Novel Design of Reliable Static Routing Algorithm For Multi-hop Linear Networks

A Thesis submitted in fulfilment of the requirements
for the Degree of Doctor of Philosophy (Ph.D.)

By

Siva Kumar Subramaniam

Department of Electronic and Computer Engineering
College of Engineering, Design and Physical Sciences
Brunel University, London
United Kingdom

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Abstract

In the recent years, increasing demand on static multi-hop wireless sensor network (WSN) had predominated the remote monitoring of oil and gas pipeline integrity. In a pipeline network, sensing points are connected through wireless nodes bridging the remotely measured points to a centralised monitoring station. The deployment of a WSN on a pipeline network has crucial factors contributing to degrading of overall network performance that is proportional to the network density. Such geographically unique network architecture has a significant impact on destabilisation of network reliability, throughput unfairness, higher latency and energy consumption from the inadequate utilisation of network resources due to competitive data transmission that results in data snowballing effect towards the destination node.

To unravel these factors, the first phase of this thesis has highlighted the Dual Interleaving Linear Static Routing (DI-LSR) for flat multi-hop topology and the Dual Cluster Head Interleaving Linear Static Routing (DCHI-LSR) for a cluster-based multi-hop topology making it feasible on a scalable pipeline network with enhanced network performance. Both DI-LSR and DCHI-LSR employs predefined interleaving routes with a beaconless network to achieve significant improvements in overall network performance with the available network resources on a pipeline network. The tested and analysed results in various simulation environment in accordance with IEEE 802.11 standard has enhanced network reliability (delivery ratio) between 77-83% and capacity (throughput) in between 100-120 Kbps without passive nodes (active nodes without transmitting opportunity) in a pipeline network.

Node starvation is another aspect that severely affects the overall network performance in a large scale multi-hop linear WSN. Inequality in network resources allocation among source nodes contributes to node starvation that is relatively an amplified factor over generated data packets and source node distances from the destination node. The second phase of this thesis has highlighted a mathematical model for calculating appropriate transmission control protocol (TCP) delayed acknowledgement timeout with reference to the distance between source to a destination node (travel cost). The optimum throughput fairness on a flat topology network can be achieved by implementation of TCP delayed acknowledgement timeout model for a fairness critical application (DATM-FFCA) and for a throughput critical application (DATM-FTCA). Whereas for a cluster-based topology network, the TCP delayed acknowledgement timeout model for a fairness critical application (DATM-CFCA) and for a throughput critical application (DATM-CTCA) delivers optimum throughput fairness for all member nodes. With the proposed technique that overwrites the traditional TCP parameters decreases packet collision and ensure optimum throughput fairness by eliminating passive nodes in a multi-hop linear WSN. Results from simulation experiments have revealed that the proposed models are able to retain the network fairness rate at above 90% without compromising the performance characteristic on a scalable pipeline network.

Energy optimisation in a multi-hop linear topology if often related to the network lifetime and is critical on heterogeneous energy consumption nodes in the network. The third phase of this thesis has highlighted Active High Transmitter-receiver energy model (AHiT) that is an adaptive sleep and wake-up interval for energy optimisation on node level based on occurring events in a multi-hop WSN. The AHiT energy model is in contrast to a traditional sleep and wake-up scheduling schemes that is solely dependent on data traffic pattern of nodes in a network. Nodes adapt their sleep and wake-up interval based on data traffic pattern that is generated by respective nodes and also from its neighbouring nodes. The nodes located in a multi-hop linear topology is connectivity critical to support data transfer from the neighbouring nodes. Simulations were carried out to analyse the energy performance of the proposed energy model that has significantly reduced the energy consumed above 40% at the node level and prolonged the network lifetime between 4-100% subjected to the data traffic pattern.

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List of Abbreviations

ADAM	Adaptive Delayed ACK Mechanism
ADAM-snd	Adaptive Delayed ACK Mechanism with shorter node distance
Ad-LEACH	Advanced Low-Energy Adaptive Clustering Hierarchy
AFVQ	ACKs-First Variable-size Queuing
AHiT	Active High Transmitter-receiver energy model
AODV	Ad hoc On-Demand Distance Vector
AODV+	Ad hoc On-Demand Distance Vector with Adaptive Delayed ACK Mechanism
AODVC	Ad hoc On-Demand Distance Vector in a two-tier cluster topology
AODVC+	Ad hoc On-Demand Distance Vector in a two-tier cluster topology with Adaptive Delayed ACK Mechanism
ATIM	Dynamic Ad-hoc Traffic Indication Map
CATRA	Cooperation between channel access control with TCP Rate Adaptation
CTS	Clear to send
CW	Contention Window
DATM-CFCA	Delayed acknowledgement timeout model for a Fairness critical application for cluster-based topology
DATM-CFCA+	Delayed acknowledgement timeout model for a Fairness critical application for cluster-based topology with Active High Transmitter-receiver energy model
DATM-CTCA	Delayed acknowledgement timeout model for a Throughput critical application for cluster-based topology
DATM-CTCA+	Delayed acknowledgement timeout model for a Throughput critical application for cluster-based topology with Active High Transmitter-receiver energy model
DATM-FFCA	Delayed acknowledgement timeout model for a Fairness critical application for flat topology
DATM-FFCA+	Delayed acknowledgement timeout model for a Fairness critical application for flat topology with Active High Transmitter-receiver energy model
DATM-FTCA	Delayed acknowledgement timeout model for a Throughput critical application for flat topology
DATM-FTCA+	Delayed acknowledgement timeout model for a Throughput critical application for flat topology with Active High Transmitter-receiver energy model

DCCP	Datagram Congestion Control Protocol
DCHI-LSR	Dual Cluster Head Interleaving Linear Static Routing
DCHI-LSR+	Dual Cluster Head Interleaving Linear Static Routing with Active High Transmitter-receiver energy model
DDEEC	Developed Distributed Energy-Efficient Clustering
DEEC	Distributed Energy-Efficient Clustering
DI-LSR	Dual Interleaving Linear Static Routing
DI-LSR+	Dual Interleaving Linear Static Routing with Active High Transmitter-receiver energy model
DSDV	Destination-sequence Distance-vector routing
DSDV	Destination-sequence Distance-vector routing with Adaptive Delayed ACK Mechanism
DSDVC	Destination-sequence Distance-vector routing in a two-tier cluster topology
DSDVC+	Destination-sequence Distance-vector routing in a two-tier cluster topology with Adaptive Delayed ACK Mechanism
DSDV-snd	Destination-sequence Distance-vector routing with shorter node distance
DSR	Dynamic Source Routing
Dst	Designated destination point
EDDEEC	Enhanced Developed Distributed Energy-Efficient Clustering
EDEEC	Enhanced Distributed Energy-Efficient Clustering
EDURo+	Energy-Delay Unified Routing protocol
FFD	Full-Function Devices
FRP	Fixed routing path
HC	Hop count
ifQlen	Queue length
LEACH	Low-Energy Adaptive Clustering Hierarchy
LEACH-C	Low-Energy Adaptive Clustering Hierarchy-centralized
LEACH-F	Fixed Number of Cluster Low Energy Adaptive Clustering Hierarchy
LSR	Link State Routing
MH-DISCPLN	Multi-hop distance-based and low-energy adaptive clustering
MH-LEACH	Multi-Hop Communication
MH-PSM	Multi-hop power saving mode

Multi-Hop LEACH	Multi-Hop Low-Energy Adaptive Clustering Hierarchy
ND	Destination node
NHS	Network-Harmonized Scheduling
NOAH	No Ad-hoc Routing Agent
nW-MAC	Multiple wake-ups provisioned duty cycle MAC protocol
Nxt	Neighbouring cluster heads or Neighbouring nodes
OLSR	Optimised link state routing
RFC	Request for Comments
RFD	Reduced-Function Devices
RIX-MAC	Receiver-Initiated X-MAC
ROLS	Routing protocol for Linear Structure
RTO	Re-transmission time-out
RTS	Request to send
RTT	Round-trip time
SACK	Selective Acknowledgements
SCTP	Stream Control Transmission Protocol
ssthresh	Slow-Start Threshold
TCP	Transmission Control Protocol
TCP-ADW	Adaptive Delay Window
TCP-IA	Intelligent Acknowledgement technique
TDMA	Time Division Multiple Access
TTL	Time to live
UDP	User Datagram Protocol
Wi-Fi	Wireless fidelity
WLAN	Wireless local area networks
WSN	Wireless sensor network

List of Publications

Submitted Conference Paper

- Siva Kumar Subramaniam, Shariq Mahmood Khan, Rajagopal Nilavalan and Wamadeva Balachandran, "Network Performance Optimization Using Odd and Even Routing Algorithm for pipeline network", in Proceedings of the 8th Computer Science and Electronic Engineering Conference, 2016, pp. 118-123.
- Siva Kumar Subramaniam, Shariq Mahmood Khan, Rajagopal Nilavalan and Wamadeva Balachandran, "Enhancing Pipeline Network Performance Using Dual Interleaving Cluster Head Routing Protocol", in Proceedings of the 1st International Conference on Innovations in Computer Science & Software Engineering (ICONICS), 2016.
- Siva Kumar Subramaniam, Shariq Mahmood Khan, Rajagopal Nilavalan and Wamadeva Balachandran, "TCP Timeout Mechanism for Optimization of Network Fairness and Performance in Multi-Hop Pipeline Network", in Proceedings of the 1st International Conference on Innovations in Computer Science & Software Engineering (ICONICS), 2016.

Poster Presentation

- Siva Kumar Subramaniam, Rajagopal Nilavalan and Wamadeva Balachandran, "Talking pipe: Wireless sensor network for condition monitoring in oil and gas pipelines", Brunel University London Research Student Conference, 23-25 March 2015.

Submitted Journal Paper

- Siva Kumar Subramaniam, Shariq Mahmood Khan, Rajagopal Nilavalan and Wamadeva Balachandran, "Static Network Performance Optimization Using Interleave Routing Algorithm", IIUM Engineering Journal.
- Siva Kumar Subramaniam, Shariq Mahmood Khan, Rajagopal Nilavalan and Wamadeva Balachandran, "Interleave Delayed Acknowledgement TCP Mechanism for Throughput Fairness Optimization in Pipeline Network", Wireless Personal Communications.

Statement of Originality

While registering as a candidate for the above degree, I have not been registered for any other research award. I certify that the results and conclusions presented in this thesis are my own work. This thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree. Due acknowledgement has been made in the text to all other material used.

Chapter 1

Introduction

1.1 Introduction and Application of Multi-hop Linear Topology

Over the last decade, the propagation of new network topologies and traffic patterns emerged for a wide range of new applications with the implementation of wireless sensor network (WSN)[1]. In many new areas of remote monitoring, the WSN deployment imposes a multi-hop linear topology where data from sensing nodes are collected over a chain of nodes linked to a receiver node located at one end of a network. The characteristic of a static multi-hop linear network has a fixed architecture in which the nodes are permanently located with constant radio propagation at all-time [2, 3]. Over the years, the static multi-hop linear topology is a well-accepted designed for special applications such as pipelines or linear structure that transmits the collected data from sensing points through a multi-hop wireless medium. In the recent years, such WSN technology and its application have gained considerable importance in remote monitoring particularly on oil and gas pipelines [4-7] with rapid advancements in underlying technologies on communication protocols, sensing capability, energy efficient wireless devices and implementation cost on vast applications [8, 9].

1.1.1 Remote Monitoring of Oil and Gas Pipelines

The oil and gas pipelines are known as a cost-effective and a safer transportation medium that are still vulnerable towards dangerous accidents or physical damages [5, 6, 10]. Numerous studies have highlighted that pipeline transportation had a long history of failures however when compared with the traditional railroad transportation, the reported accidents are still significantly low. Oil leaks from accidents in a pipeline contribute to irregularities in temperature readings beneath the pipeline, whereas a ruptured gas pipeline rapidly decreases the temperature above the pipeline [7, 10, 11]. Hence, constant monitoring of temperature and pressure changes on sensors can promptly detect leaks or ruptured pipeline proactively for faster response to an impending accident.

The oil and gas industry faces numerous challenges especially in complying with frequently changing environmental regulations in a pipeline monitoring and management system. The exceptional need to monitor the unknown states on the oil and gas pipelines is essential for the industry to wisely optimise the running resources [4, 10]. The unknown states or threats of an oil and gas pipeline could affect pipeline integrity, safety, reliability and security whilst simultaneously meeting the demands on delivery schedules as well as optimising the cost factor at the same time. To oversee the entire process as shown in Figure 1-1, a reliable and scalable WSN plays a crucial role in sensing the abnormalities on pipelines and to communicate them to a centralised monitoring station in a distance away from where the future decision is made [12-14].

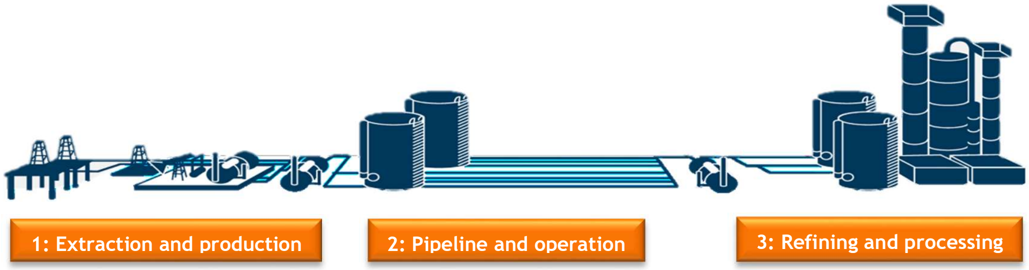


Figure 1-1: Overview of an oil and gas process

Therefore, the rapid developments of WSN are gradually adapted for remote monitoring of oil and gas pipelines which empowers the monitoring station to oversee the entire stretch of pipelines irrespective of the unique geographical terrain no matter how intense the environmental characteristics are.

1.1.2 Challenges of WSN in Oil and Gas Pipelines

The WSN is broadly categorised as infrastructure or infrastructure-less network. A WSN deployed on oil and gas pipelines are considered as an infrastructure based, comprises of static sensing nodes with a more resilient network backbone.

Such a WSN architecture are usually stretch over an extended distance from one node to another that is vulnerable to high probabilities of communication failure, intolerable latency, high error rate and limited network lifetime [6, 12]. The overall performance of a static multi-hop linear network primarily depends on the routing scheme whereby the traditional routing protocols are deemed inefficient in a pipeline network context [2, 15]. Furthermore, a multi-hop linear network also has limited network resources, especially with a single path for both sensing and data stream, to accommodate the overwhelming data flow towards a single receiver at the end of a network [12]. These features are unique that varies to the nature of application especially in a time constraint and 24/7 based system such as the oil and gas pipeline. Some of the critical challenges of WSN deployment on an oil and gas pipeline are:

- Limited communication range - The communication or the radio range of wireless nodes are critical in a linear architecture since every node is a communication backbone in ensuring the communication link between neighbouring nodes in the network. This affects the cost of installation (depending on the network size) as well as the robustness of the network.
- Large-scale network – Nodes distributed in a linear architecture is critical due to limited and shared network resources such as bandwidth, transmission slot, time in-between transmission etc. Therefore, accomplishing real-time data transmission in a static multi-hop linear topology is always challenging especially in a long range wireless network such as in a pipeline network.
- Huge data stream – The shared network resources also restricts the data stream that depends on the data rate and data size in a linear architecture such as pipeline network. Nodes in the network often generate real-time data packets and supporting packets (broadcast and control packets) that affect the bandwidth utilization rate in a pipeline network.
- Power source – Limited power supply and extended communication range is often a threat in a remote monitoring of oil and gas pipeline as this often results in energy starvation of wireless nodes in the network. Thus, such a network consumes high energy as compared to other wireless network

topologies, since each node is only able to establish a communication (long distances) with the closest neighbouring node.

In recent years, static routing protocols for a multi-hop linear network has been an extensive and demanding research area, especially the newly emerging areas with individual perspectives in terms of performance and many other related wireless metrics [16-18]. However, the ever-changing demand and stringing requirement confronting a static multi-hop linear network have a significant implication towards the fully functional deployment on an oil and gas pipeline.

1.2 Motivation

The research aims to analyse the issues addressed to a traditional multi-hop linear topology in a pipeline network. The outcome of this thesis is to highlight the proposed techniques by designing a viable solution with detailed analysis to overcome the said issues.

- The multi-hop linear topology is an important communication architecture on an extended range pipeline network. Due to the unique geographical terrain and data accumulation factor in a single path communication contributes to the occurrence of nodes without data transmission opportunity (passive nodes) between the sender and a receiver node [19, 20]. Most of the traditional dynamic and hybrid routing protocols have different characteristics from network initialization to a route discovery process [12, 21, 22]. One of the crucial factors in a multi-hop linear communication is queue overwhelming from both data and control packets which lead to a bottleneck points in the network. Such factors in routing protocols are often related to frequent communication link instability. Link instability will trigger route maintenance procedure at a certain point in the network, increases the consumption of network resources which will eventually contribute to underperforming of network characteristics. This would result in an increasing number of passive nodes or node failures (due to limited power) which is a waste of network resources and allocation that subsequently degrades the overall network performance [17]. The issues with higher routing overhead, queue overwhelming, frequent updates on route and passive nodes, drives the research motivation to the development of a static routing algorithm. This can eliminate broadcast related routing overhead, predefined routing path, reduce the effects of queue overwhelming and eventually enhance the overall network performance.

- Fairness index is a key indicator of the equality rate of a shared allocation particularly in a single path communication as in a multi-hop linear topology. Equal sharing of network resources in a single path communication is reflected in a constrained performance driven for the entire network rather than individual nodes [23, 24]. Generally, imbalance network allocation is a result of some greedy nodes usually located within a shorter communication range from a receiver node. A greedy node in a multi-hop linear network contributes towards node starvation and passive nodes that drastically degrade the overall network performance in the overtime [25, 26]. The network allocation is often related to the data rate and travel time known as round-trip time (RTT) based on the location of nodes in a linear arrangement [27, 28]. One of the most common reliable data transport protocol is the Transmission Control Protocol (TCP) that employ a data acknowledgement mechanism which plays a very important role in long range linear communication to ensure reliable data transmission. With the TCP agent, the data packet delivery ratio and fairness index [24, 29] is not at a guaranteed rate but can be manipulated for optimum results. Therefore, creating a backhand (at the receiver node) scheduling mechanism would ensure optimum network fairness and resources allocation among all source nodes to achieve an optimum network performance.
- The network energy consumption in a static multi-hop linear topology is one of the utmost intricate and challenging issues [20, 30, 31]. This is due to the snowballing data accumulation factor towards the destination node at one end of the network can cause loss of data during transmission. Even though a WSN in a structured network has a constant power source, yet the energy optimisation is always a desired goal in any wireless devices. The imbalance energy consumption of nodes does not only affect the respective node but has a consequent effect towards the network lifespan that degrades the overall network performance [31-33]. The motivation to design an energy efficient

model with the ability to adapt to the data transmission nature can reduce considerable energy usage hence extend the network lifetime without compromising the overall network performance.

1.3 Objectives of the Thesis

The presented research work in this thesis has considered working on multiple challenges in a static multi-hop linear topology, hence the aim has chain like factors when to compare:

- Design and development of a routing algorithm for the implementation on a static (flat one-tier and cluster-based two-tier) multi-hop linear topology. The aim of the proposed routing algorithm is to enhance the packet delivery ratio and reducing the routing overhead by incorporating the dual interleaving techniques on a known routing path. The proposed routing algorithm is also expected to reduce network energy consumptions and achieve a reasonable throughput fairness among source nodes in a multi-hop linear WSN.
- The research aims to design and incorporate a fairness model with the proposed routing algorithm to achieve optimum throughput fairness index among all source nodes in the network with a TCP agent. The fairness model should enhance the equality of network allocation among all nodes in the network with a reasonable performance.
- The research aims to address the energy constraint and imbalance energy usage throughout nodes in a linear topology. The research aims to design an energy efficient model that reduces the energy consumption and prolongs the network lifetime.

The research work presented in this thesis were implemented and conducted on Network Simulator 2 (NS2) a simulation tool to analyse the overall performance as well as the other wireless metrics on a static multi-hop linear topology [34]. The performance of the proposed techniques has been evaluated with numerous wireless metrics such as packet delivery ratio, end-to-end delay, throughput, throughput fairness index, received packet variation, the ratio of passive nodes, normalised routing overhead, energy consumed per-packet, consumed energy variation and network lifetime. The analysis based on the numerous wireless metrics is an indicator to understand the characteristics and behaviour of the proposed techniques in a network. The research work also explores factors based on the network density and transmission rate against the performance of the proposed techniques.

1.4 Research Methodology

To achieve the desired goals and set objectives, a detail literature reviews on static multi-hop linear topology was conducted with a comprehensive analysis of numerous published works. The related research articles from published journal and conference papers were reviewed in the initial phase of the research to understand the research directions as well as the research focus area. On the next stage, the routing process for static multi-hop routing protocols was studied thoroughly particularly in the key area of application involved in various published articles related to oil and gas pipelines. In the literature review stage, detail analysis from various published work related to static multi-hop linear topology and challenges related to the performance degrading factors in a multi-hop linear topology were identified. The proposed algorithms and techniques were implemented in NS2 [34]. The proposed algorithms and techniques were tested in numerous simulation environment using the simulator to replicate a pipeline network. Furthermore, the proposed algorithms and techniques were compared with some existing methods relevant to the application. Finally, the essential wireless metrics (overall performance and fairness) were compared and analysed against some existing methods to validate the quality of work produced.

1.5 Contribution of Knowledge

The knowledge contribution of this thesis is the design and development of a reliable and performance driven static routing scheme for a flat one-tier multi-hop linear topology and a hierarchical two-tier linear topology. The research outcome has a number of contribution to knowledge in the respective area of application. The contribution of knowledge can be categorised into five components as such:

1. A new performance-driven routing algorithm named the Dual Interleaving Linear Static Routing (DI-LSR) is a routing algorithm established for a flat one-

tier multi-hop linear topology [12]. The design concept of DI-LSR has eliminated broadcast packets for route discovery process which was eventually replaced with a predefined dual interleaving route between source to a destination node to improvise the data rate and bandwidth allocation at a receiver node. The new concept introduces a dual interleaving route among source nodes for shared data sensing and the data stream from a source to a destination node splits the network traffic to elevate the problems with queue overwhelming as well as passive nodes. The predefined route for DI-LSR is based upon the two routing tables (forward: source to destination/reverse: destination to source) contains information of route navigation for respective nodes e.g. data travel direction (forward and reverse), designated destination node and minimum travel cost which is related to time to live.

2. A new performance-driven routing algorithm named the Dual Cluster Head Interleaving Linear Static Routing (DCHI-LSR) is a routing algorithm established for a cluster-based multi-hop linear topology. The designed DCHI-LSR has eliminated the traditional broadcast packets for route discovery and was replaced with a predefined dual interleaving route between cluster head to a destination node improvises the data rate and bandwidth allocation at a receiver node. The new concept of dual interleaving route among cluster heads in a linear architecture employs a dedicated data sensing at source nodes (first tier) and transfer the data through a dedicated data stream between cluster heads (second tier) to a destination node. With the implementation of the dual interleaving cluster heads splits the network traffic to elevate the problems with queue overwhelming as well as passive nodes. The predefined route for DCHI-LSR is based upon the two routing tables (forward: source to destination/reverse: destination to source) contains information of route navigation for respective nodes e.g. data travel direction (forward and reverse), destination node and minimum travel cost.
3. The TCP delayed acknowledgement timeout model for a Fairness critical application (DATM-FFCA) and the TCP delayed acknowledgement timeout model for a Throughput critical application (DATM-FTCA) for a flat one-tier multi-hop linear architecture has been proposed for improving the fairness in network resources especially on throughput. The proposed formulation is

able to derive an ideal delayed acknowledgement timeout value based on the node sequence in the network. The established acknowledgement packet scheduling mechanism in the proposed DATM-FFCA or DATM-FTCA with DI-LSR would respectively enhance the throughput fairness index to an optimum level as well as the other wireless metrics with reduced packet collisions in a flat multi-hop linear topology.

4. The TCP delayed acknowledgement timeout model for a Fairness critical application (DATM-CFCA) and the TCP delayed acknowledgement timeout model for a Throughput critical application (DATM-CTCA) for a cluster-based multi-hop linear architecture has been proposed for improving the fairness in network resources, especially on throughput. The proposed formulation is able to derive an ideal delayed acknowledgement timeout value based on the node sequence for a dedicated cluster head in the network. The established acknowledgement packet scheduling mechanism in the proposed DATM-CFCA or DATM-CTCA with DCHI-LSR would respectively enhance the throughput fairness to an optimum level as well as the other wireless metrics with reduced packet collisions in a cluster-based multi-hop linear topology.
5. To address issues and challenges of energy consumption in a static multi-hop linear topology, an energy efficient model with the ability to adapt to the varying nature of data transmission has been proposed. The proposed Active High Transmitter-receiver energy model (AHiT) emphasise on sleep and active switching scheme for respective nodes in the network to optimise energy usage only in an active period of time. The AHiT energy model empowers the nodes from sleep state to active state according to the data transmission or receiving process in an active energy state only. Once the data transmission or receiving process is accomplished, the AHiT energy model changes the energy mode of a respective node from *on* state to *sleep* state to conserve energy from a traditional *idle* energy mode. The AHiT energy model can be deployed on both a flat one-tier architecture and a cluster-based architecture disregards to the functionality of a node in the network.

1.6 Thesis Organisation

This thesis is organised into six chapters, where Chapter 1 is the introductory chapter for the research work, Chapter 2 is the literature review, Chapter 3 to Chapter 5 is the contribution of the research work and Chapter 6 is the conclusion and future works. An overview of all the chapters are briefly described as below:

- Chapter 1 briefly introduces to the static multi-hop linear topology in an oil and gas pipelines. The subsequent subchapters address the research challenges in the relevant application and propose some viable techniques as an alternative solution for the end users. The scope of research work is clearly described based on the proposed techniques.
- Chapter 2 introduces to some background information and elaborates the taxonomy of a static multi-hop routing protocol. This chapter is sectioned into three parts, which outline the proposed techniques between chapter three to chapter five based on the contextual factors and various existing deployed techniques in a wireless network.
- Chapter 3 briefly elaborates the factors in a multi-hop linear topology and provides a detail description of the proposed DI-LSR and the DCHI-LSR. This chapter is sectioned into two parts which outline the comprehensive analysis of both DI-LSR and DCHI-LSR respectively with some existing routing protocols in numerous scenarios were presented.
- Chapter 4 briefly describes the fairness issues in a multi-hop linear topology and provides a detail description of the proposed technique to improvise the issues addressed in a multi-hop linear topology. This chapter has two section with the first section outlines the DATM-FFCA and the DATM-FTCA for a flat one-tier multi-hop linear architecture. The second section outlines the DATM-CFCA and the DATM-CTCA for a cluster-based multi-hop linear topology. A comprehensive analysis of all four techniques with some existing methods was presented.
- Chapter 5 briefly describes the energy issues in a multi-hop linear topology and focuses on the proposed AHiT energy model. The AHiT energy model concentrated on energy reduction for nodes in a multi-hop linear topology. A

comprehensive analysis of the proposed and the standard energy model was presented.

- Chapter 6 summarises the research work and followed by some suggestion for the future direction of the research work.

1.7 Conclusion

In a large scale WSN comprises of hundreds to thousands of individual devices working to support each other in a unique designed formation as required by the end user or a certain application. The characteristic of a WSN design formation solely depends on the type of application that is tailored to one of the many types of network topologies. Generally, network topologies that are commonly used in WSN are tree, star, linear, mesh and hybrid which presents a specific set of challenges (advantages and disadvantages). Thus, the static multi-hop linear topology is a feasible architecture for remote monitoring of an oil and gas pipelines (fixed infrastructure). In the next chapter, further describes the focal concepts, protocols and technologies related to WSN deployment on an oil and gas pipelines. Basic understanding and concepts behind WSN in the area of remote monitoring as a prerequisite of oil and gas pipeline monitoring will be presented.

Chapter 2

An Overview of Static Multi-hop Linear WSN

2.1 Introduction to Static Multi-hop Linear Topology

Oil and gas pipelines are fixed infrastructures which are stretched over a long distance from one point to the other which could be hundreds of miles away [14]. In general, the communication between two destination nodes takes place through intermediate nodes that are arranged in series. In pipeline networks, all nodes are statically located to establish a chain of communicating through all available nodes in the network. Pipeline network consists of a series of static nodes where each node is designed to perform as a host or/and as a router [4, 6, 7, 35].

The arrangements of nodes in a pipeline network to form a unique architecture that is known as the multi-hop linear topology depends on the network size and the complexity of the application [1, 17]. A network topology is often referred to the way or manner in which nodes are linked to one another in a network. The physical and logical arrangements of nodes in a network can be described as a schematic description of a network topology. Nodes are arranged and interconnected to one another to establish data transfer between a sender to a receiver in a unique form based on the network topology and the type of implemented routing protocol. The various network topologies can easily be implemented based on the nature and complexity of an application in a network. The consideration of a network topology can be outlined based on the implementation scale, expected traffic on the network and fault-tolerant communication links. Thus, the architecture of a multi-hop linear topology can be classified in two major structure which is the flat one-tier topology and the hierarchical multi-tier topology [3, 16, 19].

2.1.1 Flat One-tier Multi-hop Topology

Basically, a flat one-tier multi-hop topology is a simple architecture with a series of nodes containing both sensing and data transferring nodes (in an intermediate node) to a designated destination node [12, 17]. The move towards a flat one-tier topology aims to reduce the number of wireless devices based on the wireless standards in a network especially in managing higher routing overhead and to diminish latency in a multi-hop linear network [2, 16, 19]. A flat one-tier topology simplifies the traffic flow in a network making it feasible for redeployment in a long range network particularly with a way simpler in managing the general operation in a network. There are two major drawbacks of a flat one-tier topology; (1) is a simple node failure and (2) a network with higher data rate can interrupt data transfer due to snowballing effect from a certain point in a multi-hop linear topology [1, 12, 36]. Hence, energy utilisation and network resources should be at an optimum level during the network active period.

2.1.2 Hierarchical Multi-hop Multi-tier Topology

Clustering in a wireless network is often related to a network with higher efficiency, scalability and fault tolerant especially in a multi-hop linear topology [37, 38]. The multi-tier cluster can be deployed from a two-tier hierarchical clustering architecture to a certain number of tier or level in a cluster-based network [39, 40]. The cluster-based two-tier topology is one of the most popular architecture in a WSN. Generally, this topology is divided into two where on the lower level (first tier) is deployed with sensing nodes (sender) at the level two will be a series of leader nodes or is also known as cluster heads [3, 16]. A node in a specific region is only permitted to send and receive packets to a dedicated leader node or cluster head whereas the cluster heads send the collected packets to a destination node at the end of a network. The clustering technique splits the data generated level and data stream where the data packet is sent to a destination node [41]. The advantage of such architectural design contributes to lower routing overhead, reduces the network energy consumption [40] as well as fault-tolerant (a network without node failures). The types and selective of network topology depend on the wireless standards implemented by the user.

2.2 Wireless Standards

The wireless standards have a great impact in terms of performance or outcome to the type of topology implemented for a certain application. This thesis has considered only two major standards that ensembles the application on a pipeline network from all the other available standards. The two standard devices that are potential for a real scale implementation on a multi-hop linear topology is IEEE 802.11 and IEEE 802.15.4. Thus, the given standards and explanations are described in an overview instead of a detailed technical aspect.

2.2.1 The IEEE 802.11 Standard

The wireless local area networks (WLAN) also known as wireless fidelity (Wi-Fi) falls under IEEE 802.11 standards with many different variations or new sub-standards in IEEE 802.11 that has variation in technical characteristic were introduced over these years. The IEEE 802.11 architecture comprises of several individual components that are used to interact for wireless data communication that supports a set of static or mobile stations [42-44]. The IEEE 802.11 standard devices support higher data rate with scalability for large scale application as in a pipeline network. In general, the popularity of WLAN has more visibility in the end user market where a wide range of application is supported by one of the IEEE 802.11 variations [45, 46]. The brief technical operation detail of IEEE 802.11 standards is as shown in Table 2-1 which is widely available on various off the shelf devices.

2.2.2 The IEEE 802.15 Standard

The technical standard of IEEE 802.15 is defined as an operation of a low-rate wireless personal area network. The 802.15 standard has many different sub-standards that have variation in the technical characteristic of the device. The IEEE 802.15.1 standard is known as the Bluetooth wireless communication technology. Bluetooth is designed for short-range communication devices that are small, low cost and has lower power consumption [44, 47]. The other popular wireless standard that is comparable to Bluetooth is the IEEE 802.15.4 standard known as ZigBee. The ZigBee technology provides reliable communication on both multi-hop and mesh network with low power consumption [48, 49]. The basic operation feature of a ZigBee does not support frequency hopping making, thus scan for a channel that contains the least amount of interference during startup [44, 50]. Network devices in ZigBee can be categorised into two classes; Full-Function Devices (FFD) with route messages function in mesh networks and able to act as a network coordinator, whereas the Reduced-Function Devices (RFD) can only establish communication with one FFD [44, 50, 51]. ZigBee also features to operate in a beaconed or a non-beaconed mode as preferred by the user. The brief technical operation detail of IEEE 802.11 and IEEE 802.15.4 standards is as shown in Table 2-1 [44, 47, 50-55].

Table 2-1: Comparison between IEEE 802.11 and IEEE 802.15 standard

Parameters	WiFi	ZigBee	WirelessHART	Z-Wave
IEEE standard	802.11.a/b/g /n/ac	802.15.04	802.15.04	802.15.04
Operational frequency	5GHz (a,ac) / 2.4GHz (b,g) / 2.4GHz-5GHz (n)	2.4GHz	2.4GHz	868.42MHz
Nodes per master	2007	More than 65000	500	232
Range	100 meter (a,b,g) / 250 meter (n)	1600 meter	250 meter	100 meter
Data rate	11Mbps (b)/54Mbps (a,g) / 450Mbps (ac) / 600Mbps (n)	250 kbps	250 kbps	100 kbps
Battery Life/Cost	Days-weeks / High	Months-years / Low	Months-years / Moderate	Months-years / Low

WirelessHART is another technology similar to ZigBee that share the same IEEE 802.15.4 standard and the basic working principles. WirelessHART operates based on Time Division Multiple Access (TDMA) where all devices in a network are time synchronised that communicates in pre-scheduled time-slots [51]. TDMA can minimise packet collisions and also decreases the power consumption. Unlike ZigBee, WirelessHART node features hopping for every message that changes channels for every sent packet making it more reliable in a large network of nodes [51, 52]. Another comparable and popular wireless protocol in the market is the Z-Wave that is widely being used for home automation. The Z-Wave is designed based on the IEEE 802.15.4 physical radio standard that employs mesh networking in order to extend communication range between the communication points [55, 56]. The standard operating frequency at sub-1GHz supports greater communication range as compared to similar products in the current market.

2.3 Routing Protocol

The network topology selection remains an important element in a network design based on the nature of an application, whereas a routing protocol has the same counter effect when deployed on the network. Generally, the architecture of a multi-hop linear topology focuses primarily on optimum node placements and the selection of a routing protocol in a network. A node in a specific location which wants to transmit a data packet must first discover or set the route to the destination node using route discovering protocols [21, 22]. The traditional multi-hop linear topology has varying metrics and impending essential networking factors when implemented with a respective routing protocol. Generally, the routing protocol performance is measured in terms of links stability between nodes, breaking and reconstruction of links, in which it is a crucial activity in a network where most data packets might be lost [12, 21, 57]. In a wireless network, all nodes will generate broadcast messages in a timely interval to their neighbouring nodes within the sensing range to ensure their presence is acknowledge and to retain the pre-established or new routes. In general, the routing protocols have different characteristic on the route learning or identifying process and how this route is maintained during the network-active period [58, 59]. The three most common routing protocols are dynamic routing protocol, hybrid routing protocol and static routing protocol.

2.3.1 Dynamic Routing Protocol

A dynamic routing protocol is widely used in many applications especially in a wireless network environment. The dynamic routing protocol enables the nodes to learn the needed routes from direct neighbouring nodes in a network. Generally, the dynamic routing protocol shares the known number of nodes in a network in which the respective node is able to learn all the possible routes required for data transmission process [21]. In a dynamic routing protocol, the route discovery methods may differ from one another, due to the nature of routing protocols used in a network. The two most common methods in route discovery are reactive routing protocol (on demand) and proactive routing protocol (table-driven) [57, 60]. The major advantage of dynamic routing protocol is the scalability and adaptability with the real-time changes in a network. The major drawback of a dynamic routing protocol is the routing overhead for constantly updated of routing table entries which utilise a higher proportion of the bandwidth and energy in a network [12]. These processes further add complexity to the routing protocol with a degraded network performance on a multi-hop linear network.

2.3.2 Hybrid Routing Protocol

The hybrid routing protocol is commonly referred as a routing combination of both Destination-sequence Distance-vector routing (DSDV) [12, 22] and Link State Routing (LSR) that is built for fast convergence with less energy and memory [12]. The hybrid routing protocol generates accurate route information to identify the best route to the destination node with routing information updates as and when needed. Generally, DSDV shares the knowledge of the whole network with neighbouring nodes and LSR establishes router to router-sharing of neighbouring or closest nodes. The major advantage of hybrid routing protocols is the best of both dynamic and static routing features combined into one protocol. In general, the application with a hybrid routing protocol would benefit from a lower routing overhead compared to a traditional dynamic routing protocol. The drawback of a hybrid routing protocol is the reaction towards the traffic demand on a network that depends on certain gradient of incoming traffic.

2.3.3 Static Routing Protocol

A static routing protocol is commonly generated by a network administrator using known network facts or architecture for a specific application. A static routing protocol is typically implemented on a complex network where the routing table entries are generated manually based the user's demand [12, 37, 61]. Another method in static routing is known as a default routing where a default route is predefined between nodes in the network with a route to the destination node. The advantage of using a static routing protocol is the reduced routing overhead or periodic signalling packets for routing table entries [12]. The major drawback of a static routing are the unexpected changes in a network that are not indicated in a routing table cannot be detected for rerouting thus, making it difficult to be implemented in a complex network.

2.4 Commercial Routing Protocol

Ad hoc On-Demand Distance Vector (AODV) [21, 22, 62] is a well-known commercial reactive routing protocol which operates on a demand-basis for route searching. The sequence number of the destination is used to identify the newest route to the destination. In a multi-hop linear topology, if two nodes are within the communication range, the source node will route to its destination node with an option to bypass its intermediate node based on real-time changes. AODV is used in many topologies such as unstructured or flat, cluster-based, chain and hybrid. Figure 2-1 illustrates many possible routes using AODV which is generated between the source (N1 - Nn) and the destination node (ND) in a linear multi-hop WSN with two nodes located within the communication range.

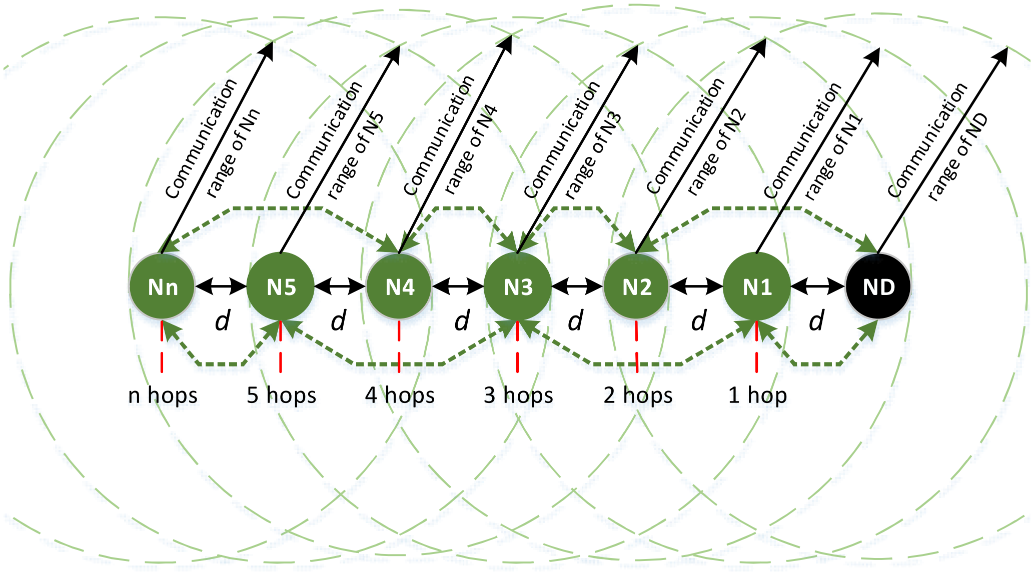


Figure 2-1: Multi-hop linear WSN with Nn and ND at opposite end

Dynamic Source Routing (DSR) [21, 62] is another well-known on demand routing protocol similar to AODV which navigate route between a source node to the destination node using its data packet. All nodes hold the accumulated route information's which is then used to route all the data packets to the designated destination as required. DSR is not viable for long range linear communication due to high routing overhead. The most known commercial, the proactive routing protocol is Destination-sequence Distance-vector routing (DSDV) [21, 22]. DSDV identify the available route to the destination node in the network which shows less delay for route set up the process. The obvious limitations of DSDV is the frequent updates on the routing table's entries are required based on real-time changes on the network. The '*HELLO*' packets generation at every second among neighbouring nodes in the communication range is required to help the nodes to identify the possible route towards the designated destination node. Such process consumes high energy and a portion of the bandwidth even at an idle state. DSDV is used in many topologies such as unstructured or flat, cluster-based, chain and hybrid. Figure 2-1 illustrates many possible routes using DSDV which is generated between the source (N1 - Nn) and the destination node (ND) in a linear multi-hop WSN with two nodes located within the communication range.

The Optimised link state routing (OLSR) [21] is another commercial table-driven routing protocol similar to DSDV but identify routes to the destination node which is known and retained before data packets are sent. Having the routes available to the destination node, the route discovery delay for finding a new route is almost at zero. The biggest concerns on using OLSR is with the high value of routing overhead generated which could be greater than a standard reactive protocol.

2.5 Related Work in Multi-hop Linear Topology

In pipeline networks, all nodes are statically located to establish a chain of communication through all available nodes in the network. Pipeline network consists of a series of static nodes where each node is designed to perform as a host or/and as a router to establish a communication between two destination nodes. A node in a specific location that intends to transmit a data packet first needs to discover or set the route to the destination node using route discovering protocols. The two most common methods in route discovery are reactive routing protocol (on demand) and proactive routing protocol (table-driven) [10, 11]. The selection of a routing protocol takes effect on to the type of topology being implemented.

The authors in [2, 63] proposed Chain-Based 1, a routing protocol for constructing multiple linear chains with a single sink node (destination node). The sender (source node) generates the data packet and forwards it to it neighbouring node where this process will continue on all intermediate nodes until all data packet arrives at the last node on the chain. The last node on each chain will aggregate the data packet before transmitting it to the sink node. Later, the authors in [2] proposed Chain-based 2 where a routing protocol which consumes less energy and prolongs the network lifetime by incorporating another chain network among the last node of each chain. The last node of each chain is also known as a leader node [2, 63]. All the leader node from multiple chains from another main chain have the higher initial energy to support the aggregation and data transmission to the sink node from each respective node in its own chain.

The research work in [64, 65] has implemented a manually configured routing table by ignoring special routing periodic signalling packets with a preselected path between the static source node/nodes to the static destination node/nodes in a grid topology. Fixed routing path (FRP) is an efficient static routing protocol with suppressed routing messages and broadcast messages occurs only locally where a route is manually pre-calculated to an optimal path or the shortest path [64, 65] as predefined by the user similar to Figure 2-2. Due to these changes, the routing table entry of FRP requires no updates or refreshing during its operation. Since FRP design has valid destination route between the source and the destination node, there are no outgoing packet queues for data packet generated from all the source nodes in the network since the IP layer queues were removed.

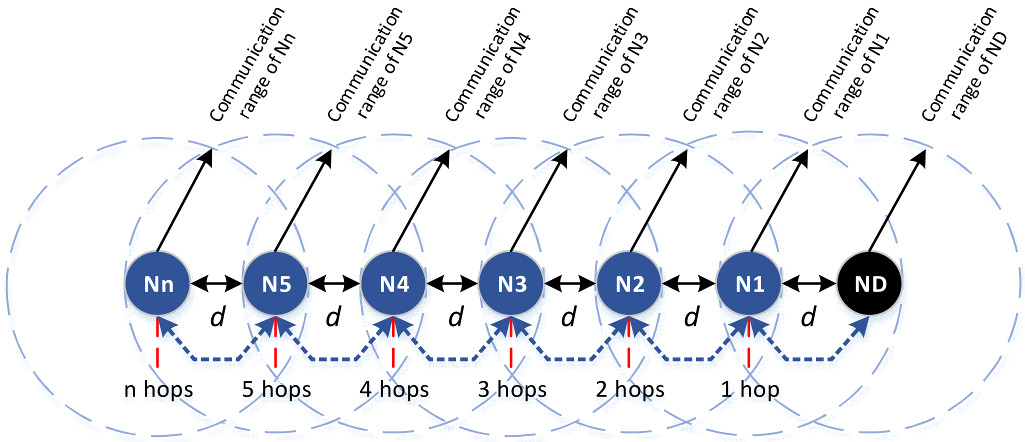


Figure 2-2: Multi-hop linear WSN (single hop technique)

The research work in [66] has implemented a manually defined communication routing path between the source and the destination node for data packet transfer. A static routing protocol is known as No Ad-hoc Routing Agent (NOAH) supports single-hop direct communication only between predefined wireless nodes without generating any routing messages. The routing table is manually created based on the desired source to a single-hop destination node which could be a mobile node or a base station. NOAH is known as a routing protocol with low routing overhead (bidirectional packets) where the routes remain unchanged once it has been configured. The use of NOAH routing protocol is not feasible in multi-hop wireless scenarios, especially in a very large WSN.

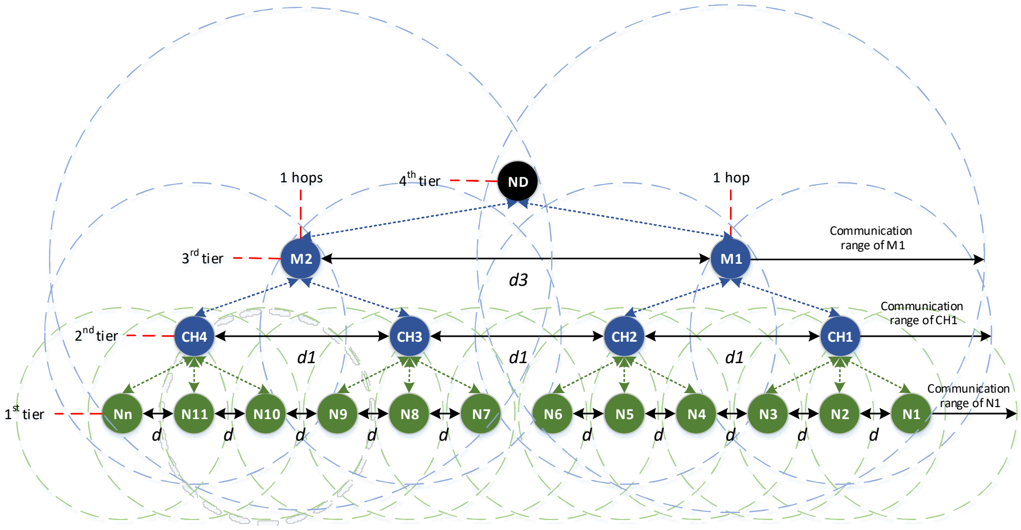


Figure 2-3: ROLS hierarchical WSN

The research work in [15, 17, 67] has implemented a hierarchical and concept of sectioning nodes into three types of nodes similar to Figure 2-3 which is defined as basic sensor nodes, data relay nodes and data discharge nodes. In Routing protocol for Linear Structure (ROLS), all nodes are placed in a linear arrangement with the respective purpose for each node [15, 17, 67] based on multi-layer node addressing scheme. The step by step data transfer from detection point to the designated node is accomplished in three levels of data transfer using two routing algorithm. The lack of connectivity in an immediate neighbour node enables the data relay nodes to double the communication range by increasing the transmission power using the jump always algorithm to successfully send a data packet to the destination node. The redirect always algorithm identifies the redirected flag and send a negative acknowledgement to back into the source node for the regeneration of the data packet in the opposite direction. The redirect always algorithm will also update its database for non-functional nodes to reach the data discharge nodes in the network.

The authors in [68] proposed an efficient oil and gas pipeline information collection algorithm using three-tiered network architecture similar to the illustration in Figure 2-4 which is defined as pipeline sensor nodes, intermediate stations sink nodes and pipeline monitoring control centre. Wireless nodes with flat data collection algorithm response to impromptu data and forwards it to the neighbouring nodes with minimum buffered waiting time [68]. With the flat data collection algorithm, multiple transmission routes are generated between all source nodes to the designated destination node. The flat data collection algorithm is incorporated with hierarchical or cluster for multi-hop scalability in wireless sensor network. With the data collection algorithm, a communication is established with a specific cluster that enables data fusion in the effort to reduce the transmitted data rate to the pipeline monitoring control centre.

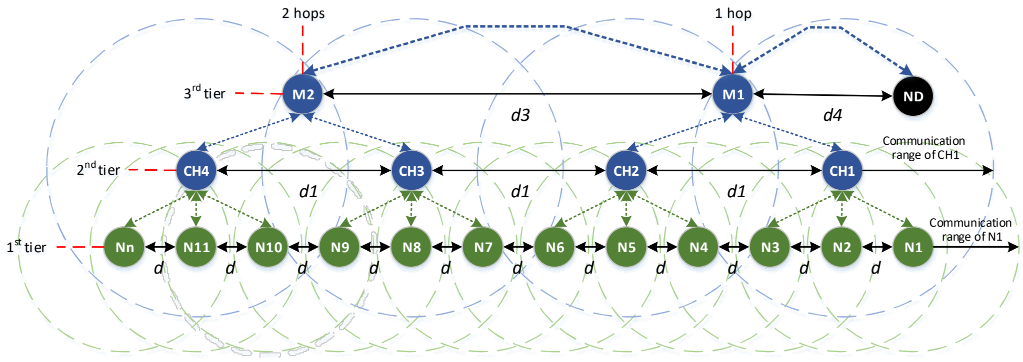


Figure 2-4: Three-tier linear cluster WSN

One of the first and well-known hierarchical routing protocols used in wireless sensor network is the Low-Energy Adaptive Clustering Hierarchy (LEACH) [3, 69]. The LEACH algorithm enables a group of sensors to self-organization and re-clustering its cluster head based on a rotation cycle. The cluster head rotation is created to retain the node with high energy to coordinate the member nodes since the energy consumption of a cluster head is very high. The role of a cluster head is to be in direct contact with all its member nodes as well as the destination node which is at a single-hop from the cluster head in both directions as shown in Figure 2-5. The cluster head collects and aggregate data packets from the source nodes and relays it to the destination node as required.

