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Enhancing Sustainability in Linear WSNs Using DSDVTRI: A Triple-Interleaving Routing Approach for Pipeline Monitoring

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Abstract: The safety and efficiency of oil and gas pipelines remain critical due to the high risks associated with leaks, pressure surges, and undetected structural damage. WSNs provide an effective solution for real-time monitoring by deploying sensor nodes along the pipeline. However, existing routing protocols such as DSDV and AODV face challenges with congestion, packet loss, and uneven energy consumption in long linear topologies. This study proposes DSDVTRI, a triple-interleaving extension of the DSDV protocol designed to improve data delivery and energy efficiency in linear pipeline networks. Simulations were performed using NS2.35 version across node counts ranging from 20 to 200. The results show that at number of nodes 100, DSDVTRI improves throughput by 14.2% and delivery ratio by 3.05% compared to DSDV, while reducing energy consumption per packet by 6.3%. These findings demonstrate that DSDVTRI enhances performance stability, making it suitable for real-time and energy-efficient pipeline monitoring applications.

Keywords: interleaving, multi-hop, real-time monitoring, pipeline monitoring, linear topology, energy efficiency, routing protocol, DSDVTRI

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1. Introduction

The oil and gas industry depends heavily on pipelines to transport resources safely and efficiently over long distances. Any leakage, corrosion, or pressure failure can cause serious environmental and financial losses, making real-time monitoring essential. Wireless Sensor Networks (WSNs) offer an effective solution for this by using multiple sensor nodes to collect and transmit data along the pipeline[1], [2]. These systems are more flexible and cost-efficient compared to traditional wired networks

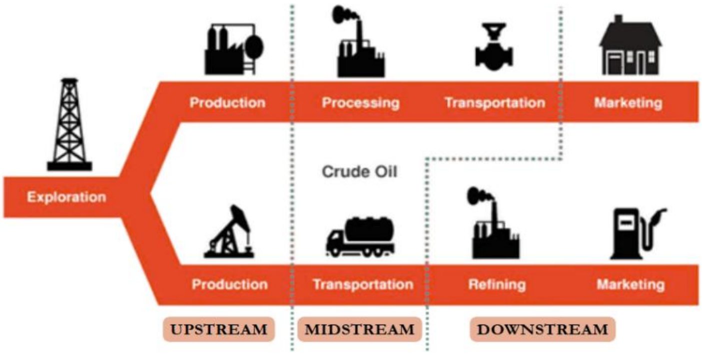

Figure 1. Shows The Overview Of Oil And Gas Industry

The Figure 1 illustrates the overall structure of the oil and gas industry, highlighting the stages where WSN-based monitoring enhances the safety and operational efficiency of pipeline systems. In a linear topology WSN, sensor nodes are deployed along the pipeline to monitor key parameters such as pressure, flow, and temperature in real time. However, ensuring reliable data delivery in this structure remains a major challenge due to limited node connectivity, frequent packet collisions, and constrained energy resources. Existing routing protocols such as Ad hoc On-Demand Distance Vector (AODV) and Destination-Sequenced Distance Vector (DSDV) often experience packet loss, congestion, and unbalanced energy consumption when operating over long linear distances [2], [3], [4]. Although numerous routing enhancements have been introduced in recent years, most focus on improving a single performance metric, such as delay or throughput, without achieving an effective trade-off between energy efficiency, reliability, and latency [5], [6].

1.1 Problem Statement

Oil and gas pipelines are important for transporting energy over long distances, but they are prone to problems like leaks, corrosion, and structural damage. A real incident of a gas pipeline explosion in Putra Heights, Malaysia, on 1 April 2025, reported by New Straits Times, caused major damages, showing how dangerous undetected pressure changes and pipeline stress can be. This clearly shows why real-time monitoring systems that can detect early warning signs are needed. WSNs offers a cost effective solution for continuous pipeline monitoring without requiring complex wired infrastructure [7], [8]. However, linear WSN deployments face challenges such as congestion, packet loss, and energy imbalance due to the multi-hop bottleneck effect [9], [10]. Traditional routing protocols like DSDV and AODV are less effective in long linear networks because proactive updates increase congestion and energy consumption, while reactive routing introduces route discovery delays[11] ,[12].

