TCP Timeout Mechanism for Optimization of Network Fairness and Performance in Multi-Hop Pipeline Network

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Abstract **– In the recent years, wireless sensor network (WSN) has a huge impact in many remote based applications especially in oil and gas pipeline monitoring. Thus, the deployment of a multi-hop linear WSN will be a practical solution on pipelines. With a large multi-hop linear WSN, the overall network performance is badly affected especially due to node starvation. Inequality among source nodes is relatively an amplified factor of generated data rate and source node distances from the destination node. In this paper, we proposed a mathematical model for TCP Delayed Timeout Acknowledgement (DTO-ACK) mechanism for non-zero passive nodes. Optimum throughput fairness can be achieved by implementation of DTO-ACK with Dual Interleaving Linear Static Routing Protocol (DI-LSRP) for flat topology. Implementation of DTO-ACK and modification of TCP parameters reduces packet collision and ensures optimal throughput fairness in a multi-hop linear topology using TCP agent.**

Keywords – TCP, throughput fairness index, delayed acknowledgement, linear topology, pipeline network

I. INTRODUCTION

The demand for remote monitoring is established with various communication technologies in relaying real-time data to a centralised monitoring station from sensors attached to critical pipeline points [1-3]. In a static geographical infrastructure of an oil and gas pipeline usually stretched over hundreds of miles between the sensing points (source nodes) to a monitoring stations (data collection for future analysis). The network of sensors which are linked in series to form a chain to sense changes on sensing points and transfer this information to a destination node with predefined route determined by a routing algorithm.

Such a pipeline network has unique underlying issues effecting full deployment of WSN on pipelines in terms of performance as well as fairness among nodes [4-7]. In a multi-hop WSN, the long range data transmission [1] has severe performance degradation issues which lead towards inefficient fairness in the network particularly using the Transmission Control Protocol (TCP) [4, 7, 8]. In the recent years, continuous research on new protocols, applications, techniques and devices have been studied in TCP for achieving optimum fairness outcomes. TCP experience performance issues where the root cause is from node starvation and unbalanced data packet flow in a long range linear topology.

II. RELATED WORKS

TCP is a popular agent in many IEEE 802.11 based application where various mechanism with high performance and congestion collapse avoidance is achieved [9, 10]. The key function of a TCP mechanism is to coordinate the data sending rate in a WSN at an optimum state. Advertised window at the destination node and congestion window at the source nodes overseas the bandwidth utilisation rate for the purposes of data packet transmission. The newer version of TCP mechanism is built with multiple algorithms such as congestion avoidance, fast retransmit, slow-start and fast recovery as stated in (RFC 5681) [11]. TCP mechanism at a source node employs a retransmission time-out (RTO) mechanism for estimated Round Trip Time (RTT). RTT is one cycle time from a source node to send a data packet to a destination node and to receive an acknowledgement packet in return to the originator. The detailed characteristic of RTT is as stated in RFC 2988 [12]. Many types of research are conducted in enhancing TCP [8] performance in handling congestion, reducing errors, handling loss and etc. hence there are many types of TCP algorithms available for users.

Delayed cumulative acknowledgement (TCP-DCA) [13] is a scheme with variable delay window size which adapts to the TCP acknowledgement packet generation based on hop counts. Path length in proportional to the distance is an important metrics in deciding the delay window size for the number of acknowledgement packets to be returned to a source node. Cooperation between channel access control along with TCP Rate Adaptation (CATRA) [14] will determine an optimal Contention Window (CW) size to the control station contention. The modified CW size for achieving per-station fairness and the channel utilisation information is sent to the transport layer for TCP sending rate adjustment to achieve per-flow fairness. TCP-Vegas-W [15] is a method used to reduce aggressive window size in a multi-hop wireless network. With this method, the congestion window can be operated at an appropriate level. TCP with Adaptive Delay Window (TCP-ADW) [16] is designed to reduce the acknowledgement packets appropriately by reaching an optimal dynamic delay window. The delay avoids the transmission time-out at the source nodes unless the retransmission timer expires, the delay window will be increased by the destination node based on the data rate. Adaptive Delayed ACK Mechanism (ADAM) [7] works by properly adjusting TCP parameter which affects the throughput fairness and further to reduce frame collisions. ADAM+ [7] is another method introduce by the author to improve throughput fairness further by eliminating RTS/CTS. Monitoring Delayed Acknowledgment (TCP-MDA) [17] is designed to interact with TCP and MAC layer to reduce the acknowledgement packets by channel condition monitoring.