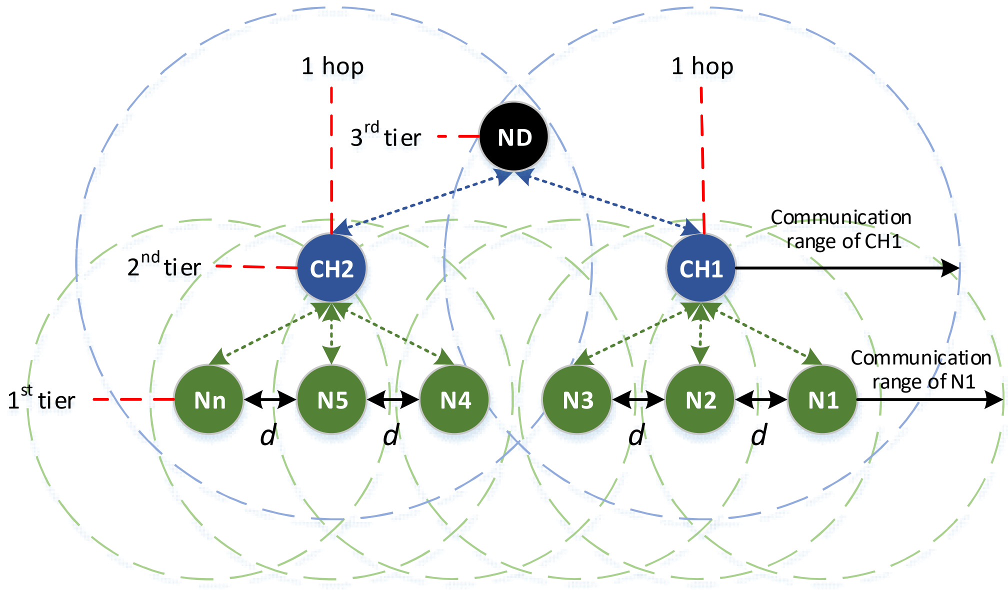


Figure 2-5: LEACH WSN

The research work in [70] Distributed Energy-Efficient Clustering (DEEC) is an algorithm designed for cluster head selection based on energy parameter in a heterogeneous WSN. DEEC algorithm selects the cluster head based on the ratio of residual energy on each node as well as the network average energy. The node in a cluster with highest initial and residual energy will have more probability to be the cluster head which can prolong the network lifetime. The continued rotation of cluster head is required for fairness usage of energy and at the same time to retain as many nodes as possible in the clustering group.

The Advanced Low-Energy Adaptive Clustering Hierarchy (Ad-LEACH) [61, 71] is a static cluster wireless sensor network for heterogeneous routing protocol which incorporated from LEACH [3] and DEEC protocol [70]. The network characteristic of Ad-LEACH is 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 concept of hierarchical or cluster encourages wireless multi-hop communication between a cluster to another in a very large wireless network. The Multi-Hop Low-Energy Adaptive Clustering Hierarchy (Multi-Hop LEACH) [41, 71]was introduced to enable multi-hop among cluster heads when the designated destination node is a distance away. All the sensor nodes which are at a single-hop to the cluster head sends a data packet to a specific cluster head where the cluster head will aggregate and relay the data packets through its neighbouring cluster head towards the destination node as shown in Figure 2-6.

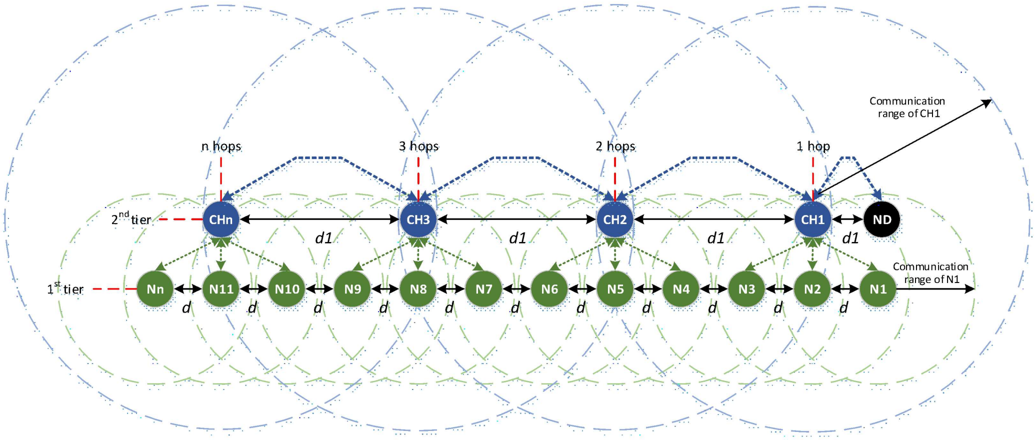


Figure 2-6: Multi-Hop LEACH WSN

The authors in [72] proposed a Distributed Algorithm for Multi-Hop Communication (MH-LEACH), an algorithm to establish multi-hop communication links between sensor nodes with optimum energy saving. The MH-LEACH enables the cluster heads to establish a data transfer to the nearest cluster head in a multi-hop path to the base station [69]. The energy characteristic of MH-LEACH is to extend the network lifetime with short distance data packet transmission which consumes lower energy. The authors in [41, 73] proposed the Fixed Number of Cluster Low Energy Adaptive Clustering Hierarchy (LEACH-F) where a cluster head is selected at the network initializing state and remains fixed. The cluster head rotation among nodes is similar to the conventional LEACH. LEACH-F utilizes the centralised cluster formation algorithm from LEACH-C and has zero overhead at the network initializing state.

2.6 Introduction to Transmission Control Protocol

A full deployment of WSN on oil and gas pipelines has a severe network performance degrading issues especially on equal sharing of network resources among nodes in a network. Sharing or managing of network resources is a crucial task particularly in a highly densest multi-hop linear network with a limited resource [24, 74]. It is quite a common scenario in which a long range multi-hop linear WSN is prone towards inefficient fairness which leads to source node starvation [23, 27] in a network with a Transmission Control Protocol (TCP) agent. In general, there are several types of agents that support a network such as TCP, User Datagram Protocol (UDP), Stream Control Transmission Protocol (SCTP), Datagram Congestion Control Protocol (DCCP) and etc.

TCP is one of the most popular agents in many IEEE 802.11 based application where various mechanism with high performance and congestion collapse avoidance is achieved. TCP is a reliable agent with a closed loop process from a data generation at a source node until a receipt of an acknowledgement packet in return from the receiver to the respective source node. The key function of this 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 oversee the bandwidth utilisation for the purposes of data packet transmission. The newer versions of TCP mechanism are built with four intertwined algorithms such as slow start, congestion avoidance, fast retransmit and fast recovery as stated in (RFC 5681) [75].

The slow start algorithm increases the congestion window with every acknowledgement packets received. This enables the congestion window to be effectively increased based on every Round Trip Time (RTT) value [76-78]. In a state where the congestion window exceeds the set threshold of *ssthresh*, the congestion avoidance algorithm reorganises the congestion window based on the type of TCP agent used in a network. In this period, the congestion window is increased by one for each RTT value until a lost packet is detected in the network. The congestion avoidance algorithm has a unique procedure in handling the real-time data traffic in a data stream based on the characteristic of a TCP agent [78, 79]. In general, a TCP agent retains a timer starting from the moment a data packet is sent which will be used as a mechanism to detect a lost packet without acknowledgement packets received after the timer has expired. It is quite common for the TCP agent to realise the lost packet caused by the lengthy waiting period before an action is taken. Thus, a fast re-transmit algorithm was proposed which uses a duplicate acknowledgement in detecting a lost packet (usually, is set to three). In a scenario where an acknowledgement packet is received with the same sequence number at a source node, the fast re-transmit algorithm considers it as a lost data packet and regenerates the data packet for the second time. The fast recovery algorithm reduces the size of a congestion window by half and expands the congestion window based on the usable window with minimum (*awnd*, *cwnd*+*ndup*) where *awnd* is the advertised window, *cwnd* is the congestion window and *ndup* is the number of duplicate acknowledgement received [23, 79]. The acknowledgement of new data also known as recovery ACK is received to return to congestion avoidance phase.

One of a key metrics in TCP is RTT, whereby an RTT value is one cycle time from the source node to send a data packet to the destination node and to receive an acknowledgement packet in return. The TCP mechanism at the source nodes employs a retransmission time-out (RTO) mechanism for an estimated RTT [23, 27, 79]. The detailed characteristic of RTT is as stated in RFC 2988 [80]. Many types of research are conducted in enhancing TCP performance in handling congestion, reducing errors and handling the loss. Thus, there are many types of TCP algorithms available for users.

2.7 Types of TCP

A TCP agent is also known as a connection-oriented protocol in a transport layer. In general, the TCP agent implements a data flow control, error control and congestion control mechanisms to establish a reliable end-to-end data and acknowledgement packet transmission at the both end (sender and receiver) of a network [78, 79]. Thus, the TCP agents can be classified in two agents, one at the source node (sender) and another at the destination node (receiver). All the TCP agents have difference characteristic only when there is a lost packet detected in a network. In a state where all data packets have reached the designated destination node successfully, all the TCP agents operate at a similar procedure.

2.7.1 TCP Tahoe

TCP Tahoe refers to the congestion control algorithm as proposed by Van Jacobson [81, 82] based on a concept of conservation of packets. The concept is unable to permit a new entry of data packet if the network is operating at full capacity until a data packet exits the data stream. The network with TCP Tahoe acknowledges the sender for every data packets sent in a sequential manner. The congestion window in TCP Tahoe is maintained to reflect the real-time network capacity during the active period. TCP Tahoe is based on a slow start procedure where at initialization or re-initialization due to packet loss, the congestion window is set to one and exponentially increased until another packet is lost. Thus, the congestion will be reduced and the network will be emptied when an agent encounters packet loss by timeout. When the agents encounter congestion in a network, TCP Tahoe saves the value of window by half as a threshold for the next cycle with linear increments till the next packet loss. The timeout process cost lengthy delays until a new packet is generated at a source node, therefore, it is not practical in a highly densest network [79].

2.7.2 TCP Reno

The TCP Reno maintains the fundamental features of a TCP Tahoe such as slow start procedure however with an early detection of loss packets, the network is not emptied when to encounter a packet loss [83]. The TCP Reno acknowledge the data packets received at a designated destination node instantly hence, a sequence of an acknowledgement packet is generated based on a predetermined time (sufficient time to travel between a source and a destination node) for the retransmission of a lost data packet [76, 77, 84]. The fast re-transmit in TCP Reno is a procedure when three duplicate acknowledgement packets are received at a source node that indicates the probability of a packet loss in the network. This procedure will also reduce the Slow-Start Threshold (*ssthresh*) value to half of the window size and set the same value for congestion window [79]. The congestion window will be increased by one for each acknowledgement packet received and is limited to the amount of data packets in the data stream. TCP Reno is known as a reliable agent in a network with small losses of data packets but will underperform in a network with multiple data packet loss in a single window [23, 24, 27].

2.7.3 TCP New-Reno

The TCP New-Reno is an enhanced version of TCP Reno with fast re-transmission in a scenario with multiple data packet loss in a single window [83, 85]. Unlike in the fast re-transmit state in TCP-Reno, TCP New-Reno remains in the state of fast recovery until all outstanding data packets are acknowledged at a period of fast recovery [76, 79]. Hence, the reduction of congestion window is not required as frequently as in TCP-Reno. The cost of one RTT is required to detect a packet loss from the sequence of issued acknowledgement packet from the destination node.

2.7.4 Selective Acknowledgements (SACK)

The TCP SACK is an extension of both TCP-Reno and TCP New-Reno which works around the limitation mainly on detection of multiple packet loss per RTT value and retransmission of more than one packet loss [83]. TCP SACK acknowledges a data packet selectively with a block indicating the packets being acknowledged. This helps the sender to trace any outstanding data packets in the data stream. In the event of fast recovery, a variable data stream is estimated on the outstanding of data packets and set the congestion window by half. The data stream is reduced by one for every acknowledgement packet and increased by one for every transmitted data packet. In a state where congestion window is larger than the data stream, the undelivered packets are checked and retransmitted accordingly [76, 79]. Thus, more than one lost packet can be retransmitted in one RTT value.

2.7.5 TCP Vegas

The TCP Vegas is an extension of TCP Reno with a proactive mechanism to encounter congestion in a network before the packet loss occurs. TCP Vegas can also be considered as a congestion avoidance mechanism that gives emphasis to packet delay rather than a lost packet [76, 86]. The proactive mechanism is utilised in controlling the congestion window based on the real-time state of the network. Thus, it detects the congestion at an early state based on the value of RTT unlike congestion is only detected as it occurs in a network using TCP Reno and TCP New-Reno. The issues with timeout are efficiently verified in a schedule which also overcomes the duplicate acknowledgements in order to detect a lost packet. The congestion in a network is not detected by the means of a lost packet but it is detected way before a packet is lost [77, 79]. The traditional mechanism for detecting a lost packet as in TCP Tahoe and TCP Reno based is still retained in TCP Vegas.

2.7.6 TCP Agent at a Receiver

The TCP sink is the simplest TCP agent at a destination node in a network with one acknowledgement packet is generated for each successfully received data packet. Whereas the TCP sink with delayed acknowledgement is a configurable delay (time) before acknowledging a received data packet at a destination node [79]. The TCP sink with delayed acknowledgement can be configured based on the user's requirements. A TCP sink with selective acknowledgement is based on selective repeat retransmission policy. The receiver generates an acknowledgement packet based on the selection made by the sender on the received data packets. The missing or lost data packets can be retransmitted from the sender to the receiver for the second time. A TCP sink with selective and delayed acknowledgement has a combination features of both selective and delayed acknowledgements [79, 83]. Based on the selective acknowledgement, the configurable delayed acknowledgement time can be added at the destination node.

2.8 Related Work in TCP Fairness

The proposed ACKs-First Variable-size Queuing (AFVQ) [87] mechanism incorporates the ACK-s first scheduling and a variable-size queuing method to reduce the effects of network unfairness. In general, the acknowledgement packets are separated from data packets that are transmitted prior to a data packets transmission. Hence, the acknowledgement packets queuing delay is reduced. The variable-size queuing is able to reduce the number of acknowledgement packets in the queue by dropping the acknowledgement packets overflow from the output queue, therefore, creating a better allocation for data packet transmission. The acknowledgement packet overflow is dropped and a new acknowledgement packet is generated to the TCP sender indicating that all data packets are successfully transmitted.

Adaptive Delayed ACK Mechanism (ADAM) [23] works by properly adjusting the TCP parameter which affects the throughput fairness and further reducing frame collisions. The ADAM is proposed for a multi-hop implementation with unparalleled data transmission among all sender nodes in a certain network. Thus, the delayed acknowledgement time for all sender nodes is calculated based on the RTT value between a sender and a receiver node to achieve optimum throughput fairness. The cycle time for a data cycle is formulated based on the accumulated network RTT value in a multi-hop network. ADAM+ [27] is another method introduce by the author to improve throughput fairness further by eliminating the request to send (RTS) and clear to send (CTS). With the RTS and CTS function being disabled, it further reduces the routing overhead and creates higher data flow towards the receiver node in a network. The author also introduced ADAM in shorter node distance (ADAM-snd) where two sender nodes are located in a communication range that enables a bypass communication with a decrease in the accumulated network RTT value. Both ADAM+ and ADAM-snd are designed based on the configuration of ADAM.

TCP with Adaptive Delay Window (TCP-ADW) [88] is designed to reduce the acknowledgement packets appropriately by reaching an optimal dynamic delay window. Based on the real-time changes in a network, the goal of TCP-ADW is to regulate the number of acknowledgement packets and to dynamically adjust (increase or decrease) the delay window. The number of acknowledgement packets is appropriately reduced by the proposed model by manipulating the delayed window (down) referring to the size of congestion window (transmission rate at a sender), the packet inter-arrival time (indicates congestion level and path distance) and lost packet event. 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.

The authors [89] have purposed a technique to dictate the buffering of data packets in a network to achieve throughput fairness. The Proposed Packet Reverse Function enhances the network performance by improving both the fairness index as well as the average end-to-end delay from multiple sources in a network. A special characteristic for the proposed scheduler enables better management for data packet transmission with a reverse function which eliminates data packet loss in a network. A dual buffer mechanism in each node manages the overflow of data packets generated by assigning them to a primary buffer in a neighbouring node (moving towards the receiver node). In a state where the primary buffer is at full capacity, the data packet will be moved to the secondary buffer in the same neighbouring node. If the buffer state is at full then the data packet will be redirected to the secondary buffer of the sender node unless. If the secondary buffer state is at full at the sender node, then the data packet is moved to another neighbouring node and will be dropped if the secondary buffer state is still at full. The proposed technique creates more room to accommodate the generated data packets in multiple locations (nodes) until the data packet is sent to the designated receiver.

The Intelligent Acknowledgement technique (TCP-IA) [90] incorporates the value of projected bandwidth and delay to the MAC header to enhance the TCP performance particularly in a network with bandwidth unfairness. The data packet arriving at a neighbouring node, the link layer calculates the bandwidth and delay in a cycle repetition until the data packet reaches the receiver node. Any data packets that are not in order or with a low bandwidth and a higher delay is an indicator to reduce the delaying window size at a receiver node. In this state, an acknowledgement packet is generated to the sender. Otherwise, the receiver node generates a single acknowledgement packet to the sender node indicating the received data packet. After receiving the acknowledgement packet from the receiver node, the sender node regulates the size of congestion window referring to the bandwidth and delay.

Cooperation between channel access control is a new cross-layer scheme along with TCP Rate Adaptation (CATRA) [91, 92] will determine an optimal Contention Window (CW) size to achieve fair share on each TCP flow. The proposed CATRA gathers useful information from both MAC and physical layers in order to dynamically adjust the CW size to manipulate the contention between stations. The modified CW size enables the network to achieve fair channel access per-station and an efficient spatial channel utilisation. The fair bandwidth allocation value is calculated for each TCP flow is directed to the transport layer. Referring to the value obtained, the TCP sending rate is adjusted on each flow to achieve fairness between flows hence results in throughput fairness.

The authors in [74] proposed a transmission scheduler algorithm to achieve improved network fairness and maximise the allocated bandwidth. The proposed transmission scheduler algorithm is designed to assign each node with a weight referring to its location in the network and the aggregated traffic load. The respective node transmission time is derived based on the weight factor which is the number of hops from a gateway, the aggregated traffic load includes own and other data packets and the number of interfering nodes in the transmission range. The proposed transmission scheduler algorithm improves the throughput of each node as well as the overall network allocation fairness among all sensing nodes.

The authors in [93] proposed a practical dual queue approach with a combination of Optimal Queue Selection known as the TCP-Optimal Queue Selection. The two different queues are designed to accommodate data packets in one queue and the acknowledgement packets on the other. Based on the priority or probability, the optimal queue size is selected to achieve a great amount of fairness in a network. In the priority and probability scheduling, there are two different methods proposed to assist the queues. In the priority scheduling, an acknowledgement packet has a higher priority whereas in the probability scheduling the queue selection is referred from the optimal probability. With the optimal probability, the ideal queue size, as well as the queuing delay for an acknowledgement packet queue for probability scheduling, is derived.

2.9 Introduction to Energy Model

The sustainability of an implementation WSN on an oil and gas pipelines solely depends on a constant energy supply in a network. A multi-hop linear architecture has limited network resources and a set of diverse challenges in terms of energy optimisation in both infrastructure and non-infrastructure based system [12, 32]. Thus, an energy efficient routing protocol and energy optimisation technique are essentially needed to drive towards a feasible implementation on an oil and gas pipelines. Energy wastage in a multi-hop linear architecture has numerous impending factors against overall network performance since a single node failure could be a threat to cannibalise the entire network at a point [1, 2, 12]. Some of the primary reason of energy starvation and declining the network lifetime in a WSN is idle listening, waiting period in-between transmission, retransmission (due to packet drop), higher routing overhead and overhearing [20, 23, 30, 94]. Therefore, an energy optimisation technique and managing of network resources are essential, particularly in a highly densest multi-hop linear network.

Generally, the unique geographical architecture of a long range multi-hop linear WSN has an imbalance or inequality use of network energy which applies to both infrastructure and a non-infrastructure based system [4, 6, 35]. The energy usage is often related to the data accumulating factor moving towards a centralised monitoring station (destination node) in an oil and gas pipelines. Therefore, a step increase in energy consumption can be visualised on nodes in a path moving towards the destination node. It is quite a common scenario in a multi-hop linear WSN that is prone to inefficient energy usage that can result in energy starvation in a network with a standard or inefficient energy model. The five basic factors that influence the energy demand in a network are the network architecture, density of nodes, distance between nodes, routing management and data rate [3, 17, 18, 95]. All these factors are dependent on the network architecture of a WSN. The two most common network architecture in a pipeline network is a flat (one-tier) topology and a cluster-based (multi-tier) topology [15, 16, 96].

2.9.1 Energy versus Network Architecture

A WSN is typically composed of a large number of nodes being deployed in a specified region of measurement. In a typical oil and gas pipeline scenario, the specified region is often related to an outdoor harsh environment where nodes are exposed to the climatic effect [5, 8]. The nodes in a pipeline network are statically deployed between a sensing point and a receiver point. In a multi-hop linear network independent to the network architecture, data packets are transmitted through a series of nodes to a centralised monitoring station (receiver node) [6, 35, 96]. A sensing point can communicate directly to a receiver point in a single-hop or a multi-hop communication through its neighbour nodes in a network. Either way, the communication links in a typical multi-hop linear architecture relay data packets to the destination node that is in a distance away, resulting in high-energy consumption in the network [20, 31].

In typical flat one-tier multi-hop architecture, each of the source nodes has a dual role where it acts as a sensing point as well as an intermediate node for the other neighbouring nodes [97]. The nodes in such an architectural design are energy driven since both sensing as well as transmitting data packets to a designated node has a high demand on energy consumption. The network nature of a multi-hop flat architecture may drain higher energy due to the combined operation of a sensing and data stream in a single path. Node starvation is not a favourable factor in a network due to higher demand for energy that could lead towards node failure which can consequently cause termination of the communication links in a multi-hop linear network [28].

In multi-hop hierarchical architectures, each source nodes are organised into clusters with a dedicated leader node known as the cluster head. In each cluster, source nodes are only permitted to communicate directly to a dedicated cluster head at all-time whereas, one or more leader nodes are responsible for establishing a multi-hop communication path with neighbouring cluster heads to a destination node [37, 97, 98]. In a static network environment, a leader node is dynamically selected based on some set network criteria which include remaining energy, the distance between source nodes with other cluster heads and node homogeneity [61, 70]. The multi-hop hierarchical architectures are a complex structure of network type with nodes at each level are designed to perform a specific task which may vary from one level to another based on the routing protocol. Source nodes located at the lowest level is dedicated for sensing changes on a sensor and transfers it to the leader node in a cluster. Based on the hierarchical architectures, the leader node may transfer it to a level above or to another neighbouring leader node in the network [72, 98]. The complexity depends on the number of levels created as well as the types of devices deployed in the network. Thus, the energy requirements in multi-hop hierarchical architecture may vary upon factors that contribute to the network complexity.

2.9.2 Energy State in a Network

The energy model response based on the characteristic of a routing protocol and the network energy demand during the network-active period. The energy model is responsible for the network power management in all network energy state [34]. The energy usage in a network denotes the various network activity that can be classified as energy for transmitting, receiving, idle, sleep and transition [99-101]. In a practical implementation, the consumed energy may vary upon the characteristic of a selected hardware which indicates the rated energy for each attribute on a network activity. Another factor that influences the increasing demand for network energy is the characteristic of a routing protocol especially the ones with a higher routing overhead [22, 57, 102]. The five most common energy mode is on, off, idle, sleep and transition are implemented to optimise the network energy [34, 103, 104].

Generally, the idle, transmit and receive states in a WSN can be constituted as a network-active state or as on state. During the on state, the source nodes are permitted to transmit and receive packets at the cost of transmission and reception power respectively [34, 104]. Both the transmission and reception power includes all the supporting packets (broadcast and control) needed in a network. In any wireless device, the power ratings in an active state are comparable with the types of network activity attempted by a node. The highest energy attributes in a WSN is from the packet transmission state where maximum energy is consumed, while nodes in a receive state consume slightly lower energy than the transmission state but higher energy than in an idle state [20, 105]. In a network environment with no network activity for a duration of time, this state can be considered as an idle state. However, a network with no data packet transmission still cost the network with idle power during the idle and listening phase of the neighbouring nodes. The energy rating for each network activity depends on the type and the characteristic of the deployed wireless device [106]. In the network-active state, all nodes consume full energy in respect to the network activity.

The sleep and off state in a WSN can be constituted as a network-inactive state or as off state. A network in a sleep state consumes energy at a lower rate than that at an idle state whereas, in the off state there is no consumed energy in a WSN [34, 103]. In the sleep state, the radio is set at off which disables the nodes from transmitting and receiving data packets but on the background, energy is consumed for detecting signals based on the characteristic of a routing protocol. However, the consumed energy at sleep state depends on the deployed routing protocol and network size. In a network environment where nodes are set to off state, the energy consumed is equivalent to zero [104]. In the off state, no network activity is permitted since the radio is at off state and unable to detect any incoming packets or even establishing an outgoing packet. This is a non-productivity state in a network which does not consume any network resources.

The transition in a WSN can constitute as a transition between the network-inactive state to network-active state. Transition in a WSN is a common activity in between different state of energy mode with a time factor. The three most common transitions in a WSN is the state from ‘idle to transmit’, ‘idle to receive’ and ‘sleep to idle’ [34, 103]. During the specific transition period, the transition state is attained with an additional energy independent to the other network activity. Generally, the transition period takes into account of the radio activation period in a wireless device.

In order to ensure sustainability as well as to prolong the lifetime of a WSN, it is essential to properly outline the workflow of source nodes, network architecture and an efficient energy model. Over the years, an increasing number of research was conducted in optimising the energy model especially in a remote monitoring and battery operated WSN [94, 101, 107-110]. Numerous research works were related to the implementation of an efficient, optimum and energy longevity in a pipeline network as a factor in a performance-driven WSN. Hence there are many types of energy model available for users.

2.10 Related Work in Energy Model

The proposed nW-MAC [111] is an asynchronously scheduled with multiple wake-ups provisioned duty cycle MAC protocol in a WSN. The nW-MAC is an asynchronous schedule selection technique to setup the maximum number of n wake-up during the receiver operational cycle. The proposed nW-MAC is best deployed in both low and high traffic application by utilising the reception window-based medium access and limiting the reception opportunity at each wakeup. With the implementation of nW-MAC, the optimum energy consumption in a network is achieved using the multiple wake-up techniques in each allocated wake-up cycle for nodes.

The authors in [101]had modified the standard IEEE 802.11 power model to improve energy efficiency and end-to-end delay in a WSN. According to the proposed method, a data packet will be able to travel many hops between a source to a destination node within a beacon interval. During the Dynamic Ad-hoc Traffic Indication Map (ATIM) window adjustment is sliced into the smaller initial slot (contention slot). An empty data packet will be sent during the contention slot which retains at on state for the sender and receiver nodes enabling the sender node to advertise with the ATIM packet. The receiver node generates an ATIM-ACK packet to establish data packets between the respective nodes during the beacon interval. All other nodes in the network are excepted to be at sleep state instead of being at on state during the ATIM window to achieving better energy efficiency.

The author had proposed [112] a technique to group the data transmissions by defining the harmonising period that is used in aligning the data transmission from multiple application at interval boundaries. A protocol is designed by referring to the harmonising period which coordinates the data transmissions across nodes by ensuring real-time guarantee in a multi-hop WSN. The proposed Network-Harmonized Scheduling (NHS) is a protocol which takes advantage from the periodicity introduced to allocate offsets across nodes based on different hop levels. The concept of different hop levels ensures that collisions among data packets will always be avoided with an enforced deterministic behaviour in a network. The NHS is designed for a light-weight and scattered protocol without any global state-keeping mechanism in a network.

The proposed Receiver-Initiated X-MAC (RIX-MAC) [113] is an energy-efficient MAC protocol established with an asynchronous duty cycle. The RIX-MAC can improve the energy efficiency by utilising short preambles and adopting a receiver-initiated approach. The RIX-MAC is capable of minimising the energy consumption of sender nodes by facilitating transmitters based on the predicted wake-up times of receiver nodes. With the receiver-initiated double wake-up, schedule reduces the sender's control frames in a wakeup period between a sender and receiver node. This method in RIX-MAC is able to reduce the energy consumption of receiver nodes through reduced control frames.

The Multi-hop power saving mode (MH-PSM) [114] is designed to improve both end-to-end delay and sleep period compared to the conventional power saving mode. The proposed MH-PSM is extended from the standard IEEE 802.11 power saving mode that allows a WSN to switch states from a high power state to a low power sleep state in order to save energy. The energy state switching is established through a traffic announcement scheme which is used in facilitating a multi-hop communication. The scheme broadcasts traffic announcements throughout a multi-hop path that ensures all intermediate nodes are remained at on state to receive and forward any pending data packets with minimum latency in a network.

The Developed DEEC (DDEEC) [70] dynamically changes the cluster head selection conditions for nodes in a network based on their residual energy. The proposed [115, 116] Enhanced DEEC (EDEEC) where the cluster head selection probability is based on the energy level indicated as super and advanced, that is higher than the normal nodes. The EDEEC continues to penalise nodes at super and advanced energy level even at the same normal nodes energy level. Therefore, nodes with super and advanced energy level will be terminated quickly compared to the normal nodes in a network with EDEEC. The authors in [116] proposed an enhanced developed distributed energy-efficient clustering (EDDEEC) scheme to be implemented on a heterogeneous WSN. The EDDEEC primarily incorporates three elements which are the heterogeneous network model, an energy consumption model and a clustering-based routing mechanism. The proposed heterogeneous network model is based upon three energy level of nodes in a network. The energy consumption model in EDDEEC considers the impact of radio environment. The clustering mechanism in EDDEEC enables the probability of the selected cluster head in an efficient and dynamic method.

The authors in [108] proposed a method on energy saving model for improving network lifetime in both homogeneous and heterogeneous environments. The proposed method introduces the node pairing concept where the pairing nodes are placed close to one another in a WSN. The proposed energy model optimises the remaining energy level of all sensor nodes (detection nodes) in a network by ON and OFF scheduling technique for data transmission. The two-phase switching method among sensor nodes enables the data transfer in phase one for a series of nodes in ON state is able to transmit data packets to the base station while the other nodes will be set to OFF state. Whereas in phase two, initial nodes in ON state is set to OFF state and initial OFF state nodes is set to ON state for data packet transmission to the base station. The cluster head is selected based on the node with highest remaining energy in a specific region. The proposed power switching between ON and OFF state allows optimisation of energy usage in a network with longer network lifetime.

The authors in [117] proposed the Energy-Delay Unified Routing protocol [EDURo+] which incorporates Prim's- Dual algorithm that considers five fundamental parameters to extend the lifetime of a sensor node in the network. The considered parameters are residual energy in nodes, the rate of packet loss, transmission power, receiving power and interference to determine the next hop. The proposed method is critical to event monitoring; thus, the sleep and wake schedule can be amended from a low power state to a high power state. All nodes in the network are set at low power state unless the nodes in a data transmission process are switched to high power state.

The multi-hop distance-based and low-energy adaptive clustering (MH-DISCPLN) [118] is an energy efficient protocol in multi-hop cluster-based WSN. The MH-DISCPLN protocol introduces the concept of multi-hop clustering with an equal number of selected cluster heads in each round. The selected cluster heads are from the middle and outer rectangle regions. In the middle region, the cluster head is selected based on highest remaining energy to aggregate and forward data packets from cluster members as well as the outer region cluster head to a designated base station. The outer region cluster head can only transfer the received data packets to the nearest middle rectangle cluster head. A selected cluster head will not be a cluster head again until all the member nodes in that region had the opportunity to be a cluster head. The MH-DISCPLN protocol is capable of increasing the network lifetime as well as achieving higher throughput with lower delay and packet loss.

2.11 Conclusion

The overview and different aspect in the application of a static multi-hop linear topology were presented in this chapter. The technical characteristic and features of a static multi-hop linear network were briefly described in terms of network topology, resources unfairness and energy constraints. The applications of a static multi-hop linear network were highlighted with different types of related works that contribute to the overall network performance. In the next Chapter, a routing algorithm for both flat (one-tier) and a cluster-based (two-tier) topology for enhancement of overall network performance will be presented. A dual interleaving scheme for multi-hop linear topology can further improve the network performance in a pipeline network.

Chapter 3

Reliable and Efficient Interleaving Linear Static Routing for Pipeline Network

3.1 Introduction

Wireless sensor network (WSN) is widely used in the monitoring of oil and gas pipeline integrity. In a large scale linear WSN deployment benefits from many prefixed sensing locations through the entire strength of an oil and gas pipeline [4, 8]. A long range multipoint linear WSN communicates valuable information to a centralised remote monitoring station which is usually located miles away from the sensing locations. A multipoint linear WSN has no fixed central authority to gather the collected data but every single sensor node on a certain network carries not only its own data but also the traffic from every other node in the pipeline network towards the destination node [12, 96]. Figure 3-1 illustrates these characteristics of an established route between Nn to ND on a multipoint linear WSN at time *t*.

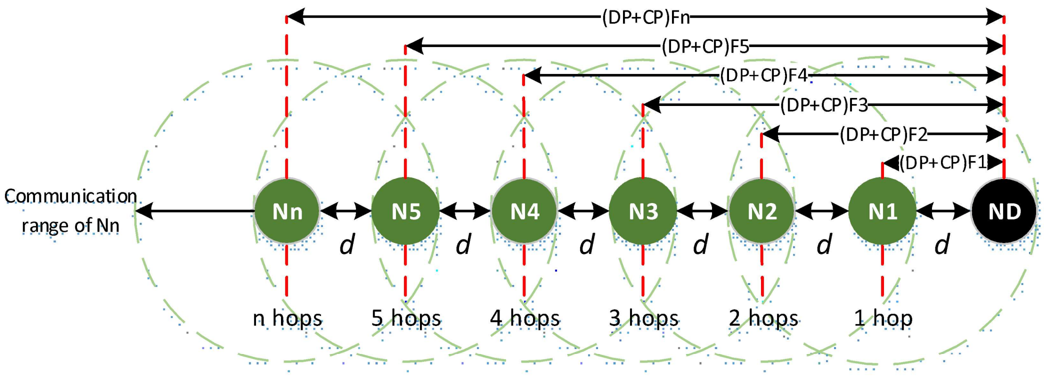


Figure 3-1: Multi-hop linear WSN

Data packets are indicated as *DP* and control packets are indicated as *CP* from respective nodes indicated inflows, *Fn* where *n* represents the maximum number of flows containing bi-directional packets moving towards a destination node. In such a WSN setup enables communication with every single node in its communication range directly to move the collected data forward to a designated node [12].

The benefit of a multi-hop linear WSN layout is the ability to establish a communication route among the neighbouring nodes within its communication range to transfer data packets towards a designated node (ND) [15, 119]. With an implementation of a reliable routing algorithm creates the ability to automatically generate a route, detect real-time route breakage and also correct them as needed. The other benefit with a multi-hop linear WSN is the capabilities to outspread a larger coverage area by adding more nodes to the existing network. The most important features of WSN in monitoring oil and gas pipeline integrity will be scalability, reliability and robustness [4, 13]. The overall wireless network performance is critical for the sustainability of the network in the long run. However, due to its unique geographical linear WSN structure on pipelines, the three foremost drawbacks of such a topology are; (1) amplified complexity which leads towards (2) node failures hence (3) declining overall network performance [35, 96, 120]. A multi-hop linear WSN tends to be challenging to regain from node failures due to a large number of network changing variables to maintain the network. A multi-hop linear WSN typically has limited and reduced capacity compared to other known wireless topologies, due to the amplified overhead in managing the network routing as well as increased contention in traffic towards the destination node. The accumulation of data from each independent nodes as shown in equation 3-1 has to share the same path to transfer the data towards the destination nodes as shown in Figure 3-1.

$$TP_i = \left[(DP_i + CP_i) + \sum_{j=i+1}^{n}\left(DP_j + CP_j\right)\right] \leq IfQlen_i \qquad \textbf{3-1}$$

Where TP is the total packets for n number of nodes, DP_i is the total data packets and CP_i is the total control packets at node i with $1 \leq i \leq n$. While DP_j is the total data packets at neighbouring node j, CP_j is the total control packets at neighbouring node j and $IfQlen_i$ is the default queue size set at 50 packets in a network [12].

Figure 3-2 illustrates the route breakage at *N4* on a multi-hop linear WSN at time *t+1* that creates a link breakage that results in communication interruptions beyond *N4*. Such a scenario creates an unfavourable state for the active nodes located beyond *N4*. In any multi-hop linear WSN, this is a crucial issue that leads towards loss of important data from the oil and gas pipeline.

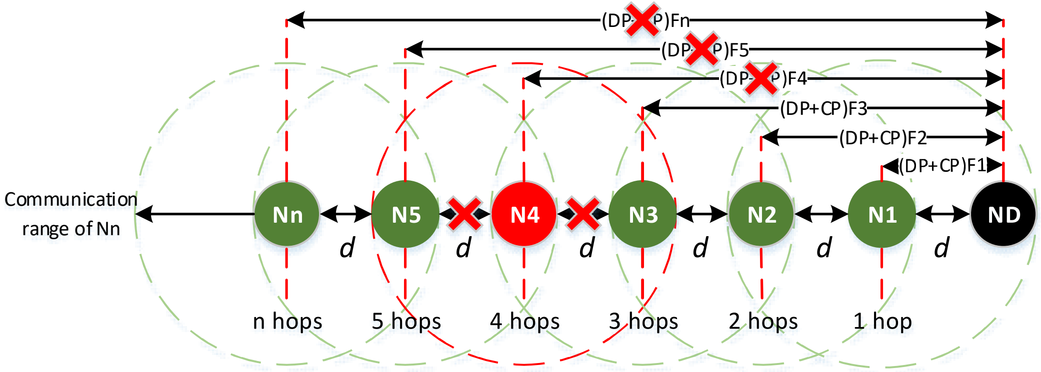


Figure 3-2: Route breakage in a multi-hop linear WSN

In a real life set-up, all nodes are considered as a sensing point which is likely to send data packets to a destination node simultaneously. In such a scenario, there are higher chances of data packet accumulation on a certain node in the network as shown in equation 3-1 which will build up and result in a bottleneck state [23, 28]. In accordance with IEEE 802.11 standard, there are a number of crucial factors which make the linear topology least popular compared to the other known topologies [18, 121]. Some of the crucial factors in WSN is the transmission range, carrier sensing range, queue size, transmission power, battery lifetime and bandwidth. Nevertheless, a multi-hop linear WSN is a useful topology in many circumstances where the geographical factor of the application matters the most. These factors could be manipulated by overwriting or with an improved routing algorithm to enhance its existing performance [95].

This chapter mainly focuses on two types of routing algorithm applied on a flat (one-tier) and a cluster-based (two-tier) topology. The Dual Interleaving Linear Static Routing (DI-LSR) [12] is a routing algorithm established for a flat multi-hop linear topology while the Dual Cluster Head Interleaving Linear Static Routing (DCHI-LSR) [96] is a routing algorithm established for a multi-hop linear cluster-based topology. Both routing algorithms are designed to accommodate an increasing amount of traffic in a multi-hop linear WSN with the possibilities to minimise passive nodes.

3.2 Routing Stability Factor in Linear Static Topology

The successfulness in sending a data packet from the originator (source node) to a receiver (destination node) in WSN depends on the optimum path generated by the routing protocol. Every routing protocol has its own characteristic and limitations which are known as routing factors against the measured performance metrics based on the type of topology it's been implemented [3, 57]. Routing factors in a WSN have a great impact towards the overall network performance and in most cases results in poor network life cycle in the long run making it unfeasible solution for a pipeline network. Understanding the root cause of this factors will help to identify methods to eliminate or minimise the effects of routing factors which is then incorporated in the proposed routing algorithm. In the following section, these factors and related parameters are defined with a feasible solution for the pipeline network.

3.2.1 Queuing Factor in WSN

In a large WSN, networks of queues among nodes are a common system where nodes will have a specific queue length to accommodate bi-directional packets passing in and out on a respective node at a specific time *t*. In a fraction of time *t+1*, the packets on a queue change it state based on the real-time status of a certain network and the type of routing protocols being implemented. Based on the queue length (*ifQlen*) in [34, 122], bi-directional packets on the queue will be controlled by a scheduling system known as first in first out [24, 78]. The bidirectional packets arriving at a respective node will be placed in the queue and will leave the node on a controlled sequence which is based on the implemented scheduling method. There are many research and methods of a queue is being deployed to accommodate and manage these bi-directional packets efficiently with minimum buffer time. In a WSN with high occupancy rate for example, in a linear topology with bi-directional packets arriving at maximum queue limit, can result in queue overflow and the respective packets will be dropped [23, 27]. Each dropped packets will then be regenerated based on the routing protocols implemented in the network. In general, a network with an efficient queue management system will reduce the unwanted dropped packets as well as reduce the queuing buffer time [28]. The queue factor is very crucial in a linear topology due to its amplified bi-directional packets travelling in a single multi-hop linear path from the source to the designated destination node especially in one sink point network (monitoring station for oil and gas pipelines) as shown in Figure 3-3. The amplified volume of data moving towards a single sink point (destination node ND) from respective source nodes will build up the queue length at maximum limit (*ifQlen*) especially for the nodes nearest to the destination node [26, 28]. This state can be also considered as a bottle neck points in a linear topology. As a result from this scenario, the data packets will be dropped which is considered a waste of available resources such as energy, time and the data packet which is the most important component in a certain application.

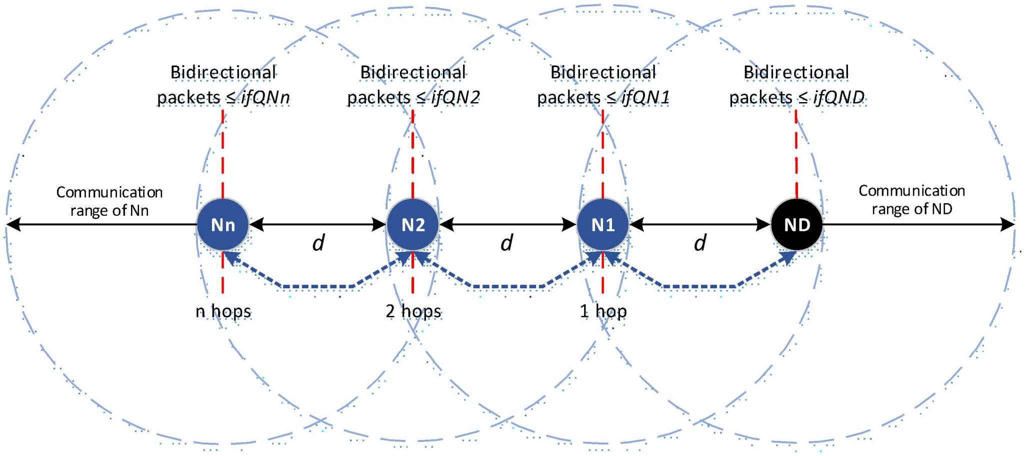


Figure 3-3: Bidirectional packets queue scheme in a linear WSN

3.2.2 Time to Live in WSN

The mechanism which dictates and limits the lifetime of a generated data packet from a certain node is called time to live (TTL). The TTL of a data packet which can also be described as hop limits discard a generated data packet once the hop limit or time span has elapsed [23, 60]. The core function of a TTL mechanism is an indicator which identifies the source node on the generated packet have been too long in the network and should be discarded. The TTL is initially set by the source node (sender) based on the characteristic of a routing protocol with a pre-calculated hop limit between a source and a destination node. The number of hops to the destination is usually indicated in the routing table where each node that receives the data packet will subtract the hop count by one to indicate the remaining hop limit to the next node in its path towards the destination node [12, 102]. The receiving node will forward the data packets to the next node if the remaining hop count is greater than zero, otherwise, the data packet will be discarded at that point. Once a data packet is discarded, a control message will be generated based on the transporting agent to a source node (sender) which will regenerate the data packet for the second time. The core function of a TTL or hop limit mechanism is to keep track of any data packets which are undeliverable to a destination node from circulating or clogging the network without a proper path. There are also possibilities for a route generation for creating and incorrect routing table which contributes to issues with the unknown path. This is a rare scenario in a static routing scheme as there no changes in node locations. In a routing table generation process, an optimum path will be identified at the source node or at the intermediate nodes based on the routing protocol used. A good routing protocol will generate an optimum path with exact hop limit between the source and a destination node to ensure an ideal time for the data packets to reach its destination node before it gets discarded. The default hop limit or hop limit with successively higher TTL value could result in a waste of network resources, especially on overall delay, delivery ratio and consumed energy.

3.2.3 Broadcast Packets

A broadcast packet is a mechanism that enables a WSN to efficiently share and update their data path among nodes in its communication range. Broadcast packets have a significant role in initializing a network by generating broadcast packets for network discovery process, identify a possible path to a destination node and as a query for a respective data packet in the network [21, 62]. In a large WSN, a broadcast packet is used as an efficient method for exchanging their local measurements with all the nodes in a certain network. The broadcast packets are generated at different time intervals based on the characteristic of routing protocols to maintain the network stability and connectivity among nodes. One of an established method of broadcasting is known as flooding where each and every node in the network will rebroadcast when the first broadcast packet is received for the first time. In a practical application, flooding is known as broadcast storm problem that creates serious broadcast redundancy, waste of bandwidth and packet collisions. Since broadcast packets are bi-directional and the methods of generating a broadcast packet are dependent on the characteristic of a routing protocol, the effects in a certain network will differ from one routing protocol to another [22, 38]. Broadcast packets in a highly dense WSN increase the routing overhead and network energy consumption especially in a linear topology which has to accommodate bi-directional packets in a single path. A routing protocol with an efficient technique for reducing broadcast packet redundancy increases bandwidth capacity and reduces energy wastage in a WSN.

3.3 Proposed Linear Static Routing

In a multi-hop linear topology, a routing protocol with one-tier or multi-tier approach can be implemented based on the scale and complexity of an application. There are two types of routing algorithm in the proposed multi-hop linear static routing that can be applied on a flat (one-tier) or a cluster-based (multi-tier) topology. The Dual Interleaving Linear Static Routing (DI-LSR) [12] is the proposed routing algorithm one with a dual interleaving technique in route generation between source nodes (multiple senders) to a single sink point (receiver) best implemented on a flat (one-tier) multi-hop linear topology. The Dual Cluster Head Interleaving Linear Static Routing (DCHI-LSR) [96] is the proposed routing algorithm two with a dual interleaving technique in route generation between cluster heads (leader node and intermediate nodes) to a destination node (receiver) best implemented on a cluster-based two-tier multi-hop linear topology.

3.4 Dual Interleaving Linear Static Routing

In the proposed Dual Interleaving Linear Static Routing (DI-LSR), a data packet from a source node (sender) is forwarded through predetermined intermediate nodes to a destination node (receiver). The dual interleaving routes are generated based on a predefined routing condition referring to the *odd* and *even* sequence of source nodes in the network. The DI-LSR is designed to complement the routing stability factor with high link reliability and to enhance overall network efficiency in a pipeline network. The DI-LSR is a passive routing algorithm where changes in the network conditions are not desired through its operation. An infrastructure based WSN requires only minimum or no changes in the route selection since most of the variable parameters which influence a routing protocol is in a static (fixed) state. The nodes in such a set-up are permanently located at a uniform interval subjected to the communication range of a wireless device with a constant power source. Based on these factors, the DI-LSR design has two major modifications made; (1) to accommodate the predefined routing path function and (2) to reduce network routing overhead. The most fundamental structure in DI-LSR is as shown in Figure 3-4, where two independent interleaving paths between each source nodes (On/En) are generated to a single destination node (ND).

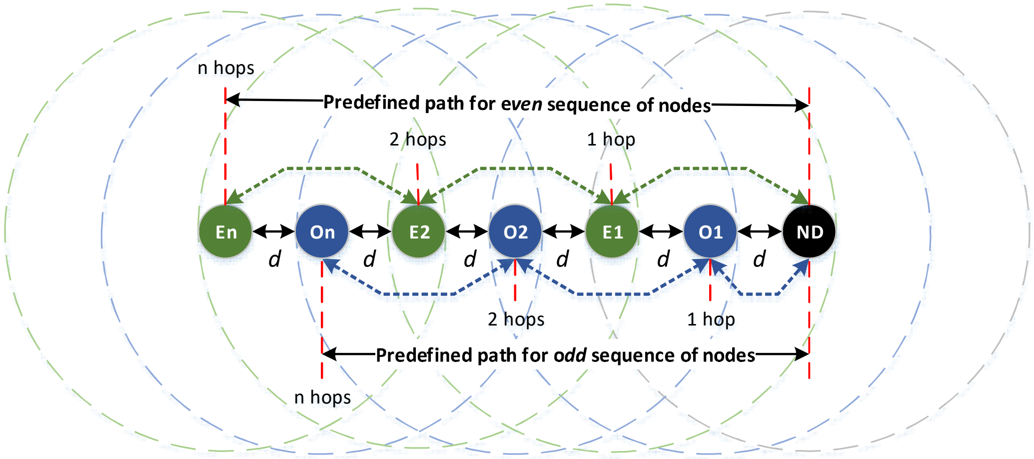


Figure 3-4: DI-LSR on a flat multi-hop linear topology

In a multi-hop linear topology, the overall network performance and link stability are often related to node placement particularly in a highly scattered network of nodes [123]. The major drawback on a highly scattered linear network of nodes is the effects of passive nodes. Passive nodes are described as source nodes with no opportunity to transmit data or with a delivery ratio of zero in a network [23, 28]. A network stability factor which relates to link connectivity and passive nodes between source and a destination node relies on the number active nodes in a specific communication range. Optimum placement of nodes and the proposed interleaving technique in a multi-hop linear topology would minimise the number of passive nodes in a WSN. Referring to Figure 3-4, the node placement in DI-LSR is uniformly distributed at *d* distance in meter within a maximum transmission range of *two d* for a pair of *odd* and *even* sequence of source nodes.