Figure 2 illustrates how packet loss occurs when packets accumulate in the buffers of intermediate nodes as they move closer to the destination node (ND). Nodes N2 and N1 experience the highest traffic load, causing their queues to fill up and resulting in packet drops, shown by the red “X”. This problem is common in protocols like DSDV and AODV, where traffic from multiple upstream nodes converges and overwhelms the final hops. The continuous queue overflow reduces the delivery ratio and reliability of long linear WSNs, especially in monitoring applications where every packet is important. This behaviour supports the need for a more balanced routing method such as DSDVTRI, which aims to reduce congestion at the final hops and minimise packet loss.

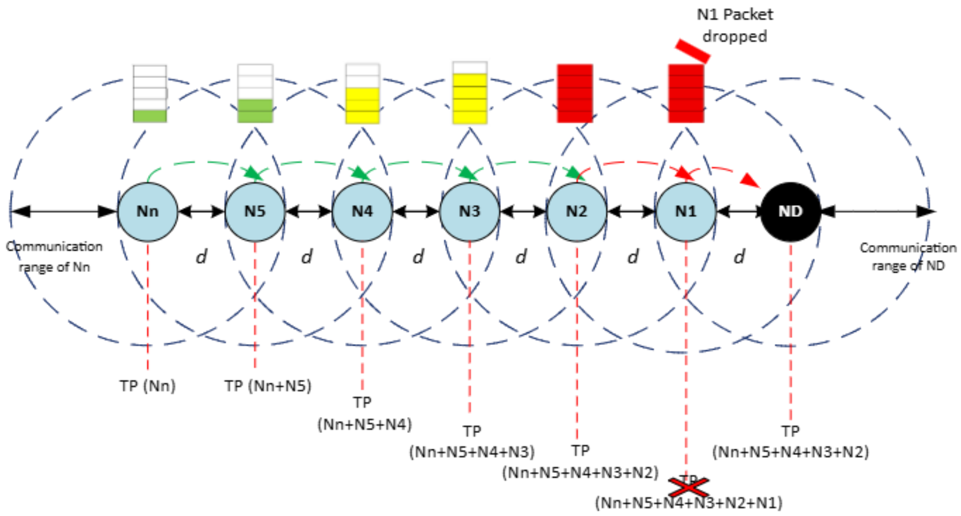

Figure 2. Shows The Packet Loss In Data Transfer To ND

2. Methods

Interleaving is a routing technique in WSNs that alternates forwarding groups to reduce simultaneous transmissions and ease congestion in multi hop networks. Recent studies on dual interleaving show that using two paths can slow queue buildup and reduce collisions, but the final hops in long linear topologies still face heavy packet concentration that leads to congestion, packet drops, and uneven energy use [13], [14]. These limitations become more noticeable when node density increases or when monitoring applications generate continuous traffic. To address this, the proposed DSDVTRI extends the structure to three coordinated forwarding groups, allowing packets to be spaced more evenly across the network. This triple interleaving design aims to reduce congestion at the destination side, improve throughput and delivery ratio, and maintain better energy balance in long distance pipeline WSN deployments[15], [16], [17].

