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Enhancing Pipeline Network Performance Using Dual Interleaving Cluster Head Routing Protocol

Siva Kumar Subramaniam [1], Rajagopal Nilavalan [3],
Wamadeva Balachandran [4]
Department of Electronic & Computer Eng.,
College of Engineering, Design & Physical Sciences,
Brunel University London, United Kingdom
Siva@brunel.ac.uk

Shariq Mahmood Khan [2]
Department of Computer Science & IT,
NED University of Engineering &
Technology, Pakistan
shariq@neduet.edu.pk

Abstract – **Remote monitoring of oil and gas pipelines has been the most prevalent application of static wireless sensor network (WSN). WSN has a great potential in facilitating real-time data transfer between sensor nodes and a centralise monitoring station. For pipeline WSN, network performance is critical among sensor nodes in a linear chain topology. Expanding the communication range by increasing number of nodes in a linear architecture compromises the performance of WSN. Thus, WSN results in a severe impact on low throughput, high latency, poor delivery ratio, high energy consumption and network inequality. In this paper, we proposed Dual Interleaving Cluster Head Linear Static Routing Protocol (DICH-LSRP), a routing protocol for cluster-based topology. DICH-LSRP in a pipeline simulation environment were evaluated with compliance to IEEE 802.11 standard on impending factors of WSN performance. The simulation results help to better understand some key areas of WSN performance metrics and the implementation of DICH-LSRP in a multi-hop linear topology.**

Keywords - Linear topology, pipeline network, static routing, TCP performance, static wireless sensor network

I. INTRODUCTION TO PIPELINE NETWORK

Pipelines are considered economical and a safer medium of transportation in oil and gas industry, although many studies have indicated a series of failures which leads towards hazardous accidents [1, 2]. In the recent years, deployment of wireless sensor network (WSN) has been a popular solution on oil and gas pipeline remote monitoring. Changes in the sensing behaviour on pipelines are relayed to a centralised monitoring station using WSN. In a linear pipeline network, end nodes (multiple source nodes) gather information from sensing points and communicates it through wireless links to a destination node (receiver).

The network of sensors is organised on a linear architecture with a geographical layout of an oil and gas pipeline. By far, the most common WSN implementations are flat linear topology and cluster-based linear topology. A flat linear topology is the simplest WSN in which one tier communication is established among sensors in the network. In a cluster-based topology, the source nodes communicate to a dedicated cluster head which then rely data packets through a multi-hop network towards a destination node [3, 4]. Depending on the wireless routing architecture, the data packets are forwarded to a destination node (receiver) through multiple intermediate nodes which also function as a source node. For a linear WSN, the key factor of implementation requires great reliability and scalability of the network. Theoretically, a linear WSN can be categorised as unreliable network with a single point failure. In a multi-hop linear WSN as shown in Fig. 1, the communication range is depended to its neighbouring nodes to achieve chain-like links to a centralised monitoring station.

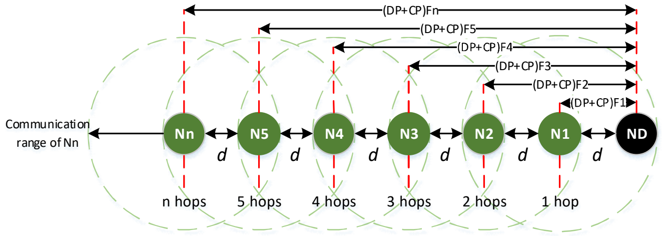

Fig. 1: Multi-hop linear topology with Nn number of source/intermediate nodes and ND is a single sink point (receiver)

Obviously, in any radio based communication devices, obstacle free line of sight is a highly desirable for optimum wireless network performance. The most common drawback of a multi-hop linear WSN is the management of high data traffic between sensing points and a receiver where the overall network performance is compromised [5].