In general, a routing protocol generates or updates its routing table based on available nodes in a transmission range at the initializing period before the first data packet is sent [3, 124]. A routing table is generated at a first active period of time *t*, will then be constantly updated at time *t+1* as traffic demand increases at a specific node in the network. A common process for generating a routing table depends on a chain sequence of route updates between a source and a destination node which will be fully or partially stored in respective nodes.

3.4.1 Routing Table Generating Algorithm in DI-LSR

Unlike a standard practice of generating a routing table, at time *t*, DI-LSR generates two predefined routing table from a sequence of *odd* and *even* source nodes deployed in a network as shown in Figure 3-4. With the elimination of both broadcast and hello packets, the routing table for DI-LSR is generated based on an ideal network environment by assuming nodes that are always in a ready state. With the elimination of physical search for neighbouring nodes and route search, hence reduces buffer time in-between start to the first packet generated by a source node. The routing condition in DI-LSR permits *odd* and *even* sequence of source nodes to send and receive data packets along with the control packets only in a predefined path in the network. There is three essential information needed in generating a forward and a reverse path routing table in DI-LSR which is the number of nodes in the network, path direction for data communication and travel cost in hop count between a source to a destination node [12]. The predefined forward and reverse path routing table generating process in DI-LSR is as briefly described in the pseudocode of Figure 3-5.

Algorithm 1: Forward and reverse path routing table

Suppose number of nodes is "nn", *odd* sequence of nodes is "O_n", *even* sequence of nodes is "E_n" and destination node is "ND = 0"

At time t:

```
1: IF nn%2 == 0 then: Forward path routing table 2 (for even sequence of nodes)
    else: Forward path routing table 1 (for odd sequence of nodes)
2: For nn then: Reverse path routing table (for odd and even sequence of nodes)
3: For $O_n/E_n-2\geq0$ then: Neighbour node/nodes at forward path
    else IF $O_n-1=0$ then: Neighbour node at forward path
4: For $O_n/E_n+2\leq nn$ then: Neighbour node/nodes at reverse path
5: For $(O_n+1)/2$ then: Required hop/hops to destination node for forward/reverse path (odd)
6: For $E_n/2$ then: Required hop/hops to destination node for forward/reverse path (even)
7: At time t+1: Source nodes $O_n/E_n$ start sending data packets to ND
8: At time t+n: ND start sending TCP acknowledgement packets to $O_n/E_n$
```

Figure 3-5: Routing table generating process in DI-LSR

The step by step process involves *odd* and *even* sequence of source nodes segregation, data flow direction and hop count between respective source nodes to a destination node. The segregation of *odd* and *even* sequence of nodes in respective forward routing table entries is created based on the total number of nodes in a network. Once the segregation process is established, nodes are only allowed to communicate with the selected nodes in the routing table. Once the routing table entries for *odd* and *even* sequence of source nodes are created, forward (to a destination node) and reverse (to all source nodes) path is predefined with available nodes in the respective routing table. In a forward path routing table, a respective node holds the needed entries of other source nodes based on the segregation process to a designated destination node. The forward and the reverse path routing table in DI-LSR is as briefly described in Figure 3-6 and Figure 3-7 respectively.

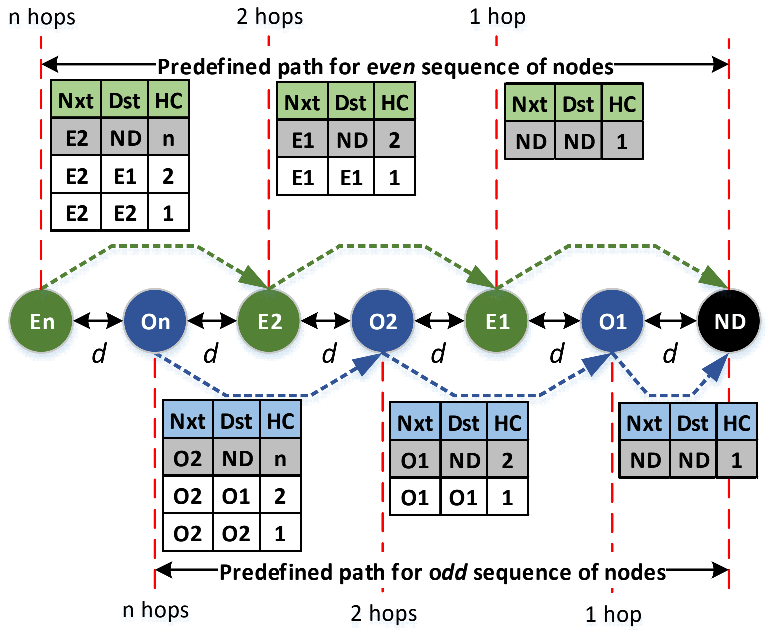


Figure 3-6: Forward path routing table in DI-LSR

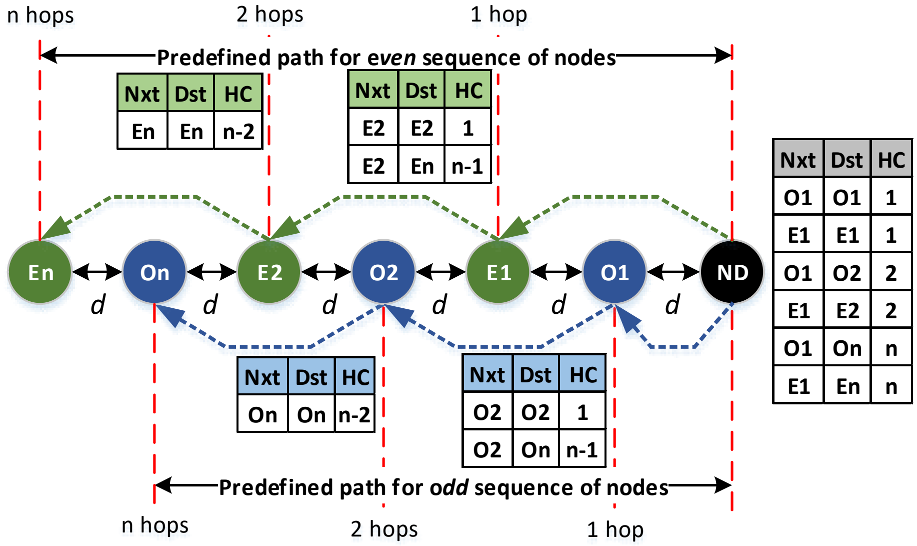


Figure 3-7: Reverse path routing table in DI-LSR

In a reverse path routing table, the destination node holds the entries of all source nodes and a respective node holds the needed entries of other source nodes in the network with predefined sequence from the segregation process. The distance from a respective source node location to a destination node is calculated in terms of packet travel cost in hop count. In DI-LSR, the hop count is always maintained at minimum travel cost between a source and a destination node in order to optimise the network resources wisely.

3.4.2 Source Node Routing Flows in DI-LSR

In a large wireless network, queue restriction on nodes is a standard mechanism which is used in controlling and managing bi-directional flowing packets. A queue restriction has a crucial factor in reducing passive nodes and bottleneck points in a single path wireless network. With the queue restriction [122], there will be increasing rate on packet dropped especially when the route is not identified to a designated node as in a conventional routing protocol. With the implementation of DI-LSR, this factors can be reduced and further increases the data packet transfer rate with the proposed dual path method. A default queue limit [34, 103] at 50 packets is set at each intermediate nodes in both paths as described in the flow chart of Figure 3-8. Any data packets arriving at an intermediate (neighbouring) node with queue length > $IfQlen_{On}$ or $IfQlen_{En}$ will be dropped from moving forward towards the destination node. This state is known as queue overflow where the dropped packets will result in an unwanted waste of network resources especially the energy consumed from packet generation till packet dropped. Generally, a queue overflow is due to overwhelming of control packets which include broadcast and hello packets depending on the characteristic of a routing protocol. The elimination of both broadcast and hello packets in DI-LSR creates less traffic, thus packet drops can be reduced compared to a routing protocol which relies on this packets to generate and maintain a routing table. Referring to the flowchart in Figure 3-8, a generated data packet from a sensing point will be forwarded from a source node to the designated destination node through a predefined sequence of intermediate nodes based on the routing table entries.

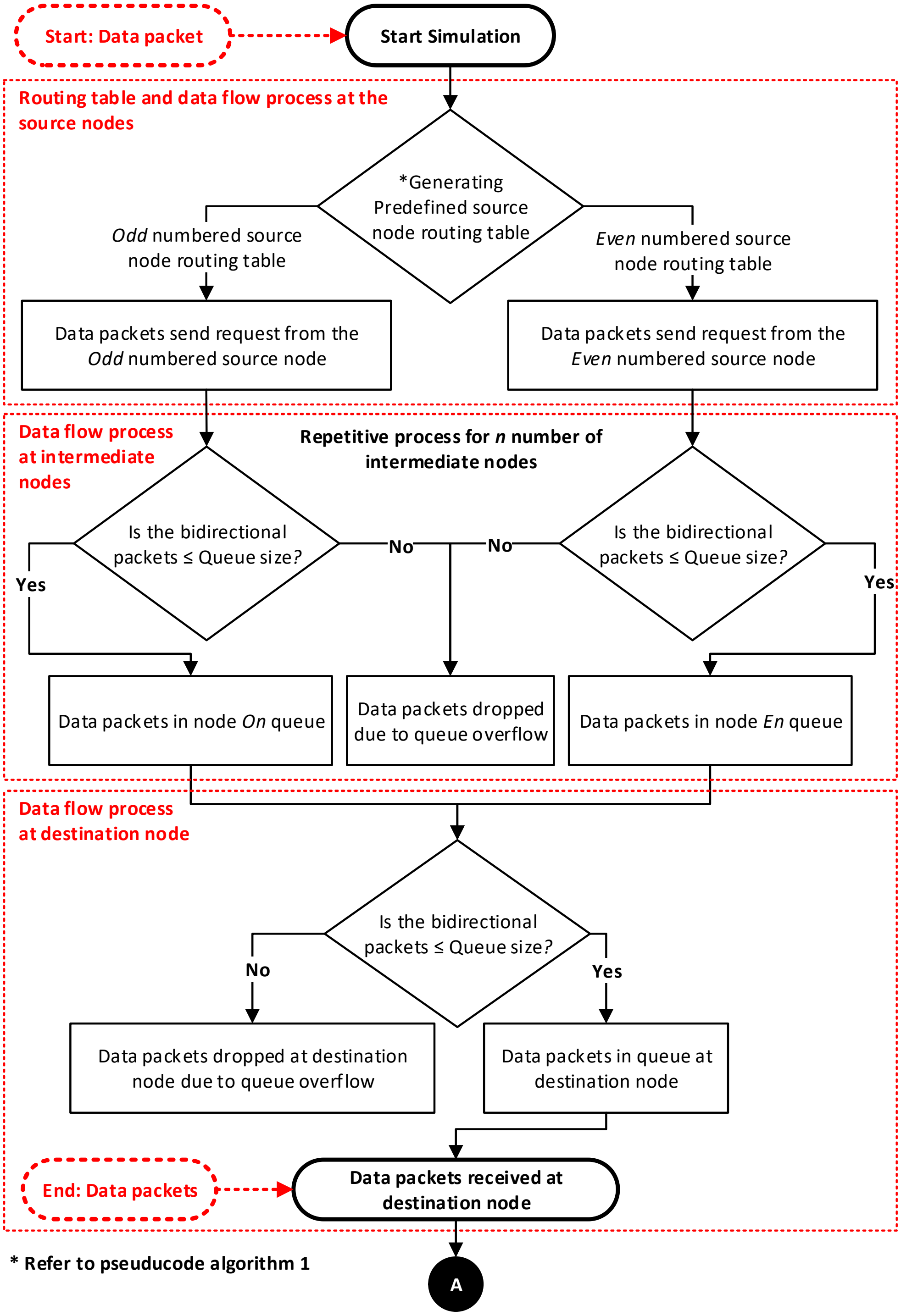


Figure 3-8: Flow chart for data packet cycle in DI-LSR

Distributing traffic in two paths further reduces the routing overhead by half, therefore allocates a better proportion of data packets compared to any conventional single-path routing protocol. Data transfer accumulation factor for both paths can be described respectively in equation 3-2 and 3-3 between a source and intermediate nodes towards a destination node.

$$TPO = \left[(DPO_i + CPO_i) + \sum_{j=i+1}^{nn}(DPO_j + CPO_j)\right] \leq IfQlenO_n \qquad \textbf{3-2}$$

Where *TPO* is the total packets for *nn* number of nodes (*odd*), DPO_i is the total data packets and CPO_i is the total control packets at node *i* with $1 \leq i \leq nn$. While DPO_j is the total data packets at neighbouring node *j*, CPO_j is the total control packets at neighbouring node *j* and $IfQlenO_n$ as the queue length in the network.

$$TPE = \left[(DPE_i + CPE_i) + \sum_{j=i+1}^{nn}(DPE_j + CPE_j)\right] \leq IfQlenE_n \qquad \textbf{3-3}$$

Where *TPE* is the total packets for *nn* number of nodes (*even*), DPE_i is the total data packets and CPE_i is the total control packets at node *i* with $1 \leq i \leq nn$. While DPE_j is the total data packets at neighbouring node *j*, CPE_j is the total control packets at neighbouring node *j* and $IfQlenE_n$ as the queue length in the network.

A destination node is placed at end of each interleaving route with an integration point as indicated in the flow chart of Figure 3-8. The successful data packets accumulation factor at the destination node (receiver) from both routes is as described in equation 3-4. Any incoming data packets at the destination node with queue length > *IfQlen* will be dropped [103].

$$NTP = TPO + TPE \leq IfQ \qquad \textbf{3-4}$$

Where *NTP* is the network total packets at the destination, the value of *TPO* is from equation 3-2 and the value of *TPE* is from equation 3-3.

3.4.3 Destination Node Routing Flows in DI-LSR

A destination node routing table holds entries of all source nodes deployed in a network based on two predefined reverse paths. At time *t*, DI-LSR generates a reverse path routing table in which will be used by control packets to reach a designated source node. Once a data packet has successfully reached the destination node, a TCP acknowledgement packet will be generated in return to acknowledge the respective source node (sender) [79]. Unlike the forward route as described in Figure 3-8, the reverse path routing table has the entire list of both *odd* and *even* sequence of source nodes. The predefined reverse path routing table generating process in DI-LSR is as briefly described in the pseudocode of Figure 3-5. The hop count is always retained at minimum travel cost between a destination to a respective source node in order to optimise the network resource wisely. The reverse path hop count is based on the same hop count in a forward path between two respective nodes in the network [12]. At time *t+2*, a generated TCP acknowledgement packet is forwarded on a predefined return path to a designated source node with a default queue limit [122] set at each intermediate nodes in both paths as described in the flow chart in Figure 3-8. Since the routing path is predefined with no changes is expected during the node active period, no aggressive broadcast packets are required to maintain neither the routing table nor the routing path in DI-LSR.

3.5 Performance Evaluation on Flat One-tier Linear Topology

The overall network performance was simulated in Network Simulator 2 version 2.35 (NS2) [34, 125] to visualise the behaviour and impending factors when full deployment of DI-LSR in a pipeline network. The DI-LSR was implemented on NS2 where detail analysis on various wireless performance metrics was compared with other routing protocols such as AODV, DSDV and FRP. The proposed DI-LSR were compared with AODV a reactive routing protocol, DSDV a proactive routing protocol [22, 62] and FRP a manual routing algorithm [64, 65] for performance comparison purposes. All the simulated results are from an average value of five runs per cycle on the manipulating variable (*nn* number of source nodes) with different seed values in between 1 to 10 over a simulation duration of 500 seconds. In a flat one-tier topology, the number of source nodes in each cycle was uniformly increased by 12 nodes starting from 12 to 120 source nodes. A data rate of one packet/sec with a packet size given in Table 3-1 were assigned with a random start function to all source nodes in the network. To replicate a real-time application, the start time and start sequence of a source node are generated using a custom random function in the simulator. The start time for a source node is generated randomly between 0 – 2 seconds with non-sequential starting nodes. All nodes indicated in the results were stationary for the entire simulation duration with one destination node (ND). The configuration and key simulation parameters employed in NS2 in simulating the effects on varying source nodes density is as tabulated in Table 3-1.

Table 3-1: NS2 simulation parameters for flat topology

Key parameters	Set value
Channel type	Wireless channel
Radio propagation model	Two Ray Ground
MAC type	802.11
Interface queue type (ifq)	Drop Tail/PriQueue
Source nodes (SN)	12, 24, 36, 48, 60, 72, 84, 96, 108, 120
Destination node (ND)	1
Queue length (ifqlen)	50 (packets)
Agent type	Transmission control protocol (TCP)
Traffic type	Constant bit rate (CBR)
Transmission range (RX Thresh)	100 meter
Sensing range (CS Thresh)	125 meter
Packet size	512 bytes

3.6 Performance Metrics on Flat One-tier Linear Topology

To test and evaluate the proposed algorithm, a number of varying scenarios were created in the simulation tool. The performance characteristic of the proposed algorithm can be visualised on the following wireless performance metrics:

3.6.1 Packet Delivery Ratio

In any wireless network, the delivery ratio is a crucial parameter measured which indicates a percentage of successfully received data packets over send data packets in the network [22, 34, 62] as described in equation 3-5.

$$Delivery\ Ratio = \frac{\sum_{i=1}^{nn}\left(\frac{RP_i}{SP_i}\right)\times 100\%}{nn} \quad \textbf{3-5}$$

Where *RPi* is the total received data packets for *nn* number of source nodes and *SPi* is the total send data packets for *nn* number of source nodes.

3.6.2 End-to-end Delay

End-to-end delay is an average value of the total time taken to transmit data packets from a source node (sender) to a destination node (receiver) in the network [22, 34] as described in equation 3-6 (10). Data packets which are dropped or lost in route becomes invalid during calculation.

$$Delay \quad \frac{\sum_{i=1}^{nn}(En \quad t_i - Start\ t_i/RP_i)}{nn} \quad \textbf{3-6}$$

Where *End* t_i – *Start* t_i is the total *Δ of Duration* t_i for *nn* number of source nodes and *RPi* is the total received packets for *nn* number of source nodes.

3.6.3 Throughput

Throughput is the total received data (data packets) at a destination node in per unit time usually measured in bits/sec. Throughput is an important parameter where the goal of a network is to achieve higher throughput with the available network resources. The average throughput over all flows in the network is calculated as in [34, 126] equation 3-7.

$$Throughpu \quad = \frac{\sum_{i=1}^{nn}\left({}^{(Pkt\ size \times 8 \times RP_i)}\big/_{(End\ t_i - Start\ t_i)}\right)}{nn} \quad \textbf{3-7}$$

Where *Pkt size* is as defined in the simulation parameter, *RPi* is the total received packets for *nn* number of source nodes and *End* t_i – *Start* t_i is the total *Δ of Duration* t_i for the entire simulation duration.

3.6.4 Throughput Fairness Index

In a linear topology, fairness or equality within a network is a crucial factor in terms of network stability. The Jain's fairness index as described in equation 3-8 where an optimum index value of one is the desired value for a non-zero and fairest data allocation among the source nodes in the network [23, 29, 127].

$$Fairness\ index = \frac{\left(\sum_{i=1}^{n} n_i\right)^2}{nn \sum_{i=1}^{n} {n_i}^2} \qquad \textbf{3-8}$$

Where n_i is the throughput for n number of flows and nn is the number of source nodes in the network.

3.6.5 Received Data Packet Variation

The variation of received data packets is the measurement difference between a maximum and a minimum number of received data packets from source nodes in a network as described in equation 3-9 [12].

$$Pkt\ variation \quad \frac{(Max\ pkt - Min\ pkt)}{Max\ pkt} \times 100\% \qquad \textbf{3-9}$$

Where *Max pkt* is the maximum number of received data packets recorded and *Min pkt* is the minimum number of received data packets recorded for a certain number of source nodes in the network.

3.6.6 Passive Source Nodes

Passive source nodes or nodes without successful opportunity to transmit data packets to the destination node are undesirable in a multi-hop linear topology. The passive source nodes can be calculated as in equation 3-10 [12].

$$Passive\ source\ node \quad \frac{PSN}{nn} \times 100\% \qquad \textbf{3-10}$$

Where *PSN* is the number of passive nodes for *nn* number of source nodes in the network.

3.6.7 Normalized Routing Load

The normalised routing load can be defined as the total number of routing packets over a received data packet at a destination node as described in equation 3-11. The high value of normalised routing load corresponds to higher network usage or cost of network resources that is not a desirable aspect in a WSN [128, 129].

$$Normalized\ routing\ load = \frac{Total\ routing\ pkt}{RP} \qquad \textbf{3-11}$$

Where *Total routing pkt* is the number of supporting packets used to send and receive data packets and *RP* is the total received data packet in a network.

3.6.8 Energy Consumption

Energy consumption in a network can be defined as the total used energy over total received data packets in the network as described in equation 3-12.

$$Energy\ perpacket \quad \frac{Total\ consumed\ energy}{RP} \qquad \textbf{3-12}$$

Where *Total consumed energy* is the total used energy by all nodes and *RP* is the total received a data packet in the network.

3.7 Simulation Results and Discussion for Flat One-tier Linear Topology

The overall network performance of DI-LSR is compared with the traditional AODV, DSDV and FRP for flat one-tier topology in terms of the performance metrics in section 3.5.

3.7.1 Packet Delivery Ratio vs. Number of Source nodes

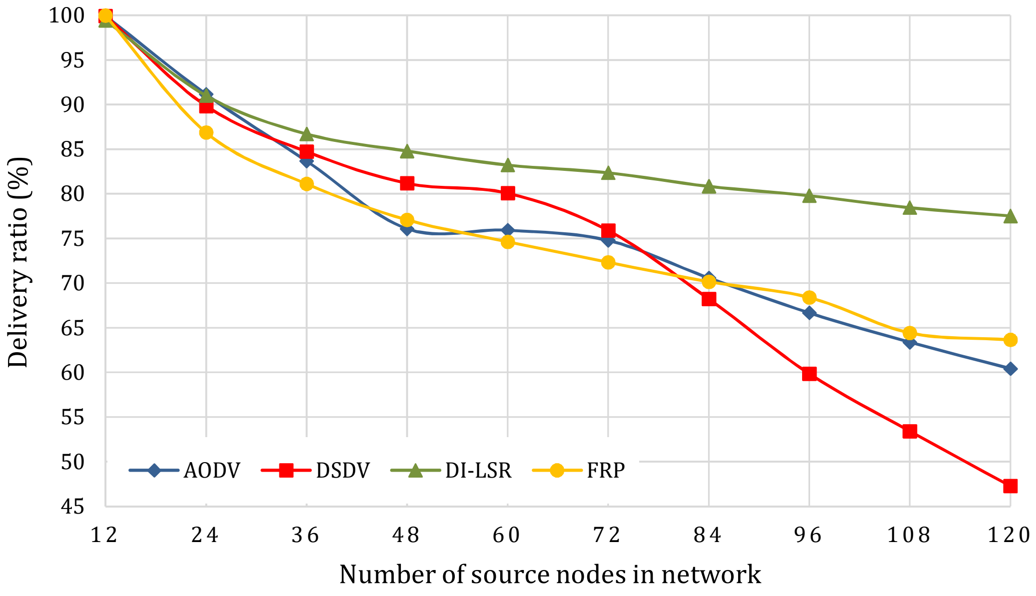


Figure 3-9: Packet delivery ratio vs. number of source nodes

The effect of varying number of source nodes on the delivery ratio is as shown in Figure 3-9. Generally, the delivery ratio is inverse proportional to the increasing number of source nodes for all compared routing protocols. It is observed that at low network density with 12 source nodes, the delivery ratio is almost at the same rate among all compared routing protocols. The delivery ratio of DI-LSR outperforms all the other routing protocol between a low network density with 12 source nodes to a larger network density with 120 source nodes. There is a significant difference in delivery ratio between 5% - 14% better than FRP, 3% - 17% better than AODV and 2% - 30% better than DSDV at varying simulation environment compared to DI-LSR. The effect of reduced control packets particularly with broadcast packets enables better allocation of data packets transfer rate hence improves the delivery ratio in DI-LSR in all varying stages. Another possible factor in achieving higher delivery ratio is based on a predefined dual routing path where the generated data packets are transferred to the destination node remains constant at all time.

3.7.2 End-to-end Delay vs. Number of Source nodes

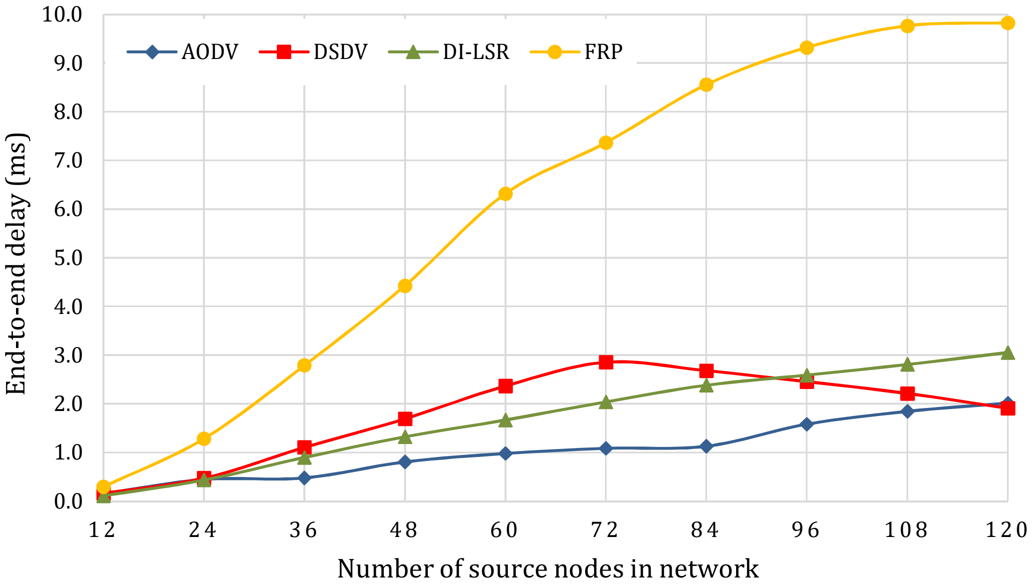


Figure 3-10: End-to-end delay vs. number of source nodes

The results comparison on average end-to-end delay for varying number of source nodes is as shown in Figure 3-10, which indicates DI-LSR has a consistent increase in delay proportional to the increasing network density with 12 source nodes to a larger network density with 120 source nodes. Generally, with the higher data rate at the destination node increases the overall delay in any network particularly in a multi-hop linear topology since the position of each source node is in a respective distance from a destination node. The delay factor in DI-LSR is fairly low compared to the moderate fairness and higher data rate achieved compared to the other routing protocols. In a multi-hop linear topology, the delay factor varies from the distance between a source and a destination node. Using a predefined dual interleaving path, DI-LSR is capable of forwarding higher data in a more efficient manner compared to a single path multi-hop method.

3.7.3 Throughput vs. Number of Source nodes

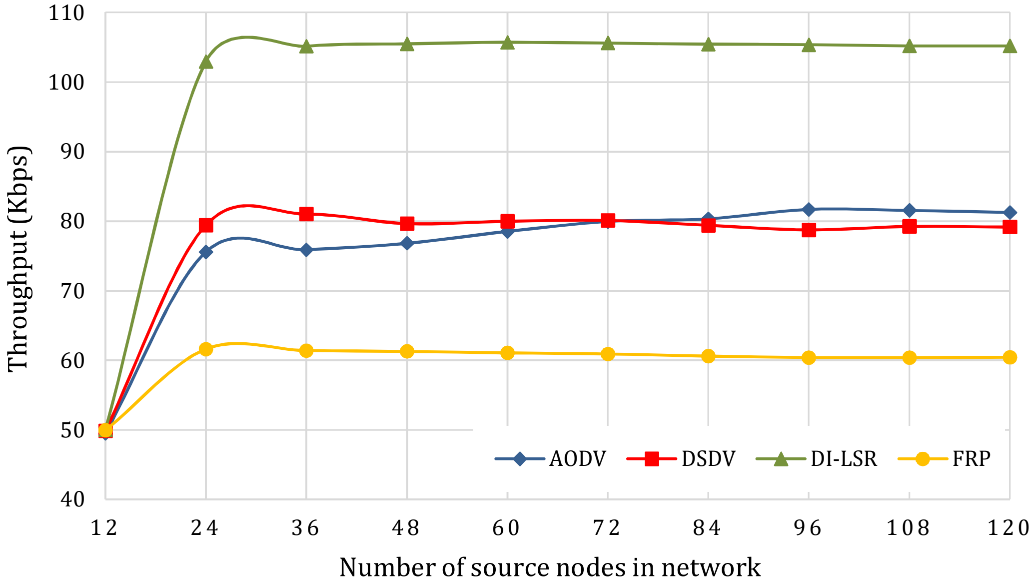


Figure 3-11: Throughput vs. number of source nodes

The effect of varying number of source nodes increases the throughput in the network for all compared routing protocols as shown in Figure 3-11. The throughput achieved by a network with the implementation of DI-LSR outperforms all other routing protocols between a low network density with 12 source nodes to a larger network density with 120 source nodes. The DI-LSR has demonstrated a significant difference in throughput between 20 Kbps – 61 Kbps particularly after 24 source nodes and above as compared with the other routing protocols. Higher throughput in DI-LSR is a result of the better proportion of data packets transfer rate in all varying stages using the predefined dual interleaving path to a destination node.

3.7.4 Throughput Fairness Index vs. Number of Source nodes

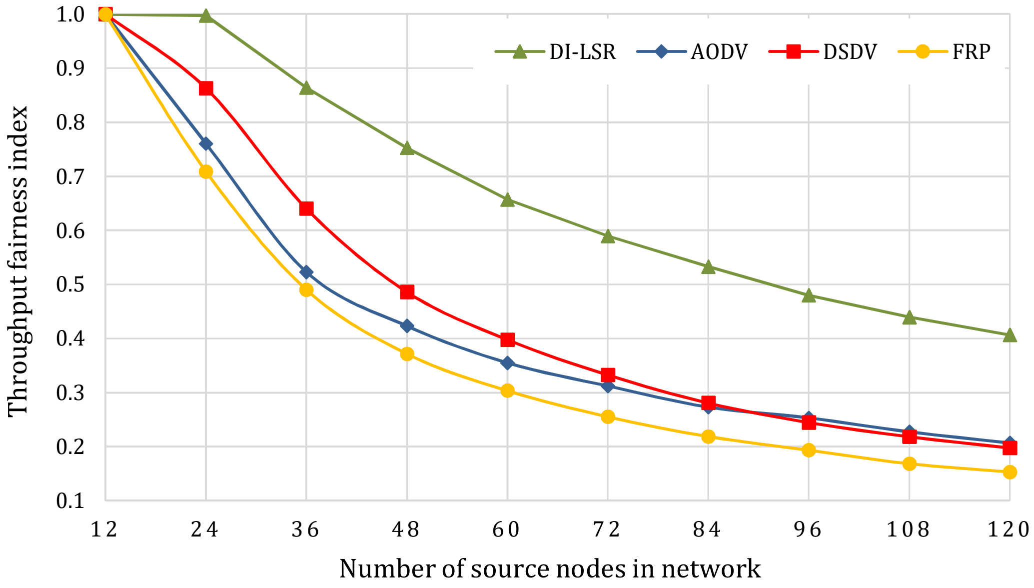


Figure 3-12: Throughput fairness index vs. number of source nodes

Achieving a fair throughput among source nodes in a multi-hop linear wireless network is a challenging task with any routing algorithm. Referring to Figure 3-12, the throughput fairness index of DI-LSR outperforms all the other routing protocol with a significant difference in fairness index that is clearly visible in a range of 0.13 to 0.25 between a low network density with 12 source nodes to a larger network density with 120 source nodes. In a low network density with 12 nodes, fairness is hardly visible since the performance of all routing algorithms is fairly similar. The higher rate of throughput fairness is comparatively achievable with throughput equality in a multi-hop linear network the proposed DI-LSR.

3.7.5 Received Data Packet Variation vs. Number of Source nodes

Variation of received data packets is another parameter in visualising fairness between source nodes in a network. Referring to Figure 3-13, the percentage of received data packet variation of DI-LSR outperforms all the other routing protocol with a significant difference between a low network density with 12 source nodes to a larger network density with 120 source nodes. The difference becomes greater with the varying number of source nodes in a network for all compared routing protocols.

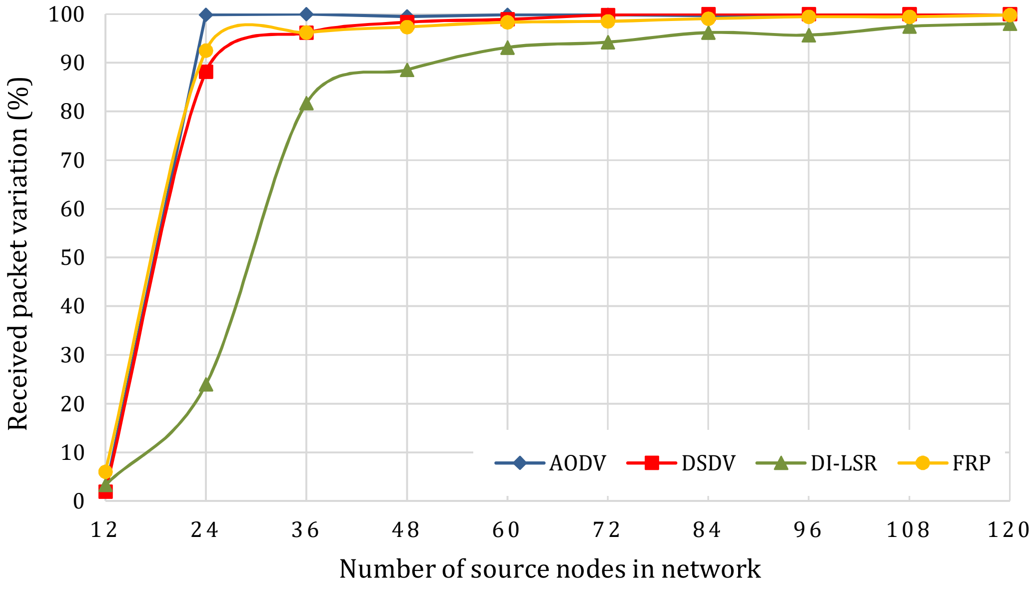


Figure 3-13: Received packet variation vs. number of source nodes

3.7.6 Passive Source Nodes vs. Number of Source nodes

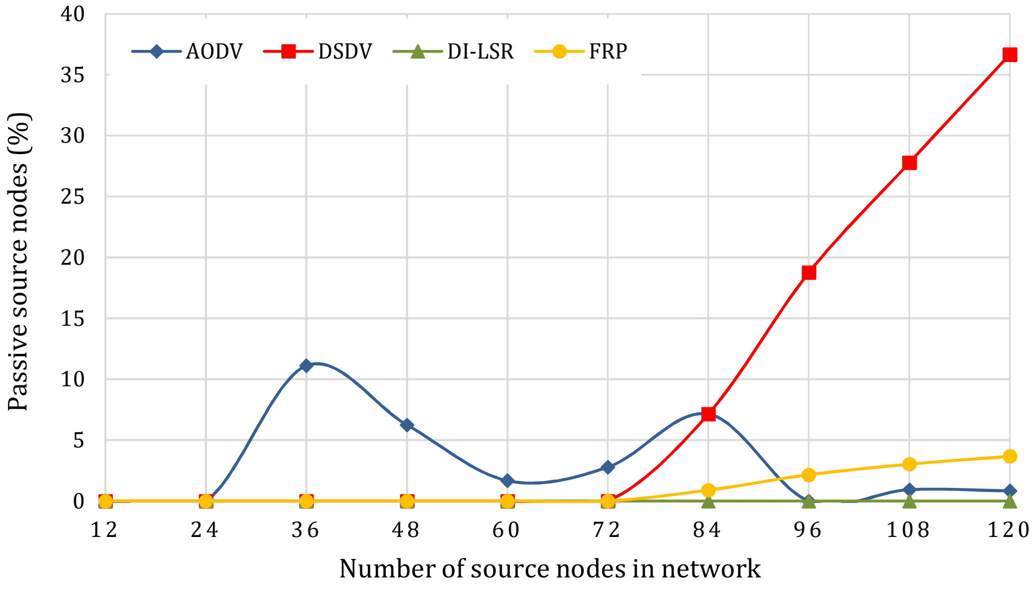


Figure 3-14: Passive source nodes vs. number of source nodes

The effect of a passive node in network reflects on the fairness index as well as the network performance in a multi-hop linear wireless network. The effect of varying number of source nodes on the passive source nodes is as shown in Figure 3-14. With the implementation of DI-LSR, zero passive nodes were achieved between a low network density with 12 source nodes to a larger network density with 120 source nodes. This is only achievable in DI-LSR since the better proportion of data packets transfer rate in a predefined dual interleaving path with low control packets. Where else the other routing protocols contribute towards passive nodes with a varying number of source nodes in a network.

3.7.7 Normalised Routing Load vs. Number of Source nodes

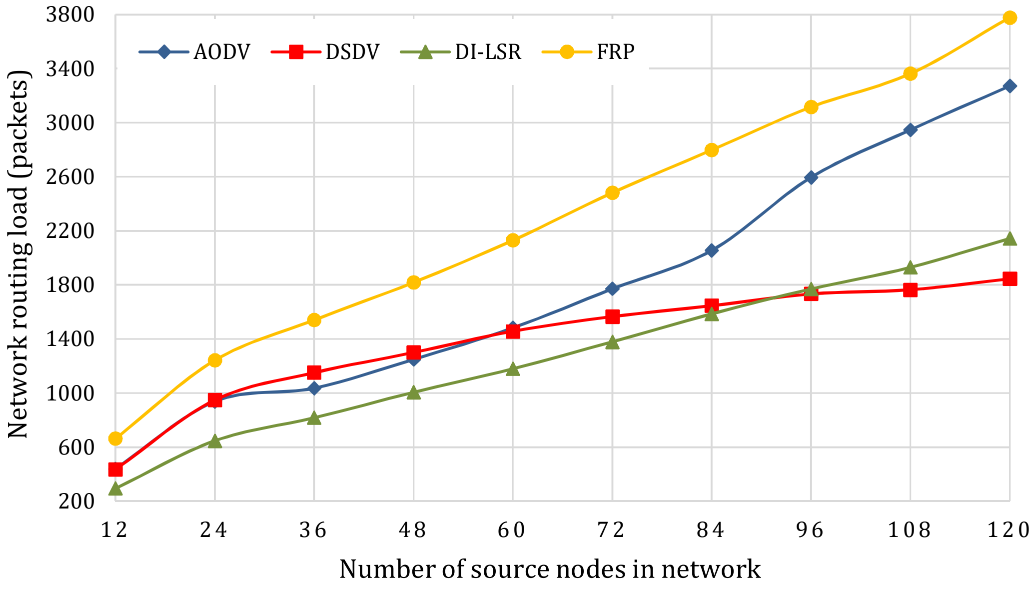


Figure 3-15: Network routing load vs. number of source nodes

The effect of varying number of source nodes increases the routing overhead in the network for all compared routing protocols as shown in Figure 3-15. The routing overhead in a network with the implementation of DI-LSR is relatively lower when compared in terms of received data packets among the other routing protocols between a low network density with 12 source nodes to a larger network density with 120 source nodes. With reduced control packets particularly with broadcast packets reduce the traffic of supporting packets in a network especially with increasing number of source nodes in a network.

3.7.8 Energy Consumption vs. Number of Source nodes

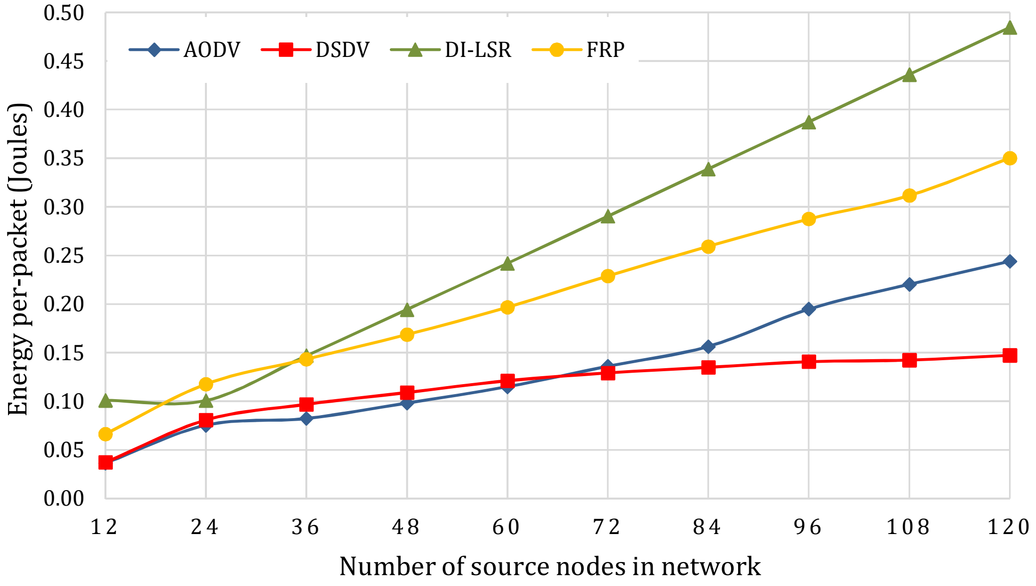


Figure 3-16: Energy per-packet vs. number of source nodes

The energy consumption per-packet effect on varying number of source nodes is as shown in

Figure 3-16, which indicates DI-LSR has a consistent increase in energy to the network size. The energy consumption per-packet increasing factor in DI-LSR is due to the amplification of data packet at each varying simulation environment. Based on the number of data packets received, DI-LSR has a fair use of energy compared to all the other routing protocol from a low network density with 12 source nodes to a larger network density with 120 source nodes. Where else the other routing protocols consumed higher energy per-packet with relatively low data rate and throughput unfairness as compared to DI-LSR in the tested environment due to higher routing load. Energy efficient routing protocol ensures a sustainability factor in a typical linear wireless network, particularly when the nodes are battery power dependent.

3.8 Dual Cluster Head Interleaving Linear Static Routing

As a complementing routing technique to the DI-LSR and a flat one-tier topology, the Dual Cluster Head Interleaving Linear Static Routing (DCHI-LSR) is designed to be implemented on a cluster-based architecture with high communication link reliability to enhance the overall network efficiency in a pipeline network [96]. A data packet in DCHI-LSR is transferred from a source node (sender) to a single destination node (receiver) through predetermined intermediate cluster heads in a network. The dual interleaving path is generated based on a predefined routing condition referring to *odd* and *even* sequence of cluster heads in a multi-hop linear network. Wireless nodes are statically positioned in a fixed infrastructure of an oil and gas pipeline to form a communication chain between a sensing point and a monitoring station [4, 15]. Unlike a flat one-tier topology, the DCHI-LSR is a reliable and efficient routing algorithm, where a route to a destination node is predefined over a cluster-based two-tier topology at simulation initialization period. The routes between all source nodes (sender) to a single destination node (centralised monitoring station) are predefined based on *odd* and *even* sequence of cluster head with two interleaving paths [96]. Cluster heads in DCHI-LSR are uniformly distributed at a *d1* distance within a maximum transmission range of two *d1* in a multi-hop linear architecture with *n* number of sensing nodes uniformly distributed at *d* distance under respective cluster head. The fundamental structure of DCHI-LSR is as shown in Figure 3-17, where sensing nodes are placed under respective cluster head which communicates data on two independent interleaving paths between cluster heads (On/En) to a destination node (ND).

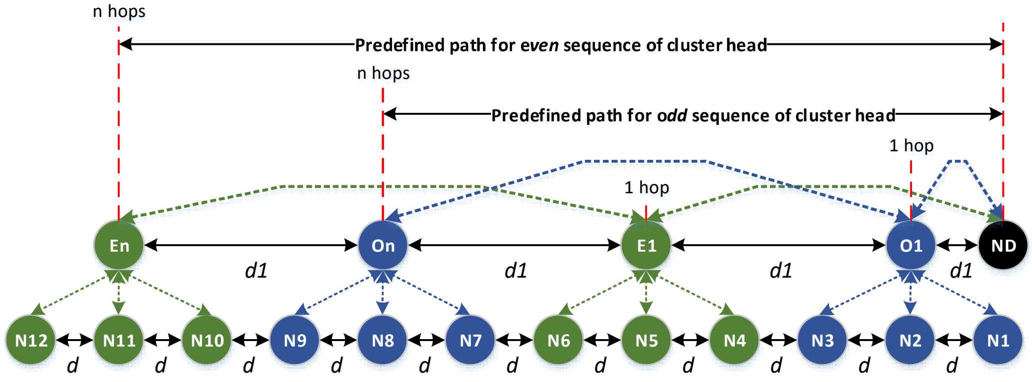


Figure 3-17: DCHI-LSR on a cluster-based multi-hop linear topology

The deployed sensors on a pipeline network, communicate data through a dedicated cluster head and over multiple-hop intermediate cluster heads in a uniform interval (distance in meter). The DCHI-LSR can be described as a passive routing algorithm where changes in the network conditions are not desired throughout its operation. An infrastructure or static (fixed) based WSN requires only minimum or no changes in the route selection since most of the variable parameters which influence a routing protocol is at low active state [37, 96, 130]. The sensing nodes and cluster heads in such a set-up are permanently located at a uniform interval subjected to the range of a wireless communication device with a constant power source. Based on these factors, the design of DCHI-LSR has two major modifications made as in DI-LSR to accommodate the predefined routing path function and to reduced network routing overhead particularly with increasing number of nodes in a cluster architecture [96] as compared to any conventional routing protocols [e.g. LEACH] [41, 69].

Node placement in a multi-hop linear cluster-based topology often influences the behaviour of a WSN particularly on link stability issues between a source and a destination node [119, 131]. Link instability results in increasing passive nodes (nodes with zero data transfer) therefore data transfer from that point onwards will be terminated. As a result, the overall network performance is compromised particularly in a highly scattered multi-hop linear network of nodes. Passive nodes are described as source nodes with no opportunity to transmit data or with a zero delivery ratio at a specific node in a network. A network stability factor which relates to link connectivity and passive nodes between source to a destination node relies on the number active nodes in a specific communication range. Thus, optimum placement of source nodes under respective cluster head further improves the sensing capacity or coverage area without influencing the main data stream towards a destination node. In DCHI-LSR, a cluster head is the main data stream to a designated destination node unlike in a flat one-tier topology sensing and data stream takes place on the same node. With the proposed interleaving technique among cluster heads in a multi-hop linear topology would minimize the number of passive nodes in a large WSN [96]. 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 multi-hop linear topology, a routing table is fully or partially stored in respective nodes between a sender and a destination node through a single routing chain build with a sequence of nodes in a network.

3.8.1 Routing Table Generating Algorithm in DCHI-LSR

The broadcast and hello packets function is eliminated in DCHI-LSR, therefore the need in physical search for neighbouring nodes for optimum route search is not required. The routing table for DCHI-LSR is generated based on an ideal network environment with nodes are always in a ready state hence reduces buffer time in-between start to the first packet generated in a network. The routing table in DCHI-LSR is generated at time *t* with two predefined routing table from a sequence of *odd* and *even* cluster heads with *nn* number of source nodes deployed in a network as shown in Figure 3-18. DCHI-LSR permits source nodes to send and receive data packets along with the control packets only through a predefined sequence of *odd* and *even* cluster head in a network. There is four essential information needed in generating a forward and reverse path routing table in DCHI-LSR which is the number of cluster heads and source nodes in the network, path direction for data communication and travel cost in hop count between source to a destination node. The detailed routing process involves *odd* and *even* sequence of cluster head segregation, allocating *nn* number of source nodes for a respective cluster head, the direction of data travel path and required hop count between respective source nodes to the destination node. The predefined forward and reverse the path routing table generating process in DCHI-LSR is as briefly described in the pseudocode of Figure 3-18.

