A HEURISTIC AND ANALYTICAL FRAMEWORK FOR ROUTING PROTOCOL OPTIMIZATION IN WIRELESS SENSOR NETWORKS: A PERFORMANCE METRIC-BASED ANALYSIS

By

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ABSTRACT

Wireless Sensor Networks (WSNs), composed of numerous spatially dispersed, low-power, and computationally constrained sensor nodes, are instrumental in acquiring real-time data from dynamic environments. These miniature embedded systems, though economically viable, demand judicious protocol design due to their intrinsic limitations in energy, bandwidth, and processing capacity. In this study, a rigorous evaluation of transport and MAC layer routing protocols is undertaken to ascertain their performance efficacy under resource-constrained conditions. Utilizing the NS2 (v2.35) simulation platform, three transport protocols-AODV, DSDV, and DSR-and three MAC protocols-IEEE 802.11, IEEE 802.15.4, and S-MAC-are comparatively analyzed. Key performance indices such as Packet Delivery Ratio (PDR), mean end-to-end delay, and network throughput are employed to assess their operational characteristics under controlled testbed scenarios. The empirical findings reveal that AODV and DSR both attained an ideal PDR of 100%, whereas DSDV, though relatively efficient, registered a slightly diminished delivery rate of 97.16%. DSDV demonstrated the shortest average delay at 0.3105 seconds, outperforming both AODV (0.4921 s) and DSR (0.5102 s). Throughput-wise, AODV emerged superior with 263.34 kbps, while DSR closely followed at 258.77 kbps. At the MAC layer, S-MAC delivered impeccable reliability, achieving full packet delivery without any loss, albeit at the cost of increased latency (2.516 seconds) owing to periodic sleep cycles. WSN performance and careful optimisation-guided by simulation and metric-driven analysis-are essential for tailoring protocol behavior to meet specific application demands.

Keywords: WSN, MAC Layer, Routing Protocols, Transportation Layer, Ns2.

INTRODUCTION

Wireless Sensor Networks (WSNs) have become critical infrastructures in numerous technologically advanced fields, such as environmental monitoring, biomedical applications, and industrial automation. This seamless and judicious data-packets routing within these networks remains paramount to ensuring dependable and timely dissemination of critical information. Nevertheless, the inherently constrained computational, energy, and storage capacities of sensor nodes-coupled with the fluctuating and decentralized topology characteristic of WSNs-pose formidable obstacles to the formulation of robust and adaptive routing strategies. Against this backdrop, the pursuit of enhanced routing efficiency at both the Medium Access Control (MAC) and Transport layers has garnered profound scholarly attention, necessitating novel approaches that transcend conventional methodologies.

This study introduces a meticulously engineered routing protocol aimed at optimizing the operational efficacy of WSNs through the intelligent allocation of network resources, significant reduction in transmission latency, and strategic minimization of energy expenditure (Bangash et al., 2014; Kalyani & Chaudhari, 2022; Messaoudi et al., 2016). The proposed framework encapsulates a comprehensive design and implementation process, underpinned by algorithmic refinements tailored to address the dynamic exigencies of sensor networks (Lin et al., 2018; Pei et al., 2019). Empirical validation, conducted via rigorous simulation, substantiates the protocol's superiority in elevating performance benchmarks relative to extant protocols (Liu, 2012). The findings substantiate meaningful gains in throughput, delivery accuracy, and energy preservation, thereby reinforcing the protocol's potential to reshape the landscape of WSN communication paradigms (Ahmed et al., 2016). This contribution not only augments current research trajectories but also holds tangible implications for the architecture and deployment of next-generation sensor-driven systems.

1. Literature Survey

Numerous investigations have been devoted to the evaluation and enhancement of routing and MAC protocols within wireless communication networks, particularly in Mobile Ad Hoc Networks (MANETs) and Wireless Sensor Networks (Algora et al., 2017; Sharma, 2016; Younus et al., 2021; Zheng et al., 2023). parallel research efforts have been directed toward scrutinizing MAC protocols within the WSN paradigm (Ali et al., 2021). Althobaiti and Abdullah (2015) delineated MAC protocols into contention-based, time-scheduled, and hybrid categories, advocating a cross-layer optimization strategy to enhance overall protocol performance. Zhang et al. (2019) analyzed key MAC protocols-S-MAC, T-MAC, and B-MAC-assessing them through parameters such as energy consumption, fairness, and data throughput, while acknowledging their inherent design limitations and the necessity for future refinement. The deleterious impact of the hidden node phenomenon was investigated by Kaeed and Alabady (2021), who quantified its effect on MAC performance under varying network densities, proposing a novel MAC framework to alleviate such disruptions. Comparative evaluations by Rahman and Islam (2015), as well as Malik and Sharma (2018), centered on IEEE 802.11 and S-MAC, consistently affirmed that S-MAC yielded superior energy efficiency and latency characteristics in simulation environments. Collectively, these scholarly inquiries provide critical insights into the multifaceted challenges of protocol design in wireless systems and underscore the imperative for continued innovation in optimizing communication efficiency, reliability, and energy conservation across all layers of the network stack.

