay and sink motes for the LCART and other transport layer protocols is shown in Fig. 10. As we can see for the Fig. 10 that the total per packet communication cost for LCART's relay motes is approximately 0.4804 mJ in comparison to 0.5881 mJ, 0.5874 mJ, 0.5722 mJ and 0.5894 mJ for TCP-WW+, TCP-WW, TCPNewReno and TCPReno respectively. Again this confirms the effectiveness of LCART's congestion control and reliability design component that uses cross-layer design feature. Since LCART congestion control mechanism keeps source mote's transmission rate to an optimum value, by best utilizing the network resources, therefore not only it prevents the unwanted packet drop due to congestion but also the associated control overhead for retransmissions thus resulting in energy efficiency. Also another good reason for this efficiency is that the LCART reliability module uses stochastically distributed time definition ('β' parameter) for packet storage at intermediate motes, again this time would be governed by the link conditions, nature of information etc. Similarly we can see from Fig. 10 that the effective per packet vs throughput energy consumed by LCART's sink is minimum (0.5398 mJ) in comparison to TCP-WW+, TCP-WW, TCPNewReno and TCPReno which consumes 0.674 mJ, 0.666 mJ, 0.5279 mJ and 0.706 mJ respectively. Again with the similar reasoning as for relay mote case it is proved that the LCART is the most energy efficient transport layer protocol in comparison to TCP-WW+, TCP-WW, TCPNewReno and TCPReno.

4 DISCUSSION AND CONCLUSIONS

In the following paper we have envisaged LCART scheme for heterogeneous WSN. The idea of LCART is based on cross-layering the WSN's communication protocol stack. We extensively simulated LCART against TCP-WW+, TCP-WW, TCPNewReno and TCPReno and results reveal that considerable reduction in E-2-E data packet latency has been observed for LCART around < 80 msec for multimedia packets and< 130 msec for other packet information. Also for LCART highest average good throughput is achieved i.e. 0.3112 Mbps while effectively maintaining $> 98\%$ achieved source priority (at sink) for various sources with only 3 buffer motes. Also for entire communication LCART exhibits energy efficient behavior in comparison to rest all and exhibits only$<$ 1.0137% packet drop which is minimum of all. In the next step we would try to incorporate sender based forward packet drop detection into the existing LCART design and this sets our future research direction.

References

1. Giancoli, E., Jabour, F., Pedroza, A.: Ctcp: Reliable transport control protocol for sensor networks. In: International Conference on Intelligent Sensors, Sensor Networks and Information Processing, ISSNIP. pp. 493 –498 (dec 2008)
2. Gungor, V., Akan, O.: Dst: delay sensitive transport in wireless sensor networks. In: International Symposium on Computer Networks. pp. 116 –122 (2006)
3. Gungor, V.C., Akan, O.B., Akyildiz, I.F.: A real-time and reliable transport (rt) 2 protocol for wireless sensor and actor networks. IEEE/ACM Trans. Netw. 16(2), 359–370 (2008)
4. Hull, B., Jamieson, K., Balakrishnan, H.: Mitigating congestion in wireless sensor networks. In: SenSys '04: Proceedings of the 2nd international conference on Embedded networked sensor systems. pp. 134–147. ACM, New York, NY, USA (2004)
5. Kim, S., Fonseca, R., Dutta, P., Tavakoli, A., Culler, D., Levis, P., Shenker, S., Stoica, I.: Flush: a reliable bulk transport protocol for multihop wireless networks. In: SenSys '07: Proceedings of the 5th international conference on Embedded networked sensor systems. pp. 351–365. ACM, New York, NY, USA (2007)
6. Minet, P., Mahfoudh, S.: Cross layering in wireless sensor networks. In: IWCMC '09: Proceedings of the 2009 International Conference on Wireless Communications and Mobile Computing. pp. 154–159. ACM, New York, NY, USA (2009)
7. Paek, J., Govindan, R.: Rcrt: rate-controlled reliable transport for wireless sensor networks. In: SenSys '07: Proceedings of the 5th international conference on Embedded networked sensor systems. pp. 305–319. ACM, New York, NY, USA (2007)
8. Pang, Q., Wong, V.W.S., Leung, V.C.M.: Reliable data transport and congestion control in wireless sensor networks. Int. J. Sen. Netw. 3(1), 16–24 (2007)
9. Potdar, V., Sharif, A., Chang, E.: Industrial Strength Wireless Multimedia Sensor Networks. In: Wilamowski, B.,Irwin, J.D. (eds.) CRC Press Taylor & Francis Group 2010. Industrial Communication Systems (2010)
10. Sharif, A., Potdar, V., Rathnayaka, A.: Dependency of transport layer protocols on the ieee 802.11 and ieee 802.15.4 mac/phy layer protocols for wsn: A step towards cross-layer design. Int J. of Busn. Data Comm. and Netw., IJDBCN 3(6), 1–30 (2010)
11. Sharif, A., Potdar, V., Rathnayaka, A.: Prioritizing information for achieving qos control in wsn. In: 24th IEEE International Conference on Advanced Information Networking and Applications,AINA. pp. 835 –842 (apr 2010)
12. Wang, C., Sohraby, K., Li, B., Daneshmand, M., Hu, Y.: A survey of transport protocols for wireless sensor networks. Network, IEEE 20(3), 34 – 40 (may 2006)
13. Zhenjiang, M.and Baozong, Y.: Implementation of a multimedia information processing and analyzing system (mipas). In: International Conference on Neuro Information Processing, ICONIP. pp. 1893 –1898 (1994)