II. FACTORS IN LINEAR TOPOLOGY AND RELATED WORKS

In a linear topology, a source (sender) node can be considered as a sensing point or as an intermediate node between a sender and a receiver [6, 7]. A linear multi-hop WSN with high data traffic can lead towards a bottleneck state at a certain node in the network. Both data and control packets in multiple flows of Fn share a common route between a sensing to a destination point as described in Fig. 1. A simple data accumulation factor is as depicted in (1) where sharing of a common route towards a destination node.

$$\mathrm{NTP} = \sum_{i=0}^{n}(DP_i + CP_i) \leq IfQlen \qquad (1)$$

Where NTP is the total packets for n number of nodes, DP_i is the total data packets, CP_i is the total control packets at node i and $IfQlen$ are queue size in the network. In general, there are some key factors which influence the overall performance of a linear wireless topology compared to other known wireless topologies especially based on IEEE 802.11 standard [8]. Measurable factors such as the carrier sensing range, communication range, queue length, network power consumption and bandwidth are often related to underperforming of such wireless network. Many research work has contributed to these factors with improved routing algorithm and controlling important network parameters to improve overall network performance [9].

The most important and a fundamental process in a routing protocol is to identify an optimum route for a generated data packet to a designated destination. A route will be generated based on the implemented characteristic of a routing protocol prior to data transmission from a source node to a destination node. An optimum route is generated based on a route discovering process and a constant update is required to keep track of any changes in the network. An efficient and a reliable routing protocol will enhance the overall network performance in a linear wireless topology. By far, the two most common routing method are proactive routing protocol (table-driven) and reactive routing protocol (on demand) [10, 11].

A table-driven routing protocol requires constant updates on from nodes in the network for real-time changes of route. The Destination-Sequence Distance-Vector routing (DSDV) [10-12] identify and updates all available route by periodical routing messages in a wireless network. Hence, the frequent updates of routing table entries consume heavy usage of energy and utilise a portion of bandwidth even at idle state. On-demand search for a valid route between a source and destination node is the characteristic of Ad hoc On-Demand Distance Vector (AODV) [10-13]. Newest route and routing table updates are accomplished using a sequence number at a destination node. Both DSDV and AODV has the capacity to reduce route cost with an option to bypass an intermediate (more than two) node within a communication range to its destination node.

The authors in [14, 15] introduced a multi-tier linear hierarchical topology with sectioning nodes as basic sensor nodes, data relay nodes and data dissemination nodes with a corresponding purpose at each node level. The Multi-Hop Low-Energy Adaptive Clustering Hierarchy (Multi-Hop LEACH) [16] was introduced to enable multi-hop among cluster heads in a wireless network when a designated destination node is a distance away. Source nodes transmit a data packet to a specific cluster head which is usually located at a single-hop between them. Once the cluster head receives data from its source node, it will aggregate and relay the data packets thru its neighbouring cluster head towards a destination node. A hierarchical or cluster-based topology and data merging technique prior to sending to a receiver node [9] encourage a multi-hop wireless communication thru a designated cluster head. Thus, data merging technique would reduce network cost over sending of individual data packets. The Advanced Low-Energy Adaptive Clustering Hierarchy (Ad-LEACH) [17] is a static cluster wireless sensor network for heterogeneous routing protocol which incorporated from LEACH [18] and (DEEC) protocol [19]. The network characteristic of Ad-LEACH has the ability to reduce its broadcast packets by limiting the sensor nodes in many small clusters groups with limited communication range only for each clustering groups. In each group, Ad-LEACH assigns a cluster head which will be the point of communication to the destination node. The authors in [20] introduced flat data collection algorithm which responses and forward a real-time data to the neighbouring wireless nodes by reduced waiting time in each stage.

In general, the performance of a routing protocol is measured in terms of link stability in a wireless network. In the event of breaking and restoration of links are reconsidered as a crucial network activity which results in high data lost rate. To retain an active link between nodes in a network, broadcast messages are generated in a timely interval among neighbouring nodes within the communication range. These messages are used to identify the active nodes and to pre-established new routes whenever is required. Such a crucial process is a vital component in a routing protocol in updating routing table as well as to establish data transfer between a sender and a receiver node in a network.