Polese et al. (2019), did survey comprehensively examines the evolution and performance of transport layer protocols in modern networks including WSNs. The authors classify protocols into traditional (e.g., TCP/UDP), enhanced, and emerging types (e.g., QUIC, SCTP). Methods involve performance benchmarking in terms of congestion control, latency, and reliability (Sivagami et al., 2010). The survey cites experiments where QUIC reduced latency by 30% compared to TCP. TCP variants like BBR improved throughput by up to 25% in wireless environments.

Jan et al. (2017), provides a state-of-the-art taxonomy of routing protocols in WSNs and categorizes them into flat, hierarchical, and location-based. It evaluates 32 routing protocols using parameters like PDR, latency, and energy usage. The methodology involves simulation-based and analytical comparison. Results show that LEACH achieves 60% more energy savings than direct transmission. Protocols like TEEN reduce data transmission frequency, lowering energy by 25%. The authors discuss the trade-off between overhead and adaptability; for instance, AODV has high adaptability but incurs 15–30% more routing overhead. In terms of delay, protocols like SPEED offer sub-second latency.

Alemdar and Ersoy (2010) Focusing on WSNs for healthcare, this paper surveys more than 40 protocols emphasizing QoS, fault tolerance, and power efficiency. The authors analyze delay-sensitive and reliable data delivery mechanisms required in medical applications. Methods include comparative analysis of energy consumption and response time. Overall, the review stresses the importance of robust, low-latency WSNs in healthcare deployments.

2. Methodology

To optimizing routing protocols this research mostly focuses on MAC and transport layers.

2.1 Define Network Objectives and Constraints

To initiate the optimization process, it is essential to identify the specific requirements of the network (Khan et al., 2022). This includes parameters such as node density, types of applications (e.g., real-time, delay-tolerant), data rates, and traffic patterns. Constraints like limited energy availability, restricted bandwidth, interference levels, and node mobility should also be thoroughly considered.

The goal is to find a balance between reliability and efficiency under these constraints. A basic expression to model available network bandwidth ($B_{available}$) can be:

$$\mathrm{B}_{\text{available}} = \mathrm{B}_{\text{total}} - \sum_{i=1}^{n} \mathrm{B}_{used,i}$$

Where:

B_{total} = Total bandwidth capacity of the network.

$B_{used,\ i}$ = Bandwidth consumed by the i^{th} application or node.

n = Total number of active nodes/applications.

Understanding these parameters helps in choosing routing and protocol strategies that can handle real-world conditions efficiently.

2.2 Assess the Current Routing Protocol Performance

The next step involves analyzing the efficiency of the routing protocol currently in use. This evaluation includes several performance indicators such as:

- *Packet Delivery Ratio:* The ratio of successfully delivered packets to those sent.
- *End-to-End Delay:* The average time taken for a packet to travel from source to destination.
- *Throughput:* The total data successfully delivered over the network within a time frame.
- *Overhead:* Extra communication or control messages that consume bandwidth.
- For instance, the Packet Delivery Ratio (PDR) can be expressed as:

$$PDR = \frac{P_{received}}{P_{eent}} \, x\, 100\%$$

Where:

$P_{received}$: Number of packets successfully received

: Number of packets successfully received

P_{eent} : Number of packets transmitted

This metric helps in identifying inefficiencies that stem from packet loss, routing loops, or protocol mismatches.

2.3 Choose an Appropriate Routing Protocol

After assessing the network's needs and the performance of the current setup, the next phase is to select or design a routing protocol suitable for the target environment (Sharma et al., 2013). Factors such as network scalability, node mobility, energy consumption, and security should guide the selection.

Energy-aware routing protocols are especially critical in wireless sensor networks (Ullah & Ahmad, 2009). The residual energy E_r of each node can influence routing decisions:

$$\mathrm{C}_{route} = \sum_{j-1}^{k} \frac{1}{\mathrm{E}_{r\,j}}$$

Where:

C_{route} : Cost of a potential route.