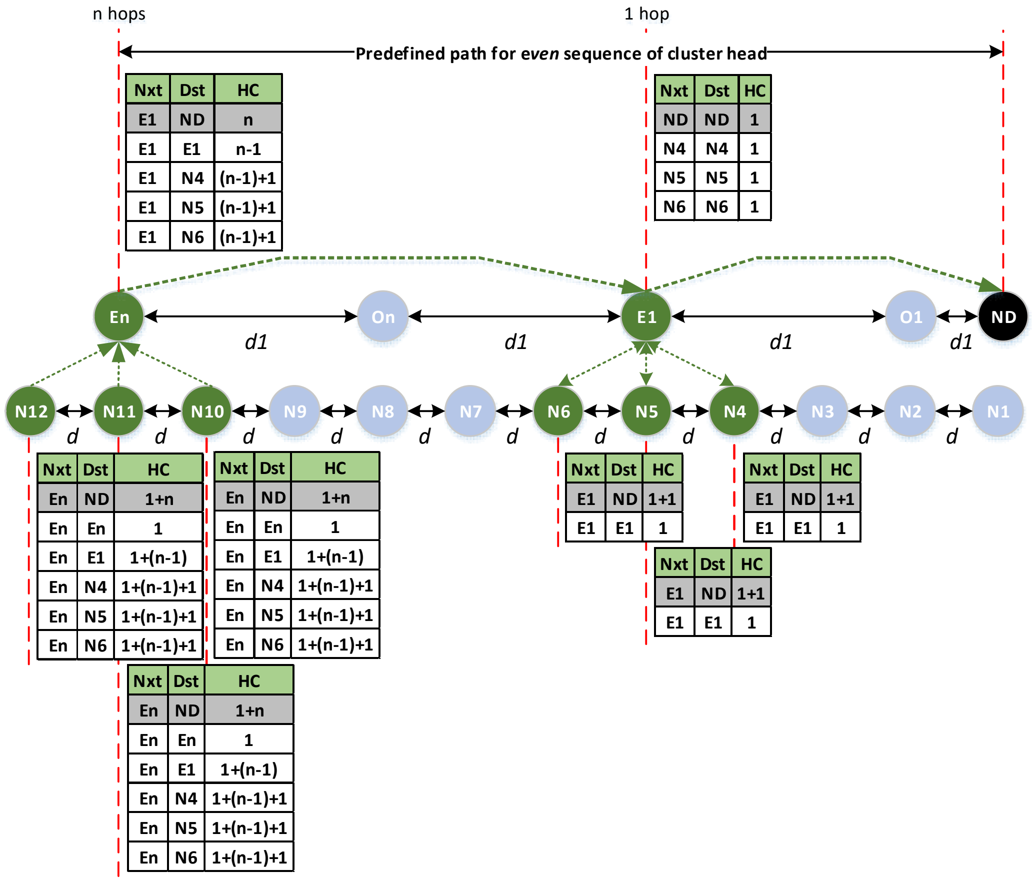
Algorithm 2: Forward and reverse path routing table

```
Suppose number of source nodes is "nn", number of cluster head is "ch", odd sequence of cluster head is "$CHO_n$", even sequence of cluster head is "$CHE_n$" and destination node is "ND = 0"

At time t:

1: IF ch%2 == 0 then: Forward path routing table 2 (for even sequence of cluster head)
```

```
   else: Forward path routing table 1 (for odd sequence of cluster head)
2: For nn then: Respective source nodes are assigned to forward path routing
       table 1 and table 2
3: For ch and nn then: Reverse path routing table (to respective source nodes
       based on odd and even sequence of cluster head)
4: For $CHO_n/CHE_n-2\geq0$ then: Neighbour cluster head at forward path
   else IF $CHO_n-1=0$ then: Neighbour cluster head at the forward path
5: For $CHO_n/CHE_n+2\leq nn$ then: Neighbour cluster head at reverse path
6: For $((CHO_n+1)/2)+1$ then: Required hop/hops to destination node for
       forward/reverse path (odd)
7: For $(CHE_n/2)+1$ then: Required hop/hops to destination node for
       forward/reverse path (even)
8: At time t+1: Source nodes nn start sending data packets to ND
9: At time t+n: ND start sending TCP acknowledgement packets to source nodes
       nn
```

Figure 3-18: Routing table generating process in DCHI-LSR

The segregation of *odd* and *even* sequence of cluster heads in a respective forward path routing table entries is created based on the *ch* number of cluster head in a network. Once the segregation process is established, *nn* number of source nodes are assigned to a respective cluster head (e.g. three source nodes are placed under a cluster head as in Figure 3-17). Source nodes in DCHI-LSR are only permitted to communicate with a series of other source nodes and cluster heads based on the generated routing table. Once the routing table entries for *odd* and *even* sequence of cluster heads are created, forward (to a destination node) and reverse (to all source nodes) path is predefined with available cluster heads in a respective routing table. The forward path routing table in DCHI-LSR is as briefly described with an *even* sequence of cluster heads in Figure 3-19 and *odd* sequence of cluster heads in Figure 3-20. In a forward path routing table, a respective source node holds the needed entries of cluster heads based on the segregation process to a designated destination node. A source node is only permitted to communicate to its direct cluster head or leader node as in any cluster based routing at all time in a network [41, 61, 71].



Nxt	Dst	HC
E1	ND	n
E1	E1	n-1
E1	N4	(n-1)+1
E1	N5	(n-1)+1
E1	N6	(n-1)+1

Nxt	Dst	HC
ND	ND	1
N4	N4	1
N5	N5	1
N6	N6	1

Nxt	Dst	HC
En	ND	1+n
En	En	1
En	E1	1+(n-1)
En	N4	1+(n-1)+1
En	N5	1+(n-1)+1
En	N6	1+(n-1)+1

Nxt	Dst	HC
En	ND	1+n
En	En	1
En	E1	1+(n-1)
En	N4	1+(n-1)+1
En	N5	1+(n-1)+1
En	N6	1+(n-1)+1

Nxt	Dst	HC
E1	ND	1+1
E1	E1	1

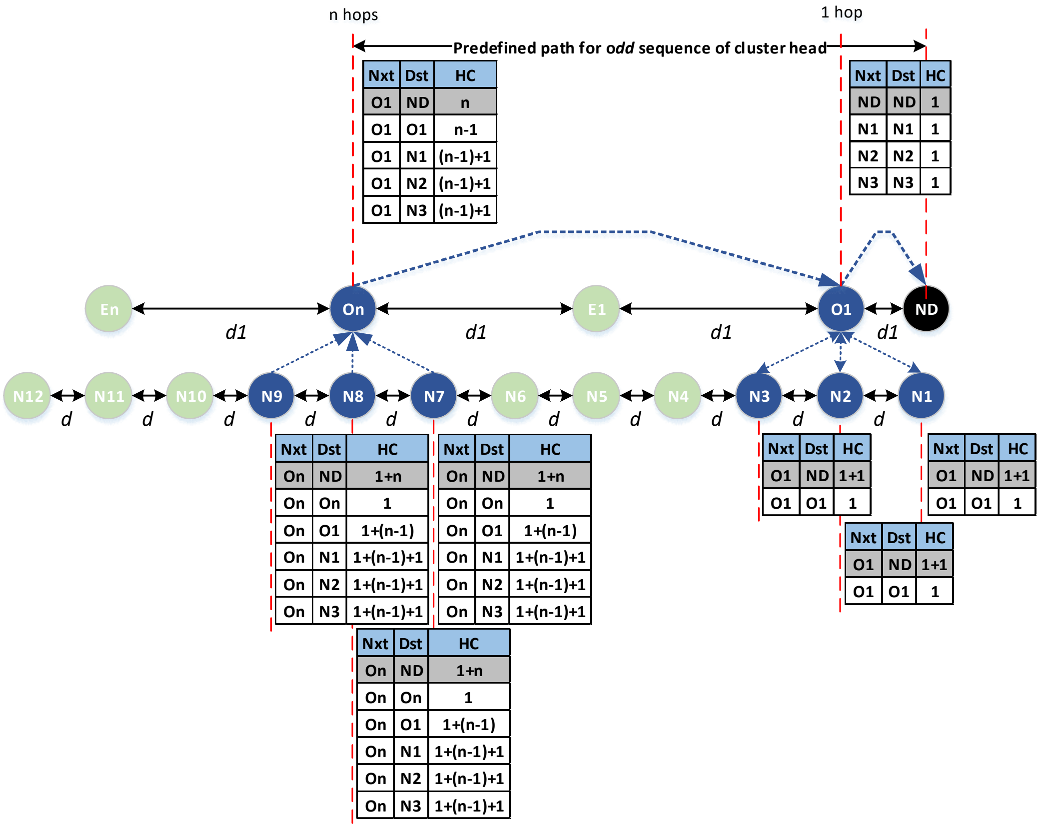
Nxt	Dst	HC
E1	ND	1+1
E1	E1	1

Nxt	Dst	HC
E1	ND	1+1
E1	E1	1

Nxt	Dst	HC
En	ND	1+n
En	En	1
En	E1	1+(n-1)
En	N4	1+(n-1)+1
En	N5	1+(n-1)+1
En	N6	1+(n-1)+1

Figure 3-19: Forward path with even sequence of cluster heads in DCHI-LSR

Based on Figure 3-19 and Figure 3-20, the data flow is indicated at respective source nodes with the path direction referring to a cluster head and neighbouring cluster heads (Nxt), the designated destination point (Dst) which is ideally the destination node (ND) or any other cluster heads and source nodes in the network. A point to point travel cost in hop count (HC) is indicated for a respective source node based on a minimum hops required to a designated destination. This mechanism ensures that there will be zero data packets floating without direction at a certain point in the network [96].



Nxt	Dst	HC
O1	ND	n
O1	O1	n-1
O1	N1	(n-1)+1
O1	N2	(n-1)+1
O1	N3	(n-1)+1

Nxt	Dst	HC
ND	ND	1
N1	N1	1
N2	N2	1
N3	N3	1

Nxt	Dst	HC
On	ND	1+n
On	On	1
On	O1	1+(n-1)
On	N1	1+(n-1)+1
On	N2	1+(n-1)+1
On	N3	1+(n-1)+1

Nxt	Dst	HC
On	ND	1+n
On	On	1
On	O1	1+(n-1)
On	N1	1+(n-1)+1
On	N2	1+(n-1)+1
On	N3	1+(n-1)+1

Nxt	Dst	HC
O1	ND	1+1
O1	O1	1

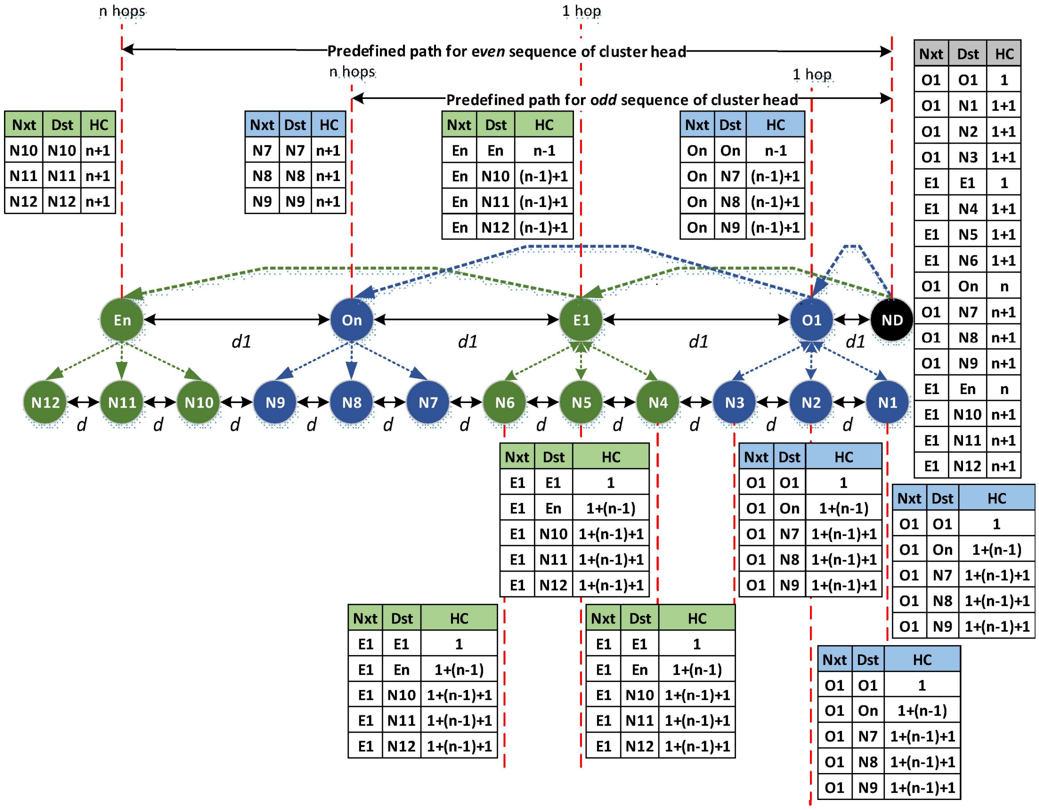
Nxt	Dst	HC
O1	ND	1+1
O1	O1	1

Nxt	Dst	HC
O1	ND	1+1
O1	O1	1

Nxt	Dst	HC
On	ND	1+n
On	On	1
On	O1	1+(n-1)
On	N1	1+(n-1)+1
On	N2	1+(n-1)+1
On	N3	1+(n-1)+1

Figure 3-20: Forward path with odd sequence of cluster heads in DCHI-LSR

In a reverse path routing table, the destination node holds the entries for *odd* and *even* sequence of cluster heads and source nodes in the network. Where else a respective cluster head holds the needed entries of other cluster heads and its source nodes (member nodes under a respective cluster head) in the network with predefined sequence from the segregation process. The distance between a source node to a destination node is calculated in terms of packet travel cost in hop count. In DCHI-LSR, the hop count is always maintained at minimum travel cost between a source and a destination node in order to optimise the network resources wisely. The reverse path routing table in DCHI-LSR is as briefly described in Figure 3-21.



Nxt	Dst	HC
N10	N10	n+1
N11	N11	n+1
N12	N12	n+1

Nxt	Dst	HC
N7	N7	n+1
N8	N8	n+1
N9	N9	n+1

Nxt	Dst	HC
En	En	n-1
En	N10	(n-1)+1
En	N11	(n-1)+1
En	N12	(n-1)+1

Nxt	Dst	HC
On	On	n-1
On	N7	(n-1)+1
On	N8	(n-1)+1
On	N9	(n-1)+1

Nxt	Dst	HC
O1	O1	1
O1	N1	1+1
O1	N2	1+1
O1	N3	1+1
E1	E1	1
E1	N4	1+1
E1	N5	1+1
E1	N6	1+1
O1	On	n
O1	N7	n+1
O1	N8	n+1
O1	N9	n+1
E1	En	n
E1	N10	n+1
E1	N11	n+1
E1	N12	n+1

Nxt	Dst	HC
E1	E1	1
E1	En	1+(n-1)
E1	N10	1+(n-1)+1
E1	N11	1+(n-1)+1
E1	N12	1+(n-1)+1

Nxt	Dst	HC
O1	O1	1
O1	On	1+(n-1)
O1	N7	1+(n-1)+1
O1	N8	1+(n-1)+1
O1	N9	1+(n-1)+1

Nxt	Dst	HC
O1	O1	1
O1	On	1+(n-1)
O1	N7	1+(n-1)+1
O1	N8	1+(n-1)+1
O1	N9	1+(n-1)+1

Nxt	Dst	HC
E1	E1	1
E1	En	1+(n-1)
E1	N10	1+(n-1)+1
E1	N11	1+(n-1)+1
E1	N12	1+(n-1)+1

Nxt	Dst	HC
E1	E1	1
E1	En	1+(n-1)
E1	N10	1+(n-1)+1
E1	N11	1+(n-1)+1
E1	N12	1+(n-1)+1

Nxt	Dst	HC
O1	O1	1
O1	On	1+(n-1)
O1	N7	1+(n-1)+1
O1	N8	1+(n-1)+1
O1	N9	1+(n-1)+1

Figure 3-21: Reverse path in DCHI-LSR

3.8.2 Source Node Routing Flows in DCHI-LSR

In a large WSN, queue limitation is a standard mechanism for controlling and managing bi-directional packets among nodes in a network [103, 122, 125]. Adequate queue limitation can eliminate passive nodes and bottleneck points in a single path wireless network. In general, a queue limitation increases the rate of packet dropped especially in a network with the undiscovered route as in any standard routing protocol [28]. With the implementation of DCHI-LSR, this factor could be minimised thus further increase the rate of data packet transfer with the proposed dual interleaving path method. Splitting a single path as in a conventional routing protocol into two paths, further, reduces the routing overhead by half hence allocates better proportion for data packets in a respective path as described in Figure 3-17. A default queue limit [122, 125] is set at each intermediate cluster heads in both paths as described in the flow chart in Figure 3-22. Referring to the flowchart in Figure 3-22, a generated data packet from a sensing point will be forwarded from a source node at level one to a cluster head at level two to a respective cluster head in the network. The data packet than will be forwarded to the designated destination node through a predefined sequence of cluster heads based on the routing table entries.

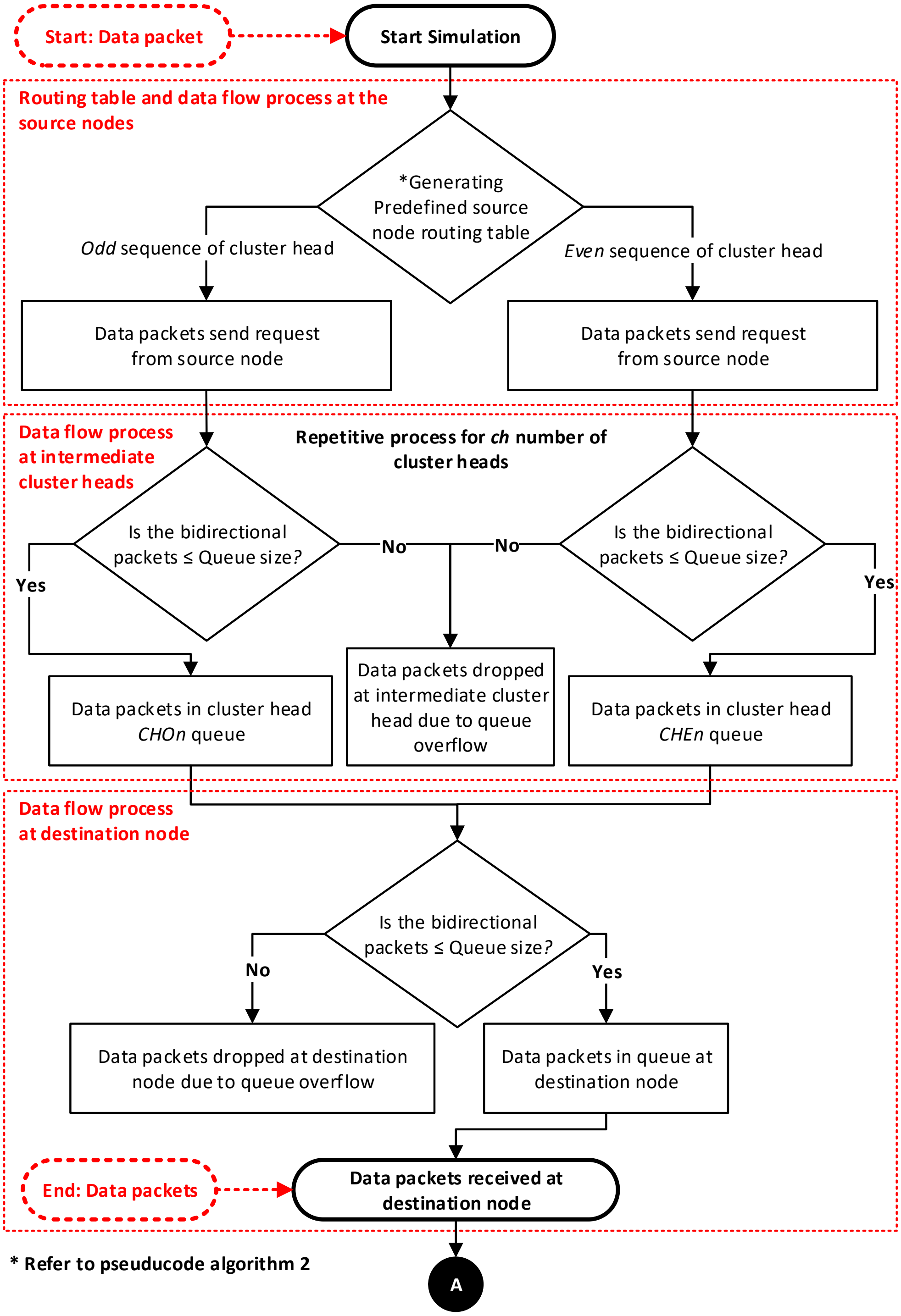


Figure 3-22: Flow chart for a data packet cycle in DCHI-LSR

With the restricted queue limit, any data packets arriving at an intermediate (neighbouring) cluster head with queue length > $IfQlen_{CHOn}$ or $IfQlen_{CHEn}$ will be dropped from moving forward towards the destination node. This is commonly known as queue overflow where the dropped packets will be regenerated after a specific duration [24, 77, 78]. In a WSN, dropped packets are not favourable due to unwanted loss of network resources particularly on the energy consumed from packet generation till packet dropped. In a WSN, queue overflow is due to overwhelming of control packets which include broadcast and hello packets depending on the characteristic of a routing protocol [3, 132]. The queue factor remains same at each intermediate cluster heads till the data packet reaches its destination node. The reduced routing overhead in DCHI-LSR creates less traffic, thus packet drops can be reduced compared to a routing protocol which relies on this broadcast and signalling packets to generate or maintain a routing table. The concept of distributing traffic in two paths further reduces the routing overhead by half, therefore, allocates a better proportion of data packets compared to any conventional single-path routing protocol. The concept of a data accumulation factor for *odd* and *even* sequence of cluster heads can be described respectively in equation 3-13 and 3-14 between a source and intermediate nodes towards a destination node.

$$TP_{CHO} = \sum_{i=1}^{ch}\left(CPO_i + \sum_{j=1}^{nn}\left(DP_j + CP_j\right)\right) \leq IfQlen_{CHOn} \qquad \textbf{3-13}$$

Where TP_{CHO} is the total packets in an *odd* sequence of cluster head, CPO_i is the total control packets for a *ch* number of cluster heads (*odd*), DP_j is the total data packets and CP_j is the total control packets for *nn* number of source nodes under a cluster head with $IfQlen_{CHOn}$ as the queue length in *odd* routing path.

$$TP_{CHE} = \sum_{i=1}^{ch}\left(CPE_i + \sum_{j=1}^{nn}\left(DP_j + CP_j\right)\right) \leq IfQlen_{CHEn} \qquad \textbf{3-14}$$

Where TP_{CHE} is the total packets in an *even* sequence of cluster head, CPE_i is the total control packets for a *ch* number of cluster heads (*even)*, DP_j is the total data packets and CP_j is the total control packets for *nn* number of source nodes under a cluster head with $IfQlen_{CHEn}$ as the queue length *even* routing path.

A destination node is placed at end of each interleaving route with an integration point as indicated in the flow chart of

Figure 3-22. A data packet forwarded from a source node through a series of cluster heads will be directed to this point at all time. The successful data packets accumulation factor at the destination node (receiver) from both routes is as described in equation 3-15. Any incoming data packets at the destination node with queue length > *IfQlen* will be dropped.

$$NTP = \quad {}_{CHO} + TP_{CHE} \leq IfQlen \qquad \textbf{3-15}$$

Where *NTP* is the network total packets at the destination for a *ch* number of cluster heads and the *nn* number of source nodes with TP_{CHO} or TP_{CHE} is from equation 3-13 and 3-14.

3.8.3 Destination Node Routing Flows in DCHI-LSR

A destination node routing table holds entries of all source nodes deployed in a network based on two predefined reverse paths. At time *t*, DCHI-LSR generates a reverse path routing table in which will be used by control packets to reach a designated source node. Once a data packet has successfully reached the destination node, a TCP acknowledgement packet will be generated in return to acknowledge the respective source node (sender). A generated TCP acknowledgement packet will be forwarded from a destination node at level one to a series of respective cluster heads based on *odd* and *eve*n path at level two. The TCP acknowledgement packet is forwarded to a respective source node through a predefined sequence of cluster heads based on the routing table entries. Unlike a forward route as described in Figure 3-18, the reverse path routing table at the destination node has the entire list of both *odd* and *even* sequence of cluster heads and source nodes. The predefined reverse path routing table generating process in DCHI-LSR is as briefly described in the pseudocode of Figure 3-18. The hop count is always retained at minimum travel cost between a destination to respective source nodes in order to optimise the network resource wisely. The reverse path hop count is based on the same hop count in a forward path between two respective nodes in the network. At time *t+2*, a generated TCP acknowledgement packet is forwarded on a predefined return path to a designated source node with a default queue limit [122, 125] is set at each intermediate cluster heads in both routes as described in the flow chart in

Figure 3-22. Since the routing path is predefined with no changes is expected during the node active period, no aggressive broadcast packets are required to maintain neither the routing table nor the routing path in DCHI-LSR.

3.9 Performance Evaluation on Linear Cluster Two-tier Topology

The overall network performance is tested in various simulation environment created in NS2 [34, 103] to visualise the behaviour and impending factors when full deployment of DCHI-LSR in a pipeline network. In all simulated environment, the proposed DCHI-LSR is compared with DI-LSR in a flat one-tier topology as a reference, AODV a reactive and DSDV a proactive routing protocol in a cluster-based two-tier topology for performance comparison in NS2. The basic configuring and predefined setting for the simulation environment is as tabulated in Table 3-2.

Table 3-2: NS2 simulation parameters for cluster-based topology

Key parameters	Set value
Channel type	Wireless channel
Radio propagation model	Two Ray Ground
MAC type	802.11
Interface queue type (ifq)	Drop Tail/PriQueue
Source nodes (SN)	12, 24, 36, 48, 60, 72, 84, 96, 108, 120
Destination node (ND)	1
Cluster head (CH)	4, 8, 12, 16, 20, 24, 28, 32, 36, 40
Queue length (ifqlen)	50 (packets)
Agent type	Transmission control protocol (TCP)
Traffic type	Constant bit rate (CBR)
Transmission range (RX Thresh)	350 meter
Sensing range (CS Thresh)	550 meter
Packet size	512 bytes

In each simulation environment, an average value of five runs per cycle for the manipulating variable (*ch* number of cluster heads and the *nn* number of source nodes) with different seed values in between 1 to 10 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 3-2. In a cluster-based two-tier topology, the number of cluster head is uniformly increased by 4 cluster heads and the number of source nodes is uniformly increased by 12 source nodes in each cycle. In a hierarchical topology, the number of cluster heads in each cycle is uniformly increased by 4 cluster head starting from 4 cluster heads to 40 cluster heads with an increasing number of member nodes from 12 source nodes to 120 source nodes. The simulation environment was created using a custom random 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 were 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 one destination node (ND).

3.10 Simulation Results and Discussion for Cluster Two-tier Linear Topology

The overall network performance of DCHI-LSR is compared with AODV and DSDV in a cluster-based two-tier topology that is presented as AODVC and DSDVC with a reference guide from DI-LSR for flat one-tier topology in terms of the performance metrics in section 3.5.

3.10.1 Packet Delivery Ratio vs. Number of Source nodes

The effect of varying number of source nodes on the delivery ratio is as shown in Figure 3-23. Generally, the delivery ratio decreases with the increasing number of source nodes for all compared routing protocols. It is observed that at low network density with 12 source nodes, the delivery ratio is almost at the same rate among all compared routing protocols. The delivery ratio of DCHI-LSR is at a moderate rate when compared with the other cluster-based routing protocol between a low network density with 12 source nodes to a larger network density with 120 source nodes. There is a significant difference in delivery ratio, particularly between DI-LSR and DCHI-LSR. The unappealing rate of the delivery ratio in DCHI-LSR is due to a higher data transfer rate, competitive data transfer and queuing factor at each cluster heads is increased by 3 member nodes (source nodes) that can be further improved with a network fairness mechanism.

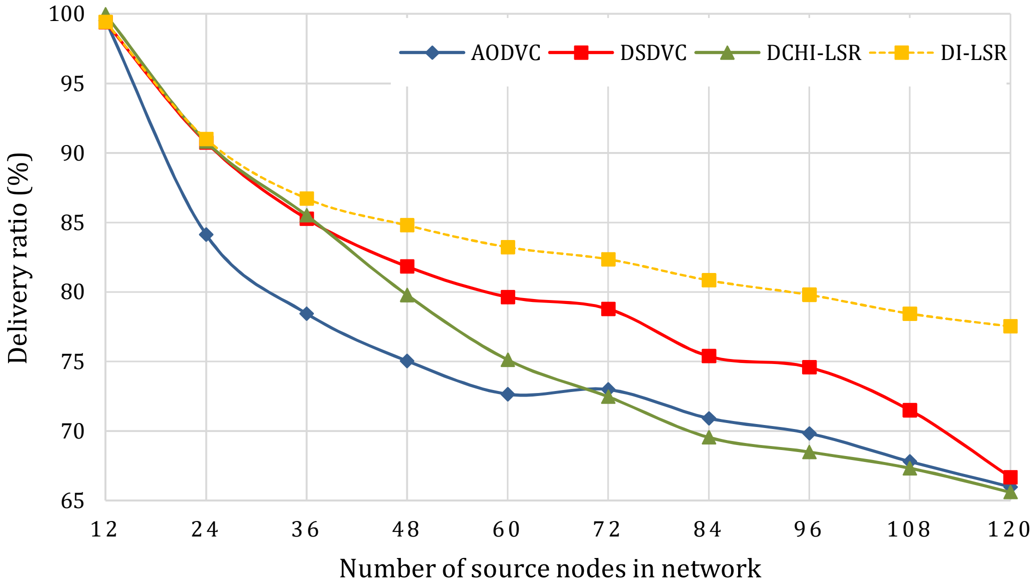


Figure 3-23: Delivery ratio vs. number of source nodes

3.10.2 End-to-end Delay vs. Number of Source nodes

The result comparison on average end-to-end delay for varying number of source nodes is as shown in Figure 3-24, which indicates DCHI-LSR has a gradual increase in delay proportional from a low network density with 12 source nodes to a larger network density with 120 source nodes. Higher data rate has direct implication in terms of overall delay typically due to the total data packets received and the fairness factor among source nodes in the network. The delay in DCHI-LSR is fairly low compared to the moderate rate of fairness and higher data rate achieved when compared to the other routing protocols. In a multi-hop linear topology, the delay factor varies from the distance between a source and a destination node. Using a predefined dual interleaving path, the DCHI-LSR is capable of forwarding data in a more efficient manner using a dedicated data stream as compared to a single one-tier multi-hop method.

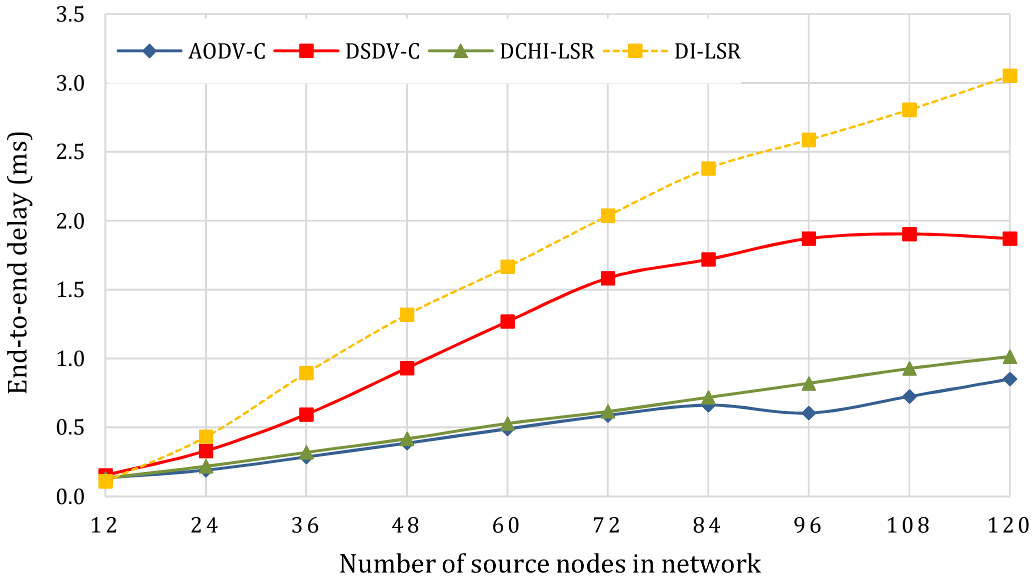


Figure 3-24: End-to-end delay vs. number of source nodes

3.10.3 Throughput vs. Number of Source nodes

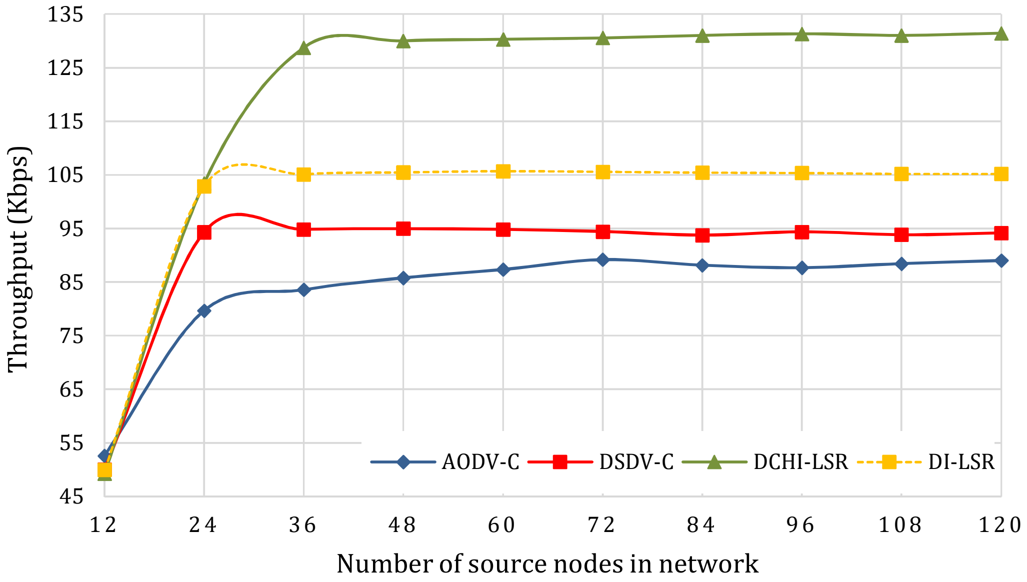


Figure 3-25: Throughput vs. number of source nodes

The effect of varying number of source nodes increases the throughput in the network for all compared routing protocols as shown in Figure 3-25. The throughput in a network with the implementation of DCHI-LSR outperforms all the other routing protocols from a low network density with 12 source nodes to a larger network density with 120 source nodes. With the implementation of dual interleaving cluster head splits the traffic into two paths, therefore a significant increase in the throughput value between 23 Kbps – 42 Kbps can be achieved at varying stages compared with the other routing protocols. With the implementation of dual interleaving cluster head in a dedicated data stream path in DCHI-LSR has the capacity to achieve higher throughput within the available network resources.

3.10.4 Throughput Fairness Index vs. Number of Source nodes

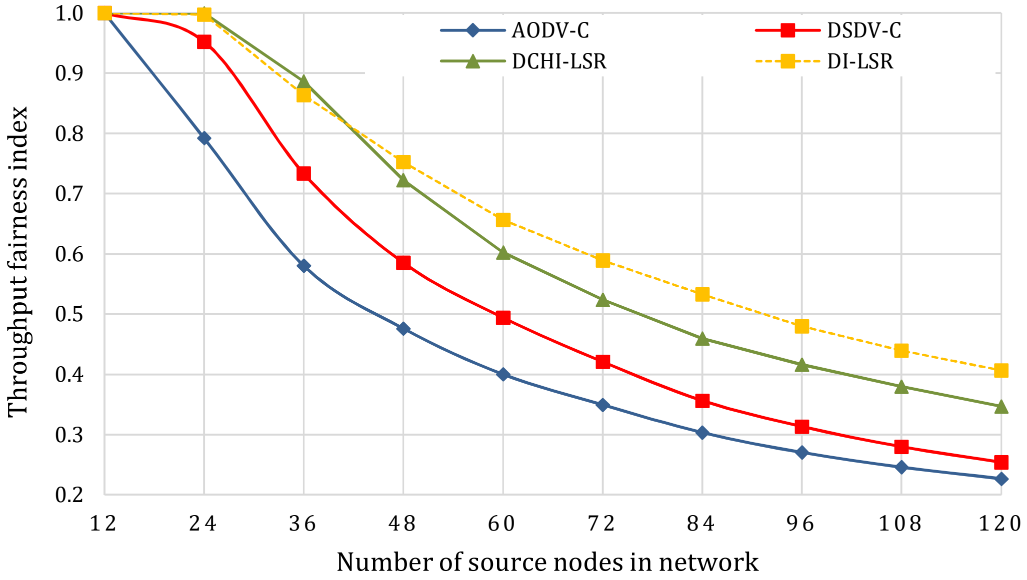


Figure 3-26: Throughput fairness index vs. number of source nodes

Network imbalance is a crucial factor in any multi-hop linear wireless network. Referring to Figure 3-26, the throughput fairness index of DCHI-LSR outperforms all the other cluster-based routing protocols with a significant difference in fairness index from a low network density with 12 source nodes to a larger network density with 120 source nodes. In a low network density with 12 nodes, fairness is hardly visible since the performance of all other routing protocol is fairly similar. When compared with DI-LSR, there is a merely a small difference in fairness index due to a greater network capacity and competitive data transfer in DCHI-LSR. A higher data rate and moderate throughput fairness are comparatively achievable in a multi-hop linear cluster-based wireless network with the proposed DCHI-LSR.

3.10.5 Received Data Packet Variation vs. Number of Source nodes

Variation of received data packets is another parameter in visualising fairness between source nodes in a network. Referring to Figure 3-27, the percentage of received data packet variation of DCHI-LSR is relatively similar to all the other routing protocol from a medium network density with 36 source nodes to a larger network density with 120 source nodes. The difference becomes greater with the varying number of source nodes and comparatively with increasing received data packets at a destination node for all compared routing protocols.

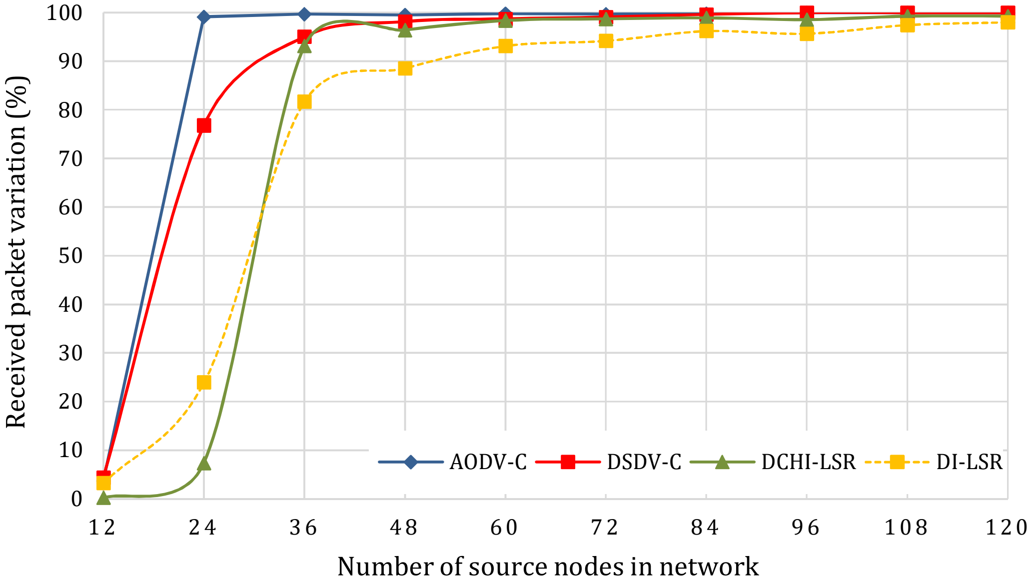


Figure 3-27: Received data packet variation vs. number of source nodes

3.10.6 Passive Source Nodes vs. Number of Source nodes

The effect of passive nodes in network reflects on the fairness index as well as the network performance in a multi-hop linear cluster-based wireless network. The effect of varying number of source nodes on the passive source nodes is as shown in Figure 3-28 where zero passive nodes were achieved between a low network density with 12 source nodes to a larger network density with 120 source nodes with DCHI-LSR. With a better proportion of data packets transfer rate in a predefined dual interleaving path with low routing overheads as in DI-LSR eliminates the passive nodes. While the other routing protocols contribute towards passive nodes with a varying number of source nodes in a network.

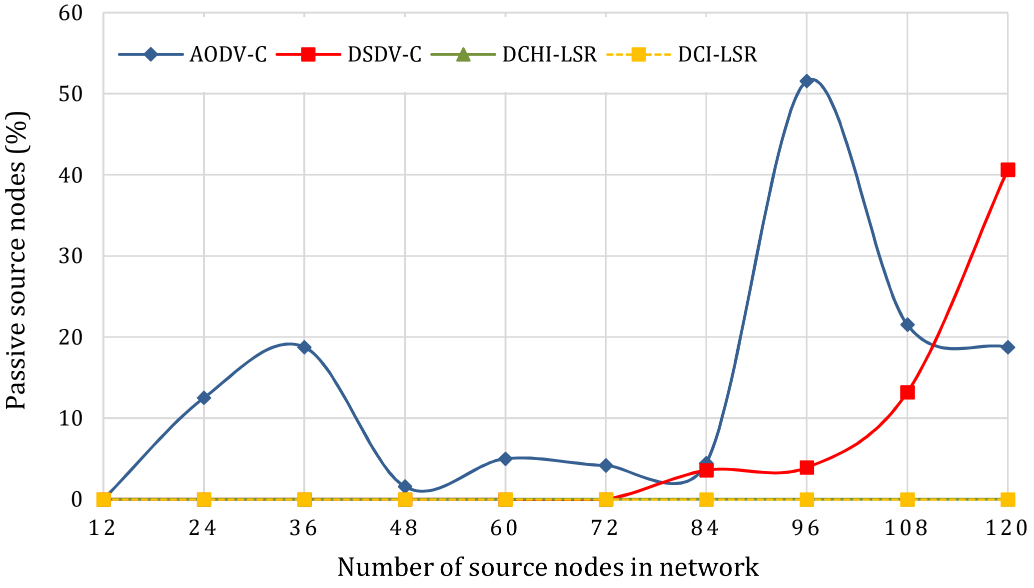


Figure 3-28: Passive source nodes vs. number of source nodes

3.10.7 Normalised Routing Load vs. Number of Source nodes

The effect of varying number of source nodes increases the network routing overhead in the network for all compared routing protocols as shown in Figure 3-29. The network routing overhead in a network with the implementation of DCHI-LSR is relatively lower when compared in terms of received data packets among the other routing protocols between a low network density with 12 source nodes to a larger network density with 120 source nodes. When compared against DI-LSR, the routing overhead is much lower after 60 source nodes with the implementation of DCHI-LSR. With reduced control packets particularly with broadcast packets reduce the traffic of supporting packets in a network especially with increasing number of source nodes.

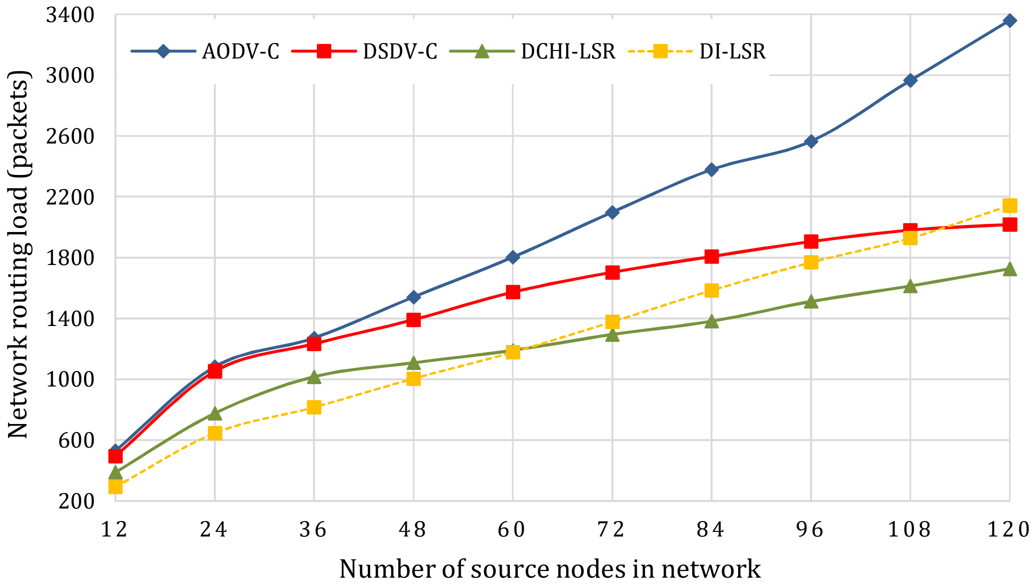


Figure 3-29: Network routing load vs. number of source nodes

3.10.8 Energy Consumption vs. Number of Source nodes

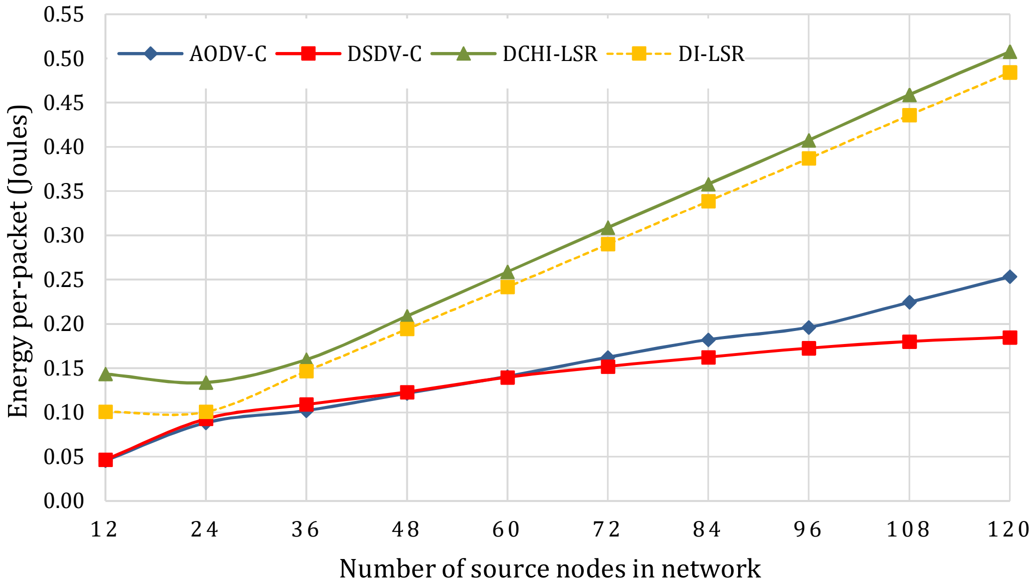


Figure 3-30: Energy per-packet vs. number of source nodes

The energy consumption per-packet effect on varying number of source nodes is as shown in Figure 3-30, which indicates that DCHI-LSR has a gradual increase in energy to the network size. The energy consumption per-packet increasing factor in DCHI-LSR is due to the amplification of data packet at each varying simulation environment. Based on the number of data packets received, DCHI-LSR has relatively lower energy consumption compared to all the other routing protocol from a low network density with 12 source nodes to a larger network density with 120 source nodes. The other routing protocols consumed higher energy per-packet with relatively low data rate compared to DCHI-LSR in the tested environment due to higher routing load. An energy efficient routing protocol ensures a sustainability factor in a typical multi-hop linear wireless network, particularly when the nodes are battery power dependent.

3.11 Conclusion

This chapter mainly presented two routing algorithms which were implemented on a flat (one-tier) and a cluster-based (two-tier) multi-hop linear topology. The outcome from implementing DI-LSR and DCHI-LSR in respective wireless topologies has highlighted potential optimisation factors towards the overall network performance on a pipeline network. Both the proposed routing algorithm features reduced network routing load with a predefined dual interleaving routing path to further enhance the overall network performance as well as to eliminate issues with passive nodes. The basic comparison between DI-LSR and DCHI-LSR is as shown in Table 3-3.

Table 3-3: Brief comparison of DI-LSR and DCHI-LSR

Features	DI-LSR	DCHI-LSR
Architecture	One-tier linear (sensing nodes acts as intermediate nodes)	Two-tier linear cluster (sensing nodes, leader node acts as intermediate cluster heads)
Sensing point and data stream	Dual interleaving sensing and data stream (shared)	Dual interleaving cluster heads as data stream and *nn* number of sensing points under each leader node
Network complexity	Low (one-tier)- fewer nodes required	High (two-tier)- more nodes required
Node failures	Sensing nodes effects data stream path (either *odd* or *even*)	Sensing nodes does not affect data stream path but cluster heads effects data stream path (either *odd* or *even*)

The simulated results have demonstrated that both DI-LSR and DCHI-LSR has achieved a significant level of improvements in reliability (delivery ratio), network capacity (throughput), latency (end-to-end delay) and responsiveness (dealing with node failures) which had crucial implication towards the overall network performance on a pipeline network. The overall network performance of DI-LSR and DCHI-LSR in average from varying simulation environment is as tabulated in Table 3-4.

Table 3-4: Overall network performance of DI-LSR and DCHI-LSR

Measured parameters	DI-LSR	DCHI-LSR
Average delivery ratio (%)	83.67	77.46
Average end-to-end delay (ms)	1.2908	0.3854
Average throughput (Kbps)	99.6	119.72
Average throughput fairness index	0.6719	0.6337
Average received packet variation (%)	77.22	79.02
Average passive nodes (%)	0	0
Average network routing load (packets)	1275.01	1201.10
Average energy per-packet (mili joules)	0.2722	0.2946

A multi-hop linear topology has a unique geographical architecture that results in limited network resources (in a single path) and high risk of communication failure (depends on the number of nodes within a communication range), especially in a large WSN. Similarly, in a pipeline network with the proposed technique, nodes are arranged to establish communication with multiple nodes in the network that incurs additional cost as compared to other wireless topologies to accommodate minimum three nodes within the communication range to reduce the risk of node failures. The results analysis outcome has indicated that the impending network factors on reliability, fairness issues in network resources and energy consumption need attention in a multi-hop linear topology. In the next Chapter, a scheduling scheme for TCP delayed acknowledgement to be incorporated with both DI-LSR and DCHI-LSR for better network equality in a multi-hop linear network will be presented. A scheduling scheme for TCP delayed acknowledgement can further optimise the fairness in network resources sharing in a multi-hop linear network.

Chapter 4

Effective TCP Delayed Acknowledgement Timeout Model for Throughput Fairness Optimization

4.1 Introduction

Over the years, remote monitoring is established with various wireless standards and communication technologies in relaying real-time data to a centralised monitoring station from sensors attached to critical pipeline points [4, 8, 14]. 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 centralised monitoring station (data collection for future analysis) [6, 9]. The network of sensors which are linked in series to form a communication chain to sense changes on sensing points and forward this information to a destination node with predefined route determined by a routing protocol. Figure 4-1 illustrates the data packets travel time factor at time *t* and data rate for a conventional multi-hop linear topology with a *Nn* number of source nodes and a single destination node (ND).