III. TCP DELAYED TIMEOUT ACKNOWLEDGEMENT (DTO-ACK)

The proposed TCP Delayed Timeout Acknowledgement (DTO-ACK) model is formulated for TCP agent acknowledgement timeout in a multi-hop linear topology. The proposed model would be a practical solution in an application where the normalised throughput fairness is desired at a ratio of one between all source nodes in the network. To achieve the ratio of (1:1) among all source nodes, the source node window size (w) equals to min value of (*awnd, cwnd*), where advertised window is (*awnd*) and congestion window is (*cwnd*).

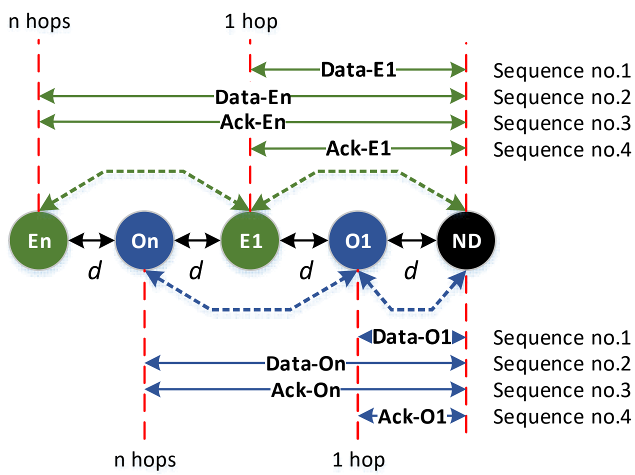

Fig. 1: The DTO-ACK model with *On/En* number of source nodes and ND as destination node evenly distributed in d within half the communication range.

The advertised window is designed to restrict the operation of source nodes within the available resources at the destination node whereas the congestion window is designed to avoid the source nodes from over sending data packets than the permitted allocations in a certain network. To achieve the desirable normalised throughput fairness among all source nodes, the advertised window is set to one (the lowest value) and the congestion window is decided by the TCP congestion control algorithm based the congestion state in the network. The default delayed acknowledgement factor of two [7, 9] is controlled by setting the acknowledgement time after the default acknowledgement expiry time thus retains the fairness index value close to one. The Dual Interleaving Linear Static Routing Protocol (DI-LSRP) with DTO-ACK mathematical formulation is used to set an ideal delayed acknowledgement time for each source nodes in a multi-hop linear topology as shown in Fig. 1. Where *On/En* is the maximum number of source nodes in each path with a maximum communication range in distance of $2d$. DI-LSRP is a static prefix dual path (*Odd/Even*) routing algorithm in a linear arrangement to a destination node. Generally, in TCP agents delayed acknowledgement factor is set at two (RFC1122) [7, 9] where an acknowledgement packet will be generated when the destination node receives one or two data packets within the default acknowledgement expiry time.

The RTT is one cycle time taken from a source node to send a data packet to the destination node and receive an acknowledgement packet to confirm its recipient of the sent data packet. In DTO-ACK model, RTT is a multiplying factor with the total number of hops for all source nodes in a certain network. A total number of hops (travel cost) is a very important parameter to determine appropriate delayed acknowledgement time for each source nodes as formulated in (1 - 2). The RTT value is used in calculating an ideal delayed acknowledgement time for each respective source nodes in the network based on distance (calculated by the total hops needed to reach a destination node).

$$\text{Sum H} = \sum_{iE=0}^{n}(H_{iE}) + \sum_{iO=1}^{n}(H_{iO}) \quad (1)$$

Where Sum H is the total hop count for n number of nodes, H_{iE} is the total hop count for n number of nodes (*Even*) and H_{iO} is the total hop count for n number of nodes (*Odd*)

$$\text{Fair cycle time } (t) = \text{Sum H} \times \text{RTT} \quad (2)$$

Where Fair cycle time (t) is one cycle time taken for n number of nodes in the network to have a fair data transmission to the destination node, Sum H is from (2), RTT is the round trip time (ms) to send one data packet and receive an acknowledgment packet in return. The DTO-ACK model formulates (3 - 7) in order to achieve optimum fairness in the process of sending data packets and receiving an acknowledgement packet from each respective source nodes in a certain network.