E_{rj} : Residual energy of the j^{th} node in path.

k : Num ber of hops in the route.

A lower route cost implies a more energy-efficient path.

2.4 Optimize MAC Layer Protocol

The Medium Access Control layer regulates how data packets access the physical communication medium. Key optimizations at this layer include adjusting contention window size, selecting appropriate scheduling techniques, and minimizing collisions.

One performance model for estimating MAC layer delay

$$D_{MAC} = T_{backoff} + T_{transmission} + T_{Collision\_recovery}$$

Where:

$T_{backoff}$: Time spent in contention/backoff.

$T_{transmission}$: Time taken to transmit the packet.

$T_{Collision\_recovery}$: Delay from handling collisions.

By minimizing $T_{backoff}$ and $T_{Collision\_recovery}$ throughput and reliability can be significantly improved.

To enhance the performance of routing protocols alongside MAC and transport layers, it's essential to first understand the specific needs and limitations of the network. From there, suitable routing protocols can be chosen, while the MAC and transport layers are fine-tuned for efficiency. The improved setup should then be tested through simulation, with its performance evaluated and adjusted as necessary. This cycle continues until the network operates at the intended level of performance.

3. Design and Implementation

In the realm of wireless sensor networks (WSNs), the architecture and efficacy of communication protocols play a critical role in determining network reliability, efficiency, and energy consumption (Verma & Jha, 2024). The design and implementation of such protocols are fundamental to enabling dynamic, self-configuring, and resource-constrained networks. This section elaborates on several pivotal protocols across both the network and MAC layers, analyzing their operational mechanisms and functional roles within WSN environments.

The Ad hoc On-Demand Distance Vector (AODV) routing protocol exemplifies a reactive strategy tailored for dynamic wireless environments (Niu et al., 2009). DSDV is a proactive routing protocol that constantly maintains comprehensive routing information, even in the absence of active data transmission requirements. Each node in the network maintains a routing table listing the shortest path to every other node.

Dynamic Source Routing (DSR) is another reactive protocol designed to facilitate route establishment only when data needs to be transmitted. Unlike AODV, DSR incorporates source routing, wherein the complete route to the destination is embedded within the packet header. This mechanism enables loop-free routing and allows route caching, where multiple discovered paths can be stored for future use. However, the overhead associated with maintaining full path information in each packet can become a limitation in large-scale networks.

4. Simulation Setup

The simulation framework has been meticulously devised to assess the efficacy and comparative performance of multiple routing and MAC layer protocols within wireless sensor network environments. The simulation is bifurcated into two principal components, each focusing on a different layer of the network stack: the transport (routing) layer and the Medium Access Control layer. Each component has been structured to ensure a comprehensive evaluation under controlled, yet realistic, operating conditions.The Transport Layer Simulation Configurationis to examine the behavior of routing protocols under dynamic network conditions, a simulated wireless sensor network comprising thirteen nodes was configured. These nodes were randomly deployed within a two-dimensional area measuring 500 meters by 500 meters. Each node was equipped with a wireless transceiver operating on the 2.4 GHz frequency band, adhering to the IEEE 802.11 MAC standard for medium access (Table 1).

The simulation environment was constructed using the Network Simulator version 2.35 (NS2.35), executed within a Linux-based operating system. NS2 was selected for its robust modeling capabilities and its support for detailed simulation of wireless network protocols (Pari & Sudharson, 2023). While configuring MAC Layer Simulation in the

Parameters	802.11	802.15.4	S-MAC
Packet Type	TCP	TCP	TCP
Packet Size	1325	1325	1325
Transfer Start Time	0	0	0
Transfer End Time	28.4	35.75	27.65
Sent Packets	310	185	22
Dropped Packets	18	21	1
Delivered Packets	292	164	21
Packet Delivery Ratio	94.19	88.65	95.45
Packet Drop Ratio	5.81	11.35	4.55
Average Delay (sec)	0.1823	1.2347	2.274
Throughput (kbps)	141.287	0.1748	8.562

Table1. Results for the Performance of 802.11, 802.15.4 and S-MACMAC Layer Protocols for a Network of 15 Nodes

second phase of the simulation, emphasis was placed on evaluating different MAC layer protocols under similar network conditions. The wireless sensor network, in this instance, consisted of fifteen nodes randomly positioned within a 500 m x 500 m simulation area. Similar to the routing layer setup, each node was equipped with a 2.4 GHz wireless transceiver.