III. DUAL INTERLEAVING CLUSTER HEAD LINEAR STATIC ROUTING PROTOCOL (DICH-LSRP)

The Dual Interleaving Cluster Head Linear Static Routing Protocol (DICH-LSRP) is proposed to enhance overall network performance in a multi-hop linear cluster-based topology. Wireless nodes are statically positioned in a fixed infrastructure of an oil and gas pipeline to form a communication chain in a network [7, 14]. The deployed sensors on a pipeline communicate data thru a dedicated cluster head and also as intermediate nodes which are arranged in series with a uniform interval. Unlike a flat one-tier topology, the DICH-LSRP is a reliable and efficient routing protocol where route to the destination node are predefined at initialization of the simulation. The routes between all source nodes (sender) to a single destination node (centralised monitoring station) are predefined based on *odd* and *even* numbered cluster head with two interleaving route as shown in Fig. 2. Node placement in a linear topology often influences the behaviour 0f a multi-hop WSN particularly on link stability between a source and a destination node. Link instability results in increasing passive nodes (nodes with zero data transfer) therefore data transfer from that point onwards will be terminated. Hence to minimise issues with passive nodes in DICH-LSRP, sensing nodes as shown in Fig.2 are arranged in d distance and the respective cluster head is arranged in d1 distance within a maximum transmission range of two d1.

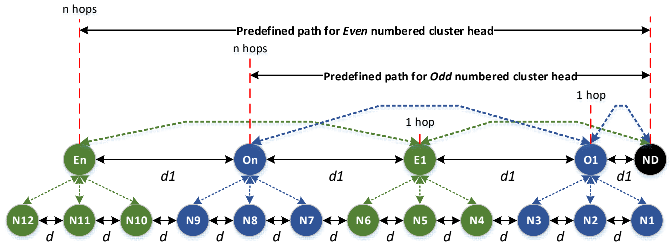

Fig. 2: DICH-LSRP with On/En number of cluster head and ND as destination node evenly distributed at *d1*

Generally, a routing protocol generates or updates its routing table based on the availability of nodes in a specific transmission range at start time *t* or *t + 1* when there are route changes among nodes. Whereby for a linear topology, a routing table is generated or updated between a sender and a destination node thru a single routing chain sequence which will be fully/partially stored by the nodes in a network. The characteristic of a generated or an updated routing table process differs between types of routing protocol used for an application. The process of generating and updating a routing table using DICH-LSRP are in contrast to any standard practices since the routes are predefined in two sets of routing table as described in the flowchart shown in Fig. 3. The routing table is generated based on *odd* and *even* sequence of cluster head in the network.

The cluster head sequence in DICH-LSRP is designed as a direct point of communication for the sensing nodes (located under each cluster head) to transfer data packets thru a specific route to a single destination node at the end of a network. Referring to Fig. 3, two routing tables are generated at start time *t* from a sequence of *odd* and *even* numbered cluster head with *n* number of sensing nodes (member nodes under each cluster head) forming two individual bidirectional paths in a wireless network. There is a zero buffer time between the start state to generating a routing table prior to data packet transmission in DICH-LSRP as shown in the flowchart in Fig. 3. The predefined conditions during a routing table generating process requires neither broadcast or hello packets which are considered as an important component in generating a routing table for most routing protocols. The eliminated broadcast and hello packets would further help in reducing traffic in a typical linear architecture. Unlike in a mobile network, minimum routing messages and updates for path changes are required in a static wireless network for a normal operation especially when in an idle condition. Hence, the communication link between nodes remain unchanged and doesn't require frequent updates for the application in a static wireless network.

The restraint start process used in DICH-LSRP has an advantage over the application of an oil and gas pipelines since nodes are permanently located with always in a ready state on a static infrastructure at all time. The cluster head and sensing nodes are distributed in *odd* and *even* routing table with the ability to transmit and receive data packets along with the required control packets only in a predefine path without path crossing possibilities during the network active period. The predefined routing path with dual interleaving cluster head eliminates aggressive broadcast packets to maintain the routing table during the network active period.