$$D_{ACKn} = \text{Fair cycle time } (t) - \text{RTTn} \quad (3)$$

Where D_{ACKn} is the TCP delayed acknowledgement timeout for n number of nodes in a dedicated path (*Odd/Even*) based on the hop count, Where Fair cycle time (*t*) is from (2) and RTTn is the round trip time based on the hop count to the destination node.

$$RPPN_{Max} = Sim_{Duration} / D_{ACK\ Min} \quad (4)$$

Where $RPPN_{Max}$ is the achievable maximum number of received packets per node in the network, $Sim_{Duration}$ is the simulation duration in seconds and $D_{ACK\ Min}$ is the minimum delayed acknowledgement timeout calculated from the formulation in (3).

$$RPPN_{Min} = Sim_{Duration} / D_{ACK\ Max} \quad (5)$$

Where $RPPN_{Min}$ is the achievable minimum number of received packets per node in a certain network, $Sim_{Duration}$ is the simulation duration in seconds and $D_{ACK\ Max}$ is the maximum delayed acknowledgement timeout calculated from the formulation in (3).

$$T_{Max} = (RPPN_{Max} \times 8 \times \text{Pkt size}) / Sim_{Duration} \quad (6)$$

Where T_{Max} is the achievable maximum throughput per node in the network based on (4). This throughput is achievable for a respective node to transmit successful packets to a destination node when the chronology of transmission and the delay acknowledgement timeout is consistent for the entire $Sim_{Duration}$.

$$T_{Fair} = (RPPN_{Min} \times 8 \times \text{Pkt size}) / Sim_{Duration} \quad (7)$$

Where T_{Fair} is the achievable fair throughput per node in the network based on (5). The T_{Fair} is based on the lowest achievable throughput in the network that best describes the throughput capacity of the furthest node in the network from the destination node. This throughput is achievable for a respective node to transmit successful packets to the destination node when the chronology of transmission and the delay acknowledgement timeout is consistent for the entire $Sim_{Duration}$. The value obtained from (7) was used in limiting the total packets generated by each dedicated source nodes in the network to achieve the desirable throughput fairness. This formulation also improves the instability when there are packets dropped during the simulation duration by narrowing the throughput maximum and minimum gap. The variation on T_{Max} and T_{Fair} is significant on a network with a large number of nodes (source). The DTO-ACK formulation (1 - 5) will result in throughput fairness for all source nodes in the wireless network. The RTT value used in all the above formulation is 14.1 ms. The RTT value is an average value of ten runs obtained through a simple simulation setup of two nodes distributed in a distance of 100 meters using DI-LSRP. With a lower value of RTT would results in a higher throughput value. The throughput fairness ratio of (1:1) can be achieved even with increasing number of source nodes in a certain wireless network by using the formulation shown in (1 - 5).

In a general TCP scenario, the RTT is defined as one cycle time from On/En to send a data packet to ND and receive an acknowledgement packet. Thus, both data and acknowledgement packet take place in one RTT value where else for DTO-ACK it works in a series of data packets and then followed by a series of acknowledgement packets as shown in Fig. 2. A simple five nodes with four source nodes (Odd path: O1 and On, Even path E1 and En) and one destination node as ND with DTO-ACK is shown in Fig. 2. DTO-ACK model can achieve optimum fairness among all source nodes as shown in Fig. 2 by planned timely sequence of data packets with pre-calculated delayed acknowledgement packets between a source and a destination node.