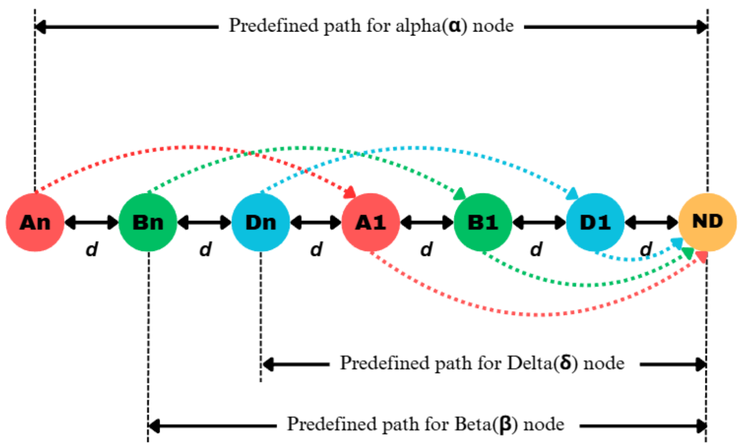

Figure 3. Shows Predefined Path For Triple-Interleaving Technique

Figure 3 illustrates the triple interleaving routing technique in a linear WSN, where nodes are divided into three groups: alpha, beta, and delta. A predefined path is followed by groups of dedicated forwarding nodes like A1, B1, and D1 to the ND. Due to this grouping, all nodes can't transmit simultaneously, which causes less collisions, lower queue delays, and congestion. Active groups do not affect each other, resulting in an even distribution of network loads [18]. Multiple paths independent of one another also improve the tensile strength, so that failure in any path to an intermediate point can continue throughout the network. This method reduces overhead and improves reliability for proactive routing protocols such as DSDV in dense or industrial environments [15].

2.1 Methodology and Algorithm Elaboration

The methodology of this work is based on extending the conventional DSDV routing process by incorporating a triple-interleaving forwarding structure to reduce congestion and balance packet distribution in linear WSNs. In standard DSDV, the number of data and control packets increases as more neighbouring nodes participate in forwarding, which leads to queue build-up and heavy load near the ND.

$$NP = (CP_i + DP_i) + \Sigma_{j=i+1}^{y} (CP_j + DP_j) \leq IfQlen_{Dn} \quad \textbf{(1.0)}$$

2.2 Ad-hoc Destination-Sequenced Distance-Vector Triple Interleaving (DSDVTRI)

The DSDVTRI protocol enhances standard DSDV by introducing a triple-interleaving structure that divides nodes into three forwarding paths and transmits them in alternating cycles. This prevents simultaneous forwarding on a single route and reduces congestion that typically builds up near the destination in linear WSNs. Previous studies on proactive and interleaving-based routing have shown that dual-path structures can reduce collisions but still suffer from bottlenecks and uneven load near the final hops in multi-hop pipeline networks [19], [20]. By spreading traffic across three coordinated paths, DSDVTRI achieves better load balancing, fewer queue overflows, and more stable end-to-end delivery, making it more reliable for long linear pipeline monitoring where continuous data flow is required.

$$NP\mathrm{x} = (CP\mathrm{x}_i + DP\mathrm{x}_i) + \Sigma_{j=i+1}^{y} (CP\mathrm{x}_j + DP\mathrm{x}_j) \leq IfQlen_{Dn} \quad \textbf{(2.0)}$$

According to equation 2.0, the variable $x$denotes the total number of nodes and may be replaced by the node counts for the α, β or δ paths to obtain NP_α, NP_βor NP_δ respectively [18]. Here $CP_i$and $DP_i$are the control and data packets associated with node i, and $IfQlen_i$is the queue length threshold (buffer capacity) at the node i. The condition $(CP_i + DP_i) \leq IfQlen_i$ therefore means that the total incoming packets to the node $i$must not exceed its buffer capacity; if this inequality is violated, new packets are dropped, leading to queue overflow and packet loss [21] ,[22].

$$y \text{ is determined as :}$$

$$y = \begin{cases} \frac{x}{3}, \text{if } x \text{ is divisible by } 3 & \mathbf{(3.0)} \\ \frac{x+1}{3}, \quad \text{if } x+1 \text{ is divisible by } 3 & \mathbf{(3.1)} \\ \frac{x+2}{3}, \quad \text{if } x+2 \text{ is divisible by } 3 & \mathbf{(3.2)} \end{cases}$$

As derived in equations (3.0,3.1,3.2) determine how the total nodes are divided into three forwarding groups for [α, β, and δ] traffics based on the value of x. When x is divisible by three, each path receives an equal number of forwarding nodes, ensuring perfectly balanced traffic. When x leaves a remainder of one or two, the equations allocate the extra node(s) proportionally so that no single path becomes overloaded. This remainder-aware grouping is essential for the triple-interleaving mechanism, as it maintains balanced load distribution across all three paths even in long linear WSNs where node counts are rarely multiples of three [14], [19].