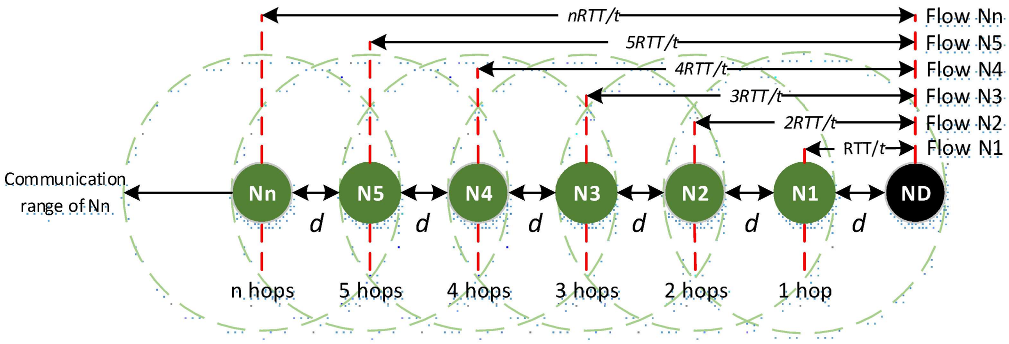


Figure 4-1: Data travel rate in multi-hop linear topology

Respective nodes are indicated inflows, *Nn* where *n* is the source node number or sequence in a network which represents bi-directional packets moving towards a destination node. The data packet travel time factor is described with Round

Trip Time (RTT) for respective source nodes in a wireless network. The RTT value is defined as one cycle time for a data packet to travel from a source to a destination node and receives an acknowledgement packet to confirm its recipient of the sent data packet [23, 28, 77]. Such a pipeline network has unique underlying issues affecting full deployment of WSN on oil and gas pipelines in terms of degrading factor on overall network performance as well as network fairness among source nodes [95, 133]. In a typical multi-hop linear WSN, the long range data transmission [134] has severe performance degradation issues that lead towards inefficient fairness in the wireless network particularly using the Transmission Control Protocol (TCP) [23, 28, 135].

Figure 4-2 illustrates the data packet travel time factor with fairness implication on a conventional multi-hop linear topology at time *t+1*. The typical characteristic of a multi-hop linear topology in such setup results in unbalanced data transfer rate between source nodes in a certain network [24, 27]. When the effect is amplified at time *t+2*, the network will suffer from severe source node starvation particularly nodes that are located in a distance away from the destination node. In any multi-hop linear WSN, this is a crucial issue that leads towards data packet loss and a waste of network resources.

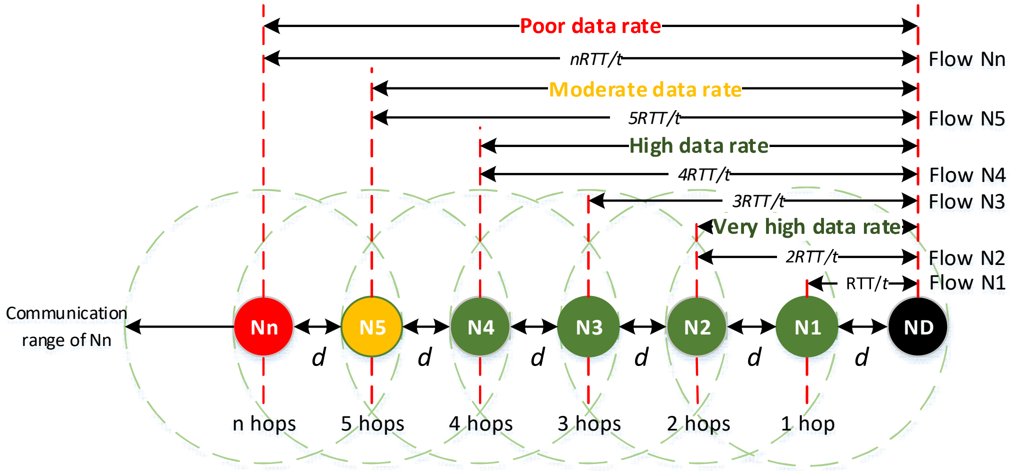


Figure 4-2: Effect on data travel rate in multi-hop linear topology

In the recent years, continuous research on new protocols, applications, techniques and devices have been studied in TCP for achieving optimum fairness outcomes. A network with TCP agent experience performance issues where the root cause is from node starvation and unbalanced data packet flow, particularly in a long range linear topology [27, 135, 136].

In terms of network fairness or equality among source nodes are rather difficult to be defined in a single fairness metric since fairness is a subjective factor when reflected against performance metrics. In practical terms and rational consideration, each implementation of fairness model has a unique characteristic in actual deployment varies between the nature of its application, the routing protocol used and in the implemented topology [24, 28, 135, 137]. Therefore sharing of network resources can be evaluated by the optimisation rate of available network resources among all source nodes with a constant rate in long-term network fairness. The actual definition of network fairness in a bigger picture is based on the attributes needed in a specific deployment either by the network user or by a respective industry. Thus, in most research on network fairness attributes towards a desired rate on the shared network resource. In a practical world, a network fairness model comes with special attributes towards the requirements and cost factor incorporated with the desired outcome.

This chapter mainly focuses on four mathematical formulations of TCP delayed acknowledgement timeout model for a flat (one-tier) and cluster-based (two-tier) multi-hop linear topology. The TCP delayed acknowledgement timeout model for a Fairness critical application (DATM-FFCA) and with a Throughput critical application (DATM-FTCA) [28] is proposed for a flat topology. While the TCP delayed acknowledgement timeout model for a Fairness critical application (DATM-CFCA) and with a Throughput critical application (DATM-CTCA) is proposed for a cluster-based topology. Both models are formulated for TCP acknowledgement timeout to accommodate the increasing data traffic with optimum throughput fairness in a multi-hop linear WSN with zero passive nodes.

4.2 Network Fairness Factor in Multi-hop Linear Topology

Network fairness or equality among source nodes (senders) in a TCP agent is a highly desirable metric in a multi-hop linear topology. The effect of network fairness over varying network density results in severely degrading throughput and increasing passive nodes [RW.ERROR - Unable to find reference:214].

Network unfairness is a condition in which affects the overall throughput and network resources equality factor in a multiple-to-one inline traffic pattern that is relatively common in a multi-hop linear WSN. This condition is quite common when multiple source nodes in a varying distance send data packets to the same destination node (receiver) as shown in Figure 4-1. The communication link between the source and the destination node becomes a bottleneck point, thus resulting in heavy loss of data packets resulting in low network throughput [78, 138].

Generally, there is three foremost network fairness factor which significantly contributes towards; (1) the network throughput, (2) end-to-end delay and (3) energy wastage which is not practical for deployment in a pipeline network [24, 26, 139]. By clearly understanding this factors would help to recognise methods to overcome effects of network fairness with a TCP delayed acknowledgement timeout model. In the following section, these factors and related parameters are defined with a feasible solution for optimum fairness rate in a pipeline network.

4.2.1 Source Node Distance in a Multi-hop Linear Topology

The unconditional sharing of network resources among source nodes deployed in a linear architecture may not mean that there is an equal allocation of the available network resources. It is quite common that each source node is assigned with an equal level of the available network capacity. However, in a multi-hop linear topology with varying distance contributes towards unfair access to network resources [24, 27, 136]. On the other hand, the concept of sharing in a multiple-to-one inline traffic pattern in a single path with overwhelming data packets contributes to data accumulation factor towards the destination node [28, 140]. Referring to Figure 4-2, in an ideal scenario where data packet travel time factor varies from each sensing points between *N1* to *Nn* in a conventional multi-hop linear topology contributes towards resultant fairness at time *t+2*. The conception of distance between source to a destination node is proportional to the data packet travel time cost which is a clear indication of unfairness in a multi-hop linear topology. The further a source node is located, a greater travel time is required for a data packet to reach its destination node. An example of data travel time factor based on Figure 4-2 is tabulated in Table 4-1 with a simulation time, *t* is 1 second.

Table 4-1: Example of data travel time for a multi-hop linear topology

Source node	Data travel time	Travel time	Packets per second
N1	*RTT*	14.1 ms	70
N2	*2RTT*	28.2 ms	35
N3	*3RTT*	42.3 ms	23
N4	*4RTT*	56.4 ms	17
N5	*5RTT*	70.5 ms	14
Nn	*nRTT*	*n* ms	*n*

Furthermore, the consideration of unfairness network allocation at some point strive towards source node starvation that mostly affects those nodes located a distance away from the destination node [26, 118]. This condition is also known as silent or passive nodes where the source node will constantly be generating data packets without allocation towards the destination node is an extremely waste of network resources in a WSN. In an adequate WSN, unwanted waste of network resources both energy and bandwidth is not a good sign in terms of fairness as well as the network performance on a pipeline network.

4.2.2 Long-term Network Fairness and Data Frequency

Considering on a period of time, network fairness measures the available network resources allocation at the end of a cycle time or over a longer usage period. Long-term fairness has a crucial factor when a network resource is infrequent or in an uncontrolled environment [23, 24]. On the other hand, data frequency is an influencing element for overwhelming data packet factor which is challenging for a guaranteed network resources allocation among all varying source nodes in a multi-hop linear network [26, 28, 92]. In a typical environment where equal network resources allocation is given at time *t+1* to all source nodes in a network doesn't significantly affect network fairness in terms of network capacity (throughput). But at time *t+2*, where the amplification of data packets moving towards a destination node implying that unfairness allocation among source nodes creates variation between individual capacity in terms of fairness rather than the network capacity as shown in Figure 4-2 [28]. The challenging network environment where adaptation of network changes relies on many varying parameters especially on the characteristic of an implemented routing protocol and how efficient is the rate of long-term network fairness. The concept of individual fairness or the overall network fairness is always related towards long-term network fairness in a multi-hop linear topology [141]. In terms of individual fairness, a respective source node is measured whether was it treated fairly in the network rather than the overall network fairness that is impossible to achieve in a network with varying distance. Therefore, when a certain network is able to achieve optimum network fairness and a certain level of performance is considered a network with fair allocated resources. Based on this fairness characteristic, network fairness can be emphasised as a subjective metric where different applications and users desired a unique resources allocation rate [28].

4.2.3 Degrading of Wireless Performance

Network fairness is often referred as a wireless metric that is quite common in a static architecture with a fixed set of source and destination nodes sharing network resources mainly for data packet transfer [92, 142]. In a practical implementation, the number of data flows or connections are highly dynamic. The unplanned varying condition of increasing and decreasing data arrival occurs between source to a destination node till the entire process is completed. In the sharing process where fairness is the prime concern in a network, the network performance will be a tradeoff metric or will be compromised in the long-run. Network fairness considers equal resources allocation disregards to the location of source nodes from a destination node [27]. Thus this scenario creates an unfair state for nodes in a closer distance compare to a node further away from a destination node. In a typical linear arrangement of source nodes, as shown in Figure 4-1 where the performance of individual nodes is normalised with an optimum fairness rather than network capacity which results in degrading of throughput, increasing end-to-end delay and higher consumed network energy [1, 95]. The performance degrading factor in a multi-hop linear network is proportional to the density of nodes with network resources that are equally allocated causing increased waiting time between data transmission [27]. On the other hand, performance degrading factor is often related to the characteristic of a routing protocol implemented in a WSN. Unfortunately, relying on to routing protocols are inadequate in achieving both fairness and performance in a multi-hop linear topology. Without a proper data flow controlling mechanism in routing protocols would result in severe degrading of performance, unfairness and source node starvation [26, 92].

4.3 The Delayed Acknowledgement Timeout Model for Flat One-tier and Cluster-based Two-tier Multi-hop Linear Topology

In a multi-hop linear topology, network fairness can be achieved based on the scale and complexity of an application established on a one-tier or multi-tier approach. A fair allocation of network resources can be described as an outcome of a process in a WSN where respective source nodes have equal opportunity in the long run. In a non-dynamic WSN such as in a pipeline network, temporal changes in resources allocation are uncommon as the system is in a control state especially with a static routing algorithm as described in Chapter 3 [15, 96]. Therefore, targeted and resultant network fairness could be retained at a set level for the entire network active duration.

On the other hand, network fairness can also be considered from a perspective of both overall network and individual source nodes based on the end user's implementation [28]. Moreover, in a multi-hop linear topology where a respective source node is designed to perform a specific sensing task and also as an intermediate router between another source node to the destination node in a network. Therefore, from the perspective of a pipeline network, the overall network fairness can be defined from the network activity in whole rather than an individual task. Referring to these network fairness characteristic and nature of the application, a mathematical formulation to calculate optimum TCP delayed acknowledgement timeout is proposed with the best implementation of the proposed routing algorithms from Chapter 3 over a pipeline network scenario shown in Figure 4-1. In this section, there are four TCP delayed acknowledgement time out models are proposed with two models to be implemented on a flat (one-tier) and a cluster-based (multi-tier) multi-hop linear topology respectively.

The first proposed model; TCP delayed acknowledgement timeout model for a Fairness critical application (DATM-FFCA) and the second proposed model; TCP delayed acknowledgement timeout model for a Throughput critical application (DATM-FTCA) is established for a flat one-tier multi-hop linear architecture [28]. The proposed DATM-FFCA and DATM-FTCA is a mathematical formulation for optimum fairness with variation in the overall network performance.

The third proposed model; TCP delayed acknowledgment timeout model for a Fairness critical application (DATM-CFCA) and the fourth proposed model; TCP delayed acknowledgment timeout model for a Throughput critical application (DATM-CTCA) is established for a multi-hop linear cluster-based topology. The proposed model is best to be implemented with the dual interleaving technique among cluster heads (leader node and intermediate nodes) to a destination node [96]. The proposed DATM-CFCA and DATM-CTCA is a mathematical formulation for optimum fairness with variation in the overall network performance.

All four proposed models would be a practical and in complex solution in an application where the desired normalized throughput fairness goal is set at a ratio of one among all source nodes in the network. The practical implementation of the proposed models requires some minor modification in the default settings of TCP parameters to ensure optimum network fairness outcome.

To achieve the network fairness ratio of one among all source nodes, the source node advertised window (awnd) and the congestion window (cwnd) is set to the lowest value to restrict packet flows at a specific time interval. In general, the effect of controlling the advertised window at a destination node can avoid or further reduces the rate of data packet overflow over the available network resources at the destination node [23, 88]. Whereas the effect of controlling the congestion window can avoid and further reduces the sending rate of data packets than the permitted allocations from a respective source node in a certain network. Thus, a constant flow of data packets can be achieved whereas the packet collisions and data dropped rate is reduced. To achieve an optimum network fairness among all source nodes, the advertised window is set to one (the lowest value) and the congestion window is decided by the type of TCP agent used which has a unique characteristic of congestion control algorithm based on the congestion state in the network. A default TCP delayed acknowledgement timeout is controlled by setting the respective source nodes acknowledgement timeout based on their location from the destination node unlike the default expiry of acknowledgement timeout which is unable to achieve a network fairness index value close to one [23, 143].

Generally, in a TCP agent the delayed acknowledgement is set by a factor of two (RFC1122) [78, 144, 145] where an acknowledgement packet will be generated when the destination node receives one or two data packets within the default acknowledgement expiry time. Based on this factor wherein a particular source node with a capability to send two data packets within the default acknowledgement expiry time reduces the number of acknowledgement packets to one. If only one data packet is received within the default acknowledgement expiry time, then the acknowledgement packet is sent to the dedicated node for the respective packet received. This technique can further reduce the routing overhead and energy consumption in a network.

One of the main component in delayed acknowledgement timeout is the value of RTT. The RTT is known as one cycle time taken for a source node to send a data packet to the destination node and receives an acknowledgement packet in return to confirm its recipient of the sent data packet [79, 138]. In a flat or a cluster-based multi-hop linear topology with varying number of source nodes have different travel time (t) implication based on the distance factor [119, 123]. Theoretically, in a scenario with linear increasing distance is proportional to the increase in travel time (t) in WSN. Thus, the default acknowledgement expiry time is unable to justify network fairness over performance especially in a hierarchal arrangement. On the first section, the two proposed models were implemented on a similar flat one-tier multi-hop linear topology setup with two varying throughput factor that reflects on other wireless performance metrics. The first model uses a higher cycle time in a transmission block with a practical implementation on a network with the highly dynamic rate of data transmission. Typically, a transmission block represents *1 Sum H cycle (t)* or *fair cycle time (t)* value describes the time period needed for fair data transmission [28]. While the second model uses a lower cycle time in a transmission block with a practical implementation on a network with the low non-dynamic rate of data transmission. The mathematical formulation in DATM-FFCA and DATM-FTCA is used to set an optimum delayed acknowledgement timeout for respective source nodes in a flat one-tier multi-hop linear topology as in Figure 4-3.

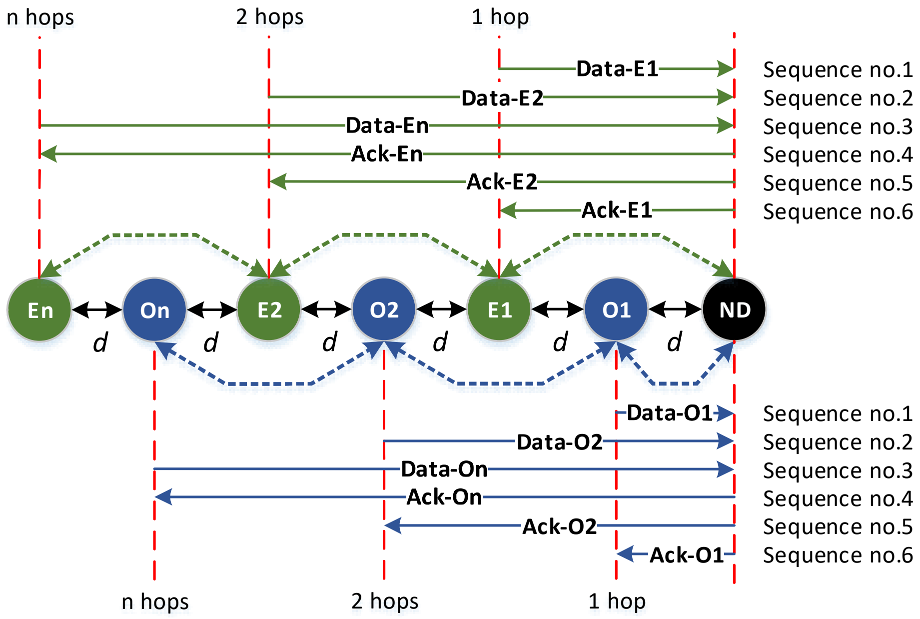


Figure 4-3: The DATM-F with source nodes (On/En) and destination node (ND)

On the second section, the two proposed models were implemented on a similar multi-hop linear cluster-based two-tier topology setup with two varying throughput factor that reflects on other wireless performance metrics. The first model uses a higher cycle time in a transmission block with a practical implementation on a network with the highly dynamic rate of data transmission. While the second model uses a lower cycle time in a transmission block with a practical implementation on a network with the low non-dynamic rate of data transmission. The mathematical formulation in DATM-CFCA and DATM-CTCA is used to set an optimum delayed acknowledgement timeout for respective source nodes in a multi-hop linear cluster-based two-tier topology as in Figure 4-4.

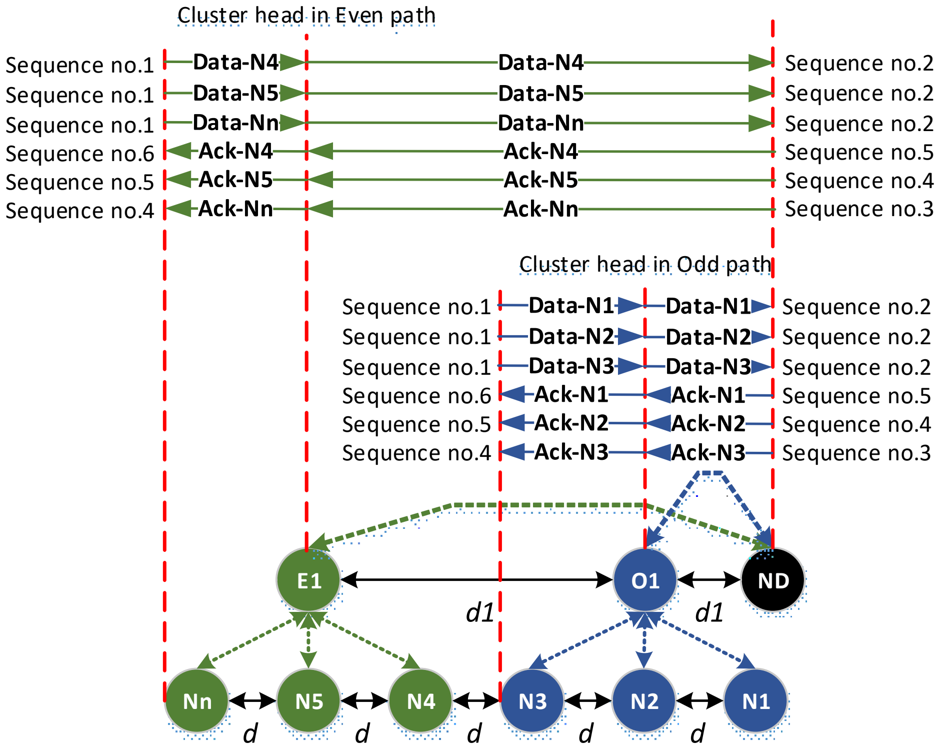


Figure 4-4: The DATM-C with source nodes (Nn) and destination node (ND)

4.3.1 Model One; TCP Delayed Acknowledgement Timeout Model for Fairness Critical Application

In the proposed model one; TCP delayed acknowledgement timeout model for a flat topology for a Fairness critical application (DATM-FFCA) considers the travel time cost between respective source nodes in only one path (either *odd* or *even* whichever has the greatest hop count) from the destination node in a network. Since the dual interleaving routing concept introduced in Chapter 3 is based on parallel data transmission that deliberates the assumption of all data packets are transmitted in a given *cycle time (t)*. The accumulated hop count which is known as travel cost is a very important parameter to appropriately determine the delayed acknowledgement timeout for each source nodes in both *odd* and *even* path as illustrated in Figure 4-3. The *RTT* value in DATM-FFCA is multiplied with the accumulated hop count for respective source nodes (only in a single path) with an addition value of *n* which is a transition factor the period between all received packets before the acknowledgement process in a certain network. The transmission period or can also be called as the cooling period between a data and acknowledgement packet phase. The transition phase is designed to clear any outstanding packets which had overflow from the data packet phase in the data stream. The factor of *n* is determined by the number of connection which is in parallel to the main calculated hop count. The *RTT* value is used as a multiplying factor in deriving an optimum delayed acknowledgement timeout for each respective source nodes in the network that is based on distance to travel (calculated by the hop count needed to reach the destination node). The one path cycle time duration in DATM-FFCA is as formulated in equation 4-1.

$$Fair\ cycle\ time\ (t)\ = ((\textstyle\sum_{i=1}^{nn}(H_i)) + n) \times RTT \qquad \textbf{4-1}$$

Where *Fair cycle time (t)* is one cycle time taken for *nn* number of source nodes in the network to have a fair data transmission rate to the destination node, H_i is the hop count for *nn* number of source nodes (either in *odd* or *even* path), *n* is the factor for transition period between end of data packet and start of acknowledgement packet at the end node and *RTT* is the round trip time (ms). The mathematical formulation in DATM-FFCA as in equation 4-2 derives respective delayed acknowledgement timeout based on a node sequence in a network to achieve optimum network fairness in the process of sending data packets and receiving an acknowledgement packet.

$$DACK_{nn} = Fair\ cycle\ time\ (t) - RTT_{nn} \qquad \textbf{4-2}$$

Where $DACK_{nn}$ is the TCP delayed acknowledgement timeout for *nn* number of source nodes in both paths (*odd* and *even*) based on the hop count, where *Fair cycle time (t)* is from equation 4-1 and RTT_{nn} is the round trip time for respective source nodes based on the separation of nodes from the destination node. In a cluster-based topology, the RTT_{nn} is replaced with RTT_{nn+1} value is in sequential increment according to the cluster heads (*odd* and *even*) that disregard the hop count. Based on equation 4-2, there is a variance between a minimum and a maximum value of delayed acknowledgement timeout, but these variances are not obvious as all data and acknowledgement packet transmission will be retained in a *Fair cycle time (t)*. The common difference between all four proposed models is typically in terms of how the travel cost is derived in hop count and the factor of transition period (*n*). Generally, the proposed DATM-FFCA has higher travel cost in a highly densest network compared to DATM-FTCA. The selection of a RTT value has a crucial impact towards the practical concept of the proposed models. The set value of RTT in all the above formulation is 14.1 ms which is obtained through a simple simulation setup of two nodes distributed in a distance of 100 meters (line-of-sight) using DI-LSR from an average value of ten runs [28]. Each routing algorithm has a unique time factor which contributes towards the RTT value. Theoretically, with a lower value of RTT would result in a higher throughput value for a given wireless scenario [27, 146]. Thus, the *Fair cycle time (t)* value obtained from all four proposed models are based on the suggested value of RTT.

The data and acknowledgement packet process flow in all four models are generally similar. However, each model was designed with a unique formulation factor with a slightly different technique between each model that contributes towards the network fairness and overall network performance. In a scenario with conventional TCP agent, the RTT is defined as one cycle time from On/En to send a data packet to *ND* and receives an acknowledgement packet in return. Thus, both data and acknowledgement packet takes place in one RTT value unlike in proposed models where a series of data packets are generated from source nodes to the destination node and then followed by a series of acknowledgement packets generated to the respective source nodes in a certain network. The proposed models are a comprehensive model for a multi-hop linear topology to achieve optimum throughput fairness among all source nodes in varying number of source nodes. With a planned timely sequence of generated data packets and pre-calculated delayed acknowledgement packets between a source and a destination node ensures optimum network fairness in the long run.

A multi-hop linear network with six source nodes (*odd* path: O1 to On, *even* path E1 to En) and a destination node as ND with the proposed DATM-FFCA in a controlled environment is shown in Figure 4-5. Figure 4-5 illustrates the entire data packet sending sequence and receiving the acknowledgement packet sequence with a transition waiting period in DATM-FFCA.

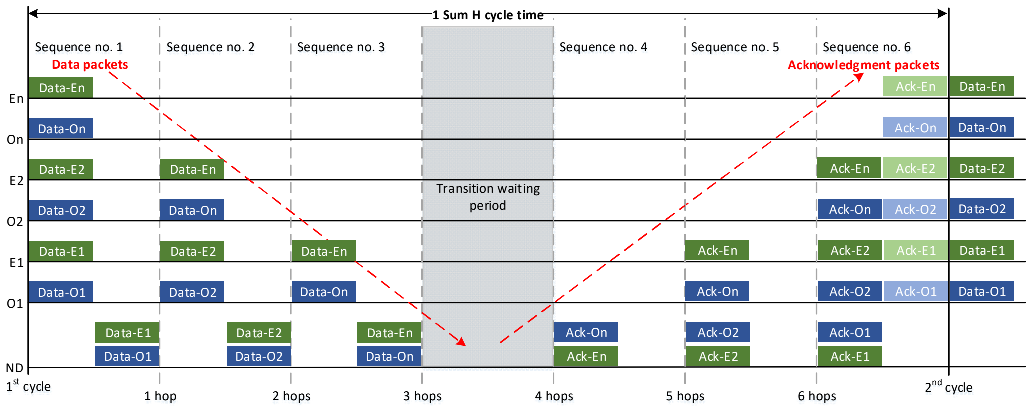


Figure 4-5: The timing diagram of DATM-FFCA

Referring to Figure 4-5, all source nodes (O1/E1/O2/E2/On/En) initiates the first data packet (Data-O1/Data-E1/Data-O2/Data-E2/Data-On/Data-En) transmission at time *t+1* to the destination node (ND) at the start of each *1 Sum H cycle (t)* or *fair cycle time (t)*. The generated data packets (Data-O1/Data-E1) from source nodes (O1/E1) requires one hop to the designated destination node (ND) in sequence no. 1 at a duration of one *RTT* where else for the generated data packets (Data-O2/Data-E2) from source nodes (O2/E2) requires two hops through the intermediate node (O1/E1) to reach the destination node (ND) in sequence no. 2 with two *RTT* value. The generated data packets (Data-On/Data-En) from source nodes (On/En) requires three hops through the intermediate node (O2/E2 and O1/E1) to reach the destination node (ND) in sequence no. 3 with three *RTT* value.

Based on the mathematical formulation of DATM-FFCA, the first acknowledgement packets (Ack-On/Ack-En) at sequence no. 4 will be generated at the destination node (ND) with three hops required through the intermediate node (O1/E1 and O2/E2) to reach the respective source nodes (On/En) at the edge of seven *RTT* value. In the second acknowledgement packets at sequence no. 5 (Ack-O2/Ack-E2) from the destination node (ND) requires two hops to reach the respective source nodes (O2/E2) at the edge of seven *RTT* value. For the third and final acknowledgement packets at sequence no. 6 (Ack-O1/Ack-E1) from the destination node (ND) requires only one hop to reach the respective source nodes (O1/E1) at the edge of seven *RTT* value.

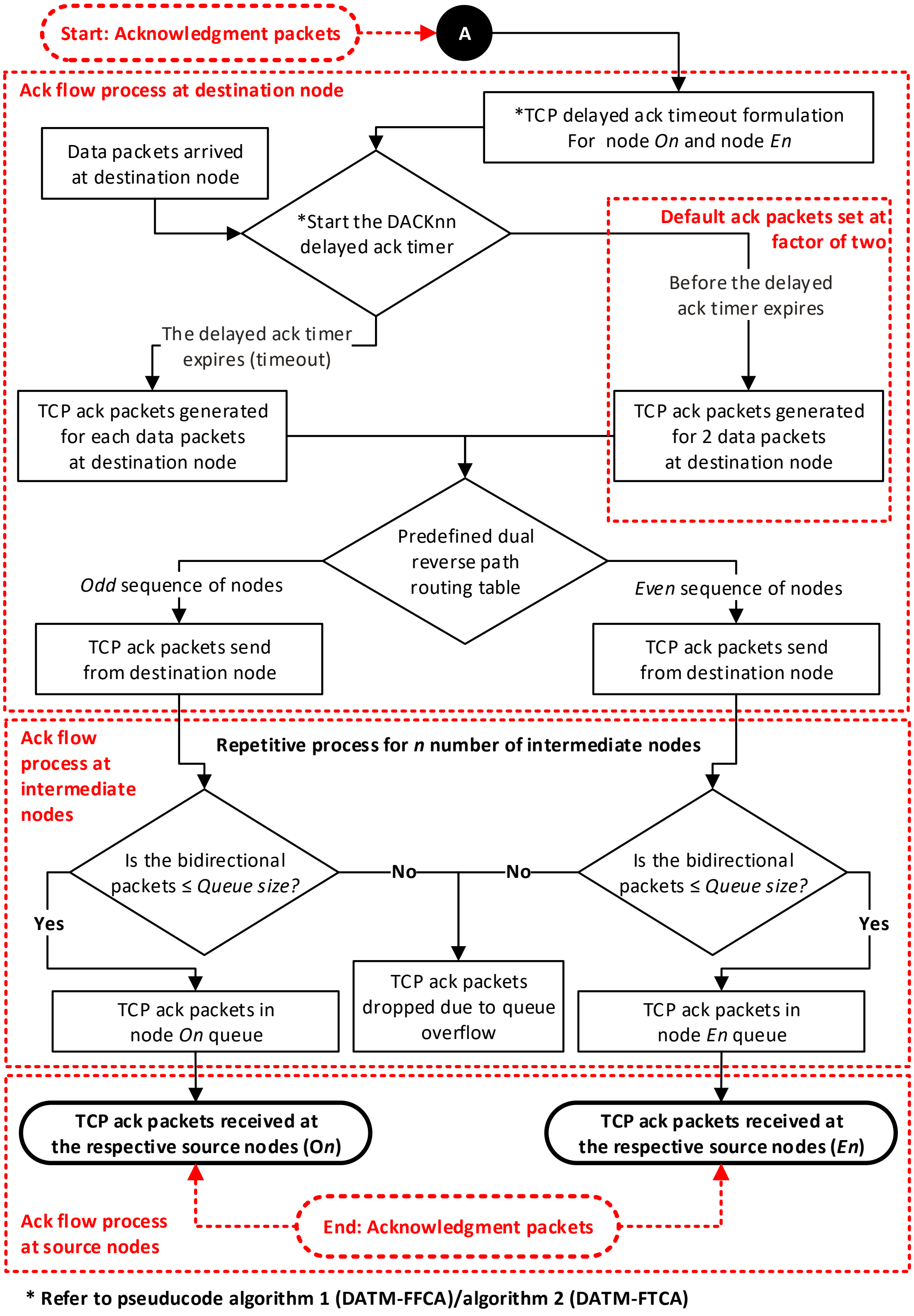


Figure 4-6: Delayed acknowledgement process in DATM-FFCA and DATM-FTCA

From the dual path sequence (*odd* and *even* route) shown in Figure 4-3, this would take seven *RTT* value e.g. 3*RTT* + 2*RTT* + 1*RTT* (*odd* or *even* source node) + 1*RTT* (factor of transition period) for *1 Sum H cycle (t)* or *fair cycle time (t)* to achieve the equal data packet transmission opportunity for all source nodes (O1/E1/O2/E2/On/En) in the network. The briefly delayed acknowledgement timeout model for both DATM-FFCA and DATM-FTCA is shown in the flow chart in Figure 4-6 with significant variant as described in Figure 4-7 and Figure 4-9 respective. The proposed method is implemented at the destination node based on a series of data and acknowledgement sequence with specific delayed acknowledgement timeout that is predefined before the acknowledgement packets are sent out to the respective source node as shown in flow chart in Figure 4-6.The mathematical formulation process flow in DATM-FFCA is as briefly described in the pseudocode of Figure 4-7.

```
Algorithm 1: Delayed acknowledgement time for DATM-FFCA

Suppose number of nodes is "nn", odd sequence of nodes is "$O_n$", even sequence of nodes is "$E_n$" and destination node is "ND = 0"

At time t:

1: For $O_n$ or $E_n - 2 \geq 0$ then: Accumulated required hop(s) for every increment in a loop for one path
    else IF $O_n - 1 \geq 0$ then: Required hop(s) for one path
2: For (HopCount$O_n$ or HopCount$E_n$) × (RTT) then: +1 cycle time per data transmission block ($n$)
3: For (1 cycle time) - (On or En × RTT) ≤nn then: Respective delayed acknowledgement time for $nn$ number of source nodes
4: At time t+1: Source nodes $O_n$/$E_n$ start sending data packets to ND
5: At time t+n: ND start sending TCP delayed acknowledgement packets to source nodes $O_n$/$E_n$ based on values in step 3.
```

Figure 4-7: Generating delayed acknowledgement timeout in DATM-FFCA

4.3.2 Model Two; TCP Delayed Acknowledgement Timeout Model for Throughput Critical Application

The proposed model two; TCP delayed acknowledgement timeout model for a flat topology for a Throughput critical application (DATM-FTCA) considers only the maximum travel time cost on a respective source node located furthest in both *odd* and *even* paths from the destination node in a network. Since the dual interleaving routing concept introduced in Chapter 3 is based on parallel data transmission that deliberates the assumption of data packets are transmitted in cycle time (t) dedicated to a single path which accommodates all the source nodes within the allocated duration.

The maximum number of hop count per-path is accumulated with an addition of n which is a factor of the transition period between all received packets phase and the acknowledgement process in a certain network as previously explained in the proposed model. In the transmission period phase of DATM-FTCA, any outstanding data packets in the data stream is given a lag time to reach the destination node if needed, especially in a network with lower *cycle time (t)*. The factor of n is determined by the number of connections to the originator path in calculation process (both *odd* and *even*) in parallel to the maximum calculated hop count on both paths. The n factor is added in each respective paths in a network. The travel cost is a very crucial parameter to appropriately determine delayed acknowledgement timeout for each and every source nodes (*odd* and *even* path) as illustrated in Figure 4-3. The travel cost in DATM-FTCA is calculated from a maximum hop count (based on the distance in the network) for the respective path with an addition of n which is a factor of the transition period for each path in a certain network. The RTT value is used as a multiplying factor in deriving an optimum delayed acknowledgement timeout for each respective source nodes in the network based on distance to travel (calculated by the hop count needed to reach the destination node in parallel data transmission). The cycle time in DATM-FTCA is as formulated in equation 4-3.

$$Fair\ cycle\ time\ (t) = \left((Ho_{max} + n) + \ (He_{max} + n)\right) \times RTT \qquad \textbf{4-3}$$

Where *Fair cycle time (t)* is one cycle time taken for *nn* number of source nodes in the network to have a fair data transmission rate to the destination node, Ho_{max} is the maximum distance hop count for *nn* number of source nodes on *odd* path, He_{max} is the maximum distance hop count for *nn* number of source nodes on *even* path, *n* is the factor of transition period and *RTT* is the round trip time (ms). Equation 4-2 derives the respective delayed acknowledgement timeout for DATM-FTCA based on the node sequence in a network to achieve optimum network fairness in the process of sending data and receiving acknowledgement packets. Since DATM-FTCA were designed using a common technique and implemented on the same platform as in DATM-FFCA, the values obtained from equation 4-3 can be used in the common mathematical formulation of DATM-FFCA from equation 4-2. Both DATM-FFCA and DATM-FTCA allows the users to achieve optimum network fairness with a minimum trade-off on overall performance in a flat one-tier multi-hop linear topology. However, when it comes to performance outcome, that's where the two technique differs slightly. The measurable difference between the proposed DATM-FTCA and DATM-FFCA is typically how the travel cost is derived in terms of hop counts with the *n* factor which will result in terms of the overall network performance. Generally, the proposed DATM-FTCA has lower travel cost in a highly densest network compared to DATM-FFCA. The sequence of data and acknowledgement packet transmission in DATM-FTCA is similar to DATM-FFCA, where in the first phase a series of data packets are generated from source nodes to the destination node. The second phase is the transition waiting period between data and acknowledgement packets in one *cycle time (t)*. The third phase is followed by a series of acknowledgement packets which is generated based on the sequence of source nodes in a certain network.

A multi-hop linear network with six source nodes (*odd* path: O1 to On, *even* path E1 to En) and one destination node as ND with the proposed DATM-FTCA in a controlled environment is as shown in Figure 4-8. Figure 4-8 illustrates the entire data packet sending sequence and receiving the acknowledgement packet sequence with a transition waiting period in DATM-FTCA.

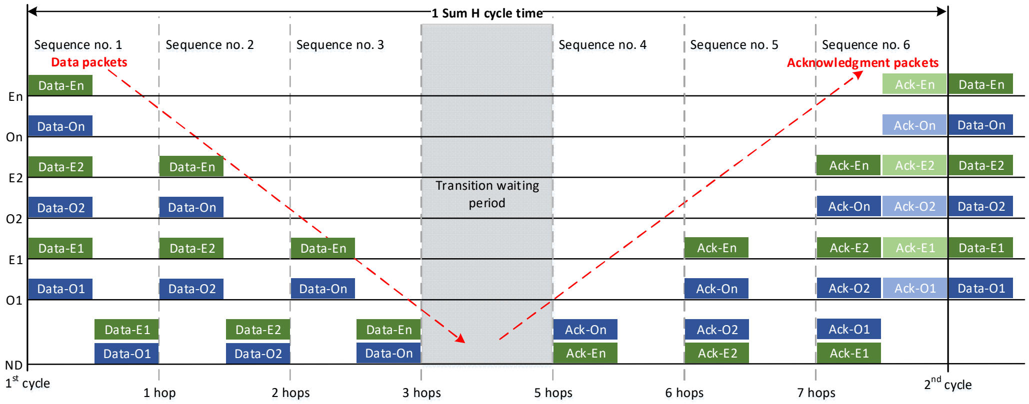


Figure 4-8: The timing diagram of DATM-FTCA

Referring to Figure 4-8, the first phase of the timing diagram is as same as in DATM-FFCA where all source nodes (O1/E1/O2/E2/On/En) initiates the first data packet (Data-O1/Data-E1/Data-O2/Data-E2/Data-On/Data-En) transmission at time *t+1* to the destination node (ND) at the start of each *1 Sum H cycle (t)* or *fair cycle time (t)*. The generated data packets (Data-O1/Data-E1) from source nodes (O1/E1) requires one hop to the designated destination node (ND) in sequence no. 1 at a duration of one *RTT* where else for the generated data packets (Data-O2/Data-E2) from source nodes (O2/E2) requires two hops through the intermediate node (O1/E1) in sequence no. 2 to reach the destination node (ND) with two *RTT* value. The generated data packets (Data-On/Data-En) from source nodes (On/En) requires three hops through the intermediate node (O2/E2 and O1/E1) in sequence no. 3 to reach the destination node (ND) with three *RTT* value. The difference in the second phase between DATM-FTCA and DATM-FFCA is the use of *n* factor of the transition period. In DATM-FTCA the *n* factor of the transition period is used in both *odd* and *even* path unlike in DATM-FFCA is only used in one path. Based on the mathematical formulation of DATM-FTCA, the first the acknowledgement packets (Ack-On/Ack-En) at sequence no. 4 will be generated at the destination node (ND) with three hops required through the intermediate node (O1/E1 and O2/E2) to reach the respective source nodes (On/En) at the edge of eight RTT value. In the second acknowledgement packets at sequence no. 5 (Ack-O2/Ack-E2) from the destination node (ND) requires two hops to reach the respective source nodes (O2/E2) at the edge of eight RTT value. For the third and final acknowledgement packets at sequence no. 6 (Ack-O1/Ack-

E1) from the destination node (ND) requires only one hop to reach the respective source nodes (O1/E1) at the edge of eight RTT value. From the dual path sequence (*odd* and *even* route) shown in Figure 4-3, this would take eight RTT value e.g. $3RTT$ (*odd* source node) + $1RTT$ (factor of transition period) + $3RTT$ (*even* source node) + $1RTT$ (factor of transition period) for *1 Sum H cycle (t)* or *fair cycle time (t)* to achieve the equal data packet transmission opportunity for all source nodes (O1/E1/O2/E2/On/En) in the network. The mathematical formulation process flow in DATM-FTCA is as briefly described in the flowchart of Figure 4-6 and in the pseudocode of Figure 4-9.

Algorithm 2: Delayed acknowledgement time for DATM-FTCA

```
Suppose number of nodes is "nn", odd sequence of nodes is "$O_n$", even sequence of nodes is "$E_n$" and destination node is "ND = 0"

At time t:

1: For $0<(O_n \text{ and } E_n+2)\leq nn$ then: Maximum number of required hop(s) on each path

2: For MaxHop$O_n$ and MaxHop$E_n$ then: Add to the n factor for both odd and even
                                         maximum hops

3: For ((MaxHopOn+n)+(MaxHopEn+n))×(RTT) then: 1 cycle time per data
                                                transmission block

4: For (1 cycle time)- ($O_n$ or $E_n$× RTT) ≤nn then: Respective delayed
                                          acknowledgement time for nn
                                          number of source nodes

5: At time t+1: Source nodes $O_n$/$E_n$ start sending data packets to ND

6: At time t+n: ND start sending TCP delayed acknowledgement packets to $O_n$/$E_n$
   based on values in step 4.
```

Figure 4-9: Generating delayed acknowledgement timeout in DATM-FTCA

Using DATM-FFCA and DATM-FTCA in a TCP agent will ensure optimum throughput fairness with variation in wireless performance metrics for varying number of source nodes in a multi-hop 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 (travel cost) between respective source nodes and the destination node in a dual path with an appropriate RTT value for each node which is based on distance will benefit from network equality. Changes in the scenario where a scalable WSN with selective source nodes is applicable in both DATM-FFCA and DATM-FTCA by assigning the precise hop count referring to equation 4-1 and 4-3 respectively in order to overcome issues with bandwidth reservation for repeater nodes (non-source nodes) in a long range network.

4.3.3 Network Fairness and Performance Evaluation on Flat One-tier Multi-hop Linear Topology

The network fairness and overall network performance were simulated in NS2 [103, 125] to visualise the outcome and impending factors when full deployment of DATM-FFCA and DATM-FTCA in a pipeline network. The static routing algorithm proposed in Chapter 3 [12] was implemented with both DATM-FFCA and DATM-FTCA on NS2 where detail analysis was carried on various wireless performance metrics. Both the proposed model was compared with ADAM+ and ADAM-snd [23] as discussed in Chapter 2 that was implemented with AODV a reactive routing protocol and DSDV a proactive routing protocol [21, 22]. All the simulated results are from an average value of five runs per cycle on the manipulating variable (*nn* number of source nodes) with different seed values in between 1 to 10 over a simulation duration of 500 seconds. In a flat one-tier topology, the number of source nodes in each cycle was uniformly increased by 12 nodes starting from 12 to 120 source nodes. To replicate a real-time application, the start time and start sequence of a source node are generated using a custom random function in the simulator. The start time for a source node is generated randomly between 0 – 0.5 seconds with non-sequential starting nodes. All nodes indicated in the results were stationary for the entire simulation duration with one destination node (ND). The configuration and key simulation parameters employed in NS2 to visualise the effects of varying source nodes density is as tabulated in Table 4-2.

Table 4-2: NS2 simulation parameters for flat topology

Key parameters	Set value
Channel type	Wireless channel
Radio propagation model	Two Ray Ground
MAC type	802.11
Interface queue type (ifq)	Drop Tail/PriQueue
Source nodes (SN)	12, 24, 36, 48, 60, 72, 84, 96, 108, 120
Destination node (ND)	1
Queue length (ifqlen)	50 (DATM) & 100 (other methods)
Agent type at source node	TCP/Reno
Agent type at destination node	TCPSink/DelAck
Traffic type	Constant bit rate (CBR)
Transmission range (RX Thresh)	100 meter
Sensing range (CS Thresh)	125 meter
Packet size	512 bytes

4.3.4 Simulation Results and Discussion for Flat One-tier Multi-hop Linear Topology

The ADAM+ and ADAM-snd as discussed in Chapter 2 was implemented with AODV and DSDV which is presented as AODV+, AODV-snd, DSDV+ and DSDV-snd. The network fairness, as well as the performance of DATM-FFCA and DATM-FTCA, is compared with AODV+, AODV-snd, DSDV+ and DSDV-snd for flat one tier topology in terms of the performance metrics in section 3.5.

4.3.4.1 Throughput Fairness Index vs. Number of Source Nodes

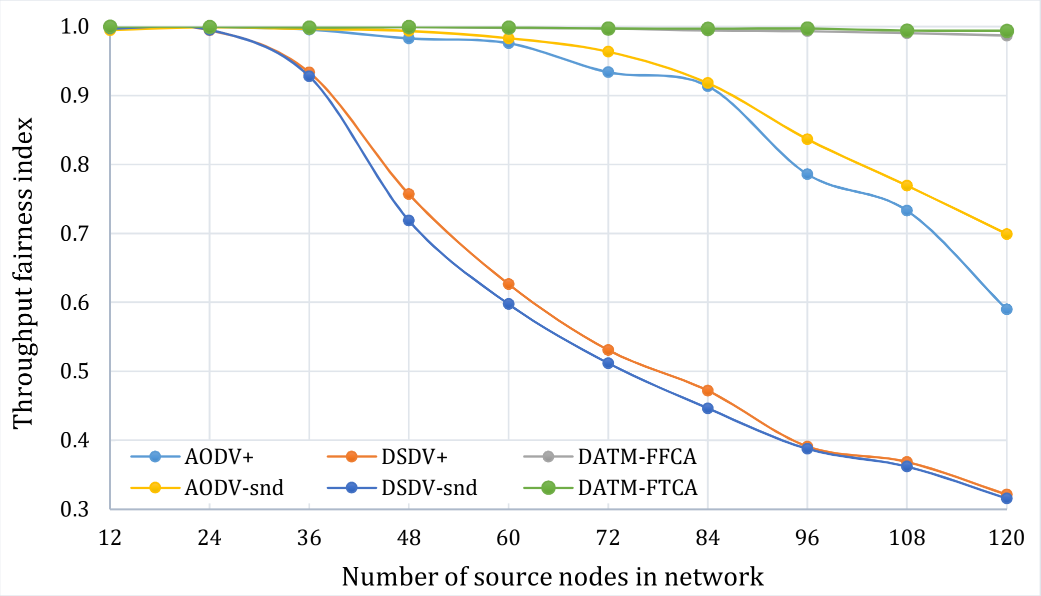


Figure 4-10: Throughput fairness index vs. number of source nodes

In a multi-hop linear topology with *nn* number of source nodes with only one destination node has a crucial implication towards network stability due to unfair allocation of network resources. The highest desirable throughput fairness index of 1.0 represents that a network has achieved 100% normalised throughput fairness among all source nodes. Referring to Figure 4-10, the throughput fairness index of both DATM-FFCA and DATM-FTCA outperforms all the other compared methods with a significant difference of 0.11 to 0.66 between low network densities with 12 source nodes to larger network densities with 120 source nodes. With the proposed DATM-FFCA and DATM-FTCA achieved a throughput fairness index of 0.99 and above with a varying number of source nodes in the simulated environment. The technique of delayed acknowledgement based on node distance used in both models has a significant improvement in terms of throughput fairness index compared to a conventional TCP agent used in Chapter 3.