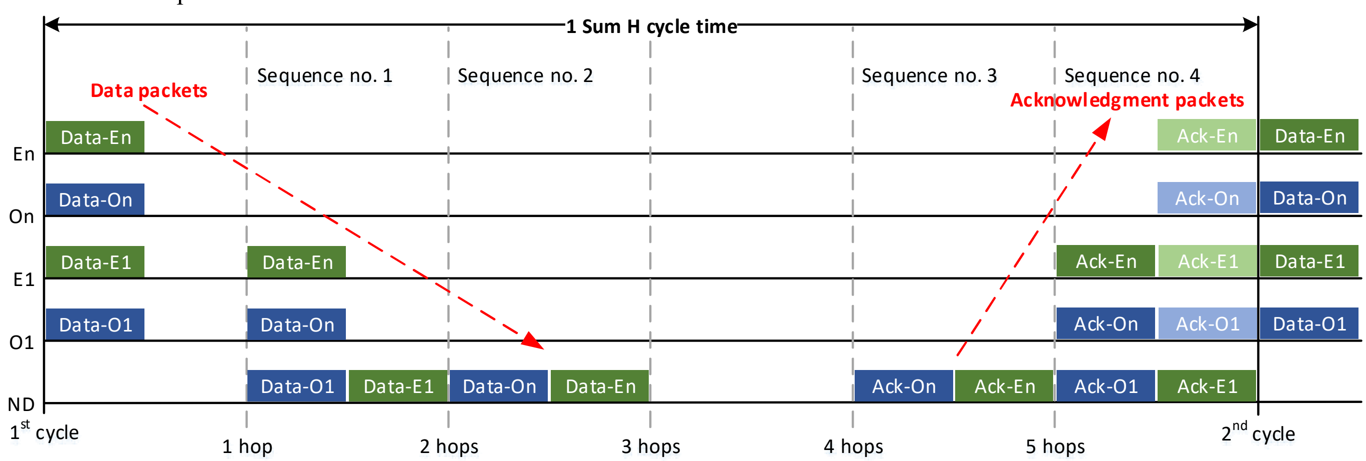

Fig. 2: Two (1 Sum H cycle) timing diagram DTO-ACK model with On/En number of source nodes and ND as the destination node.

All source nodes (O1/E1/On/En) will initiate the first data packet (Data-O1/Data-E1/Data-On/Data-En) transmission to the destination node (ND) at the start of each 1 Sum H cycle (t). The data packets (Data-O1/Data-E1) from source nodes (O1/E1) requires one hop to the desired destination node (ND) at duration of one RTT where else for the data packets (Data-On/Data-En) from source nodes (On/En) requires two hops through the intermediate node (O1/E1) to reach the destination node (ND) at with two RTT value.

Based on the DTO-ACK model, the first sequence of acknowledgement packets (Ack-On/Ack-En) will be generated at the destination node (ND) with two hops required through the intermediate node (O1/E1) to reach the source nodes (On/En) at the edge of six RTT value. In the second sequence of acknowledgement packets (Ack-O1/Ack-E1) from the destination node (ND) requires only one hop to reach the source nodes (O1/E1) at the edge of six RTT value. From the dual path sequence (*Odd* and *Even* route) shown in Fig. 1, this would take six RTT (3RTT + 3RTT) value for 1 Sum H cycle (t) to achieve the equal data transmission opportunity to all source nodes (O1/E1/On/En) in the network to send a data packet and receive an acknowledgement packet from the destination node (ND).

Using DTO-ACK model in TCP agent will ensure throughput fairness among all source nodes in a linear topology environment which will suit well in an oil and gas pipeline monitoring application. The key parameter to be defined is the total number of hops to a destination node in a dual path with an appropriate RTT value which is based on distance will benefit on the network equality. Changes in the scenario where a scalable WSN with selective source nodes is applicable with DTO-ACK model by assigning the right Sum H in (1) in order to overcome with bandwidth reservation for passive nodes (non-source nodes).

IV. Simulation Analysis and Discussion

This section of the paper illustrates results on overall network performance with optimum throughput fairness with the proposed DTO-ACK model. All the presented results are obtained through simulation using Network Simulator 2 (Version 2.35) [18]. The DTO-ACK model was incorporated with DI-LSRP was compared with reactive routing algorithm AODV, proactive routing algorithm DSDV and FRP using the method proposed in [7]. The basic simulation setting in Network Simulator 2 is as tabulated in Table I. All results are from an average value of five multiple runs with seed values (1-15) over a simulation duration of 500 seconds. Two random functions (uniform) were used to re-create the real-life application of the tested method, where the first data packet start time for each source node is generated using a custom random function with a range between 0.0 – 5.0 seconds. Another random function was used to randomly select a non-sequence source node chronology for data transmission. Nodes in the simulation are stationarily located with a fixed uniform distance as shown in Table I for the entire simulation duration with only one destination node.