2.3 Simulation Environment

Table 1. shows Simulation Parameters

Parameter	**Value**
Simulator	NS2.35
Topology	Linear multi hop pipeline network
Node count	20 to 200 nodes
Node spacing	50 m
Simulation area	20,000 m × 20,000 m
Mobility model	Static (no mobility)
Routing protocols	DSDVTRI (proposed), DSDV, AODV
Traffic type	CBR over TCP
Transport agent	TCP
Packet size	512 bytes
CBR interval	1.0 s
MAC layer	IEEE 802.11
Propagation model	Two Ray Ground
Interface queue type	DropTail / PriQueue
Queue length	50 packets
Radio reception range	~125 m
Energy model	Basic Energy Model (initial energy 1000 J)
Number of seeds	14 seeds (averaged)
Trace outputs	Packet trace and energy trace enabled

The simulation parameters listed in Table 1 follow the linear pipeline structure and reflect the real constraints discussed in earlier studies on long distance WSN deployments [7], [23]. A packet size of 512 bytes and a CBR over TCP configuration were selected to emulate continuous sensing traffic commonly used in pipeline monitoring applications. The use of IEEE 802.11 MAC, Two Ray Ground propagation, fixed node spacing of 50 meters, and an initial energy of 1000 J aligns with prior research settings for evaluating energy aware proactive routing in pipeline networks .To ensure reliability, all experiments were executed using fourteen independent seeds, and the results were averaged across these runs [24], [25].

2.4 Pseudocode for the DSDVTRI

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Algorithm : DSDVTRI Triple Interleaving

Input: N nodes, ND as destination
Output: Forwarding schedule for α, β, δ paths

1.  Divide nodes into three forwarding groups:
        Group1 = {nodes at positions 0,3,6,...}
        Group2 = {nodes at positions 1,4,7,...}
        Group3 = {nodes at positions 2,5,8,...}

2.  For each node i:
        If i ∈ G1 → assign Path α
        If i ∈ G2 → assign Path β
        If i ∈ G3 → assign Path δ

3.  When a packet arrives at node i:
        Check queue length Qlen(i)
        If Qlen(i) < MaxQueue:
            Forward packet to next hop on assigned path
        Else:
            Drop packet

4.  Update DSDVTRI routing table with latest sequence numbers
5.  Broadcast incremental updates when any change is detected
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Figure 4. Shows Pseudocode For The DSDVTRI

The DSDVTRI algorithm shown in Figure 4 divides nodes into three interleaving groups and assigns each group to a dedicated forwarding path (α, β, δ). When a packet reaches a node, it is forwarded along the node's assigned path as long as the queue is not full; otherwise, it is dropped. This spacing of transmissions across three coordinated groups reduces congestion at the final hops, allowing packets to arrive more evenly at the ND [24]. The forwarding and update operations follow the standard DSDV table maintenance rules, keeping the overall complexity linear with respect to the number of nodes.

3. Results & Discussion

3.1 Delivery Ratio

The delivery ratio shown in Figure 5 demonstrates that DSDVTRI consistently outperforms both DSDV and AODV across all node counts from 20 to 200. At 20 nodes, DSDVTRI achieves a delivery ratio of 98.31%, compared to 95.71% for DSDV and 91.11% for AODV, marking a 2.6% lead over DSDV and 7.2% over AODV. As node density increases, the advantage becomes more apparent. At 100 nodes, DSDVTRI maintains 63.94%, while DSDV reaches 60.89% and AODV drops to 37.94%, giving DSDVTRI a 3.05% lead over DSDV and a substantial 26% lead over AODV. Even at 200 nodes, where all protocols experience lower performance due to high network density, DSDVTRI still achieves delivery ratio of 34%, compared to 30.03% for DSDV and only 18.64% for AODV, showing a 4.03% margin over DSDV and 13.94% over AODV. These results confirm that DSDVTRI delivers higher reliability and data delivery success consistently across various network sizes.