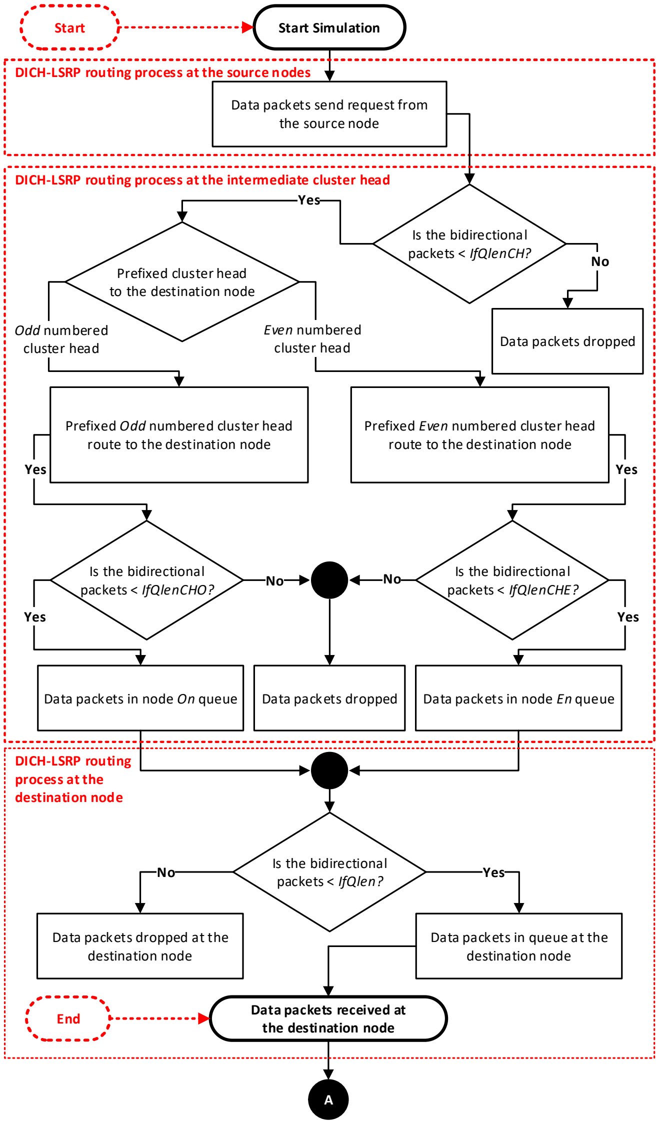

Fig. 3: Overview of the data packet flow process in DICH-LSRP

In a large network, queue limitation is set as a standard mechanism for controlling and managing bidirectional packets among nodes in a wireless network. The queue limitation is a crucial factor in eliminating passive nodes and bottle neck in a single route wireless network. The queue limitation also increases the dropped packet rate especially when the route is not identified yet in a standard routing protocol. With the implementation of DICH-LSRP, this factor could be minimised and further increase the rate of data packet transfer with the proposed dual path method. Splitting the single route as in a conventional routing protocol into two paths, further, reduces the routing overhead by half hence allocates better proportion for data packets in both routes as described in (2) and (3). The data accumulation factor for *odd* and *even* numbered cluster head are shown in (2) and (3) between a sensing and a destination node.

$$\mathrm{TP_{CHO}} = \sum_{i=0}^{n}(DP_i + CP_i) \leq IfQlen_{CHO} \qquad (2)$$

Where $\mathrm{TP_{CHO}}$ is the total packets for n number of nodes (*odd* numbered cluster head), DP_i is the total data packets and CP_i is the total control packets for n number of nodes (*odd* numbered cluster head) with $IfQlen_{CHO}$ as the queue size in the network.

$$\mathrm{TP_{CHE}} = \sum_{i=0}^{n}(DP_i + CP_i) \leq IfQlen_{CHE} \qquad (3)$$

Where $\mathrm{TP_{CHE}}$ is the total packets for n number of nodes (*even* numbered cluster head), DP_i is the total data packets and CP_i is the total control packets for n number of nodes (*even* numbered cluster head) with $IfQlen_{CHE}$ as the queue size in the network.

Any data packets arriving at an intermediate (neighbouring) cluster head with queue length > $\mathrm{IfQlen_{CHO}}/\mathrm{IfQlen_{CHE}}$ will be dropped from moving forward towards the destination node due to queue overflow. A sink point or a destination node is located at the end of each interleaving route with an integration point for both *odd* and *even* numbered cluster head as indicated in the flowchart in Fig. 3. The relationship of the queue with both data packets arriving from *odd* and *even* numbered cluster head is as described in (4).

$$\mathrm{NTP} = \mathrm{TP_{CHO}} + \mathrm{TP_{CHE}} \leq \mathrm{IfQlen} \qquad (4)$$

Where NTP is the network total packets at the destination for n number of nodes and the value of $\mathrm{TP_{CHO}}/\mathrm{TP_{CHE}}$ is from (2/3). Wise use of available resources such as bandwidth allocation, buffer time in route discovery and queue overhead results in better network performance. The restricted control packets in DICH-LSRP can produce a significant proportion of data rate compared to selected routing protocols as discussed in the next section of this paper in a linear topology.