4.3.4.2 Received Data Packet Variation vs. Number of Source Nodes

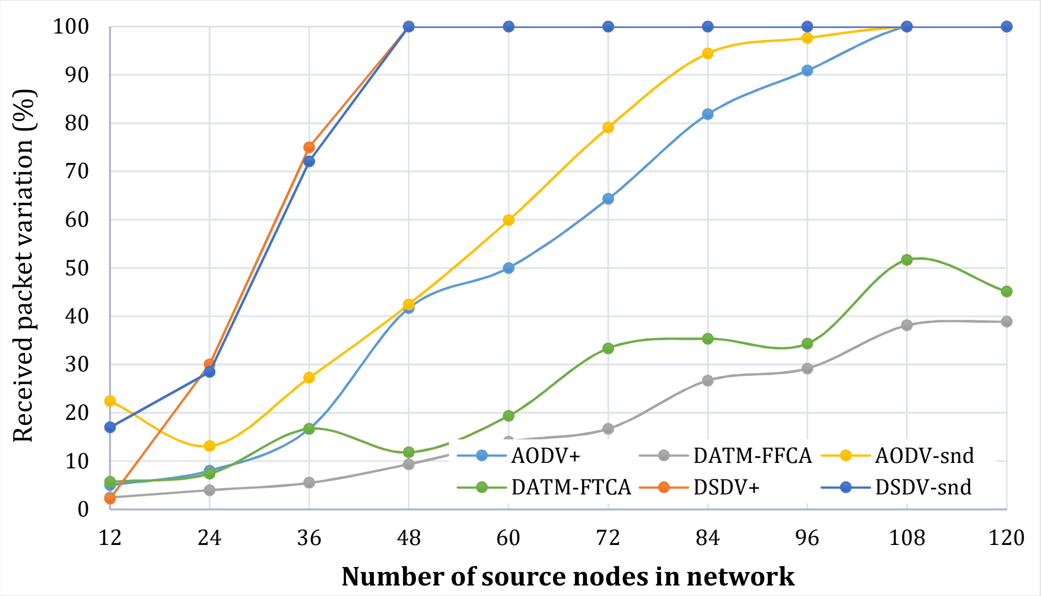


Figure 4-11: Received data packet variation vs. number of source nodes

Variation of received data packets is another parameter in visualising fairness between source nodes in a multi-hop linear network. Referring to Figure 4-11, the percentage of received data packet variation in the proposed models were relatively lower when compared with the other models between low network densities with 12 source nodes to larger network densities with 120 source nodes. Generally, the difference becomes greater with the increasing number of source nodes in a network for all compared methods. The variation between source node data receiving rate is typically due to the data travel cost (total hop metric) in a multi-hop linear network in particular to the allocated proportion for respective nodes. Another crucial factor which contributes towards this variation is dropped data rate where it is considered as wasted network allocation in a bigger context. The proposed models have a better proportioning of network resources which narrow the variation gap that ensures optimum throughput fairness index.

4.3.4.3 Packet Delivery Ratio vs. Number of Source Nodes

A percentage of receiving packets over send packets in a network is a key performance indicator from the perspective of network reliability. The effect of delivery ratio on varying number of source nodes has indicated that both DATM-FFCA and DATM-FTCA has achieved a delivery ratio at a constant rate of above 99 % between low network densities with 12 source nodes to larger network densities with 120 source nodes as shown in Figure 4-12. The proposed models have significantly reduced the number of dropped packets which is a desirable goal in any WSN compared to the other methods in the simulation environment. Generally, the delivery ratio of the compared methods is inverse proportional to the increasing number of source nodes in varying network conditions. Incorporating the proposed models with DI-LSR would add a great value towards successful data packet delivery and further reduces unwanted waste of network resources in a pipeline network.

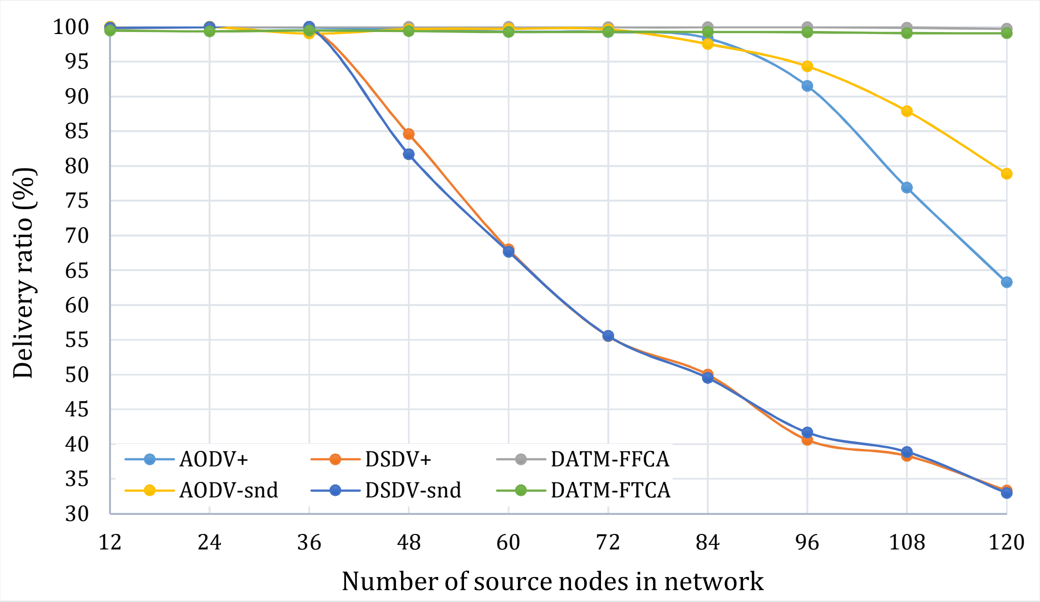


Figure 4-12: Packet delivery ratio vs. number of source nodes

4.3.4.4 Throughput vs. Number of Source Nodes

The average throughput over all flows in the network is a performance indicator in a WSN that reassembles the ability of a network to achieve higher throughput. Generally, the throughput (Kbps) rate in a network with the proposed models outperforms all the other compared methods between low network densities with 12 source nodes to larger network densities with 120 source nodes as shown in Figure 4-13.

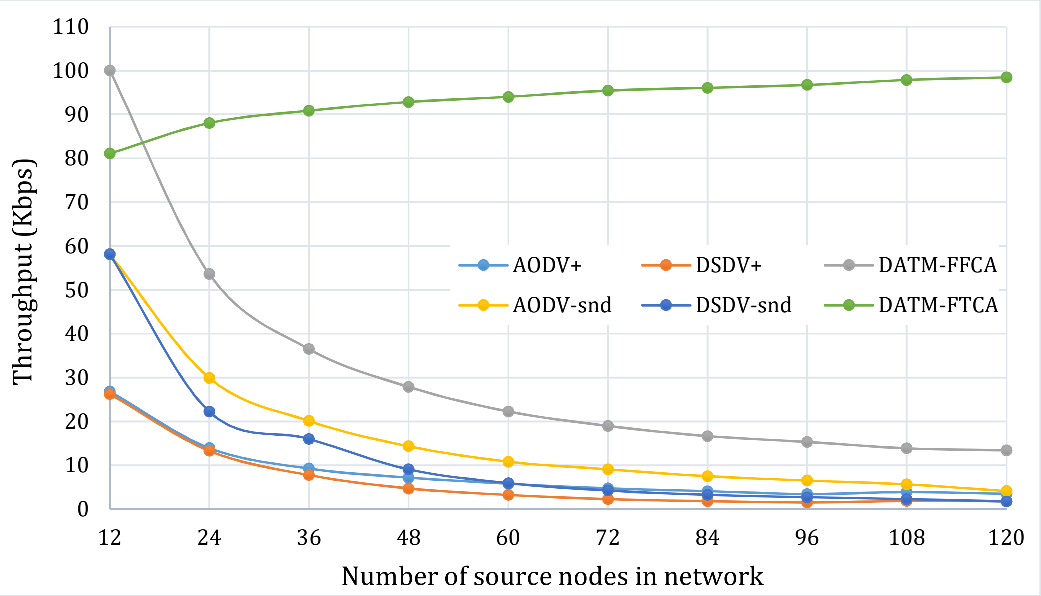


Figure 4-13: Throughput vs. number of source nodes

Since the formulation of the proposed models 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 in the simulated environment. The techniques used in both proposed models were adequate enough to increase the rate of throughput in a unique characteristic by retaining a constant throughput fairness index on all varying environment as shown in Figure 4-10. That's because both variants were designed using a common technique and implemented on the same platform, however, there is a significant variation in terms of throughput performance. The DATM-FFCA will be practical for an application with a moderate rate of throughput while the DATM-FTCA will be practical for an application with a higher rate of throughput. The mathematical formulation of the proposed models has a different effect in low network densities and reflects towards a split direction from an intersection point as shown in Figure 4-13. The other compared method has demonstrated a significant difference and degrading throughput rate with a varying number of source nodes in a network. The proposed models enable higher data transfer rate with the available network resources without fairness trade-off a pipeline network.

4.3.5 Model Three; TCP Delayed Acknowledgement Timeout for Fairness Critical Application

In the proposed model three; TCP delayed acknowledgement timeout model for cluster-based topology for a Fairness critical application (DATM-CFCA) considers the travel time cost between *nn* number of source nodes through a dedicated leader node (cluster head) followed by a series of intermediate cluster heads in only one path (either *odd* or *even* whichever has the greatest hop count) from the destination node in a network. Since the dual cluster head interleaving routing concept introduced in Chapter 3 is based on parallel data transmission that deliberates the assumption of all data packets are transmitted in *cycle time (t)* dedicated for one path [96]. The accumulated hop count known as travel cost is a very important parameter to determine appropriately delayed acknowledgement timeout for *n* number of source nodes located under a dedicated cluster head in both *odd* and *even* path as illustrated in Figure 4-4. The *RTT* value in DATM-CFCA is multiplied with the accumulated hop count for *n* number of source nodes (respective to the total connection under each leader node) in a dedicated leader node (cluster head) followed by a series of intermediate cluster heads with an addition of *cn* which is a transition factor the period between all received packets before the acknowledgement process in a certain network. The factor of *cn* is determined by the number of connection in parallel at a leader node to the main calculated hop count. The transition period between a data packet phase and acknowledgement packet phase is implemented to clear any outstanding data packets in the data stream. The *RTT* value is used as a multiplying factor in deriving an optimum delayed acknowledgement timeout for respective source nodes in the network that is based on distance to travel (calculated by the hop count needed to reach the destination node). Unlike the previous flat one-tier topology models [28], the cluster-based models have an increasing number of hop count due to the implementation on a cluster-based two-tier topology as shown in Figure 4-4. The one path cycle time duration in DATM-CFCA is as formulated in equation 4-4.

$$Fair\ cycle\ time\ (t)\ = \left(\left(\sum_{i=1}^{ch} (H_i + 1) \times n \right) + c \ \ \right) \times RTT \qquad \textbf{4-4}$$

Where *Fair cycle time (t)* is one cycle time taken for *ch* number of cluster heads in a network, H_i is the hop count for *ch* number of cluster heads (either in *odd* or *even* path), *n* is the number of source nodes in a dedicated leader node, *cn* is the factor of transition period and *RTT* is the round trip time (*ms*). Both in the cluster-based and flat topology model allows the users to achieve optimum network fairness (equal share) with a minimum trade-off on the overall network performance, particularly on throughput. That's because both variants were designed using a common technique and implemented on the same platform, without compromising on network fairness and overall network performance. Thus, the values obtained from equation 4-4 can be used in the mathematical formulation of equation 4-2 due to the similarity with the other proposed models. The throughput fairness index of close to one can be achieved with the increasing number of source nodes and cluster heads in a certain wireless network with the proposed DATM-CFCA formulation shown in equation 4-4 and equation 4-2. The sequence of data and acknowledgement packet transmission in DATM-CFCA is similar to the concept in the previous models, wherein the first phase a series of data packets are generated from source nodes to the destination node through a series of cluster heads. The second phase is the transition waiting period between data and acknowledgement packets in one cycle time (*t*). The third phase is followed by a series of acknowledgement packets which are generated respectively based on the sequence of source nodes in a certain network. Unlike in the previous proposed flat one-tier topology models, all data and acknowledgement process in the proposed cluster-based two-tier topology models occurs in a dedicated data stream with the proposed dual cluster head interleaving technique from Chapter 3 which can accommodate a higher amount of traffic in a network.

A multi-hop linear cluster-based network with six source nodes (N1 to Nn) connected under two cluster heads (*odd* path: O1, *even* path E1) to a destination node as ND with the proposed DATM-CFCA in a controlled environment is shown in Figure 4-4. Referring to Figure 4-14, wherein a typical control scenario presumes that all source nodes (N1/N2/N3/N4/N5/Nn) initiate the first data packet (Data-N1/Data-N2/Data-N3/Data-N4/Data-N5/Data-Nn) transmission at time *t+1* to the destination node (ND) at the start of each *1 Sum H cycle (t)* or *fair cycle time (t)*. Figure 4-14 illustrates the timing diagram for a series of data and acknowledgement packets transfer flow with a transition waiting period in the proposed DATM-CFCA.

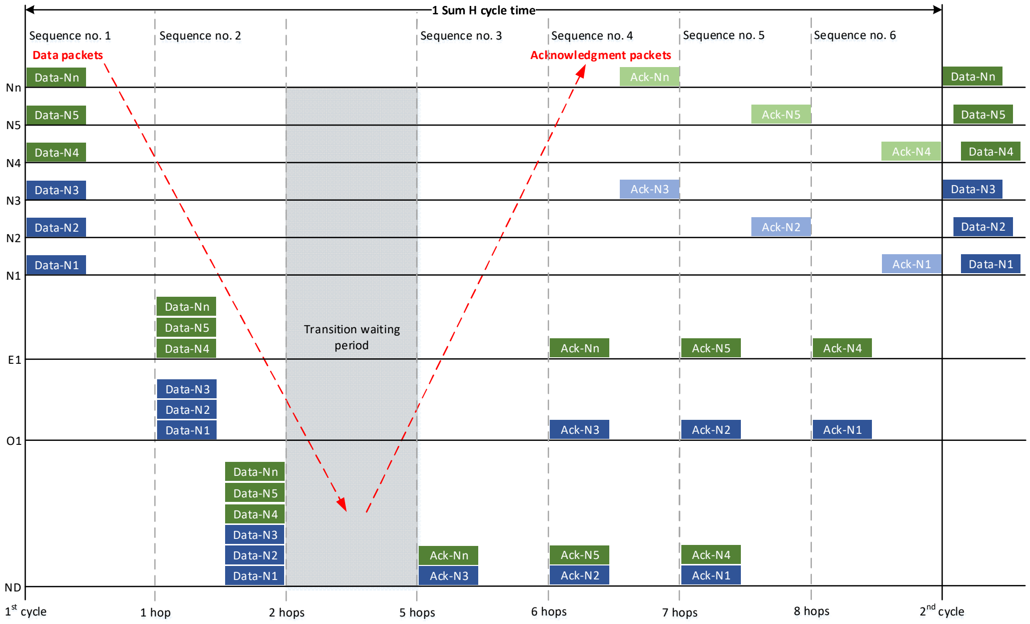
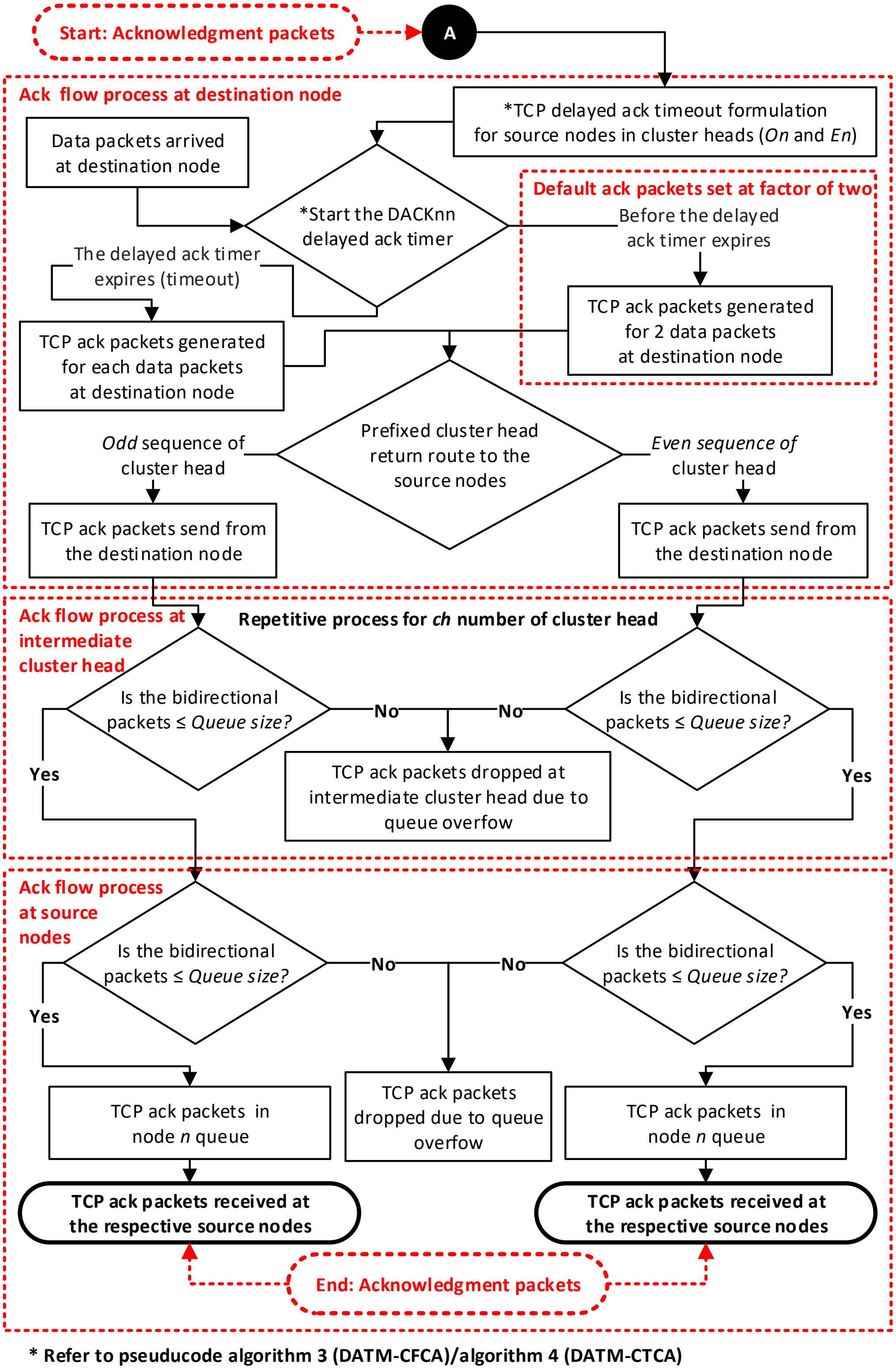


Figure 4-14: The timing diagram of DATM-CFCA

In the *odd* cluster head sequence, the generated data packets (Data-N1/Data-N2/Data-N3) from source nodes (N1/N2/N3) requires one hop to the dedicated leader node (O1) in sequence no. 1 and another hop to reach the destination node (ND) in sequence no. 2 with a total travel cost of two *RTT* value. Where else in the *even* cluster head sequence, the generated data packets (Data-N4/Data-N5/Data-Nn) from source nodes (N4/N5/Nn) requires one hop to the dedicated leader node (E1) in sequence no. 1 and another hop to reach the destination node (ND) in sequence no. 2 with a total travel cost of two *RTT* value. All the data transmission occurs simultaneously as the travel cost rate is same for the explained scenario which is subjected to the data generation time in a network. In a resultant cycle, if there is a glitch in the data sending sequence or latency, the data packets can overflow to the non-activity region which is the transition waiting period.

Based on the mathematical formulation of DATM-CFCA, the first series of acknowledgement packets (Ack-Nn/Ack-N3) at sequence no. 3, (Ack-N5/Ack-N2) at sequence no. 4 and (Ack-N4/Ack-N1) at sequence no. 5 will be generated at the destination node (ND) with one hop required to the respective intermediate cluster head or leader node (O1 and E1). There is a small variation of time (t) between the start time since the respective source nodes are located at a different distance even with the same travel cost under a leader node. This interval will also ease the bottleneck issues and control the volume of traffic at a certain cluster head due to concurrent acknowledgement packet transfer. The acknowledgement packets (Ack-Nn/Ack-N3) at sequence no. 4, (Ack-N5/Ack-N2) at sequence no.5 and (Ack-N4/Ack-N1) at sequence no.6 will be forwarded to one hop required to the respective source nodes from the intermediate cluster head or leader nodes E1 and O1 respectively. The acknowledgement packet from sequence no. 4 will reach the destination node at the edge of seven RTT value. Followed by the acknowledgement packet from sequence no. 5 will reach the destination node at the edge of eight RTT value. While the acknowledgement packet from sequence no. 6 will reach the destination node at the edge of nine RTT value. Since the delayed acknowledgement timeout formulation in DATM-CFCA has a small variation between source nodes, the next cycle data packet generation will be based on this interval. In a controlled environment, the chronology will retain throughout the data and acknowledgement packets transfer process with minimum changes due to cross over at intermediate cluster heads particularly for a network with high densities of source nodes.



*** Refer to pseudocode algorithm 3 (DATM-CFCA)/algorithm 4 (DATM-CTCA)**

Figure 4-15: Delayed acknowledgement process in DATM-CFCA and DATM-CTCA

The brief delayed acknowledgement timeout model for both DATM-CFCA and DATM-CTCA is shown in the flow chart in Figure 4-15 with a significant performance variant as described in Figure 4-16 and Figure 4-18 respectively. From the dual cluster head sequence (*odd* and *even*) shown in Figure 4-4, this would take nine RTT value e.g. (*odd* or *even* cluster head: $2RTT$ + $2RTT$ + $2RTT$) + $3RTT$ (factor of transition period) for *1 Sum H cycle (t)* or *fair cycle time (t)* to achieve the equal data packet transmission opportunity for all source nodes (N1/N2/N3/N4/N5/Nn) in the network. The *cn* factor creates stability when applied to the proposed model to counter the effects of concurrent data and acknowledgement packet transfer at a certain intermediate cluster head. The mathematical formulation process flow in DATM-CFCA is as briefly described in the pseudocode of Figure 4-16.

```
Algorithm 3: Delayed acknowledgement time for DATM-CFCA

Suppose number of source nodes is "nn", number of cluster head is "ch", odd
sequence of cluster head is "$CHO_n$", even sequence of cluster head is "$CHE_n$"
and destination node is "ND = 0"

At time t:

1: For $CHO_n$ or $CHE_n-2\geq 0$ then: (Accumulated required hop(s) + 1 hop) × cn for
                                        every increment in a loop for one path
    else IF $CHO_n-1\geq 0$ then: Required hop(s) for one path + 1 hop

2: For (HopCount$CHO_n$ or HopCount$CHE_n$)×(RTT) then: +1 cycle time per data
                                                          transmission block (cn)

3: For (1 cycle time)- (Nn × RTT)≤nn then: Respective delayed
                                           acknowledgement time for nn
                                           number of source nodes

4: At time t+1: Source nodes nn start sending data packets to ND

5: At time t+n: ND start sending TCP delayed acknowledgement packets to
                source nodes nn based on values in step 3.
```

Figure 4-16: Generating delayed acknowledgement timeout in DATM-CFCA

4.3.6 Model Four; TCP Delayed Acknowledgement Timeout for Throughput Critical Application

The proposed model four; TCP delayed acknowledgement timeout model for a cluster-based topology for a Throughput critical application (DATM-CTCA) considers only the maximum travel time cost on a respective source node located furthest in both *odd* and *even* sequence of cluster head path in a network. Since the dual cluster head interleaving routing concept introduced in Chapter 3 is based on parallel data transmission that deliberates the assumption of data packets are transmitted in *cycle time (t)* dedicated for a path which accommodates all the source nodes within the allocated duration [96]. The accumulated hop count known as travel cost is a very important parameter to determine appropriately delayed acknowledgement timeout for *n* number of source nodes located under a dedicated cluster head in both *odd* and *even* path as illustrated in Figure 4-4.

The travel cost in DATM-CTCA is the maximum number of hop count per path or referred as the maximum hop count of the *n* number of source nodes (respective to the total connection under each leader node) in a dedicated leader node (cluster head) to a destination node. Then, the maximum hop count in each path is accumulated with an addition of *cn* which is a factor of the transition period between all received packets before the acknowledgement process in a certain network as explained in the previously proposed models. The factor of *cn* is determined by the number of predefined paths (both *odd* and *even* sequence of cluster heads). The travel cost is a very crucial parameter to determine appropriately delayed acknowledgement time for each and every source node in both interleaving paths as illustrated in Figure 4-4. The *RTT* value is used as a multiplying factor in deriving an optimum delayed acknowledgement timeout for respective source nodes in the network that is based on distance to travel (calculated by the hop count needed to reach the destination node). The cycle time duration in DATM-CTCA is as formulated in equation 4-5.

$$Fair\ cycle\ time\ (t) = ((((ch_{omax} + 1) \times n) + cn) + (((ch_{emax} + 1) \times n) + cn)) \times RT \qquad \textbf{4-5}$$

Where *Fair cycle time (t)* is one cycle time that accommodates; ch_{omax} is the number of maximum cluster heads in *odd* sequence, ch_{emax} is the number of maximum cluster heads in *even* sequence in a network, *n* is the number of source nodes in a dedicated leader node, *cn* is the factor of transition period and *RTT* is the round trip time (*ms*). The common difference between the proposed DATM-CTCA and DATM-CFCA is typically how the travel cost is derived in terms of hop count with the *cn* factor. Generally, the proposed DATM-CTCA has lower travel cost in a highly densest network compared to DATM-CFCA. The throughput fairness index of close to one can be achieved with the increasing number of source nodes and cluster heads in a certain wireless network with the proposed DATM-CTCA formulation shown in equation 4-5 and equation 4-2. The sequence of data and acknowledgement packet transmission in DATM-CTCA is similar to the concept in the previous models, wherein the first phase a series of data packets are generated from source nodes to the destination node through a series of cluster heads. The second phase is the transition waiting period between data and acknowledgement packets in one cycle time (*t*). The third phase is followed by a series of acknowledgement packets which are generated respectively based on the sequence of source nodes in a certain network.

A multi-hop linear cluster-based network with six source nodes (N1 to Nn) connected under two cluster heads (*odd* path: O1, *even* path E1) to a destination node as ND with the proposed DATM-CTCA in a controlled environment is shown in Figure 4-4. Referring to Figure 4-17, all source nodes (N1/N2/N3/N4/N5/Nn) initiates the first data packet (Data-N1/Data-N2/Data-N3/Data-N4/Data-N5/Data-Nn) transmission at time *t+1* to the destination node (ND) at the start of each *1 Sum H cycle (t)* or *fair cycle time (t)*. In the *odd* cluster head sequence, the generated data packets (Data-N1/Data-N2/Data-N3) from source nodes (N1/N2/N3) requires one hop to the dedicated leader node (O1) in sequence no. 1 and another hop to reach the destination node (ND) in sequence no. 2 where with a total travel cost of two *RTT* value. Where else in the *even* cluster head sequence, the generated data packets (Data-N4/Data-N5/Data-Nn) from source nodes (N4/N5/Nn) requires one hop to the dedicated leader node (E1) in sequence no. 1 and another hop to reach the destination node (ND) in sequence no. 2 where with a total travel cost of two *RTT* value. All the data transmission occurs simultaneously as the travel cost rate is same for the explained scenario which is subjected to the data generation time in a network. In a resultant cycle, if there is a glitch in the data sending sequence or latency, the data packets can overflow to the non-activity region which is the transition waiting period. Figure 4-17 illustrates the basic timing diagram for a series of data and acknowledgement packets transfer flow with a transition waiting period in DATM-CTCA.

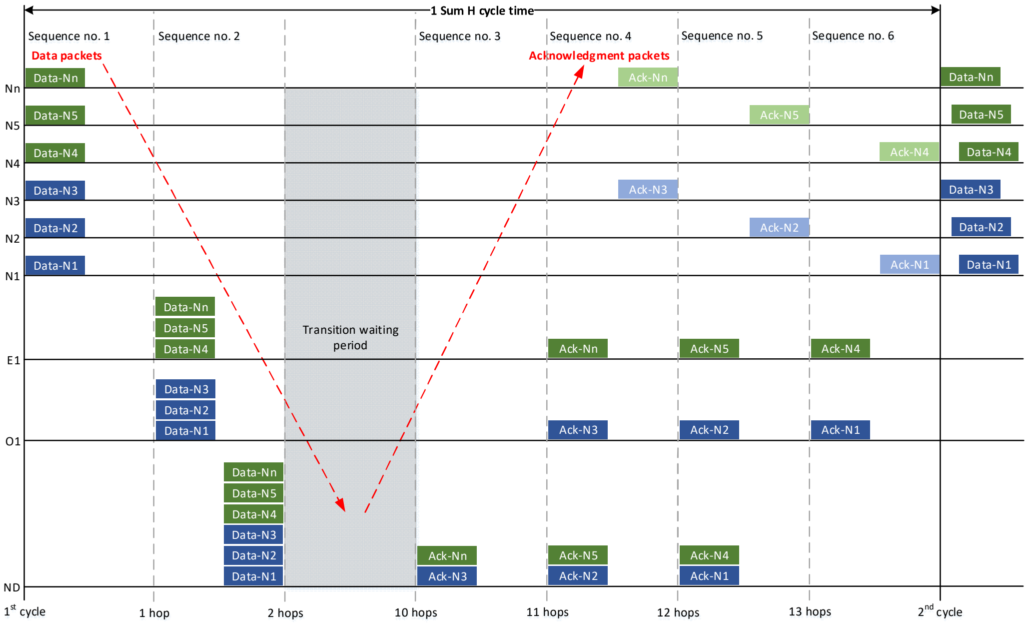


Figure 4-17: The timing diagram of DATM-CTCA

Based on the mathematical formulation of DATM-CTCA, the first series of acknowledgement packets (Ack-Nn/Ack-N3) at sequence no. 3, (Ack-N5/Ack-N2) at sequence no. 4 and (Ack-N4/Ack-N1) at sequence no. 5 will be generated at the destination node (ND) with one hop required to the respective intermediate cluster head or leader node (O1 and E1). There is a small variation of time (*t*) between the start time since the respective source nodes are located at a different distance even with the same travel cost under a leader node. This interval will also ease the bottleneck issues and control the volume of traffic at a certain cluster head due to concurrent acknowledgement packet transfer. The acknowledgement packet from sequence no. 4 will reach the destination node at the edge of twelve *RTT* value. Followed by the acknowledgement packet from sequence no. 5 will reach the destination node at the edge of thirteen *RTT* value. While the acknowledgement packet from sequence no. 6 will reach the destination node at the edge of fourteen *RTT* value. Since the delayed acknowledgement timeout formulation is DATM-CTCA has a small variation between source nodes, the next cycle data packet generation will be based on this interval. In a controlled environment, the chronology will retain throughout the data and acknowledgement packets transfer process with minimum changes due to cross over at intermediate cluster heads particularly for a network with high densities of source nodes.

The proposed model is implemented at the destination node based on a series of data and acknowledgement sequence with specific delayed acknowledgement timeout which is predefined before the acknowledgement packets are sent out to the respective source node as shown in flow chart in Figure 4-15. The mathematical formulation process flow in DATM-CTCA is as briefly described in the pseudocode of Figure 4-18.

Algorithm 4: Delayed acknowledgement time for DATM-CTCA

```
Suppose number of source nodes is “nn”, number of cluster head is “ch”, odd sequence of cluster head is “$CHO_n$”, even sequence of cluster head is “$CHE_n$” and destination node is “ND = 0”
At time t:
1: For $CHO_n$ or $CHE_n-2 \geq 0$ then: (Accumulated required hop(s) + 1 hop) × cn for every increment in a loop for one path
    else IF $CHO_n-1 \geq 0$ then: Required hop(s) for one path + 1 hop
2: For (HopCount$CHO_n$ or HopCount$CHE_n$)×(RTT) then: 1 cycle time per data transmission block
3: For (1 cycle time)- (Nn × RTT)≤nn then: Respective delayed acknowledgement time for nn number of source nodes
```

4: At time t+1: Source nodes *nn* start sending data packets to ND

5: At time t+n: ND start sending TCP delayed acknowledgement packets to
source nodes *nn* based on values in step 3.

Figure 4-18: Generating delayed acknowledgement timeout in DATM-CFCA

The proposed cluster-based models is a comprehensive model for a cluster-based two-tier multi-hop linear topology to achieve optimum throughput fairness among all source nodes in varying number of cluster heads in a network. With a planned timely sequence of generated data packets and pre-calculated delayed acknowledgement packets between a source and a destination node ensures optimum network fairness. Using DATM-CFCA and DATM-CTCA in a TCP agent will ensure optimum throughput fairness with variation in wireless performance metrics for varying number of cluster heads in a multi-hop 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 between respective source nodes and the destination node in a dual path with an appropriate RTT value for each node which is based on distance will benefit from network equality. Changes in a scalable WSN scenario with selective source nodes is applicable in both DATM-CFCA and DATM-CTCA by assigning an accurate hop count referring to equation 4-4 and 4-5 respectively to overcome issues with bandwidth reservation for repeater nodes (non-source nodes) in a long range network.

4.3.7 Network Fairness and Performance Evaluation on Cluster-based Two-tier Multi-hop Linear Topology

The network fairness and overall network performance were simulated in NS2 [103, 125] to visualise the outcome and impending factors when full deployment of DATM-CFCA and DATM-CTCA in a pipeline network. The static routing algorithm proposed in Chapter 3 was implemented with both DATM-CFCA and DATM-CTCA on NS2 where detail analysis was carried on various wireless performance metrics. Both the proposed model was compared with ADAM+ as discussed in Chapter 2 that was implemented with AODV a reactive routing protocol and DSDV a proactive routing protocol [23]. In each simulation environment, an average value of five runs per cycle for the manipulating variable (*ch* number of cluster heads and the *nn* number of source nodes) with different seed values in between 1 to 10 over a simulation duration of 500 seconds. In a cluster two-tier topology, the number of cluster heads is uniformly increased by 4 cluster heads and the number of source nodes is uniformly increased by 12 source nodes in each cycle to 120 source nodes. The configuration and key simulation parameters employed in NS2 to visualise the effects of varying source nodes density is as tabulated in Table 4-3.

Table 4-3: NS2 simulation parameters for cluster-based topology

Key parameters	Set value
Channel type	Wireless channel
Radio propagation model	Two Ray Ground
MAC type	802.11
Interface queue type (ifq)	Drop Tail/PriQueue
Source nodes (SN)	12, 24, 36, 48, 60, 72, 84, 96, 108, 120
Destination node (ND)	1
Cluster head (CH)	4, 8, 12, 16, 20, 24, 28, 32, 36, 40
Queue length (ifqlen)	50 (DATM) & 100 (other methods)
Agent type at source node	TCP/Reno
Agent type at destination node	TCPSink/DelAck
Traffic type	Constant bit rate (CBR)
Transmission range (RX Thresh)	350 meter
Sensing range (CS Thresh)	550 meter
Packet size	512 bytes

The simulation environment was created using a custom random function to test the efficiency and robustness of the proposed models in a near real-time application where the selection of non-chronological sending order and start time for source nodes were randomly chosen for each simulation cycle. The data packet transmission is assigned randomly between 0 – 0.5 seconds at the beginning of the simulation. All nodes mentioned in the simulation are statically placed during the simulation duration with one destination node (ND).

4.3.8 Simulation Results and Discussion for Linear Cluster Two-tier Topology

The ADAM+ as discussed in Chapter 2 was implemented with AODVC and DSDVC that is presented as AODVC+ and DSDVC+ respectively. The network fairness, as well as the performance of DATM-CFCA and DATM-CTCA, is compared with AODVC+ and DSDVC+ for the cluster-based two-tier topology in terms of the performance metrics in section 3.5.

4.3.8.1 Throughput Fairness Index vs. Number of Source Nodes

Network unfairness has a crucial implication towards network stability factor and allocation of network resources in any multi-hop linear wireless network, particularly with only one destination node. The throughput fairness index of 1.0 is the highest desirable rate that represents a network with 100% normalised throughput among all source nodes. Referring to Figure 4-19, the throughput fairness index of both DATM-CFCA and DATM-CTCA outperforms all the other compared methods with a significant difference of 0.07 to 0.5 between low network densities with 12 source nodes to larger network densities with 120 source nodes. With the proposed model, both DATM-CFCA and DATM-CTCA achieved a throughput fairness index between 0.99 to 0.98 and 0.99 to 0.95 respectively with a varying number of cluster heads and source nodes in the simulated environment. The technique of delayed acknowledgement based on node distance used in both methods has significant improvements in terms of throughput fairness index as compared to the TCP agent used in Chapter 3.

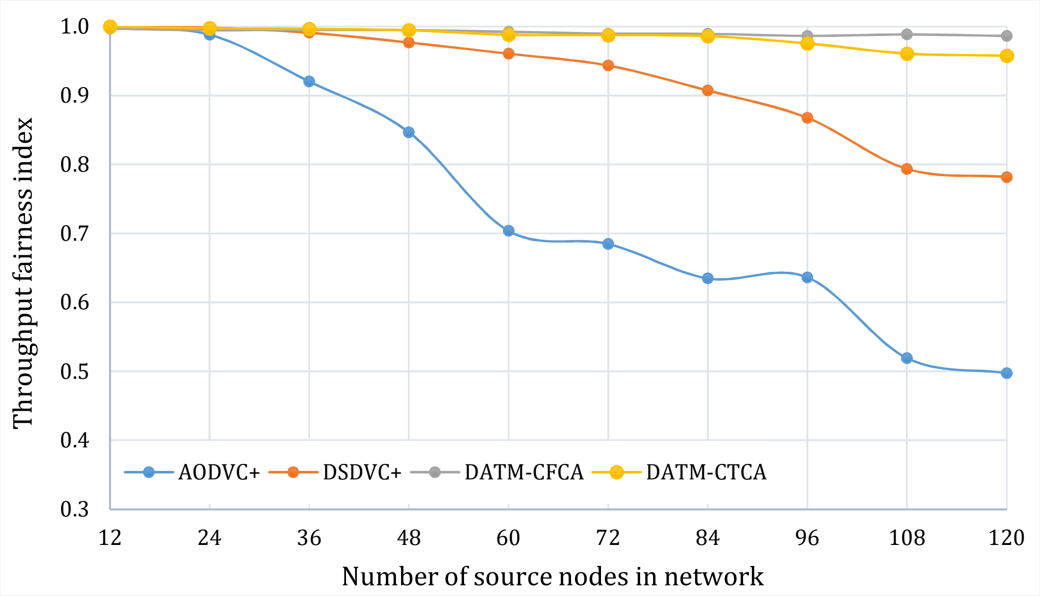


Figure 4-19: Throughput fairness index vs. number of source nodes

4.3.8.2 Received Data Packet Variation vs. Number of Source Nodes

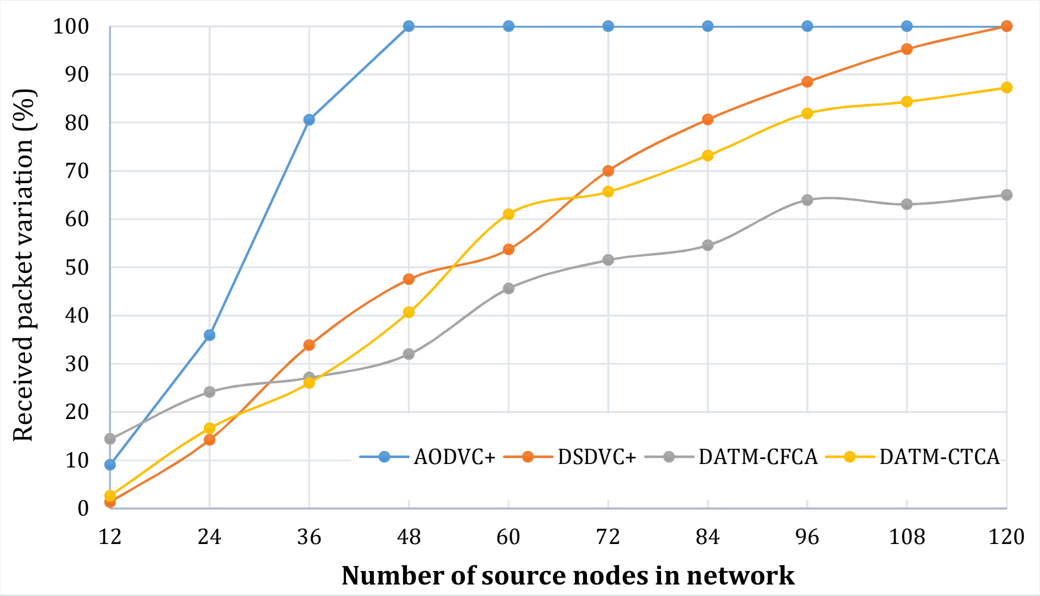


Figure 4-20: Received data packet variation vs. number of source nodes

Variation of received data packets is another perspective of fairness between source nodes in a multi-hop linear network. Referring to Figure 4-20, the percentage of received data packet variation in the DATM-CFCA were relatively lower when compared with the other models from network densities with 36 source nodes to larger network densities with 120 source nodes while the DATM-CTCA has slightly higher variation compared to DATM-CFCA. Generally, the difference becomes greater with the increasing number of source nodes in a network for all compared methods. The variation between source node data receiving rate is typically due to the data travel cost (total hop metric) in a multi-hop linear network in particular to the allocated proportion for respective nodes. Another crucial factor which contributes towards this variation is dropped data rate where it is considered as wasted network allocation in a bigger context. The proposed models have a better proportioning of network resources which narrow the variation gap that ensures optimum throughput fairness index.

4.3.8.3 Packet Delivery Ratio vs. Number of Source Nodes

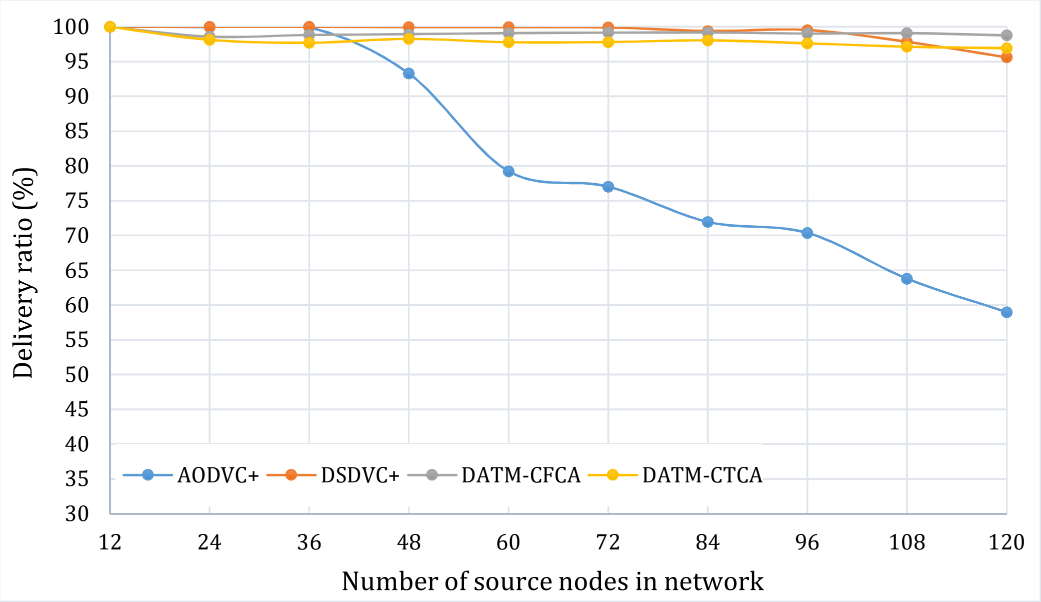


Figure 4-21: Packet delivery ratio vs. number of source nodes

A percentage of receiving packets over send packets in a network is a key performance indicator from the perspective of network reliability. The effect of delivery ratio on varying number of source node and cluster heads has indicated that both DATM-CFCA and DATM-CTCA has achieved a delivery ratio at a constant rate of above 98 % and 96% respectively between low network densities with 12 source nodes to larger network densities with 120 source nodes as shown in

Figure 4-21. The proposed models have significantly reduced the number of dropped packets which is a desirable goal in any WSN compared to the other methods in the simulation environment. Generally, the delivery ratio of the compared methods is inverse proportional to the increasing number of source nodes in varying network conditions. Incorporating the proposed models with DCHI-LSR would add a great value towards successful data packet delivery and further reduces unwanted waste of network resources in a pipeline network.

4.3.8.4 Throughput vs. Number of Source Nodes

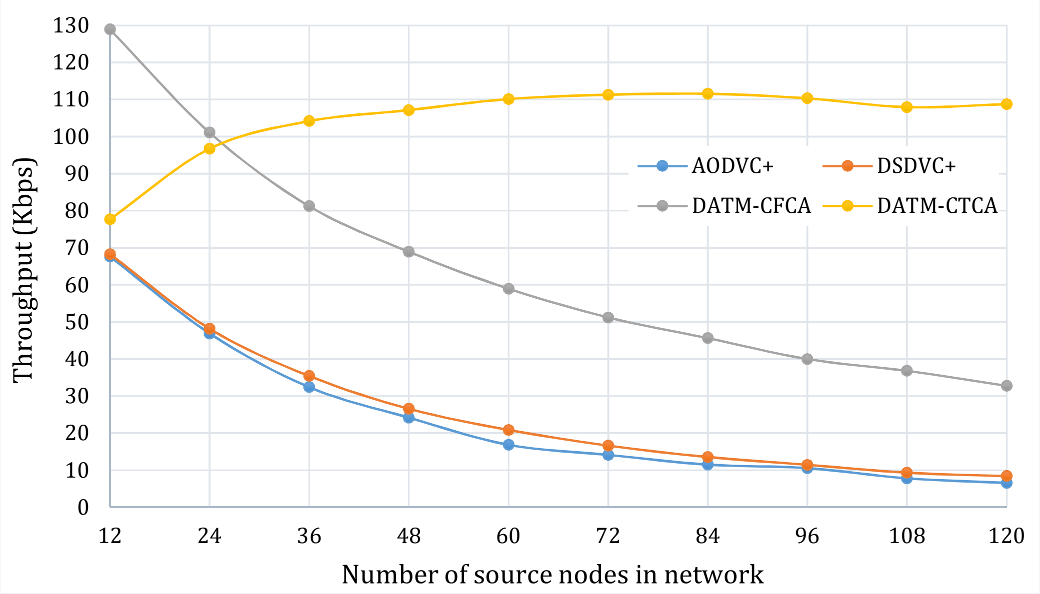


Figure 4-22: Throughput vs. number of source nodes

The average throughput over all flows in the network is a performance indicator in a WSN that reassembles the ability of a network to achieve higher throughput. Generally, the throughput (Kbps) rate in a network with the proposed models outperforms all the other compared methods between low network densities with 12 source nodes to larger network densities with 120 source nodes as shown in Figure 4-22. Since the formulation of the proposed models 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 in the simulated environment. The techniques used in both proposed models were adequate enough to increase the rate of throughput in a unique characteristic with throughput fairness index above 0.95 on all varying environment. However, the techniques used in both proposed models have a significant variation in terms of throughput performance in a cluster-based network. The DATM-CFCA will be practical for an application with a moderate rate of throughput while the DATM-CTCA will be practical for an application with a higher rate of throughput. The mathematical formulation of the proposed models has a different effect in low network densities and reflects towards a split direction from an intersection point as shown in Figure 4-22. The other compared method has demonstrated a significant difference and degrading the throughput rate with a varying number of source nodes in a network. The proposed models enable higher data transfer rate with the available network resources without fairness trade-off in a pipeline network.

4.4 Conclusion

This chapter mainly presented four proposed TCP delayed acknowledgement timeout models; the DATM-FFCA and DATM-FTCA were implemented on a flat (one-tier) multi-hop linear topology whereas DATM-CFCA and DATM-CTCA were implemented on a cluster-based (two-tier) multi-hop linear topology. The implementation of all four proposed models in respective wireless topologies has highlighted optimum network fairness as well as a significant variation in terms of overall network performance on a pipeline network. The proposed models have a unique formulation in deriving a delayed acknowledgement timeout to achieve equality in network allocation among source nodes in varying distance arranged in a linear one-tier and two-tier architecture. The simulated results have demonstrated that both DATM-FFCA and DATM-FTCA has achieved a significant level of improvements in network fairness, reliability (delivery ratio), latency (end-to-end delay), responsiveness (dealing with node failures) and network capacity (throughput) which had crucial implication towards the overall network performance on a pipeline network.

The average value and percentage difference comparison with and without the implementation of the proposed DATM-FFCA and DATM-FTCA on a flat one-tier multi-hop linear topology are shown in Table 4-4 and Table A-1.

Table 4-4: Comparison between DI-LSR, DATM-FFCA and DATM-FTCA

Measured parameters	Standard DI-LSR	DATM-FFCA	Difference	Percentage (%)
		DATM-FTCA		
Average throughput fairness index	0.672	0.996	↑ 0.324	+48.21
		0.998	↑ 0.326	+48.51
Average received packet variation (%)	77.22	18.47	↓ 58.75	+58.75
		26.06	↓ 51.16	+51.16
Average delivery ratio (%)	83.67	99.9	↑ 16.23	+16.23
		99.28	↑ 15.61	+15.61
Average throughput (Kbps)	99.6	31.85	↓ 67.75	-68.02
		93.16	↓ 6.44	-6.47

The simulated results have demonstrated that both DATM-CFCA and DATM-CTCA has achieved a significant level of improvements in network fairness, reliability (delivery ratio), latency (end-to-end delay), responsiveness (dealing with node failures) and network capacity (throughput) which had crucial implication towards the overall network performance on a pipeline network.

The comparison with and without the implementation of the proposed DATM-CFCA and DATM-CTCA on a cluster-based two-tier multi-hop linear topology is shown in Table 4-5 and Table A-2.

Table 4-5: Comparison between DCHI-LSR, DATM-CFCA and DATM-CTCA

Measured parameters	Standard DCHI-LSR	DATM-CFCA	Difference	Percentage (%)
		DATM-CTCA		
Average throughput fairness index	0.634	0.992	↑0.358	+56.47
		0.985	↑0.351	+55.36
Average received packet variation (%)	79.02	44.12	↓34.9	+34.9
		53.91	↓25.11	+25.11
Average delivery ratio (%)	77.46	99.07	↑21.61	+21.61
		97.94	↑20.48	+20.48
Average throughput (Kbps)	119.72	64.56	↓55.16	-46.07
		104.58	↓15.14	-12.65

The four proposed TCP delayed acknowledgement timeout models were designed to achieve optimum network fairness and overall network performance on a pipeline network. However, acknowledgement packets and number of data transmission are scheduled at each block (based on fair cycle time), which requires partial time synchronization among nodes in the network. Due to the scheduling factor and reduced data transmission, the average network capacity is capped based on the characteristic of the proposed model (fair cycle time). The proposed TCP delayed acknowledgement timeout models cater only for unpredicted data transmission rather than a scheduling based data transmission or a combination of both. Furthermore, this contributes towards higher energy consumption that is subjected to the number of nodes and communication range of nodes in the network. In the next chapter, a proposed scheduling scheme to optimise network energy consumption for the proposed models to create an energy efficient network energy model in a multi-hop linear network will be presented.