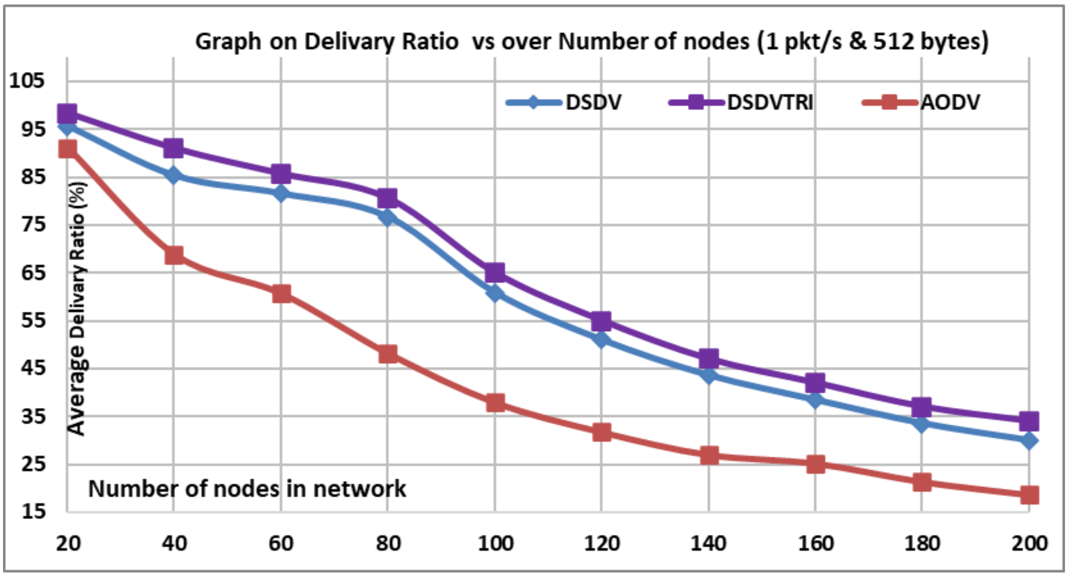

Figure 5. Shows Delivery Ratio Over The Number Of Nodes

3.2 Throughput

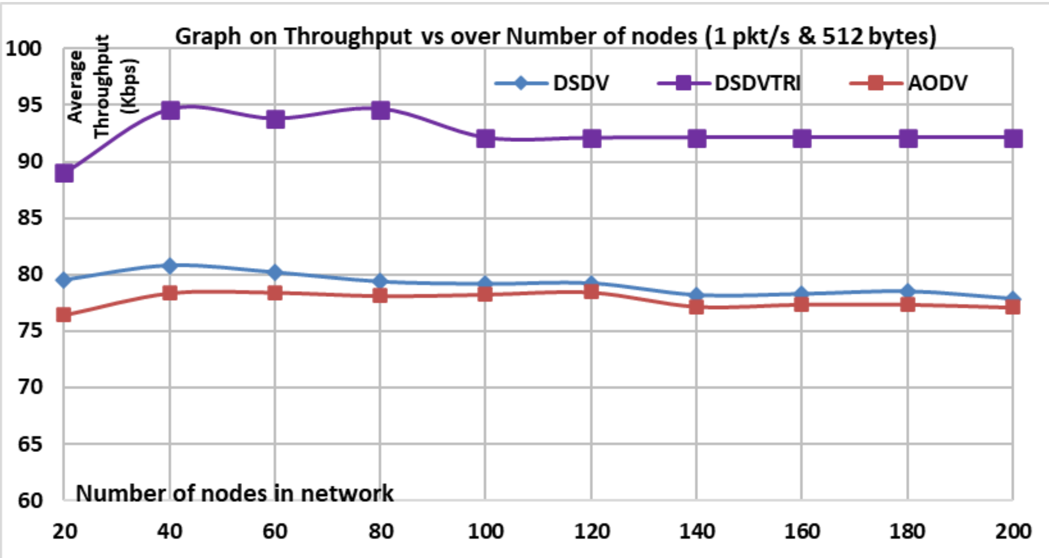

Figure 6. Shows Throughput Over The Number Of Nodes

The throughput analysis in Figure 6 shows that DSDVTRI consistently achieves higher throughput across all node densities compared to DSDV and AODV. At 20 nodes, DSDVTRI records approximately 89 kbps, outperforming DSDV at around 79 kbps and AODV at about 76 kbps, representing an improvement of roughly 12.7% over DSDV and 17.1% over AODV. As the network size increases to 100 nodes, DSDVTRI maintains a throughput of about 92 kbps, while DSDV and AODV achieve approximately 79 kbps and 78 kbps, giving DSDVTRI about 16.5% higher throughput than DSDV and 17.9% higher than AODV. Even at 200 nodes, DSDVTRI continues to sustain a throughput near 92 kbps, whereas DSDV and AODV drop slightly to around 78 kbps and 77 kbps, showing improvements of about 17.9% over DSDV and 19.5% over AODV. These results indicate that DSDVTRI maintains more stable and higher throughput, particularly as the network becomes denser.