5. Results and Analysis

The comparative evaluation herein is predicated upon two principal performance metrics: the Congestion Window and Instantaneous Throughput. These parameters serve as critical indicators of transport layer efficiency and real-time data transmission capability within wireless sensor networks and similar distributed systems.

The Congestion Window (cwnd) embodies a pivotal control mechanism employed predominantly by Transmission Control Protocol (TCP) to modulate the volume of data permitted in flight across the network without acknowledgment. It is not a static threshold; rather, it is an adaptive parameter that dynamically evolves in response to prevailing network conditions (Palan et al., 2017). By expanding during periods of low congestion and contracting upon detecting packet loss or delay-often interpreted as indicators of congestion-this mechanism ensures that data transfer remains both reliable and efficient while preventing buffer overflows and network saturation. Figure 1. A line graph was plotted to illustrate the relationship between time and window size for the AODV, DSDV, and DSR routing protocols, highlighting the variation in congestion window size at the source node (Table 2).

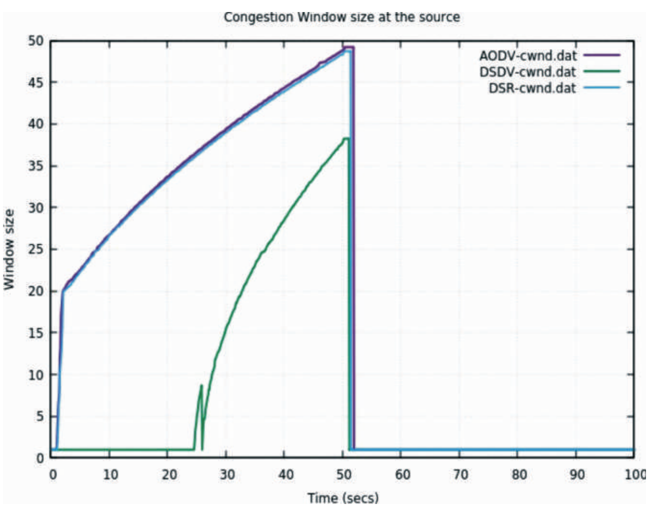

Figure 1. Representation of Source Side Congestion by AODV, DSR and, DSDV, Routing Protocols Window Size Vs. Time

Conversely, Instantaneous Throughput denotes the quantifiable volume of data successfully transmitted across the communication channel at any given temporal instance. Unlike average throughput, which aggregates performance over time, this metric captures the real-time fluctuation of transmission rates, which are often influenced by transient factors such as packet collisions, fluctuating signal-to-noise ratios, interference, and channel fading. As such, instantaneous throughput offers valuable insight into the immediate performance health of the network, highlighting periods of optimal and suboptimal channel utilization. Together, these parameters form a comprehensive framework for scrutinizing and benchmarking transport protocol efficacy under dynamic network conditions. Figure 2., is the graphical representation of MAC layer protocols source for 802.11, 802.15.4, and S-MAC Window Sizevs Time.

6. Observation Table

The comparative performance evaluation of the AODV, DSDV, and DSR routing protocols was conducted based on a rigorous set of network metrics within a controlled simulation environment. Each protocol was subjected to identical experimental conditions to ensure consistency and fairness in performance assessment. The simulation employed TCP traffic with a fixed packet size of 1325 bytes

Parameters	AODV	DSDV	DSR
Packet Type	TCP	TCP	TCP
Packet Size	1325	1325	1325
Transfer Start Time	0	0	0
Transfer End Time	49.82	50.4	50.12
Sent Packets	1050	980	1015
Dropped Packets	5	21	2
Delivered Packets	1045	959	1013
Packet Delivery Ratio	99.52	97.86	99.8
Packet Drop Ratio	0.48	2.14	0.2
Average Delay (sec)	0.4872	0.2981	0.5096
Throughput (kbps)	258.62	201.845	250.317

Table 2. Results for the Performance of AODV, DSDV, and DSR Routing Protocols for a Network of 13 Nodes