TABLE I
NS2 SIMULATION PARAMETERS FOR DTO-ACK AND COMPARED MODEL

Parameters	Value
Channel type	Wireless channel
Radio propagation model	Two ray ground
MAC type	802.11
Interface queue type	Drop Tail / PriQueue
Source nodes	19, 39, 59, 79, 99
Max packet in ifq	50 (packets) DTO-ACK /100 (packets) Others
Agent type	Transmission control protocol (TCP) - Reno
Traffic type	Constant bit rate (CBR)
RX Thresh/ CS Thresh	125 meters/250 meters
Packet size	512 bytes

Dual Interleaving Linear Static Routing Protocol (DI-LSRP) is a predefined dual path routing protocol with reduced control packets. The simulation was tested with AODV, DSDV, FRP using the method proposed in [7] and DI-LSRP using DTO-ACK are evaluated on the following metrics:

A. Delivery ratio: A percentage of receiving packets over send packets in a network is an essential performance indicator for the reliability of a certain wireless network. With the implementation of DTO-ACK in a linear wireless network, helps to retain the delivery ratio at a constant rate of always above 99 % from a small network size of 24 source nodes to a large network size of 120 source nodes as shown in Fig.3.

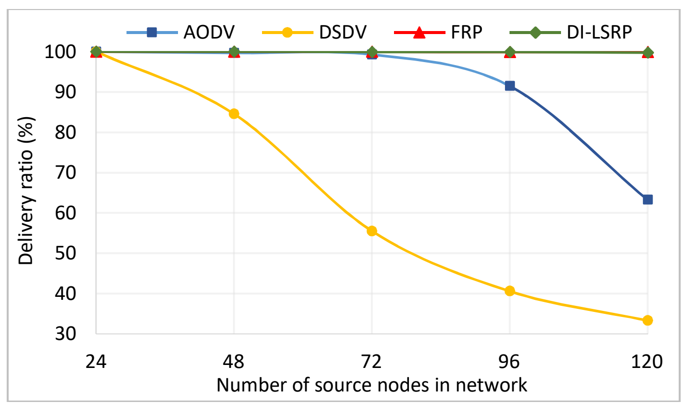

Fig. 3: Graph of delivery ratio (%) over number of source nodes

The proposed method reduces the number of dropped packets which is a desirable parameter in any wireless sensor network.

For the other compared routing protocol, only FRP with the model in [7] retains the delivery ratio at a constant rate of above 99 % equal to the proposed method where else for AODV and DSDV the delivery ratio decrease with the increasing number of source nodes. Utilising a TCP delayed acknowledgement mechanism would add a great value towards successful data packet delivery in a linear wireless network.

B. Fairness index: In a linear topology with *n* number of source nodes with only one destination node has a crucial stability factor due to unfairness within the wireless network. The scalar measurement of resources (throughput) allocation discrimination among all source nodes [7, 16]. The Jain's fairness index [19, 20] is as described in (8) is used in calculating the factor of fairness in a multi-hop network. The highest desirable throughput fairness index of 1.0 represents that a network has achieved 100% normalised throughput fairness index.

$$Fairness\ index = \frac{\left(\sum_{i=0}^{n} n_i\right)^2}{N \sum_{i=0}^{n} {n_i}^2} \quad (8)$$

Where n_i is the normalised throughput for n number of flows and for N is the number of nodes in the network. In a small size linear network with a low density of sensor, node fairness is hardly visible since the effects as mentioned in Section II of this paper. Throughput fairness index in a network with DTO-ACK outperforms all the other routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes as shown in Fig.4.