3.3 Energy Consumption Per Packet

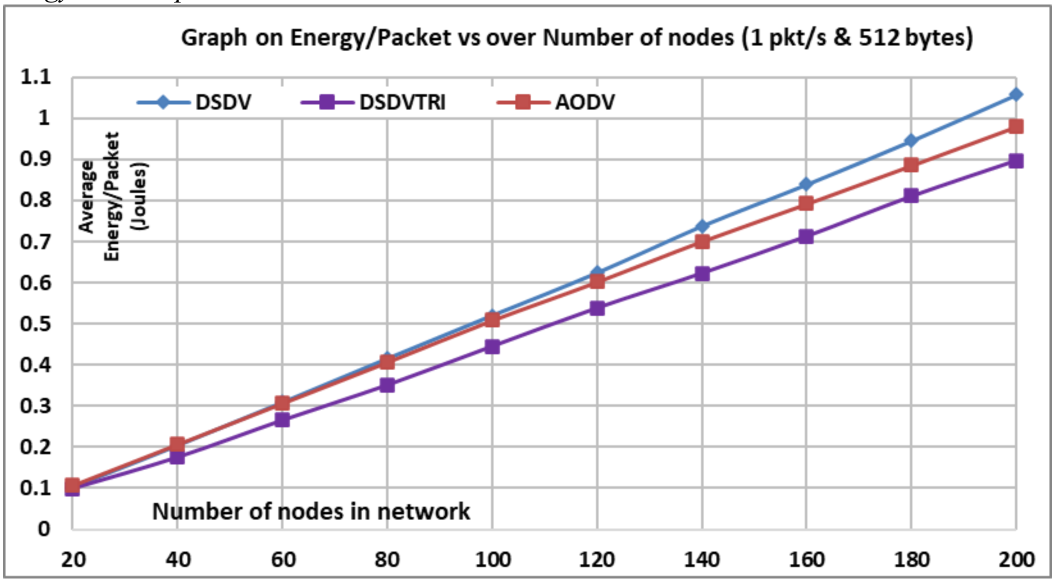

Figure 7. Shows Energy Consumption Over The Number Of Nodes

The evaluation of energy consumption shown in Figure 7 indicates that DSDVTRI consistently consumes less energy per packet compared to DSDV and AODV across all node densities. At 20 nodes, DSDVTRI records approximately 0.10 J/packet, which is similar to DSDV and AODV at around 0.11 J/packet. As the network increases to 100 nodes, DSDVTRI consumes about 0.45 J/packet, while DSDV and AODV consume approximately 0.51 J/packet, showing about 11.8% lower energy consumption for DSDVTRI. At 200 nodes, DSDVTRI records roughly 0.89 J/packet, compared to 1.06 J/packet for DSDV and 0.98 J/packet for AODV, representing around 16% reduction compared to DSDV and 9.2% lower than AODV. These results demonstrate that DSDVTRI is more energy efficient, which is beneficial for wireless sensor network applications where energy conservation is critical.

3.4 Received Packets

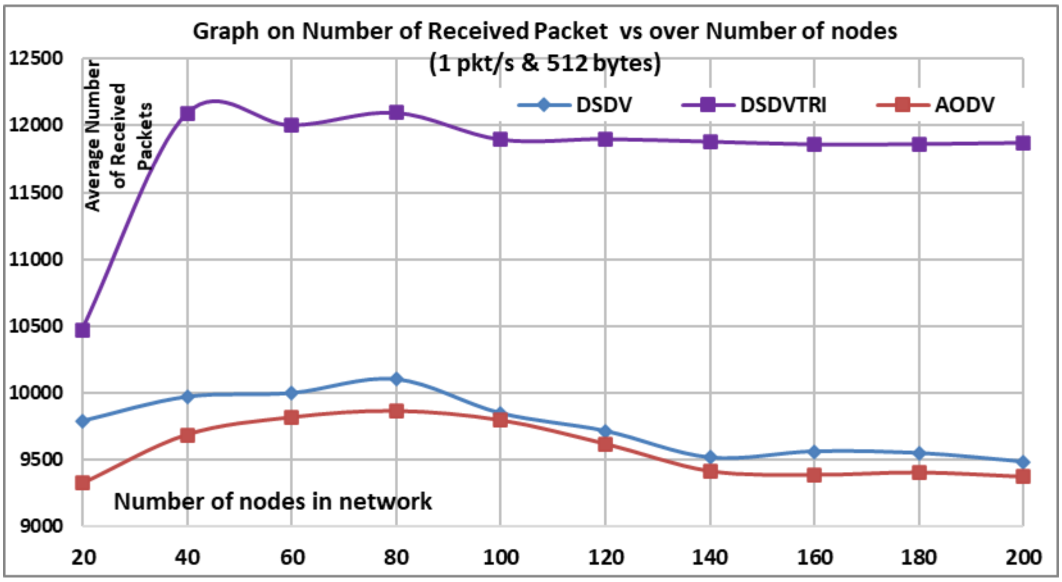

Figure 8. Shows Received Packet Over The Number Of Nodes

The analysis of received packets in Figure 8 clearly shows that DSDVTRI outperforms both DSDV and AODV across all node counts, demonstrating its superior capability to deliver more data to the destination. At 20 nodes, DSDVTRI successfully receives 10,472 packets, slightly ahead of DSDV's 9790 and considerably better than AODV's 9325. As the network scales, the performance gap widens. At the significant point of 100 nodes, DSDVTRI records 11894 received packets, while DSDV and AODV drops to 9797 , it is an impressive 68% improvement. At 200 nodes, despite overall reductions due to congestion, DSDVTRI maintains its lead with 11870 packets received, compared to 9485 for DSDV and only 9375 for AODV. This shows that DSDVTRI maintains consistent packet delivery even under high-density conditions. Its triple interleaving mechanism helps distribute load efficiently and avoid route saturation, enabling more packets to reach the destination compared to traditional single-path approaches.