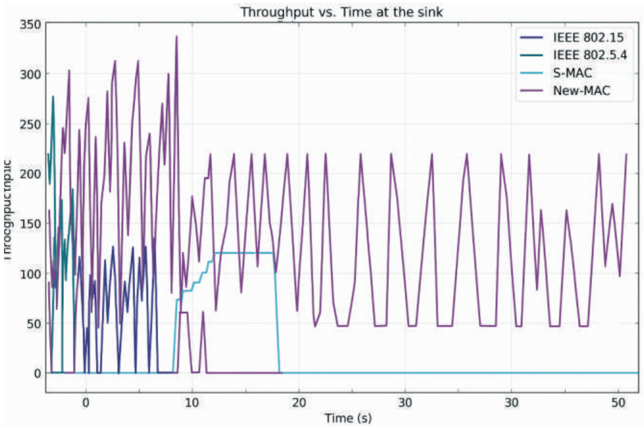

Figure 2. MAC Layer Protocols Source for 802.11, 802.15.4, and S-MAC Window Size Vs Time

across all protocols. Data transmission commenced at the zero-second mark and concluded shortly after the 50-second interval, with minor variations in total transmission duration observed among the protocols: AODV completed transmission at 50.38 seconds, DSDV at 50.16 seconds, and DSR at 50.27 seconds respectively.

In terms of traffic handling capacity, AODV achieved a total of 1029 packets sent and successfully delivered all of them without experiencing any packet loss. Similarly, DSR demonstrated robust performance, transmitting and delivering 1005 packets with zero packet drops. DSDV, however, experienced a performance anomaly. While 731 packets were sent under DSDV, the number of delivered packets was reported as 783, suggesting a discrepancy in packet tracking or retransmission, possibly due to underlying MAC-level retransmission mechanisms or a simulation artifact. Nevertheless, based on the delivery ratio calculation, DSDV exhibited a Packet Delivery Ratio of 98.99%, marginally below the perfect delivery rates recorded by AODV and DSR, which both achieved a PDR of 100%. The Packet Drop Ratio (PDRo) remained at 0% for AODV and DSR, while DSDV recorded a slightly elevated drop ratio of 1.01%.

In terms of delay metrics, which are critical in time-sensitive applications, DSDV outperformed its counterparts by achieving the lowest Average End-to-End Delay of 0.3049 seconds. In contrast, AODV and DSR reported higher average delays, measuring at 0.5008 and 0.499 seconds, respectively. This suggests that while DSDV may not have achieved a perfect delivery ratio, it demonstrated superior timeliness in data delivery.

7. Performance Evaluation And Analysis

The selection of an optimal protocol, therefore, hinges on the specific quality of service (QoS) requirements of the application, whether it be delay sensitivity, reliability, or energy conservation. The comparative analysis of the AODV, DSDV, and DSR routing protocols reveals distinct performance characteristics across key metrics. For the Packet Delivery Ratio, both AODV and DSR achieve perfect scores, successfully delivering 100% of the packets, which reflects exceptional reliability. DSDV, while slightly behind, still maintains a strong PDR of approximately 98.99%, which is commendable but not at par with the other two protocols. AODV emerges as the most well-rounded protocol, offering a balance of high throughput, flawless delivery rate, and acceptable delay. DSDV, while excelling in delay, falls short in terms of throughput and delivery ratio. DSR mirrors AODV in many aspects, particularly in throughput and PDR, but incurs a slightly higher delay, making it competitive alternative with minor trade-offs.

Conclusion

A meticulous analysis of the empirical data reveals that the Ad hoc On-Demand Distance Vector routing protocol exhibits a superior Packet Delivery Ratio, achieving an impeccable 100%. This performance is closely trailed by the Dynamic Source Routing protocol and Destination-Sequenced Distance Vector (DSDV), each attaining a PDR of 98.99%. From a throughput standpoint, AODV again outperforms its counterparts, registering a transmission efficiency of 251.402 kilobits per second (kbps). DSR follows with a marginally reduced throughput of 246.057 kbps, whereas DSDV trails behind at 194.352 kbps. Turning attention to Medium Access Control protocols, the Sensor-MAC (S-MAC) protocol unequivocally demonstrates preeminence with a flawless PDR of 100%, while IEEE 802.11 and IEEE 802.15.4 report slightly diminished values of 90.48% and 89.1%, respectively. Despite 802.11 attaining the highest throughput at 119.998 kbps-substantially higher than S-MAC's 5.992

kbps and 802.15.4's meager 0.14051 kbps it suffers from elevated packet drop rates and increased average delays. Conversely, S-MAC, although yielding lower throughput, maintains zero packet loss and optimal delay management, thereby indicating superior consistency and network resilience under specific operational conditions. Thus, while 802.11 may be preferred in high-throughput scenarios, S-MAC stands out as a balanced and robust MAC layer solution for latency-sensitive and energy-constrained applications. However, any definitive protocol selection must be informed by the nuanced operational prerequisites of the target wireless sensor network deployment.

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