Chapter 5

AHiT Energy Model for Multi-hop Linear Topology

5.1 Introduction to Energy Model

The WSN is evolving towards higher scale applications and deployment that demands extensive preference particularly in the monitoring of oil and gas pipelines. The widespread adoption of WSN in the oil and gas industry is crucial and performance driven that incorporates several remote independent measurements points through a communication chain for accomplishing diverse goals. The deployment of a WSN in a pipeline network is for long-term monitoring of all physical as well as dynamically changing environments in a remote location distance away from the monitoring station. In a widespread implementation of WSN in a pipeline network mostly comprise of stationary sensing points that are randomly deployed based on the geographical layout of the pipeline for data collection. The collected data is transmitted to the monitoring station (destination node) in a multi-hop communication architecture. In such application, the rapidly generated volume of planned and unplanned data demand a reliable routing algorithm with an efficient energy model for the uninterrupted operation to accommodate the randomly changing environment in a multi-hop linear topology.

The deployed wireless nodes can either be powered by a constant power source or with a power pack (battery operated) that requires charging or replacement over a period of time. With the intervention of renewable energy in remote monitoring applications, the lifespan of batteries is often prolonged with a recharging mechanism through energy harvesting for uninterrupted operation. Generally, the nodes in a multi-hop linear WSN have a varying energy consumption against the node distance from the destination node located at the end of the network. The energy consumption of nodes located nearest to the destination node has an increased energy usage to accommodate the data and control packets from the neighbouring nodes. Figure 5-1 illustrates the source node energy consumption characteristics between nodes *Nn* to *ND* on a multi-hop linear WSN. The data packets are indicated as *DP* and the control packets are indicated as *CP* from respective nodes indicated inflows, *Fn* where *n* is the node number that represents the bi-directional packets between a destination node.

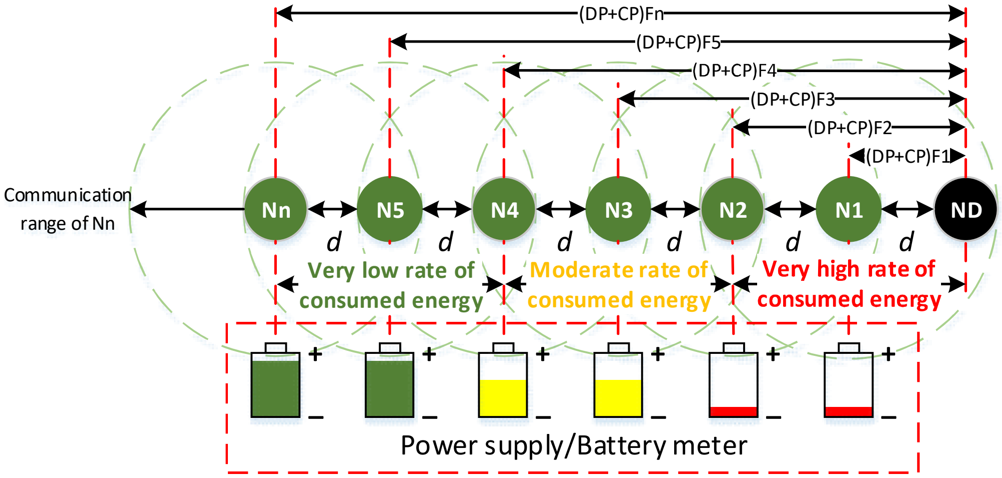


Figure 5-1: Energy consumption in a multi-hop linear WSN

In such a WSN setup, a source node establishes communication with every single node in its communication range directly to move the collected data forward to a designated node. In a multi-hop linear WSN, the energy consumption of wireless nodes is a critical factor for the sustainability of the network in the long run. However, due to its unique geographical linear structure of pipelines, the two foremost WSN drawbacks of such a topology are; (1) energy optimisation and (2) network lifetime. In recent years, many new directions on both hardware and software are attempted in making an energy efficient WSN for long term deployment in oil and gas pipelines. Particularly, enhancing the routing algorithm and improvising the existing energy model that caters to the high needs of energy requirements on a conventional multi-hop linear WSN.

This chapter mainly introduces the Active High Transmitter-receiver (AHiT) energy model that emphasises an adaptive *on* and *sleep state* switching scheme for respective nodes in the network to optimise energy usage only in an active period of time. The AHiT energy model can be established on both flat one-tier and cluster-based two-tier multi-hop linear topology for network energy optimisation.

5.2 Factors in Energy Model

A wireless node is independently equipped with a communication mechanism, processing unit and a power unit that executes data collection to transfer data as required by the user. Extensive research was focused on energy efficiency particularly in IEEE 802.11 standard in the recent years with a wide range of communication algorithm and energy model as a solution [100, 147, 148]. In most cases, studies were focused on generic WSN applications rather than the progressive technology advancements on both the hardware and software for future applications. The generic WSN focused on an assumption where the sensors are randomly deployed in a specific region where a repetitive predefined task is performed [147]. The devices based on IEEE 802.11 standard are known for higher energy consumption compared to low energy devices on IEEE 802.15.4 standard such as ZigBee, 6LoWPAN and WirelessHART. [147, 149]. Although this standard solution has an extensive range of application yet it is not optimised to support in large-scale areas particularly in an application on oil and gas pipelines. In a specific WSN application as in the oil and gas pipelines, the customization and practicality of an energy model to accommodate unique needs in the long run operation is rather crucial for the users. However, the energy consumption of this WSN poses several challenges based on the characteristic of a multi-hop linear topology; (1) network lifetime, (2) communication range and (3) network scalability [106, 147, 150]. In the following section, the WSN factors and related parameters for an efficient pipeline network environment are described.

5.2.1 Consumed Energy and Network Lifetime

Energy consumption in a multi-hop linear topology is a crucial parameter and often related to network lifetime [100]. A multi-hop linear topology with uniformly distributed nodes that communicates to a destination node at the end of a network generally has a high tendency in node energy depletion especially among nodes that are located close to the destination node at a much higher rate than the one furthers in the network. On the other hand, the hop count as discussed in Chapter 3 is the fundamental metric in a multi-hop linear topology for optimum energy consumption by considering only the minimum communication links between a source and a destination node. In a real-world application, the un-uniformed distribution of nodes and communication distance may contribute to variation in energy usage at each node level that can affect the network lifetime significantly. Hence, shortens the network lifetime that further result in communication chain breakage when these nodes are out of energy source [150]. These are a common scenario for both infrastructure and non-infrastructure based WSN, where energy optimisation is neglected, unlike any other topology where a substitute path is formed in such critical energy state in a given region. In many publications on energy model for WSN has highlighted that the key parameters of improvements in communication protocols are the energy consumption and extension of network lifetime [150].

5.2.2 Communication Range

The communication range in a WSN is an important parameter that is often related to energy consumption with the variation on the IEEE 802.11 standard. Generally, the energy consumption for data transfer between two nodes in a network can be defined with the energy specification of transmission power and antenna gain. Some of the crucial factors affecting the communication range of a WSN is the physical layer quality and the data transmission efficiency in the network [150]. The communication range of a WSN solely depends on the type of hardware used by the user. Thus, the optimisation of communication range overlapping among nodes and uniform distribution of nodes in a linear topology is a weighing factor for energy consumption. On the other hand, node position in relation to communication range as mentioned in Chapter 3 contributes to unbalanced traffic and bottleneck in a network that can result in higher energy consumption that significantly reduces the network lifetime. Scalability is the property interrelated to communication range and the ability to adapt with the network extension on an existing infrastructure particularly energy resources [150].

5.2.3 Energy Optimization

Energy optimisation among nodes in a multi-hop linear topology is an essential element that contributes significantly towards the network lifetime extension [151]. Energy optimisation should be established on individual nodes rather than the entire network in whole as in the multi-hop linear topology has a varying energy consumption rate. At individual nodes, energy optimisation can be achieved with an optimum data transmission period. The general operation pattern of a WSN in *on state* is sending data and receiving control packets in between *idle state* for a length of time [100, 148]. In some cases, the energy is not being utilized in a prolonged *idle state* in a certain network due to periodic data transmission pattern. The energy consumption of nodes in the *idle state* is equivalent to the data transmission energy unlike the energy consumption in the *sleep state* that is much lesser than the *idle state* that is subjected to the hardware specification [108, 148, 152]. The radio frequency module at a node is set at high energy state to send or receive data, active or listen mode and at *idle state*. Whereas the radio frequency module at a node is set at low energy state in the *sleep state* and with some devices the radio frequency module is at *off state*. Therefore, energy consumption of a node is set at high in *on* and *idle state* with radio frequency module is always *on* [100]. To reduce the energy consumption, the *sleep-wake* scheduling techniques can be exploited from energy wastage during the *idle state*. Therefore, energy optimisation in a WSN can extend the network lifetime with a tailored energy model relevant to the data traffic and implemented topology.

5.3 Active High Transmitter-receiver Energy Model (AHiT)

The proposed energy model is designed to optimise consumed energy by reducing energy in a non-productive network state. The AHiT energy model deploys an adaptive sleep intervals in between active states at respective nodes that take full advantage of the sleep duration to reduce energy wastage in idle energy state at each node level. The energy saving in *sleep state* varies from one source node to another that contributes towards prolonged network lifetime. Based on the addressed problems in the previous section, all sensor nodes send their data packets to the destination node located at the end of the network in a typical multi-hop linear WSN with nodes closest to the destination node have to handle relatively higher data traffic [100]. Thus, increasing energy consumption of those nodes nearest to the destination node in a multi-hop linear WSN is a critical factor for decreasing network lifetime in the long run. Generally, a sleep and wake up scheduling model disregard the fact that high volume packets go through nodes closest to the destination node resulting in deteriorated of energy and performance in the network [100, 153, 154].

The AHiT energy model is proposed to minimise the known fact of the deteriorating energy in a multi-hop linear WSN by considering the fact that each node has a different forwarding requirement according to the distance from the destination node in such network. The adaptive sleep intervals and wake up of nodes/cluster heads are individually associated with the generated data packets and forwarding pattern of the respective source or intermediate node through the path towards the destination node. The network activity is often subjected to the data rate at the source nodes and the type of transport agent used. The data traffic of source nodes is concurrently generated at a preset time to the destination node whereas in a real scale application, the data traffic may differ according to the detection of sensors (both scheduled and unscheduled) and to the proximity event occurrence at neighbouring nodes/cluster heads in the network. Referring to all these factors, each node/cluster head has an asynchronous sleep and wake up pattern affecting the neighbouring nodes in regards to the distance from the destination node.

In an event where the nodes/cluster heads nodes are interrupted during the *sleep state*, the node will remain active until the required task is performed before changing to the *sleep state* again. The active duration of each node/cluster head is based on the data traffic that the respective node/cluster head is required to handle. Thus, the energy consumption of a certain node/cluster head can be reduced in the period between one active states to another active state in the network. The timing diagram for the *Nn* number of source nodes in a flat one-tier multi-hop linear topology with the proposed energy model is as shown in Figure 5-2. Sleep indicates the *sleep state*, *on* indicates the node *active state* (wake up) and the *transition state* is based on transition *t*, the time required for the node to change state from sleep to wake up. In the *active state*, the node is able to transmit data packets and receive acknowledgement packets accordingly. The *active state* from the *sleep state* is accomplished with an internal interrupt to reduce the scheduled data packet losses as in a traditional sleep scheduling method. The internal interrupt enables the nodes to efficiently forward data packets as required with optimum energy consumption at each node level.

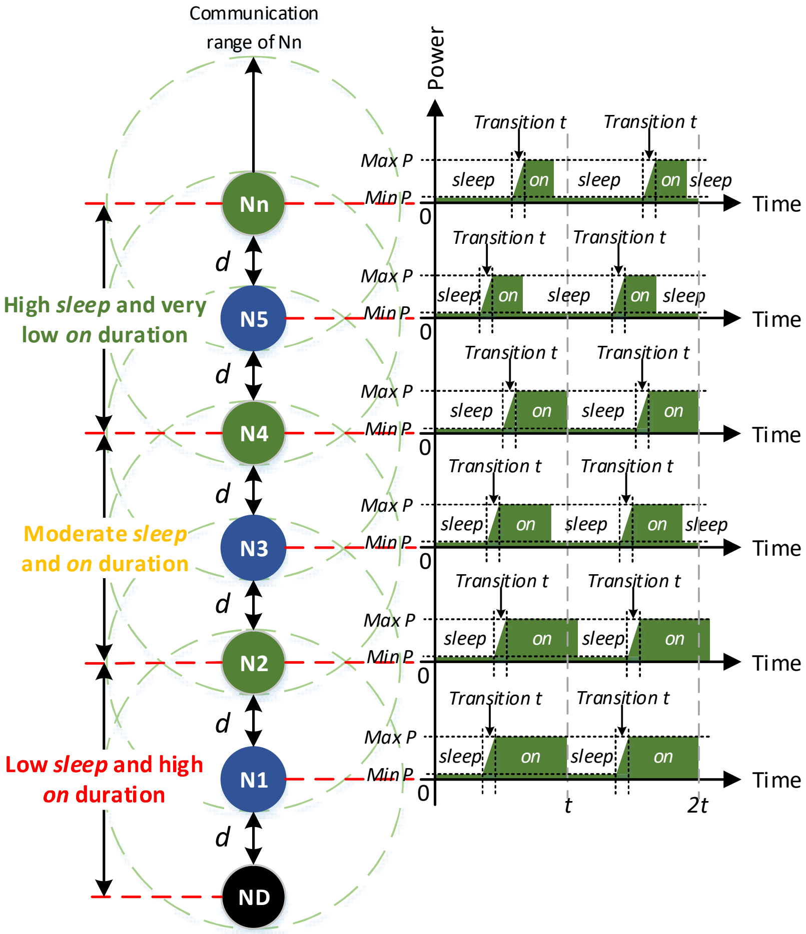


Figure 5-2: Timing diagram in a flat one-tier multi-hop linear topology

With the proposed energy model implemented in both flat one-tier and cluster-based two-tier network, the nodes/cluster heads that is located closest to the destination node will be in a *sleep state* with shorter probability whereas the nodes/cluster heads that are located further from the destination node will be in a *sleep state* with longer probability. Therefore, the active duration of the nodes/cluster heads increases proportionally as the nodes/cluster heads are closer to the destination node to support the data forwarding from the neighbouring nodes. A node/cluster head with a shorter distance to the destination node, the greater the active interval is assigned to accommodate greater data traffic compared to the nodes/cluster heads located away from the destination node. In each active cycle, the source node prompts to occurring events not only within the nodes but also to support the data communication chain towards the destination node. Thus the active duration will remain in longer intervals as these nodes/cluster heads are connectivity critical nodes in a multi-hop linear topology. The scenario is different for source nodes in a cluster-based topology as shown in Figure 5-3, whereby this node acts as a transponder at all-time where else the cluster heads act as a data stream to support the data transfer for the entire network.

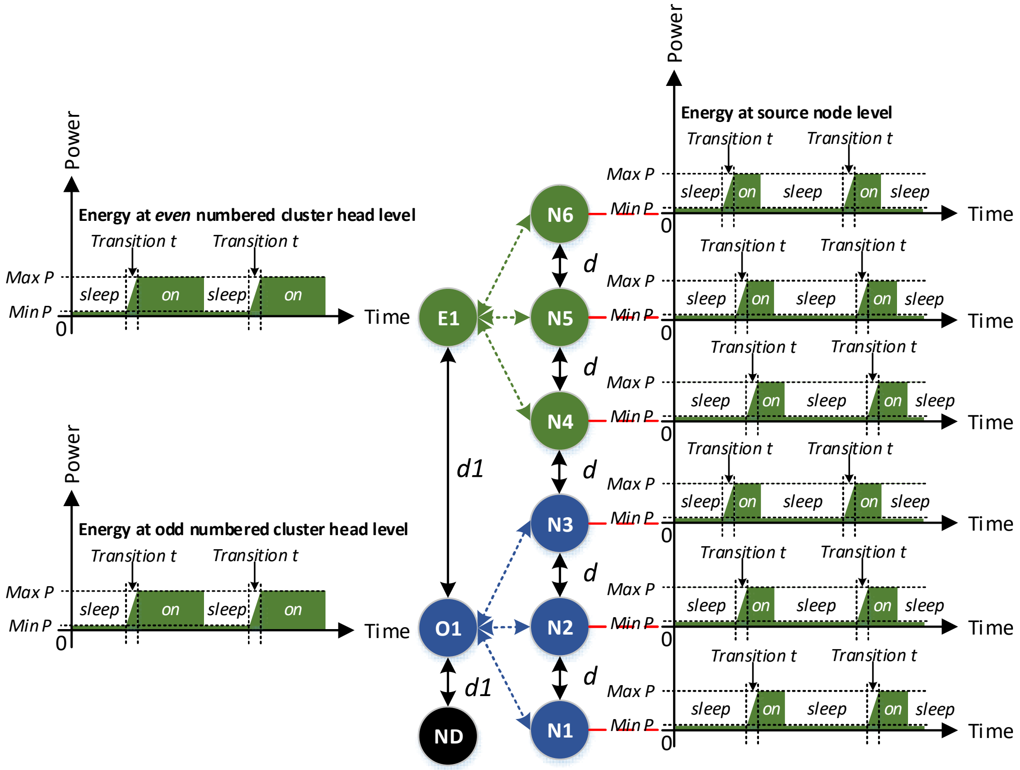


Figure 5-3: Timing diagram in a cluster two-tier multi-hop linear topology

The changeover from the *sleep state* to *wake up state* with an internal interrupt provided to a certain node/cluster head according to the traffic pattern is essential to regain communication connectivity to the designated destination node. Generally, connectivity critical source or intermediate nodes/cluster heads require longer wake up duration to accommodate higher data traffic in ensuring uninterrupted data transfer whenever required in the network. On the other end of the network (end node/cluster head), non-connectivity critical nodes require shorter wake up duration to accommodate lower data traffic to save the consumed energy. The energy consumed in a network can be sectioned in several energy states that are gained from all nodes in the network as described in Equation 5-1.

$$Total\ E = \sum_{i=1}^{nn}(Tx\ E_i + Rx\ E_i + idle\ E_i + sleep\ E_i + transition\ E_i) \qquad \mathbf{5\text{-}1}$$

Where *Total E* is the total energy across a certain network, $Tx\ E_i$ is the transmission energy, $Rx\ E_i$ is the reception energy, $idle\ E_i$ is the idle energy spent in nodes in an *idle state*, $sleep\ E_i$ is the sleep energy and $transition\ E_i$ is the transition energy for a certain number of nodes in the network. In the proposed energy model, $idle\ E_i$, $sleep\ E_i$ and $transition\ E_i$ are constant whereas $Tx\ E_i$ and $Rx\ E_i$ varies upon the communication distance.

In a real life application, an event occurs (sensor detection) at a random and un-uniformed interval at source nodes in the network. With the internal interrupt detecting the incoming packets at the physical layer and outgoing packets in data scheduler adapts itself according to the data transmission pattern to change from *sleep* to *wake up state*. This is possible since the node in a *sleep state* is able to listen to the network activity of the neighbouring nodes. In a hardware-based system, the interrupt (external and internal) activates the nodes from *sleep* to *wake up state* based on an occurring event in the sensing section of nodes at any time slot and is likely to affect the subsequent nodes in the network towards the destination node. Thus, with the interrupt, the nodes are able to adapt to the network data traffic needs by optimising the *sleep state* before the *wake up state* rather than wasting energy in the waiting period. Similarly, the interrupt from one node will influence the neighbouring nodes in the direction of the destination node for data packets and otherwise in the opposite direction for acknowledgement packets. In a chain-like reaction, the optimum sleep time can be achieved at each node/cluster head level and can significantly reduce energy wastage in the network to prolong the network lifetime. The flow chart presented in Figure 5-4 summarises the energy states in the proposed energy model is for better understanding.

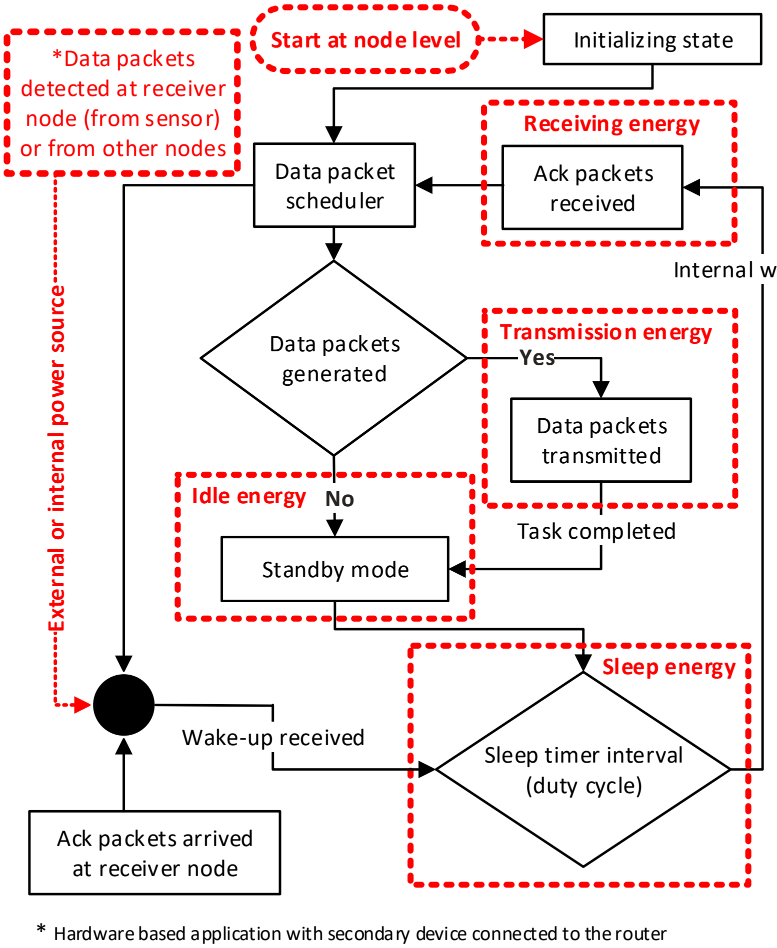


Figure 5-4: Flow chart of the AHiT energy model

5.4 Energy Efficiency Evaluation on Energy Model

The energy performance was simulated in NS2 [34, 125] to visualise the behaviour and impending factors with full deployment of methods proposed in Chapter 3 and Chapter 4 in a pipeline network. The static routing algorithm proposed in Chapter 3 and network fairness model proposed in Chapter 4 was implemented with the proposed energy model for detail analysis on various wireless energy performance metrics was compared with and without the implementation of the energy model. The configuration and key simulation parameters employed in NS2 on the effects of varying source nodes density is as tabulated in Table 3-1 and

Table 4-2 for a flat topology whereas Table 3-2 and Table 4-3 for cluster-based topology.

5.5 Energy Performance Metrics

To test and evaluate the proposed energy model, a number of varying scenarios were created in the simulation tool. The energy characteristic of DI-LSR, DCHI-LSR, DATM-FFCA, DATM-CFCA, DATM-FTCA and DATM-CTCA can be visualised on the following wireless energy performance metrics:

5.5.1 Energy Consumption

Energy consumption in a network can be described as in equation 3-12.

5.5.2 Variation of Energy Consumed

The variation of consumed energy is the measurement difference between a maximum and a minimum consumed energy among source nodes in a network as described in equation 5-2.

$$Variation\ CE\ = \frac{(Max\ CE - Mi\ \ \ CE)}{Max\ CE} \times 100\% \qquad \textbf{5-2}$$

Where *Max CE* is the maximum consumed energy and *Min CE* is the minimum consumed energy for a ceratin number of source nodes in the network.

5.5.3 Network Lifetime

The network lifetime in a multi-hop linear topology can be defined as the first node to switch state from *on* to *off* due to high energy exhaustion among source nodes in a network [155] as described in equation 5-3.

$$Network\ lifetime = \frac{ES}{Max\ CE} \times (\ t_{End} -\ t_{Start}) \qquad \textbf{5-3}$$

Where *ES* is the energy supplied, *Max CE* is the maximum consumed energy for a certain number of source nodes and t_{End} - t_{Start} is the *Δ Duration t* for the entire simulation duration.

5.6 Simulation Results and Discussion: DI-LSR and DCHI-LSR

The energy performance of both DI-LSR and DCHI-LSR was implemented with the AHiT energy model is presented as DI-LSR+ and DCHI-LSR+ respectively. The DI-LSR+ was compared with the traditional DI-LSR for flat one-tier topology and the DCHI-LSR+ was compared with the traditional DCHI-LSR for cluster-based two-tier topology in terms of the energy performance metrics in section 5.5.

5.6.1 Flat Topology: Energy Consumption vs. Number of Source Nodes

The energy consumption per-packet effect on varying number of source nodes is as shown in Figure 5-5, that indicates the DI-LSR+ and DI-LSR has a consistent increase in consumed energy to the network size. With the implementation of AHiT, DI-LSR+ has relatively lower energy consumption as compared with the traditional DI-LSR from a low network density with 12 source nodes to a larger network density with 120 source nodes. The adaptive sleep mode enables optimum energy saving in an inactive energy state among source nodes in the network. The increased energy saving is linearly proportional to the source nodes in a sequential arrangement from the destination node in the network. The source nodes located in the incrementing distance from the destination node has less data transmission activity or infrequent data transfer in between nodes, thus enables optimum sleep duration to save energy usage instead of in a waiting period at each varying simulation environment. An energy efficient model ensures continued and uninterrupted operation in a typical multi-hop linear wireless network, particularly when the nodes are battery power dependent.

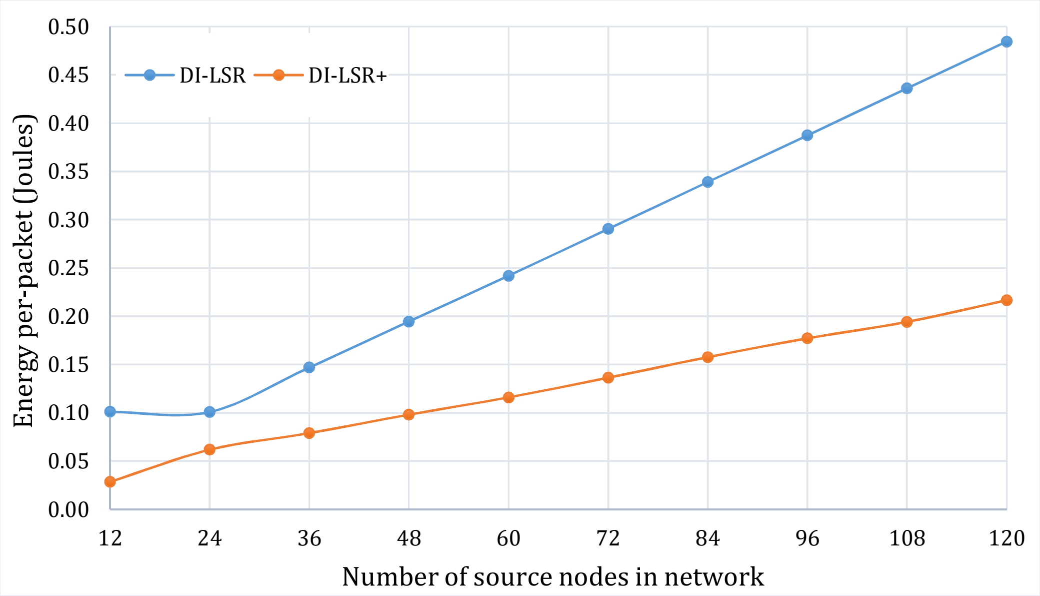


Figure 5-5: Energy per-packet vs. number of source nodes

5.6.2 Flat Topology: Consumed Energy Variation vs. Number of Source Nodes

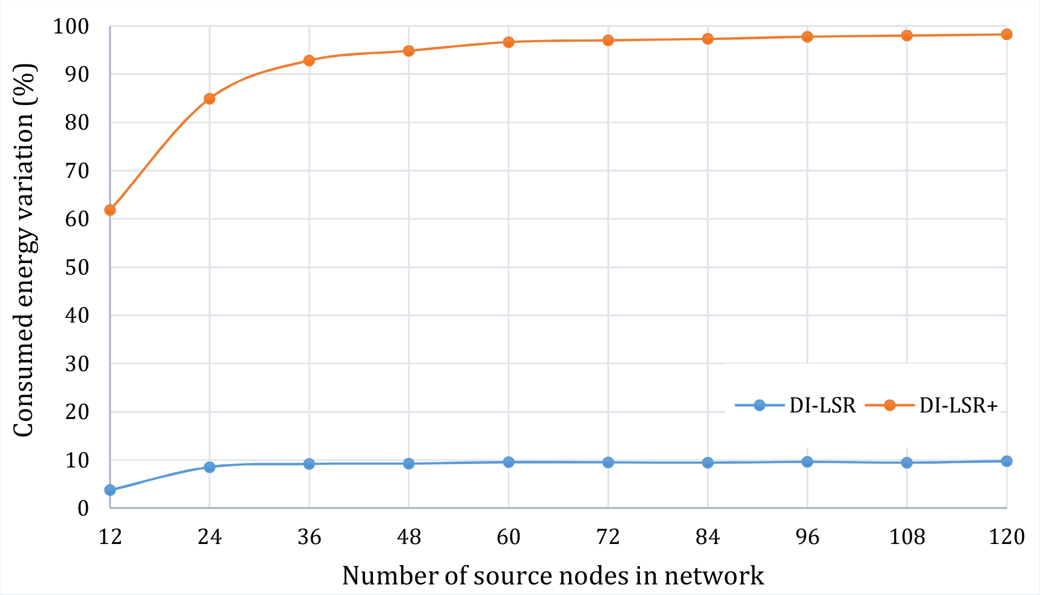


Figure 5-6: Variation of consumed energy vs. number of source nodes

The variation of consumed energy is another parameter in visualising optimum energy usage among respective source nodes in a multi-hop linear network.

Referring to Figure 5-6, the percentage indicated that the variation of energy consumed by DI-LSR+ has a significant difference at a rate of 90% and above in average from a low network density with 36 source nodes to a larger network density with 120 source nodes. With the implementation of adaptive sleep mode that enables optimum energy saving based on the required active states at each node level in the network, thus results in a significant difference in percentage becomes greater with the varying number of source nodes in a network when compared with the traditional DI-LSR. Source nodes located at the far end of the network consumes the least energy compared to the source node nearest to the destination node that creates the significant variation of energy consumed at each varying simulation environment.

5.6.3 Flat Topology: Network Lifetime vs. Number of Source Nodes

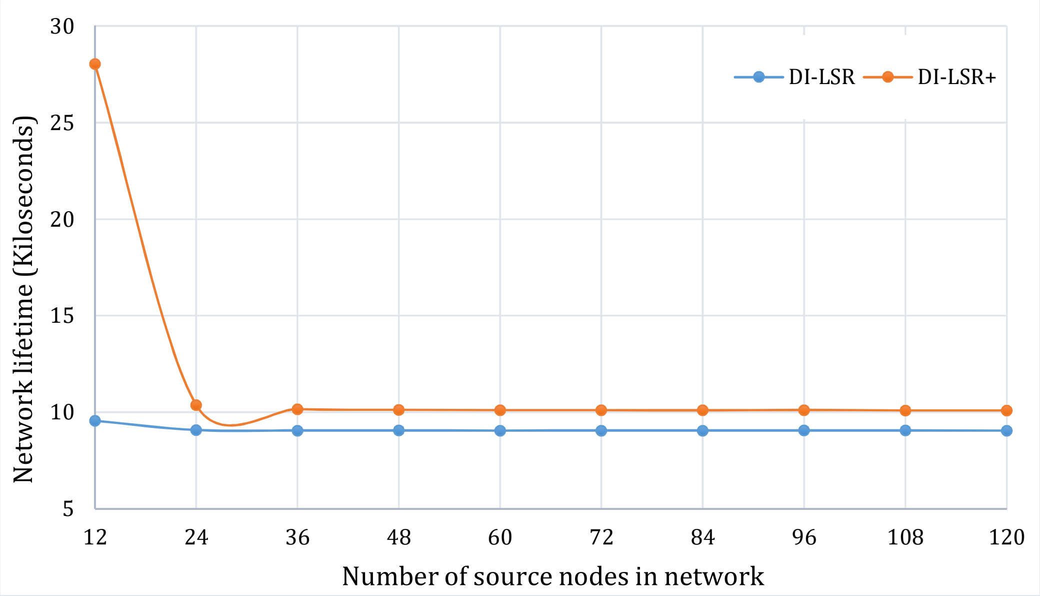


Figure 5-7: Network lifetime vs. number of source nodes

It is observed from Figure 5-7 that DI-LSR+ extends the network lifetime between 10% - 65% as compared to the traditional DI-LSR from a low network density with 12 source nodes to a larger network density with 120 source nodes. This is possible with the implementation of adaptive sleep mode that enables optimum energy saving in between *active* and *sleep state* at node level among source nodes in the network. Respective source nodes are active only during data transmission and receiving control packet, thus the nodes are enabled to save energy in between this process compared to the traditional DI-LSR. The network lifetime in a multi-hop linear topology solely depends on the critical node (closest to the destination node) that changes its energy from *on* to *off state*.

5.6.4 Cluster Topology: Energy Consumption vs. Number of Source Nodes

The energy consumption per-packet effect on varying number of source nodes/cluster heads is as shown in Figure 5-8, indicates that DCHI-LSR+ and DCHI-LSR has a gradual increase in energy to the varying network size.

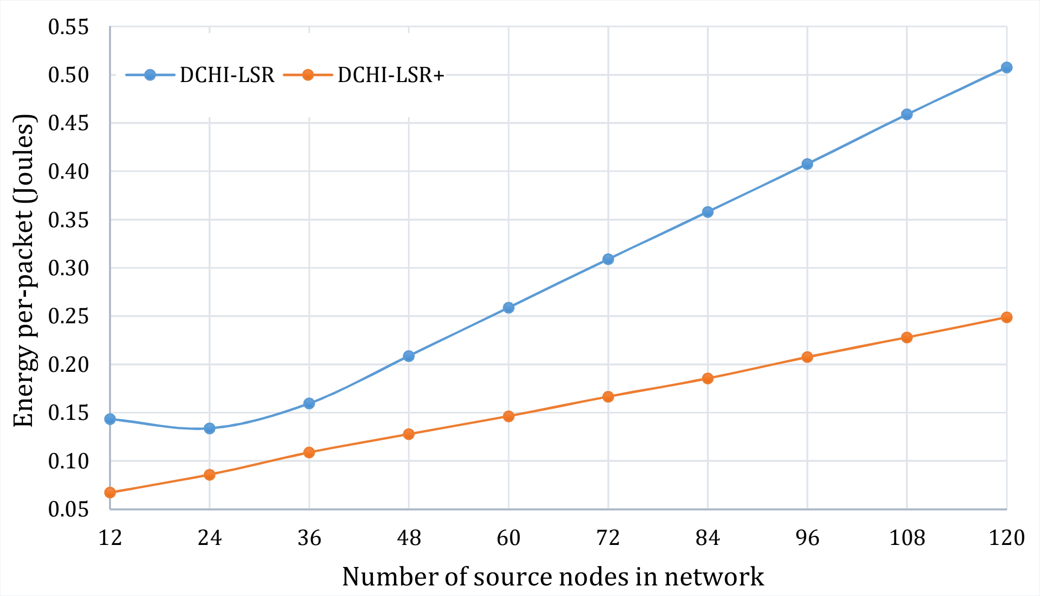


Figure 5-8: Energy per-packet vs. number of source nodes

The energy consumption per-packet with DCHI-LSR+ is comparatively lower than the traditional DCHI-LSR from a low network density with 12 source nodes to a larger network density with 120 source nodes. The adaptive sleep mode enables optimum energy saving in an inactive state at node level on both cluster head and source nodes in the network. The energy saving is linearly proportional to the cluster heads in a sequential arrangement from the destination node in the network where else optimum energy saving is achieved for all source nodes. The cluster heads located in the incrementing distance from the destination node has less data transmission activity or infrequent data transfer from both its member nodes and its neighbouring cluster heads, thus enables optimum sleep duration to save energy usage during *idle state* at each varying simulation environment. With an energy efficient model as AHiT, the energy optimisation rate can be increased based on the *active state* at both source node and cluster head to ensures uninterrupted operation in a typical multi-hop linear wireless network, particularly when the nodes are battery power dependent.

5.6.5 Cluster Topology: Consumed Energy Variation vs. Number of Source Nodes

The variation of consumed energy is another parameter in visualising optimum energy usage among respective source nodes and cluster heads in a multi-hop linear network. The consumed energy variation with DCHI-LSR+ in percentage has a significant difference at a rate of 95% and above in average from a low network density with 48 source nodes to a larger network density with 120 source nodes as in Figure 5-9.

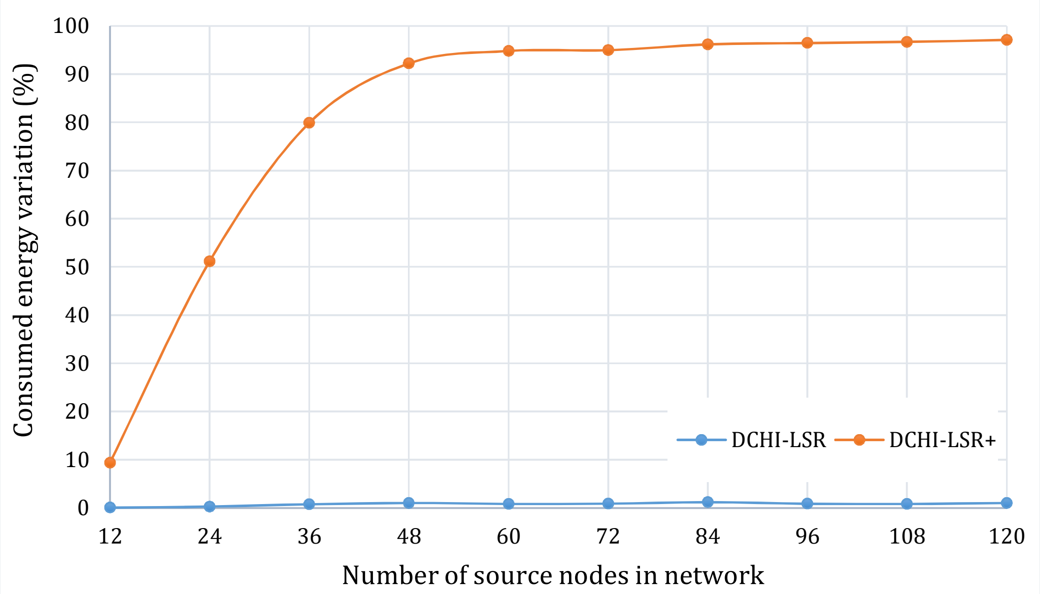


Figure 5-9: Consumed energy variation vs. number of source nodes

With the implementation of adaptive sleep mode that enables optimum energy saving in an inactive state among cluster heads and particularly among source nodes in the network. The consumed energy saving among cluster heads becomes greater with the varying number of source nodes in a network when compared with the traditional DCHI-LSR. With the AHiT energy model, a significant saving in consumed energy can be achieved among source nodes as these nodes are just a transponder in the network. Thus, the sleep duration can be increased significantly compared to the active period of these nodes in the network. Whereas for a cluster head located at the far end of the network consumes the least energy compared to the cluster head nearest to the destination node that creates the significant variation of energy consumed at each varying simulation environment.

5.6.6 Cluster Topology: Network Lifetime vs. Number of Source Nodes

The network lifetime of a multi-hop linear topology can be extended at a reasonable rate between 14% - 75% as shown in Figure 5-10 as compared to the traditional DCHI-LSR from a low network density with 12 source nodes to a larger network density with 120 source nodes.

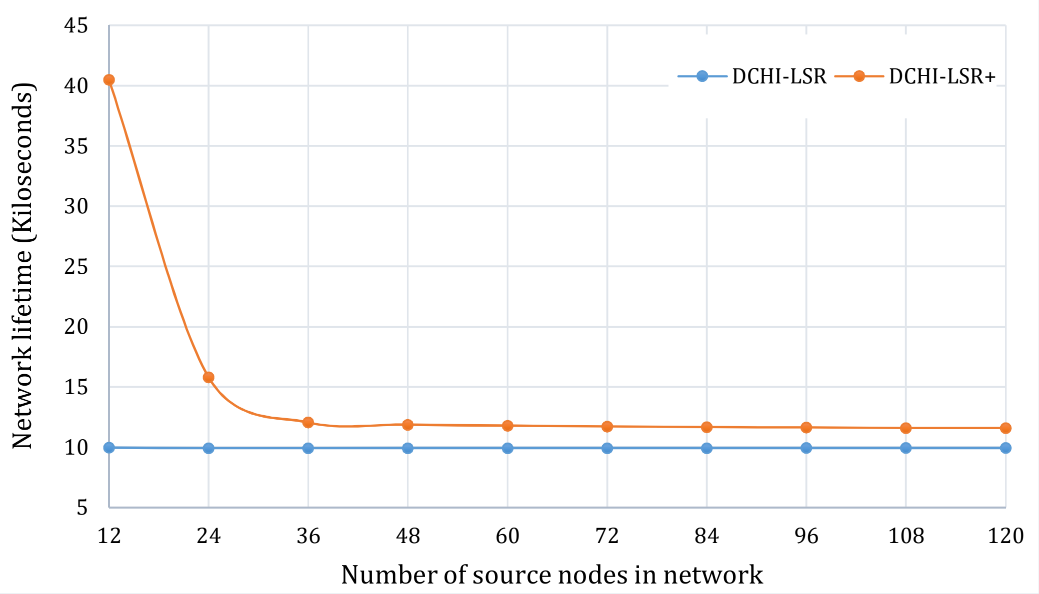


Figure 5-10: Network lifetime vs. number of source nodes

This is possible with the implementation of an adaptive sleep mode that enables optimum energy saving in an inactive state of source nodes and cluster heads in the network. Therefore, optimum energy usage is tailored at respective source node level and cluster heads in the network as compared to the traditional DCHI-LSR. The network lifetime in a multi-hop linear topology solely depends on the critical cluster heads (closest to the destination node) that change its energy from *on* to *off state*.

5.7 Simulation Results and Discussion: TCP Delayed Acknowledgement Timeout Model for Flat One-tier Topology and Cluster-Based Two-tier Topology

The energy performance of both DATM-FFCA and DATM-FTCA for flat one-tier topology was implemented with the AHiT energy model is presented as DATM-FFCA+ and DATM-FTCA+ respectively. Whereas the energy performance of both DATM-CFCA and DATM-CTCA for cluster-based two-tier topology was implemented with the AHiT energy model is presented as DATM-CFCA+ and DATM-CTCA+ respectively. All four models from Chapter 4 was compared with the AHiT energy model in terms of the energy performance metrics in section 5.5.

5.7.1 Flat Topology: Energy Consumption vs. Number of Source Nodes

The energy consumption per-packet effect on varying number of source nodes with the implementation of AHiT as shown in Figure 5-11 has a significant decline in consumed energy for both DATM-FFCA+ and DATM-FTCA+ when compared with the traditional energy model. With the implementation of AHiT, both DATM-FFCA+ and DATM-FTCA+ has relatively lower energy consumption between 31% - 89% and 22% - 51% respectively when compared with the traditional DATM-FFCA and DATM-FTCA. The adaptive sleep mode enables optimum energy saving in an inactive energy state among source nodes from a low network density with 12 source nodes to a larger network density with 120 source nodes. In general, both DATM-FFCA+ and DATM-FTCA+ has a similar increasing energy saving pattern that is linearly proportional to the source nodes in a sequential arrangement from the destination node in the network. The source nodes located in the incrementing distance from the destination node has less data transmission activity or infrequent data transfer in between nodes, especially with the DATM. Thus, enables optimum sleep duration to save energy usage during waiting period at each node level in the varying simulation environment. An energy efficient model implemented with DATM ensures continues and uninterrupted operation in a typical multi-hop linear WSN, particularly when the nodes are battery power dependent.

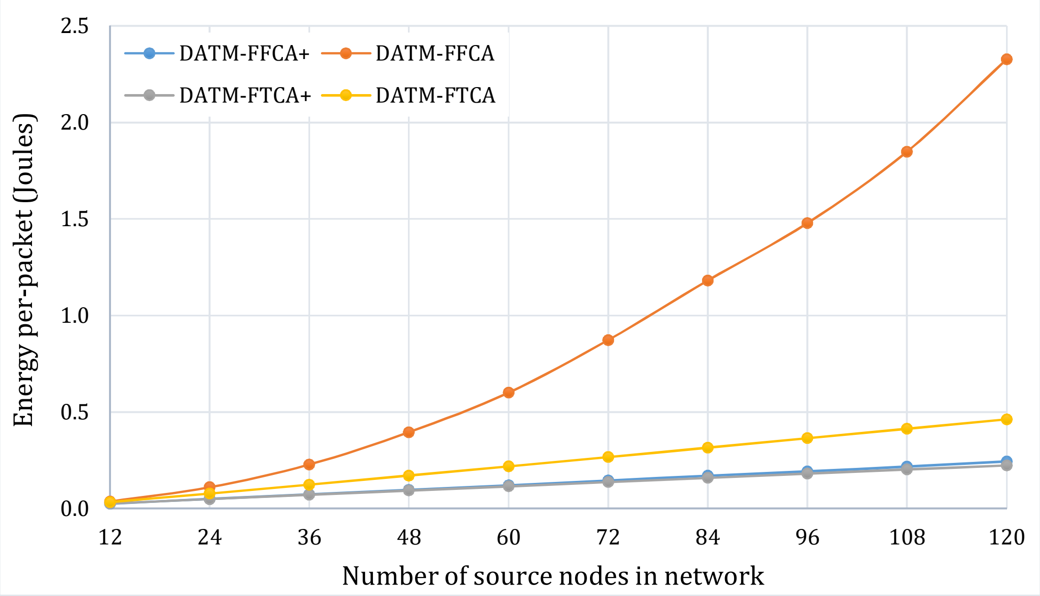


Figure 5-11: Energy per-packet vs. number of source nodes

5.7.2 Flat Topology: Consumed Energy Variation vs. Number of Source Nodes

The consumed energy variation in percentage indicated that both DATM-FFCA+ and DATM-FTCA+ has a significant difference at a rate of 95% and above in average as compared to the traditional DATM-FFCA and DATM-FTCA from a low network density with 24 source nodes to a larger network density with 120 source nodes as shown in Figure 5-12. The optimum energy saving is accomplished among source nodes in the network on both DATM-FFCA+ and DATM-FTCA+ with the implementation of adaptive sleep state that results in a significant difference in the percentage that becomes greater with the varying number of source nodes in a network when compared with the traditional DATM. In general, the simulation results indicated that source nodes located at the far end of the network which has a longer waiting interval in between data transmission consume the least energy as compared to the source node nearest to the destination node that creates the significant variation of consumed energy at each varying simulation environment.

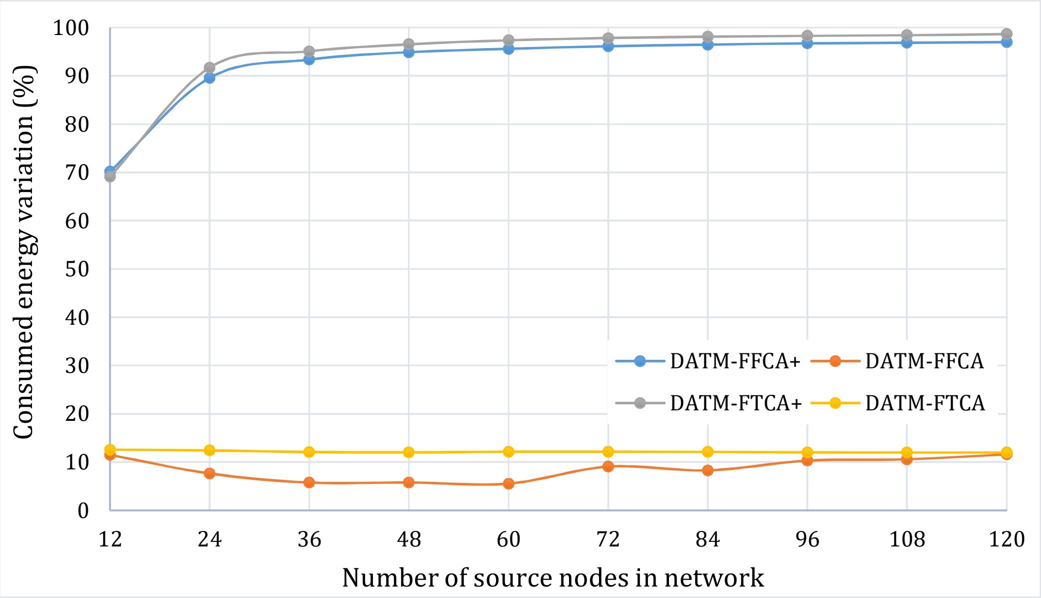


Figure 5-12: Consumed energy variation vs. number of source nodes

5.7.3 Flat Topology: Network Lifetime vs. Number of Source Nodes

The network lifetime plot from a low network density with 12 source nodes to a larger network density with 120 source nodes is presented in Figure 5-13. It is observed that DATM-FFCA+ has improved approximately five times the network lifetime as compared to the traditional DATM-FFCA where else DATM-FTCA+ extends the network lifetime by approximately by 4% - 6% as compared to the traditional DATM-FTCA. There is no significant difference in network lifetime extension for DATM-FTCA+ as compared to the traditional DATM-FTCA as the data traffic at the source node closest to the destination node is higher with less sleep interval. While the scenario with DATM-FFCA+ has much larger sleep intervals are based on the lower data traffic in the network. Therefore, the data traffic pattern has a great impact towards the energy saving in the network with the proposed energy model.