IV. NETWORK PERFORMANCE AND ANALYSIS

In this section, the overall network performance for the proposed DICH-LSRP is illustrated from various simulation environment created in Network Simulator 2 (Version 2.35) [13, 21]. The basic setting for the simulation environment is as tabulated in Table I. In all simulated environment, the proposed DICH-LSRP is compared with Dual Interleaving Linear Static Routing Protocol (DI-LSRP) in a flat one-tier topology, a reactive (AODV) [10, 11] and proactive (DSDV) [11, 12] routing algorithm in a two-tier cluster topology for performance comparison in Network Simulator 2. Each simulation environment is an average value of five independent runs using a seed function over a simulation duration of 500 seconds. The data rate of one packet/sec were assigned to all source nodes with other corresponding parameters as given in Table I.

TABLE I
NS2 BASIC SIMULATION PARAMETERS

Parameters	Value
Channel type	Wireless channel
Radio propagation model	Two Ray Ground
MAC type	802.11
Interface queue type	Drop Tail / PriQueue
Cluster head	8, 16, 24, 32, 40
Source nodes	24, 48, 72, 96, 120
Max packet in ifqlen	50 (packets)
Agent type	Transmission control protocol (TCP)
Traffic type	Constant bit rate (CBR)
RX Thresh/CS Thresh	300 meters/350 meters
Packet size	512 bytes

The simulation environment was created to test the efficiency and robustness of the proposed routing algorithm in a near real-time application where the selection of non-chronological sending order and start time for source nodes was randomly chosen for each simulation cycle. The data packet transmission is assigned randomly between 0 – 2 seconds at the beginning of the simulation. All nodes mentioned in the simulation are statically placed during the simulation duration with only one destination node. DICH-LSRP and the other routing algorithm were tested and evaluated in the simulation on the following metrics:

A. Delivery ratio: A percentage of receiving packets over send packets in a network [11-13] is an essential performance indicator for the reliability of a certain wireless network. Referring to Fig. 4, the delivery ratio of DICH-LSRP is at a moderate rate when compared with the other outperformed routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes. Referring to Fig. 4, the delivery ratio in percentage (%) merely indicates an overview of the percentage of successful packets delivered rather than the total number of received packets which contributes significantly in terms of performance. The unappealing rate of the delivery ratio in DICH-

LSRP is due to a higher data transfer rate which can be further corrected with network fairness.

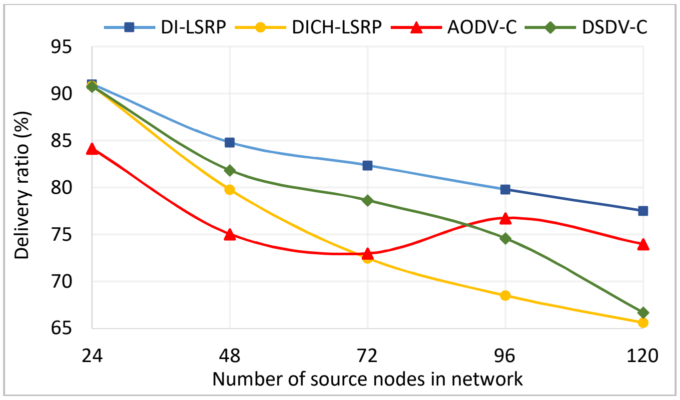

Fig. 4: Graph on delivery ratio (%) over number of source nodes

B. Throughput: Throughput over all flows in a network can be calculated as in [13, 22]. A network with higher throughput within the available network resources is the desired performance metric. Referring to Fig. 5, Throughput (Kbps) in a network with DICH-LSRP outperforms all the other routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes. With the implementation of dual interleaving cluster head splits the routing over head into two paths, therefore a significant throughput value between 25 Kbps – 45 Kbps can be achieved at all time. In a multi-hop linear topology, DICH-LSRP has the capacity to achieve higher throughput within the available network resources.