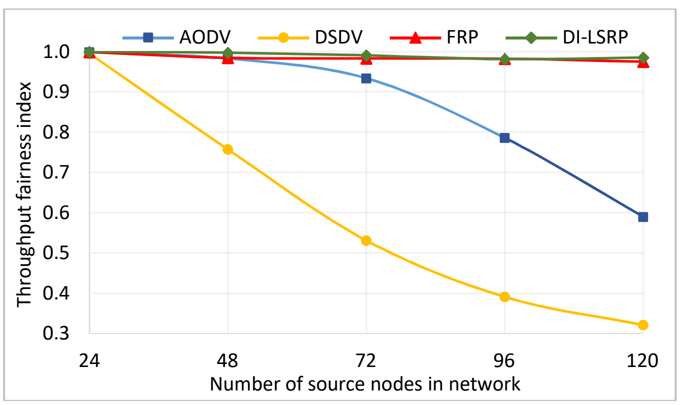

Fig. 4: Graph of throughput fairness index over number of source nodes

For the other compared routing protocol, only FRP with the model in [7] achieved higher throughput fairness index similar to DI-LSRP, but when compared in terms of data rate this is relatively low. The higher throughput value as shown in Fig. 5 has a corresponding effect towards the variation in throughput fairness index between DI-LSRP and FRP. Where else, the throughput fairness index for AODV and DSDV decrease with the increasing number of source nodes in the tested simulation environment. The greatest challenge in a linear wireless sensor network is in achieving optimum throughput fairness index among all source nodes in a certain network. One of a measurement indicator for throughput fairness index is throughput, where equality and performance plays a major role in any WSN. The next set of results will describe the performance metric in all the simulated environment to indicate a viable solution for fairness as well as performance.

C. Throughput: The average throughput overall flows in the network can be calculated as given in [7, 21]. When network performance is a concern in a WSN, a network with the ability to achieve higher throughput are always a desirable goal. Referring to Fig. 5, throughput (Kbps) in a network with DTO-ACK outperforms all the other routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes. Since the formulation in DTO-ACK is based on dual interleaving route which reduces the data travel cost (total hop metric) hence, increases the data transfer rate between source nodes to the destination node by two folds in the tested simulation environment. The DTO-ACK model enables high data transfer rate with the network resources by retaining optimum throughput fairness index in a linear WSN.

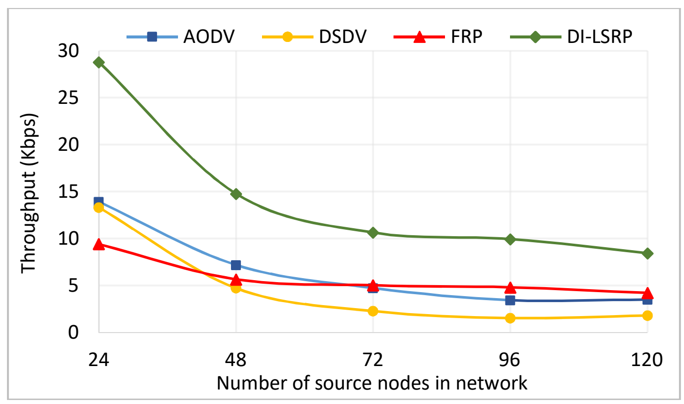

Fig. 5: Graph on throughput (Kbps) over number of source nodes

D. End to end delay: End to end delay is the average total time taken to transmit data over all the flows in the network [21-23]. Referring to Fig. 6, the end to end delay with DTO-ACK model had relatively outperformed the other routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes. The value of fairness index from Fig. 4 and throughput from Fig. 5 has a corresponding effect on end to end delay with DTO-ACK model. Even though DSDV has a lower end to end delay, but this has a corresponding effect in poor fairness index as in Fig. 4 and low throughput as in Fig. 5 hence, DI-LSRP has comparatively lower end to end delay when compared to the other related metrics. The increase in the end to end delay is proportional to the increasing received data rate as well as the increasing distance between source nodes and the destination node. The other routing protocol has relatively higher end to end delay with lower data rate. Every routing protocol has its drawback towards end to end delay which mainly relates to the number of control packets to support network connectivity. With DTO-ACK model, end to end delay is fairly low even with the higher RTT value compare in [7].