3.5 Routing Overhead

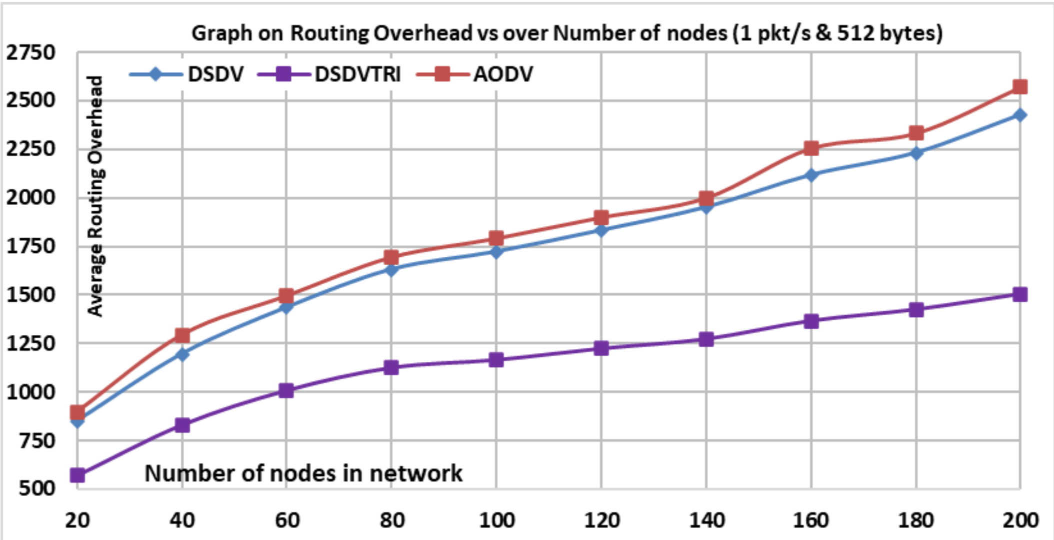

Figure 9. Shows Routing Overhead Over The Number Of Nodes

The evaluation of routing overhead in Figure 9 shows that DSDVTRI consistently produces lower routing overhead compared to DSDV and AODV across all node densities. At 20 nodes, DSDVTRI records approximately 560 routing packets, which is significantly lower than DSDV at around 880 and AODV at about 900. As the network increases to 100 nodes, DSDVTRI generates roughly 1150 routing packets, while DSDV records about 1720 and AODV around 1780, showing that DSDVTRI reduces routing overhead by about 33% compared to DSDV and 35% compared to AODV. At 200 nodes, DSDVTRI records approximately 1500 routing packets, whereas DSDV reaches around 2420 and AODV about 2560, representing a reduction of roughly 38% compared to DSDV and 41% compared to AODV. These results indicate that DSDVTRI effectively controls routing overhead even as the network becomes denser, demonstrating better scalability for linear wireless sensor network environments.

4. Conclusion

This study presented the DSDVTRI routing protocol as a technique to address performance limitations in linear WSNs used for pipeline monitoring. Traditional protocols like AODV and DSDV struggle with packet loss, congestion, and energy inefficiency, particularly in long, dense multi-hop networks. The triple interleaving technique introduced in DSDVTRI effectively mitigates these issues by distributing data traffic across three predefined paths, reducing node congestion and improving overall network balance.

Simulation results shows that DSDVTRI consistently outperforms both DSDV and AODV in delivery ratio, throughput, energy consumption, and received packets. Even as node density increases, DSDVTRI maintains better reliability and efficiency, while keeping routing overhead low. These results validate that the proposed approach is well-suited for real-time applications like pipeline monitoring, where stability, speed, and energy efficiency are critical.

For future work, this study recommends optimising the interleaving scheduling algorithm to support dynamic path switching in the event of node failure. Additionally, extending DSDVTRI for grid or hybrid topologies and incorporating mobility patterns could make the protocol suitable for broader industrial applications. Integrating machine learning for adaptive routing decisions and testing on hardware platforms are also suggested to enhance real-world applicability.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the author(s) used SciSpace AI Research Agent to find the proper and legitimate paper to refer. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Research Involving Human/Animal Participants: This article does not involve any studies conducted by authors on animals or human participants.

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