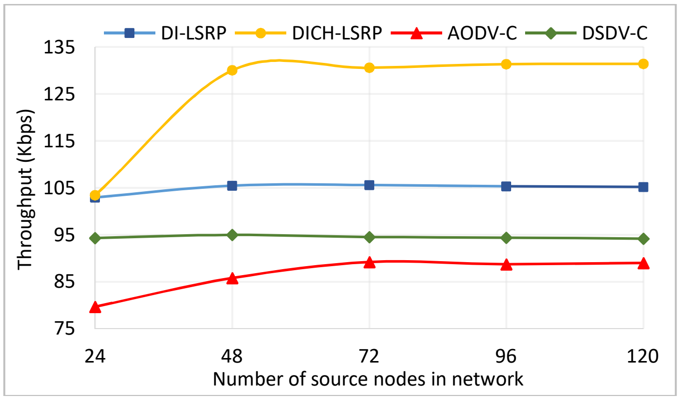

Fig. 5: Graph on throughput (Kbps) over number of source nodes

C. Throughput fairness index: Network fairness or equality within a network is the scalar measurement of resources (data packets) and allocation discrimination among all source nodes as mentioned by the authors in [22]. Network imbalance is a crucial factor in a linear wireless network with any routing protocol. Throughput fairness in a network with DICH-LSRP outperforms all the other routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes. Referring to Fig. 6, a small throughput fairness variation between DICH-LSRP and DI-LSRP is clearly visible between 0.03 – 0.07 in the tested environment. The higher throughput value as shown in Fig. 5 has a corresponding effect towards the variation in throughput fairness index of DICH-LSRP below DI-LSRP. Based on the other routing protocol, the throughput fairness index of DICH-LSRP has outperformed when compared to handling higher data rate with a great throughput equality in a certain network condition.

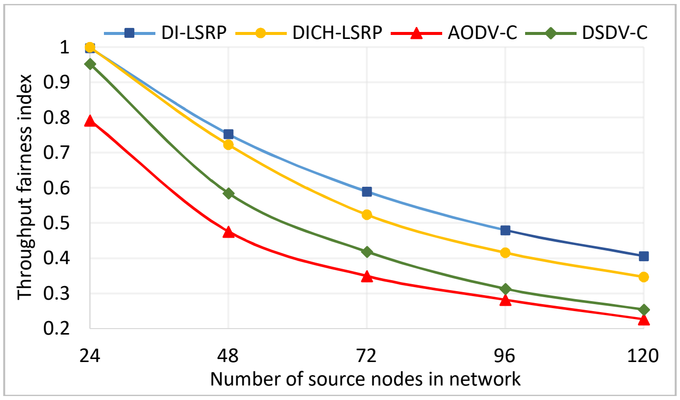

Fig. 6: Graph on throughput fairness index over number of source nodes

D. End to end delay: Wireless network latency is described as a time taken for a single data packet to travel from a sender to a designated node over all flows in the network [11, 13]. Referring to Fig. 7, the end to end delay of DICH-LSRP had 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 throughput from Fig. 5 and the value of fairness index from Fig. 6 has a corresponding effect of end to end delay of DICH-LSRP.

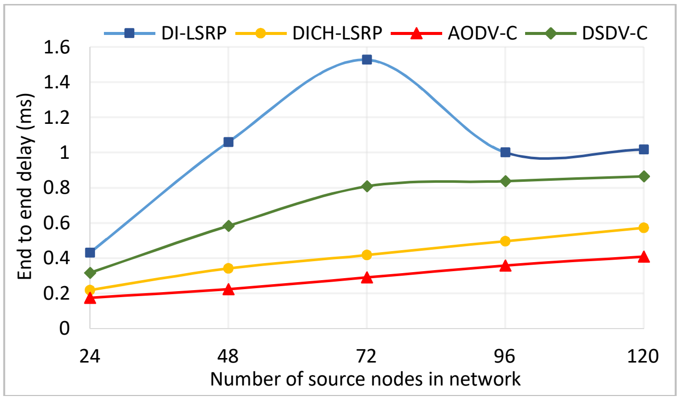

Fig. 7: Graph on end to end delay (ms) over number of source nodes

Even though AODV-C has a lower end to end delay, but this has a corresponding effect on the low throughput produced as in Fig.