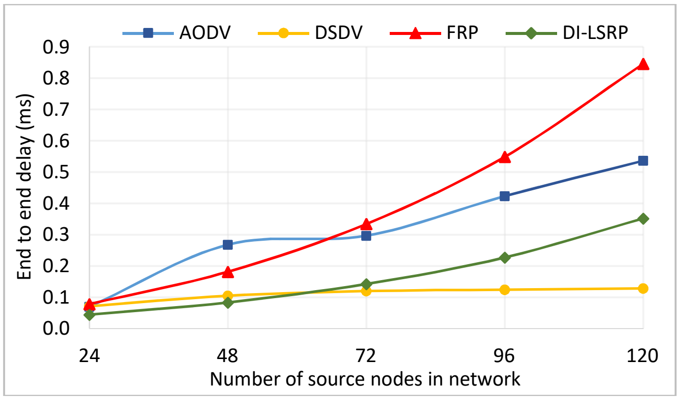

Fig. 6: Graph on end to end delay (ms) over number of source nodes

E. Routing overhead: In a WSN, normalised routing overhead is defined as the total number of routing packets used in the network over the total received data packets for the entire simulation duration [23] which can be calculated by (9).

$$NRO = \frac{Total\ control\ packets}{Total\ received\ data\ packets} \quad (9)$$

Where NRO is normalised routing overhead is another crucial factor in any wireless sensor network as there is a queue length for bidirectional packets and performance factor related to this metric. Referring to Fig. 7, normalised routing overhead with DTO-ACK model is fairly low compared to the other routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes. The normalised routing overhead increases relatively with the increasing number of source nodes in a network. Each routing protocol has a unique characteristic which contributes towards the increasing number of routing overhead in a network. The implementation of DTO-ACK and the method proposed in [7] influences the increasing number of routing overhead even in an idle or waiting between data transmission state. Hence, a routing protocol with low control packets will reduce the effect on routing overhead such as in DI-LSRP. In general, by controlling the normalised routing overhead would result in better throughput fairness index as in Fig. 4 and overall network performance as in Fig. 5 to Fig.6 in a WSN particularly in a long-range wireless network.

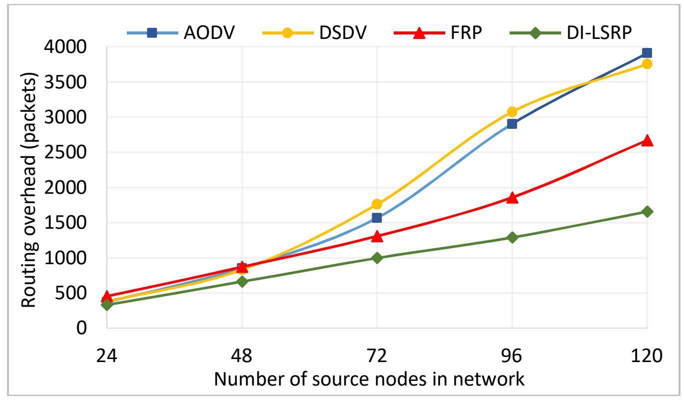

Fig. 7: Graph on normalised routing overhead (Joules) over number of source nodes

F. Passive nodes: Passive nodes are considered nodes with zero data transfer to the destination node in a network. Passive nodes create communication breakdown from a certain point in a network due to a single point failure factor in a linear topology. A certain network with a higher number of passive nodes will be a waste of available resources, especially when working in a network of high traffic and limited energy source. With the implementation of DTO-ACK and the method proposed in [7] eliminates the problem with passive nodes in the tested environment.

V. Conclusion

This paper has highlighted a research conducted to achieve better throughput fairness index and overall network performance on a linear one-tier topology using DTO-ACK in TCP agent. The distance between source and a destination node in a linear topology is a significant factor towards imbalance in network resources which results in complete data flow starvation. Data flow starvation leads towards performance related issues in WSN, particularly in a linear topology. The mathematical formulations in DTO-ACK model for setting an appropriate delayed acknowledgement timeout for respective source nodes with low advertised window size would retain the throughput fairness index at an optimum level. DI-LSRP using the proposed DTO-ACK model was verified through simulation where significant improvements in throughput fairness index and overall network performance were achieved when applied in TCP agent. DTO-ACK has a unique formulation to retain throughput fairness along with moderate throughput and low end to end delay for a variable linear network size which makes it a viable solution for a pipeline network.

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