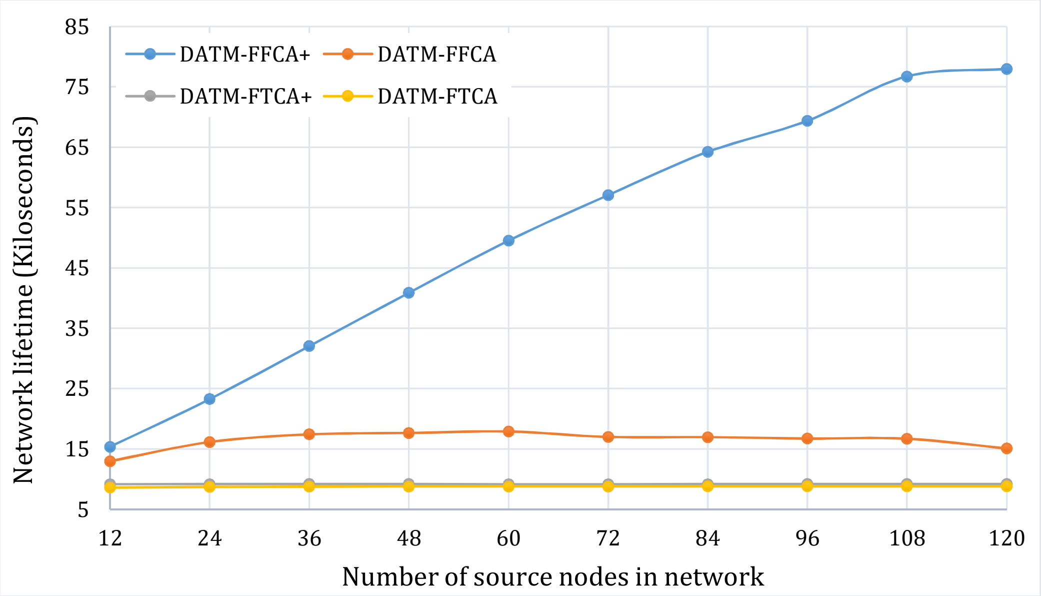


Figure 5-13: Network lifetime vs. number of source nodes

5.7.4 Cluster Topology: Energy Consumption vs. Number of Source Nodes

The energy consumption per-packet effect in Figure 5-14 shows that with the implementation of adaptive sleep state on both DATM-CFCA+ and DATM-CTCA+ reduces energy consumption with optimum energy saving in an inactive state. The energy saving of both DATM-CFCA+ and DATM-CTCA+ linearly proportional to the cluster heads in a sequential arrangement from the destination node in the network whereas optimum energy saving is achieved among all source nodes at 22% - 64% and 9% - 39% respectively compared with the traditional energy model. The cluster heads located in the incrementing distance from the destination node has less data transmission activity or infrequent data transfer in between neighbouring cluster heads, thus enables optimum sleep duration to save energy usage during waiting period at each varying simulation environment. Such an energy efficient model ensures continued and uninterrupted operation in a typical multi-hop linear wireless network where there are involving multi-tier nodes that are battery power dependent.

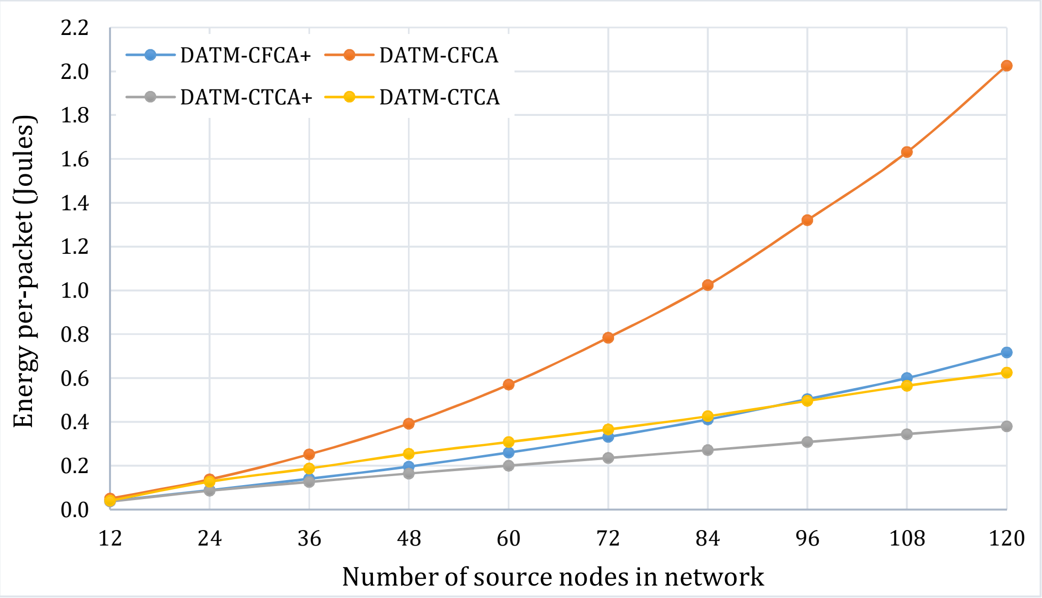


Figure 5-14: Energy per-packet vs. number of source nodes

5.7.5 Cluster Topology: Consumed Energy Variation vs. Number of Source Nodes

The consumed energy variation in percentage indicated that both DATM-CFCA+ and DATM-CTCA+ has a significant difference with the implementation of a traditional energy model at a rate of 80% and above in average from a low network density with 24 source nodes to a larger network density with 120 source nodes as shown in Figure 5-15. The optimum energy saving among cluster heads and particularly among source nodes in the network can be achieved with optimum *sleep* and *on state*. A network with DATM-CFCA+ and DATM-CTCA+ has a significant difference in the percentage that becomes greater with the varying number of source nodes in a network when compared with the traditional DATM. Generally, significant energy saving can be achieved with the proposed energy model among source nodes as these nodes are just a transponder in the network that acts as a data generator at a specific interval. On the other hand, significant variation of consumed energy among cluster heads varies based on the distance to the destination node at each varying simulation environment. The cluster heads located at the far end of the network which has a longer waiting interval in between data transmission consumes the least energy compared to the cluster head closest to the destination node.

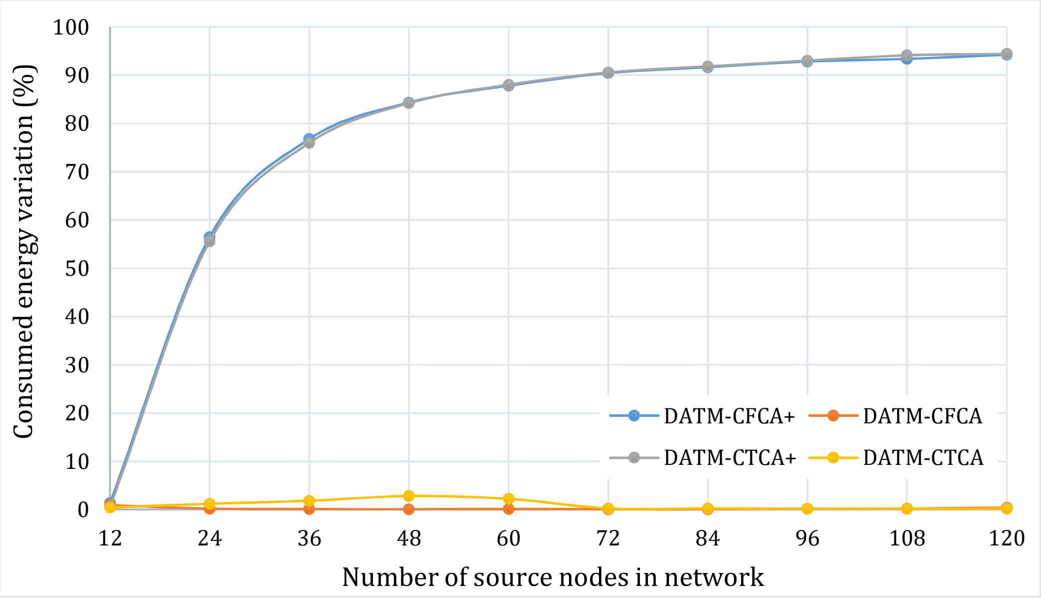


Figure 5-15: Consumed energy variation vs. number of source nodes

5.7.6 Cluster Topology: Network Lifetime vs. Number of Source Nodes

The network lifetime plot from a low network density with 12 source nodes to a larger network density with 120 source nodes is presented in Figure 5-16. A network with DATM-CFCA+ has a significant increase in network lifetime by approximately four times as compared to the traditional DATM-CFCA while the DATM-CTCA+ extends the network lifetime by approximately 15% - 21% as compared to the traditional DATM-CTCA. There is a small difference in network lifetime extension for DATM-CTCA+ as compared to the traditional DATM-CTCA as the data traffic at the cluster head closest to the destination node is higher with less sleep interval. While the scenario with DATM-CFCA+ has much longer sleep intervals based on lower data traffic in the network. Therefore, the data traffic pattern at source nodes and cluster heads has a great impact towards the energy saving as well as the extension of network lifetime with the AHiT energy model.

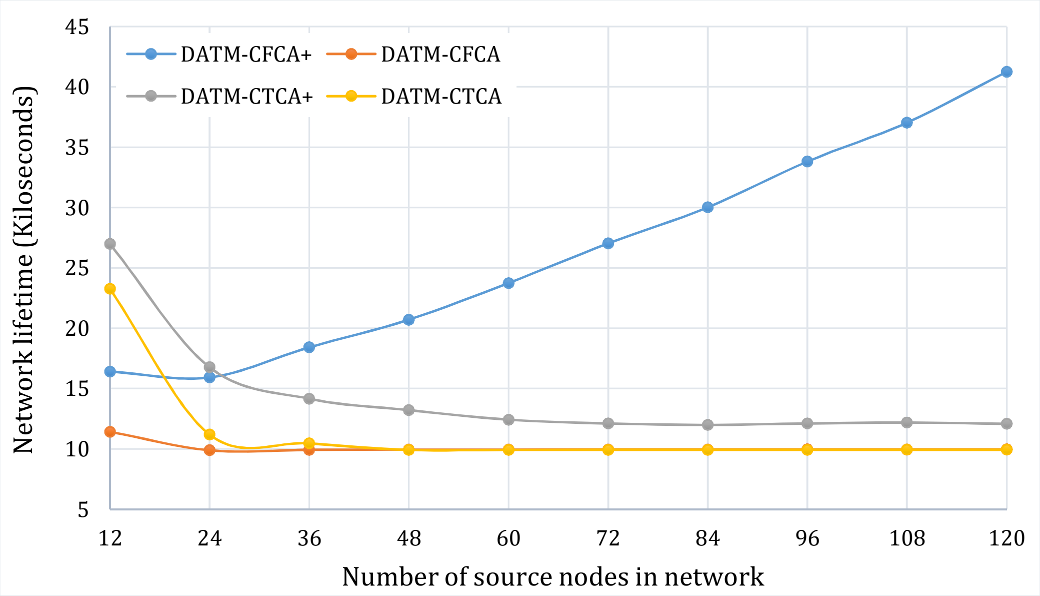


Figure 5-16: Network lifetime vs. number of source nodes

5.8 Conclusion

This chapter mainly presented the AHiT energy model which is a viable solution for pipeline network with a better network energy efficiency. The proposed energy model empowers adaptive sleep and wake up cycle to achieve optimum energy saving among source nodes in varying distance arranged in a linear one-tier or two-tier architecture without affecting the overall network performance. The simulated results have demonstrated that AHiT energy model has achieved a significant level of improvements in energy optimisation rate in a multi-hop linear network which has a crucial implication towards network lifetime extension. The proposed energy model is best implemented with the routing algorithm proposed in Chapter 3 for a performance based network while for a fairness network can be implemented with the fairness model proposed in Chapter 4 as a viable solution for an energy efficient application in a pipeline network. The average value and percentage difference comparison with and without the implementation of AHiT energy model are as summarised in Table 5-1.

Table 5-1: Energy efficiency with and without AHiT energy model

Measured parameters	Without AHiT		With AHiT	Difference	Percentage (%)
Average energy per-packet (mili joules)	DI-LSR	0.272	0.127	**↓0.145**	**+53.31**
	DATM-FFCA	0.908	0.134	**↓0.774**	**+85.24**
	DATM-FTCA	0.245	0.126	**↓0.119**	**+48.57**
Consumed energy variation (%)	DI-LSR	8.81	91.94	**↑83.13**	**+83.13**
	DATM-FFCA	8.593	92.68	**↑84.09**	**+84.09**
	DATM-FTCA	12.137	94.115	**↑81.98**	**+81.98**
Network lifetime (Kiloseconds)	DI-LSR	9.11	11.934	**↑2.824**	**+31**
	DATM-FFCA	16.455	50.644	**↑34.189**	**+207.77**
	DATM-FTCA	8.762	9.178	**↑0.416**	**+4.75**
Average energy per-packet (mili joules)	DCHI-LSR	0.295	0.157	**↓0.138**	**+46.78**
	DATM-CFCA	0.819	0.328	**↓ 0.491**	**+59.95**
	DATM-CTCA	0.339	0.215	**↓0.124**	**+36.58**
Consumed energy variation (%)	DCHI-LSR	0.761	80.882	**↑80.121**	**+80.12**
	DATM-CFCA	0.254	76.944	**↑76.69**	**+76.69**
	DATM-CTCA	0.976	76.835	**↑75.86**	**+75.86**
Network lifetime	DCHI-LSR	9.924	15.017	**↑5.093**	**+51.32**
	DATM-CFCA	10.093	26.439	**↑16.346**	**+161.95**
	DATM-CTCA	11.444	14.406	**↑2.962**	**+25.88**

On the downside of proposed technique, besides energy efficiency concerns on node level, the choice of multi-hop linear topology has a relative imbalance energy use that limits the network lifetime based on the first node to fail in both paths (usually the nodes closest to the destination node). Generically, higher energy consumption corresponds to both node location and separation between nodes in the network, which is considered as a crucial factor in a battery powered devices. Such energy constraint requires a heterogeneous power scheme among nodes based on their distance from the destination node that could be very complex on a large scale WSN.

Chapter 6

Conclusions and Future Works

6.1 Conclusion

This thesis highlights the research outcome on the numerous challenges faced by the oil and gas industry with the full deployment of a WSN on an oil and gas pipelines. The key focus area of this research was the tailored development of a static routing algorithm for a multi-hop linear topology. Thorough investigation and analysis on various routing algorithms as well as design strategies were performed based on both flat one-tier and cluster-based two-tier multi-hop linear topology. The unique characteristic and its impact towards the overall performance of the static routing on a multi-hop linear topology was the focal direction of this research.

This research had introduced a number of diverse approaches on the proposed routing algorithm from Chapter 3 and a network fairness model from Chapter 4 as a contributing factor towards the routing performance enhancement. Extending the research further with the impending issues on energy starvation in a multi-hop linear topology has proposed an energy efficient model from Chapter 5. The proposed routing algorithm and fairness model implemented with an energy efficient model were evaluated to mimic the unique geographical environment of the application on an oil and gas pipelines that had exhibited significant improvements in the overall network performance within the available network resources. The long-term sustainability of the pipeline network depends upon three crucial factors; (1) The scalability and functionality of a routing algorithm that is intertwined with (2) Fair distribution of network resources as required by the user along with the (3) Adaptability of an energy optimization model to the real time needs of the network. The real-time functionality that guarantees all the key aspects of a multi-hop linear topology is achieved is when all the three proposed techniques in able to operate based on the related attributes of a pipeline network.

The presented research was established on selected varying simulation environment that resembles a pipeline network. Therefore, the actual outcome has limitations and may respond with variation in a real scale implementation on an oil and gas pipelines with potential room for further improvements related to the research area. This research work had introduced two static routing algorithms, four throughput fairness models and an energy efficient model that enhanced the overall performance of the pipeline network. The proposed techniques and methods are as summarised below:

6.1.1 Reliable and Efficient Interleaving Linear Static Routing for Pipeline Network

The static multi-hop linear WSN based on IEEE 802.11 standard features a unique architecture with various interrelating factors that affect the overall network performance. The operational nature of a multi-hop linear WSN is limited to network resources that become critical in a very dynamic environment due to overwhelming data traffic in the network. As a result, overwhelming data traffic contributes to frequent data packet drops and passive nodes which are considered as a waste of network resources. These factors are amplified in a large-scale implementation that degrades the overall network performance. This thesis has highlighted an alternative solution to optimise the crucial factors affecting the overall network performance on a multi-hop linear topology. The proposed Dual Interleaving Linear Static Routing (DI-LSR) [12] for a flat one-tier multi-hop linear topology and the Dual Cluster Head Interleaving Linear Static Routing (DCHI-LSR) [96] for a cluster-based two-tier multi-hop linear topology is a reliable and efficient routing algorithm with low routing overhead. The beaconless and predefined dual interleaving routing path efficiently accommodates higher data traffic and minimise passive nodes in a multi-hop linear WSN. Dealing with passive nodes ensures stability in communication links as a crucial parameter towards a sustainable and uninterrupted network operation. The proposed routing algorithm has functional implications particularly with higher throughput, lower latency and eliminate issues with passive nodes in a pipeline network.

6.1.2 Effective TCP Delayed Acknowledgement Timeout Model for Throughput Fairness Optimization

Fairness of network resources is an essential element in ensuring equal data transmitting opportunity among source nodes disregards to the distance of the node from the destination node in a multi-hop linear WSN. In general, the distance between a source and a destination node has a weight factor (travel cost) to inequality of network resources that results in data flow starvation in a linear topology. Unfair distribution of network resources is highly potential of data congestion (bottleneck points) that contributes to passive nodes and overall network performance degradation. A throughput fairness index rate of close to one can be achieved by a mathematical formulation for setting an appropriately TCP delayed acknowledgement timeout for source nodes corresponding to distance from the destination node with low advertised window size as highlighted in this thesis. The proposed TCP delayed acknowledgement timeout model for a fairness critical application (DATM-FFCA) and throughput critical application (DATM-FTCA) is established for a flat multi-hop linear topology [28], whereas the proposed TCP delayed acknowledgement timeout model for a fairness critical application (DATM-CFCA) and throughput critical application (DATM-CTCA) is established for a cluster-based multi-hop linear topology is an efficient model for achieving higher rate of equal opportunity in a pipeline network. The proposed models have a unique formulation in retaining the throughput fairness index as a primary metrics with a minimum trade-off on throughput and end-to-end delay in a multi-hop linear topology. The proposed models optimise the network resources on both flat and cluster-based multi-hop linear WSN that makes it a tangible model for a scalable pipeline network.

6.1.3 AHiT Energy Model for Multi-hop Linear Topology

Energy optimisation is frequently associated with the network lifetime as a crucial aspect in a geographically unique architecture as in a pipeline network. In order to be self-sustainable for a remote application, adequate techniques and strategies in WSN power management are essential for an uninterrupted operation. Generally, the energy characteristic of nodes in a multi-hop linear WSN has a varying energy consumption that is inversely proportional to the node distance from the destination node located at the end of the network. Thus, the energy consumption increases rapidly in the sequence of nodes towards the destination node to accommodate accumulating data traffic in the network. On the other hand, the power pack restoring and charging are bound to supporting components such as a renewable or pre fixed energy supply system to the network. Nodes with draining energy state do not only affect its own operation but can be a threat to cannibalise the entire operation on a multi-hop linear network. Thus, energy optimisation has a great significance at both node and network level to prolong the network lifetime in multi-hop linear topology. This thesis has proposed the Active High Transmitter-receiver energy model (AHiT), an efficient and energy sensible model that is tailored at respective nodes in the network. The proposed energy model optimises energy with an adaptive sleep and wake up intervals corresponding to the data traffic at a certain source node level. At source node level, the sleep duration is optimised to save energy instead of the traditional idle energy state whereas the wake up intervals are accomplished by the means of an internal interrupt based on the incoming and outgoing data traffic. The sleep and wake up states can be characterised as dynamic aspects that contribute significantly to energy saving at respective nodes in the network. Therefore, the accumulated energy saving at node level contributes to the network lifetime extension and also minimise the probability risk of nodes failing from energy starvation due to improper energy utilisation. The AHiT energy model dynamically optimises energy consumption on both flat and cluster-based linear WSN that provides network lifetime extension making it feasible for a scalable pipeline network.

6.2 Research Impact

This research has a significant impact towards remote monitoring of the oil and gas pipelines as it is considered as an essential and critical transportation medium in the oil and gas industry. The research outcome has highlighted the use of WSN as an important tool in remote monitoring of pipeline activities in relation to environmental justice in the oil producing region. Based on the fundamental and theoretical framework of the pipeline network, this research has also highlighted that the WSN plays a significant role in monitoring and managing the pipeline activities on the real-time basis that contributes to towards a safer operating environment. The integration of WSN on oil and gas pipelines significantly narrows the gap between occurring incidence to prompt counter measures to reduce the environmental effect of pollution. For that reason, the impact of WSN on pipelines is highly appreciated towards an environmentally friendly and cost effective medium of transportation in the oil and gas industry.

6.3 Future Research Directions

The research work on this thesis was primarily emphasised on the enhancement of the overall network performance on both flat and cluster-based linear WSN. The proposed routing algorithm, fairness models and energy model were investigated through simulation for the possible varying scenario on a pipeline network. Thus, the results obtained were analysed and compared with available methods for validation. The overall results have indicated a reasonable level of enhancement in the overall network performance within the available network resources in a static multi-hop linear topology. In the preliminary design stages, several techniques and strategies were investigated that can be further explored as a possible future direction of the research done to improve further the overall network performance in a static multi-hop linear topology. Some of the methods and strategies are as summarised for potential future research in the application area of oil and gas pipelines:

- This thesis has highlighted a beaconless and static routing algorithm for both flat and cluster-based multi-hop linear WSN. To add intelligence to the routing algorithm, a semi-dynamic routing algorithm can be implemented to adapt to real-time network happening particularly dealing with physical node failures. The suggested technique should be capable of overwriting the predefined interleaving routing path when node failures occur in the network in order to ensure the communication link between a source to a destination node. This technique can be implemented on a cluster-based network to create a substitute cluster head in a group of nodes when the existing cluster head failed to regain the required communication links.

- The proposed research work in this thesis is based on IEEE 802.11 standard devices that have limited communication range between nodes in a network and higher energy consumption as compared to IEEE 802.15.4 standard devices. Therefore, the proposed routing algorithm can be implemented on the suggested standard to evaluate the overall network performance and its viability in a scalable pipeline network.
- This research utilised CBR traffic with TCP agent that is known for greater reliability with substantial routing overheads. As an alternative, the User Datagram Protocol (UDP) agent can be implemented on the present routing algorithm to analyse the performance characteristic as compared to the TCP agent. The combination of both TCP and UDP can be tested to set priority on ad hoc data and periodic data from the sensing points in the network.
- An adaptive throughput fairness model based on the active source nodes in a network can be implemented for optimum results in a multi-hop linear network. This technique can be extended on cluster-based architecture for greater improvements in cluster group and later for the whole network. Such an adaptive throughput fairness model can be considered practical in a real scale implementation on a pipeline network for optimum results.
- All the proposed solutions in this thesis were implemented and evaluated through simulation as a result validating tool. Therefore a laboratory or real scale implementation can be explored for realistic results.

Appendix A

A.1 Additional Simulation Results and Discussion for Flat One-tier Multi-hop Linear Topology:

The ADAM+ and ADAM-snd as discussed in Chapter 2 was implemented with AODV and DSDV which is presented as AODV+, AODV-snd, DSDV+ and DSDV-snd. The network fairness, as well as the performance of DATM-FFCA and DATM-FTCA, is compared with AODV+, AODV-snd, DSDV+ and DSDV-snd for flat one tier topology in terms of the performance metrics in section 3.5.

A.1.1 End-to-end Delay vs. Number of Source Nodes

End-to-end delay is the average total time taken to transmit data over all the flows in the network [21-23] which typically reflects against the total received data packets at the destination node. The result comparison on end-to-end delay for varying number of source nodes is as shown in Figure A-1, which indicates both the proposed models have a consistent increase in delay proportional to the increasing network densities with 12 source nodes to larger network densities with 120 source nodes. This is quite a common scenario in a multi-hop linear network with higher data rate since the position of each source nodes is in a respective distance from the destination node. The delay factor in DATM-FFCA is fairly low compared to the rate of throughput fairness index and moderate data rate achieved where else for DATM-FTCA, the delay factor is higher than other methods when compared to the higher data rate achieved and throughput fairness index. Delay is a critical factor in a pipeline network as in the monitoring of spillage, cracks and etc. that should be relayed to the monitoring station as accidents are detected at measuring points in the network. While in non-critical applications as in flow monitoring, temperature and etc. the delay factor has the least priority. The technique used in both models reduces the waiting period in-between transmission and acknowledgement thus reduce the delay factor.

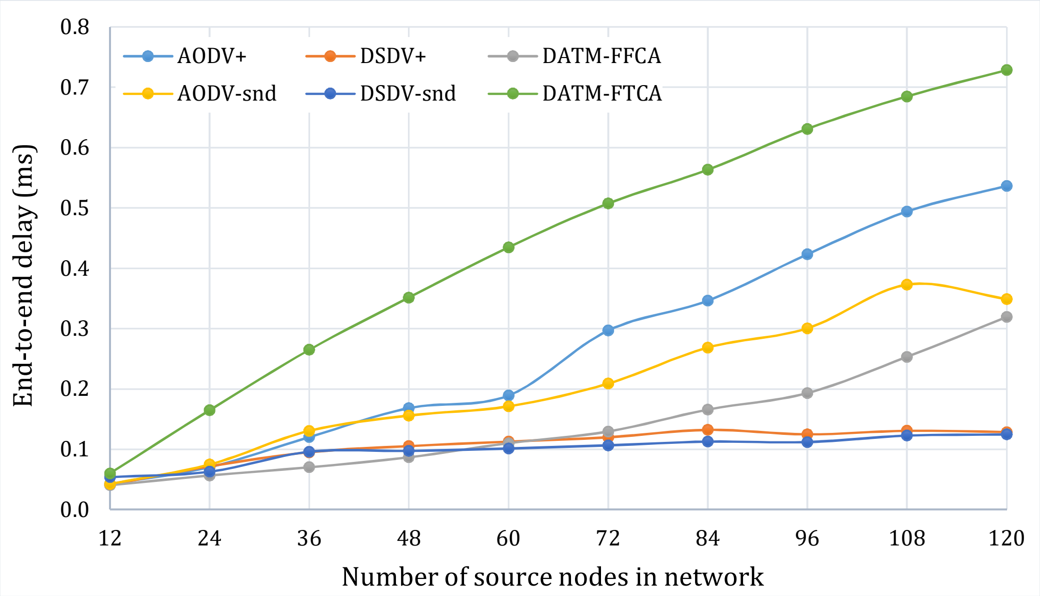


Figure A-1: End-to-end delay vs. number of source nodes

The value of fairness index and throughput from Figure 4-10 and Figure 4-13 respectively has a corresponding effect on end-to-end delay with the proposed models. Hence, both DATM-FFCA and DATM-FTCA has a comparatively lower end-to-end delay when compared to the other related metrics. The other routing protocol has a relatively higher end-to-end delay with lower data rate and other related metrics. Every routing protocol has its drawback towards the end-to-end delay which mainly relates to the number of control packets to support network connectivity. In a multi-hop linear topology, the delay factor varies from the distance between a source and a destination node. Incorporating the proposed models with DI-LSR is capable of forwarding higher data in a more efficient manner.

A.1.2 Passive Source Nodes vs. Number of Source 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. The effect of a passive node in network reflects on the fairness index as well as the network performance in a multi-hop linear wireless network. The effect of varying number of source nodes against passive source nodes is as shown in Figure A-2. With the implementation of the DATM-FFCA and DATM-FTCA, zero passive nodes were achieved between low network densities with 12 source nodes to larger network densities with 120 source nodes. The possibilities to achieve a better proportion of data transfer rate is depending on the independent scheduling techniques as proposed to ensure every source node has an equal allocation of network resources with a low routing overhead algorithm proposed in Chapter 3. Where else the other routing protocols contribute towards passive nodes with a varying number of source nodes in a network as shown in Figure A-2.

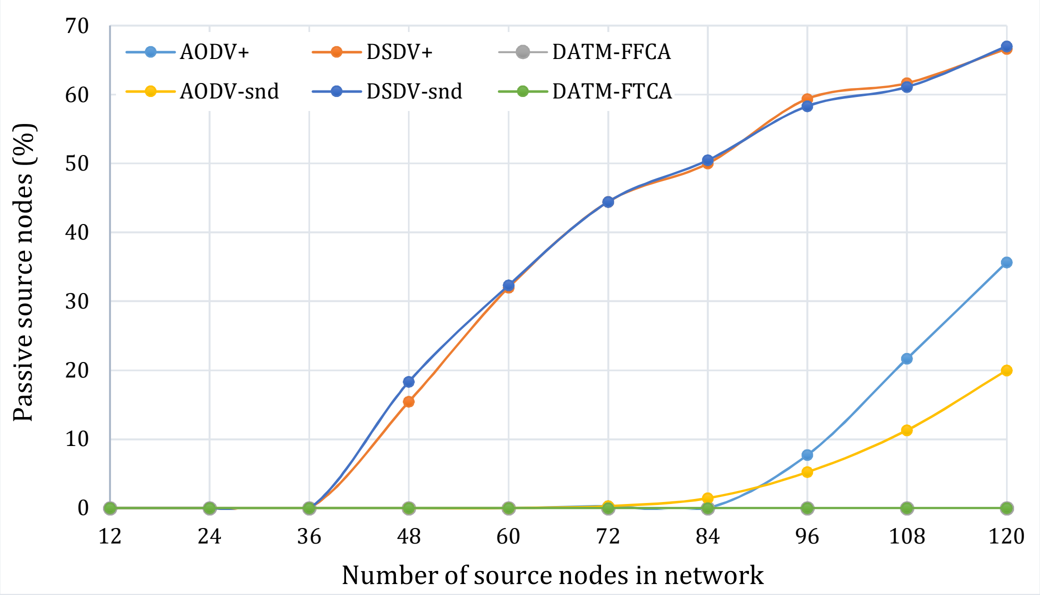


Figure A-2: Passive source nodes vs. number of source nodes

A.1.3 Normalised Routing Load vs. Number of Source Nodes

The normalised routing overhead is another crucial factor in any WSN that influences network fairness with queue overflow and result in performance degradation. Referring to Figure A-3, the normalised routing overhead with the proposed models are fairly low compared to the other compared methods between low network densities with 12 source nodes to larger network densities with 120 source nodes. There is a gradient increase in the routing overhead with the increasing number of source nodes in a network. This is generally contributed by the routing algorithm used especially in the simulation environment with irregular waiting time. Technically when there is a waiting period in a source node may increase the control packets and energy consumption based on a unique characteristic of the used routing algorithm. The implementation of DATM-FFCA and DATM-FTCA with DI-LSR a routing algorithm with low control packets had reduced the effect on routing overheads, unlike the compared routing algorithm that influences the increasing number of routing overhead even in an idle or waiting between data transmission state. With reduced control packets particularly without broadcast packets reduce the traffic of supporting packets in a network especially with increasing number of source nodes.

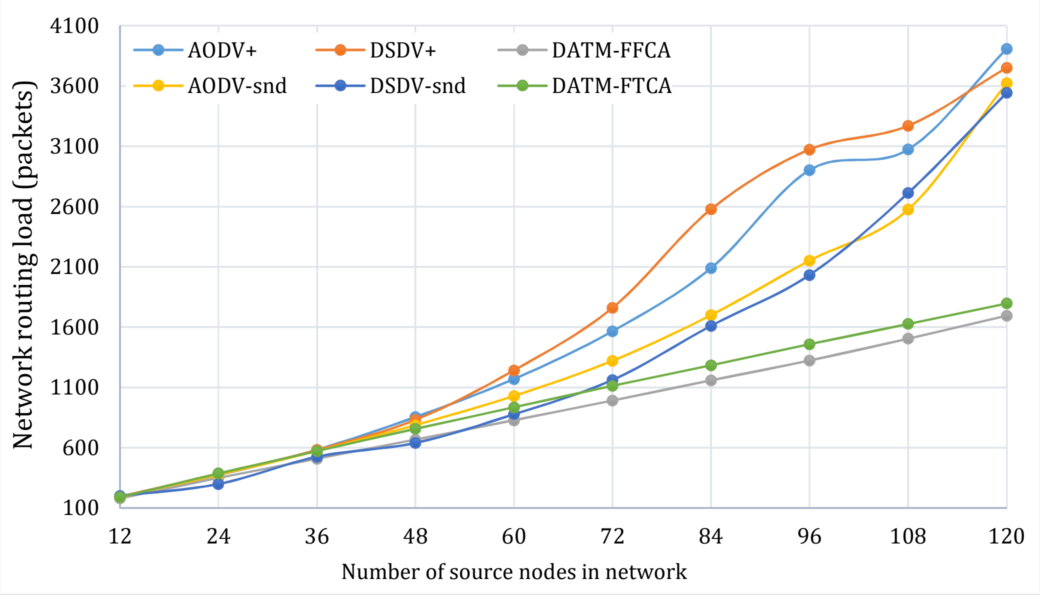


Figure A-3: Network routing load vs. number of source nodes

A.1.4 Energy Consumption vs. Number of Source Nodes

The effect of energy consumption per-packet on varying number of source nodes is as shown in Figure A-4, which indicates that the proposed models have relatively lower energy consumption over the network capacity. Generally, the energy consumption is proportional to the increasing number of source nodes in a network. The reduced energy consumption per-packet factor in DATM-FFCA and DATM-FTCA is the proper selection of time between data transmission on each varying simulation environment. The implementation on DI-LSR is another factor which contributes towards reduced energy consumption with the proposed models. Based on the number of data packets received, the proposed models have a great energy usage compared to all the other compared methods between low network densities with 12 source nodes to larger network densities with 120 source nodes. Where else the other methods consumed higher energy per-packet with relatively low data rate compared to the proposed models in the tested environment. Energy efficient routing algorithm and an adequate fairness model ensure a sustainability factor in a typical multi-hop linear wireless network, particularly when the nodes are battery power dependent.

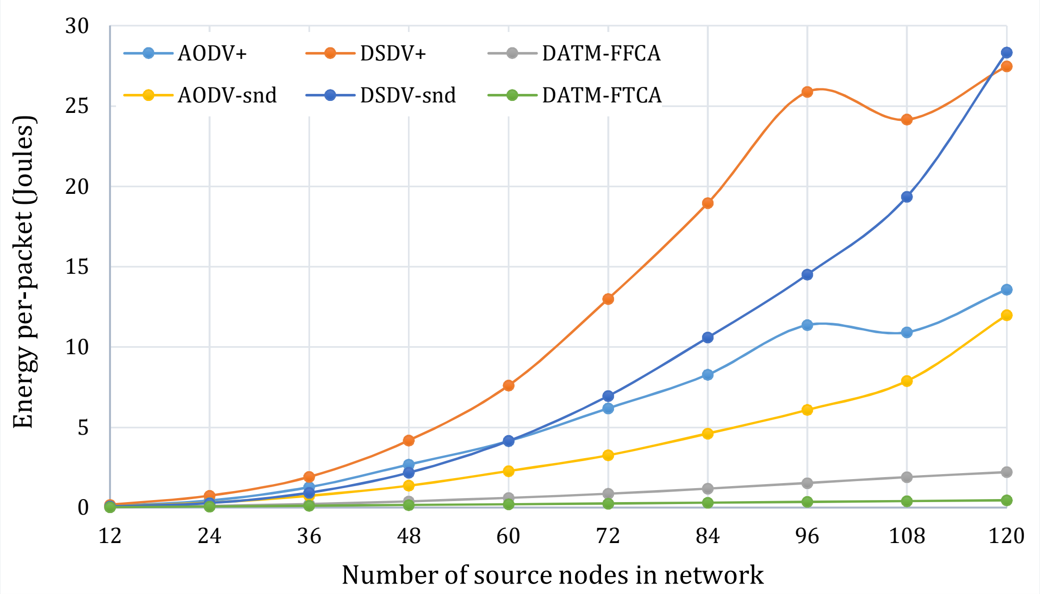


Figure A-4: Energy per-packet vs. number of source nodes

The average value and percentage difference comparison with and without the implementation of the proposed DATM-FFCA and DATM-FTCA on a flat one-tier multi-hop linear topology are shown in Table A-1.

Table A-1: Comparison between DI-LSR, DATM-FFCA and DATM-FTCA

Measured parameters	Standard DI-LSR	DATM-FFCA	Difference	Percentage (%)
		DATM-FTCA		
Average end-to-end delay (ms)	1.291	0.143	↓1.148	+88.92
		0.439	↓0.852	+66
Average passive nodes	0	0	No changes	No changes
		0	No changes	No changes
Average network routing load (packets)	1275.01	921.13	↓353.88	+27.76
		1012.28	↓262.73	+20.61
Average energy per-packet (mili joules)	0.272	0.911	↑0.639	+234.93
		0.245	↓0.027	+9.93

A.2 Additional Simulation Results and Discussion for Linear Cluster Two-tier Topology:

The ADAM+ as discussed in Chapter 2 was implemented with AODVC and DSDVC that is presented as AODVC+ and DSDVC+ respectively. The network fairness, as well as the performance of DATM-CFCA and DATM-CTCA, is compared with AODVC+ and DSDVC+ for the cluster-based two-tier topology in terms of the performance metrics in section 3.5.

A.2.1 End-to-end Delay vs. Number of Source Nodes

End-to-end delay is the average time taken to transmit data over all the flows in the network [21-23] which typically reflects against the total received data packets at the destination node. The result comparison on average end-to-end delay for varying number of source nodes is as shown in Figure A-5, where DATM-CFCA outperforms all the other compared models with relatively lower latency with a moderate rate of throughput fairness index. This is achieved with a minimum total travel cost (t) needed between the source and destination nodes in the network. Whereas the DATM-CTCA has a higher latency rate against higher data rate as shown in Figure 4-22 which is proportional to the increasing network densities with 12 source nodes to larger network densities with 120 source nodes. This is relatively a common scenario in a multi-hop linear network with higher data rate since the position of each source nodes is in a respective distance from the destination node. The technique used in both models relatively reduces the waiting period in-between transmission and acknowledgement with a delay variation in a long run application. The value of fairness index and throughput rate from Figure 4-19 and Figure 4-22 respectively has a corresponding effect on end-to-end delay with the proposed models. Hence, both DATM-CFCA and DATM-CTCA has a unique effect on end-to-end delay when compared to the other related metrics. The other routing protocol has a relatively moderate rate of end-to-end delay with lower data rate. In a linear topology, the delay factor varies from the distance between a source and a destination node. Incorporating the proposed models with DCHI-LSR is capable of forwarding higher data in an efficient manner.

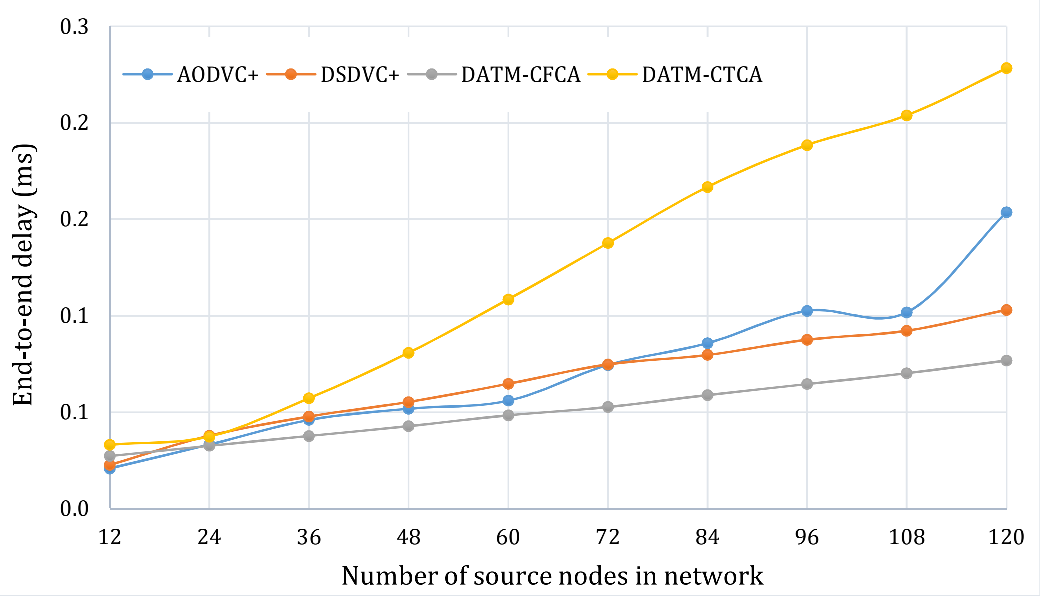


Figure A-5: End-to-end delay vs. number of source nodes

A.2.2 Passive Source Nodes vs. Number of Source Nodes

Passive nodes are considered nodes with zero data transfer to the destination node in a network. 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. The effect of a passive node in network reflects on the fairness index as well as the network performance in a multi-hop linear wireless network. The effect of varying number of source nodes against passive source nodes is as shown in Figure A-6. With the implementation of the DATM-CFCA and DATM-CTCA, zero passive nodes were achieved between low network densities with 12 source nodes to larger network densities with 120 source nodes. The possibilities to achieve a better proportion of data transfer rate is depending on the independent scheduling techniques as proposed in this chapter to ensure every source node has an equal allocation of network resources with a low routing overhead algorithm proposed in Chapter 3. Where else the other routing protocols contribute towards passive nodes with a varying number of source nodes in a network as shown in Figure A-6.

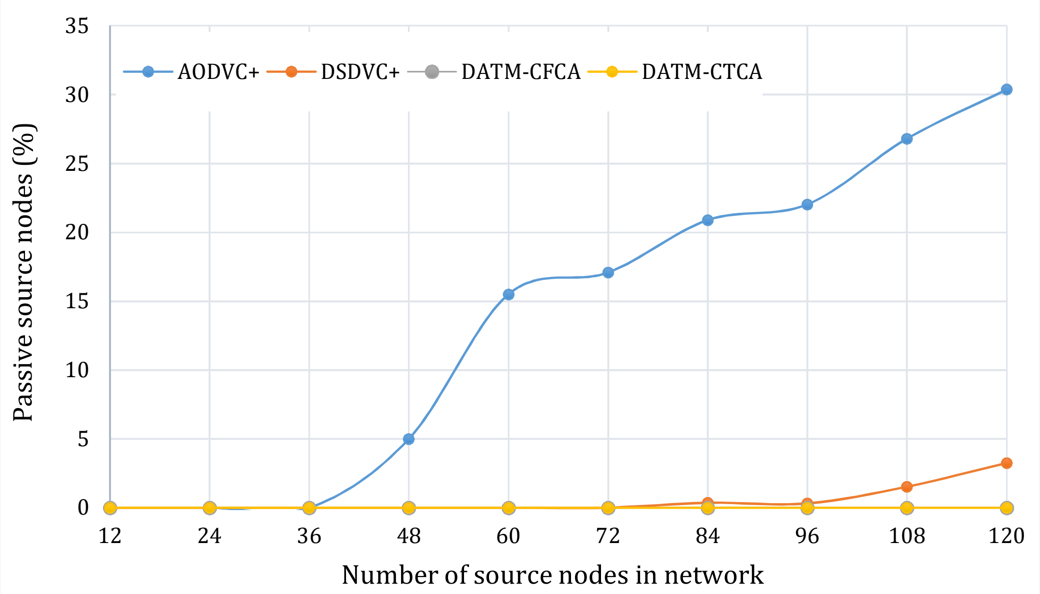


Figure A-6: Passive source nodes vs. number of source nodes

A.2.3 Normalised Routing Load vs. Number of Source Nodes

The normalised routing overhead is another crucial factor in any WSN that influences network fairness with queue overflow and result in performance degradation. Referring to Figure A-7, the normalised routing overhead with the proposed models are fairly lower compared to the other compared methods between low network densities with 12 source nodes to larger network densities with 120 source nodes. There is a gradient increase in the routing overhead with the increasing number of source nodes in a network. This is generally contributed by the routing algorithm used especially in the simulation environment with irregular waiting time in a linear topology. Technically with a waiting period in a source node may increase the routing overhead and energy consumption based on the characteristic of a routing algorithm. The implementation of DATM-CFCA and DATM-CTCA with DCHI-LSR a routing algorithm with lower control packets will reduce the effect on the routing overheads, unlike the compared routing algorithm. With reduced control packets particularly without broadcast packets, reduces the traffic of supporting packets in a network especially with increasing number of source nodes.

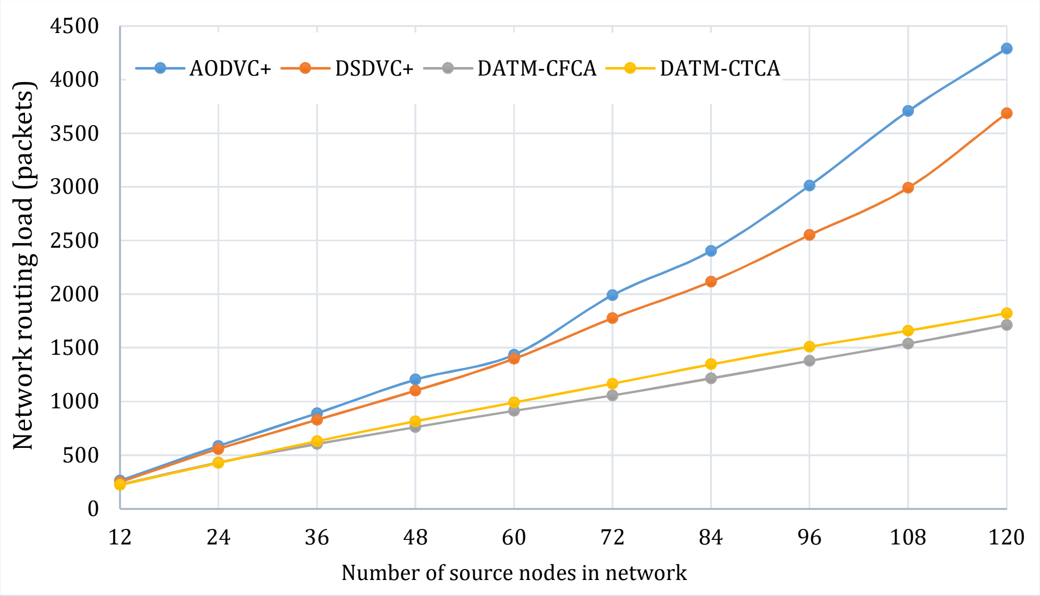


Figure A-7: Network routing load vs. number of source nodes

A.2.4 Energy Consumption vs. Number of Source Nodes

The effect of energy consumption per-packet on varying number of source nodes is as shown in Figure A-8, which indicates that the proposed models have relatively lower energy consumption over the network capacity. Generally, the energy consumption is proportional to the increasing number of source nodes in a network. With a proper selection of time between data transmission on each varying simulation environment in DATM-CFCA and DATM-CTCA significantly contributes towards the reduced energy consumption per-packet factor. The implementation on DCHI-LSR is another factor which contributes towards reduced energy consumption with the proposed models. Based on the number of data packets received, the proposed models have great energy saving compared to all the other compared methods between low network densities with 12 source nodes to larger network densities with 120 source nodes. Where else the other methods consumed higher energy per-packet with relatively low data rate compared to the proposed models in the tested environment. Energy efficient routing algorithm and an adequate fairness model ensure a sustainability factor in a typical multi-hop linear wireless network, particularly when the nodes are battery power dependent.

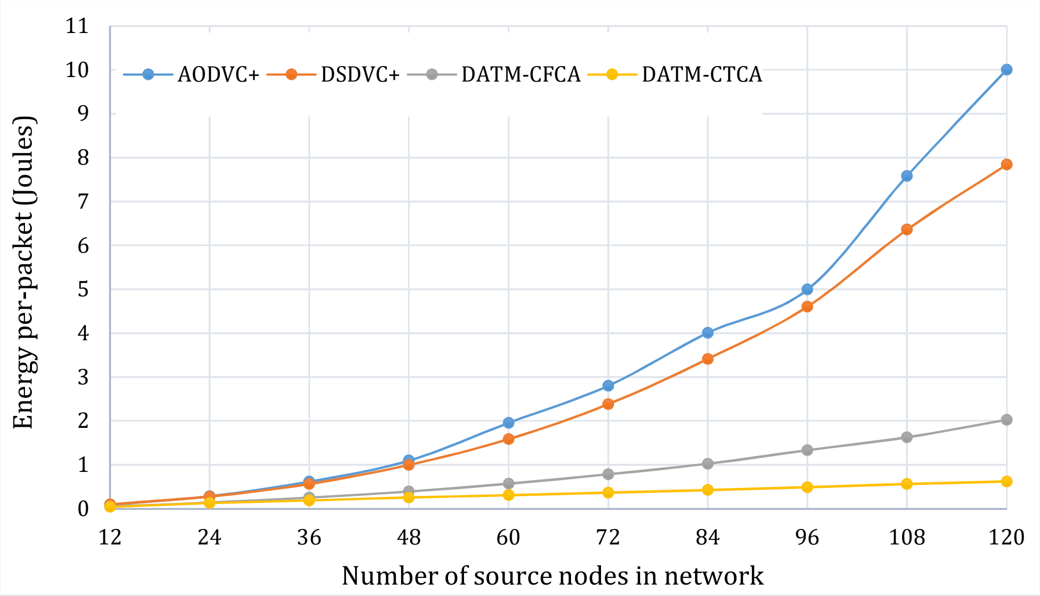


Figure A-8: Energy per-packet vs. number of source nodes

The simulated results have demonstrated that both DATM-CFCA and DATM-CTCA has achieved a significant level of improvements in network fairness, reliability (delivery ratio), latency (end-to-end delay), responsiveness (dealing with node failures) and network capacity (throughput) which had crucial implication towards the overall network performance on a pipeline network. The comparison with and without the implementation of the proposed DATM-CFCA and DATM-CTCA on a cluster-based two-tier multi-hop linear topology is shown in Table 4-5.

Table A-2: Comparison between DCHI-LSR, DATM-CFCA and DATM-CTCA

Measured parameters	Standard DCHI-LSR	DATM-CFCA	Difference	Percentage (%)
		DATM-CTCA		
Average end-to-end delay (ms)	0.385	0.051	↓ 0.334	+86.75
		0.124	↓ 0.261	+67.79
Average passive nodes	0	0	No changes	No changes
		0	No changes	No changes
Average network routing load (packets)	1201.10	982.86	↓ 218.24	+18.17
		1058.43	↓ 142.67	+11.88
Average energy per-packet (mili joules)	0.295	0.819	↑ 0.524	+177.63
		0.337	↑ 0.042	+14.24

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