5 and poor fairness index as in Fig. 6 hence, DICH-LSRP has comparatively better end to end delay when compared. Higher data rate has direct implication in terms of overall delay typically due to the total data packet received and the fairness factor among source nodes. The end to end delay of DSDV-C and DI-LSRP id higher compared to DICH-LSRP with much lower throughput. This shows that each routing protocol has a unique characteristic in each and every measured parameter in a wireless network.

E. Energy consumption: Energy consumption in a network can be define as the total used energy over total received data packet in a network[13, 23]. Energy usage in a wireless linear topology is an important parameter since a single node failure can create a discontinuity in the communication link. Energy consumption per-packet in a network with DICH-LSRP outperforms all the other routing protocol from a small network size of 24 source nodes to a large network size of 120 source nodes. Referring to Fig. 8, a small variation in consumed energy per-packet between DICH-LSRP and DI-LSRP is clearly visible in the tested environment. The consumed energy per-packet in DICH-LSRP is slightly higher then DI-LSRP is due to higher rate of transmitted data packets which is comparative to the control packets used in the network. The other routeing protocol consumed higher energy per-packet with relatedly low data rate compared to both DICH-LSRP and DI-LSRP in the tested environment. Energy efficient routing protocol ensures a sustainability factor in a typical linear wireless network, particularly when the nodes are battery power dependent.

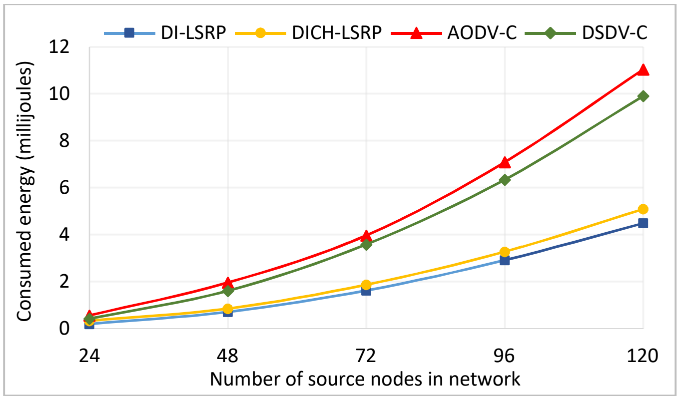

Fig. 8: Graph on consumed energy (millijoules) over number of source nodes

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. Passive nodes are results of poor equality management in a network particularly is a crucial factor in a linear topology. The greatest advantage of both DICH-LSRP and DI-LSRP over the other routing protocol is that, there are no passive nodes in the tested environment as shown in Table II.

TABLE II
NUMBER OF PASSIVE NODE BASED ON ROUTING PROTOCOLS OVER NUMBER OF SOURCE NODES IN NETWORK

Number of source nodes	Number of passive nodes			
	DI-LSRP	DICH-LSRP	AODV-C	DSDV-C
24	0	0	2.5	0
48	0	0	1.25	0
72	0	0	0.83	0
96	0	0	1.09	0.78
120	0	0	3.75	8.13

In general, a passive node influences the fairness index [22] as well as the network performance on a linear topology. Passive nodes can be eliminated by controlling generated data packets per-node with a TCP acknowledgement method or by data scheduling at the sender node. Such a mechanism would add a great improvement factor to the overall network performance.

IV. CONCLUSION

There are many interrelating factors influencing overall network performance in a multi-hop pipeline network. The proposed DICH-LSRP is a reliable and efficient routing protocol with low route maintenance required in a static linear topology. The reduced routing traffic with predefined dual routing path enhances the overall network performance in a multi-hop pipeline network. Further implementation of DICH-LSRP has a significant effect on core network parameters such as reliability, latency, responsiveness and energy efficiency for optimum network performance. Dealing with passive nodes creates communication link stability and sustainability of a multi-hop pipeline network. The implementation of DICH-LSRP in the simulated environment would be a great benefit for static linear application, particularly with a single route. The analysis and findings from simulation have functional implications particularly in reliability rate, higher throughput and network fairness issues at this state of research. Hence, further analysis will be carried out next on optimisation of the proposed performance metric.

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