A Cross-Layer Framework for Optimizing Energy Efficiency in Wireless Sensor Networks: Design, Implementation, and Future Directions

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***Abstract*—Environmental monitoring, healthcare, and industrial automation are among the numerous modern applications in which Wireless Sensor Networks (WSNs) are becoming increasingly indispensable. Despite this, the scalability and endurance of these networks are still significantly impeded by the energy constraints of sensor nodes. This study proposes a novel cross-layer framework that dynamically optimizes energy consumption across the entire communication hierarchy by integrating the Application, Network, Data Link, and Physical layers to address this issue. The framework introduces significant innovations, including an adaptive Low-Traffic Aware Hybrid Medium Access Control (LTH-MAC) protocol that is intended to adjust transmission schedules in response to real-time traffic conditions, and energy-aware routing algorithms that consider both node energy levels and network topology when determining the most energy-efficient communication paths. The framework exhibits substantial enhancements in energy efficiency, reaching a reduction in energy consumption of up to 43%, as evidenced by extensive simulations conducted with OPNET. Furthermore, the network lifetime is extended by 8%, and transmission is improved by 10% compared to conventional statically defined layered architectures. These findings underscore the potential of the proposed cross-layer framework to not only improve overall network performance but also reduce energy consumption, thereby guaranteeing sustainable and efficient operation in resource-constrained environments. Additionally, the solution's scalability renders it suitable for a diverse array of WSN applications, providing a promising solution for overcoming the constraints of energy and establishing the foundation for more durable and efficient sensor networks. This study establishes the foundation for future research on adaptive, cross-layer protocols that can further enhance energy-efficient communication in WSNs.**

Keywords*—*Wireless sensor network; cross-layer; energy efficient; performance; OPNET

I. Introduction

Wireless Sensor Networks (WSNs) have emerged as a critical technology for a diverse range of applications, from environmental monitoring to smart cities. However, the inherent energy limitations of sensor nodes pose a critical challenge to their long-term operation and widespread deployment. This research seeks to address the following key question: How can a cross-layer design effectively minimize energy consumption in WSNs while maintaining acceptable levels of network performance?

WSNs are increasingly indispensable in numerous modern applications, including environmental monitoring, healthcare, and industrial automation. In environmental monitoring, WSNs can be deployed to track critical parameters such as temperature, humidity, and air quality, enabling applications like forest fire detection, precision agriculture, and pollution control. In healthcare, WSNs facilitate remote patient monitoring through wearable sensors, allowing for continuous tracking of vital signs and improving the quality of care for patients with chronic conditions. For industrial automation, WSNs enable applications such as predictive maintenance, asset tracking, and smart grid management, enhancing operational efficiency and reducing downtime. Despite their wide-ranging potential, the scalability and endurance of these networks are significantly impeded by the energy constraints of sensor nodes.

To address these challenges, particularly the need for improved energy efficiency and network lifetime, researchers have explored various techniques, including cross-layer design. This approach offers the potential to optimize energy consumption across multiple protocol layers. However, significant questions remain: What specific inter-layer interactions contribute most significantly to energy savings in WSNs, and furthermore, how can these interactions be effectively implemented in a dynamic network environment, characterized by node mobility and fluctuating traffic patterns? This paper introduces an innovative cross-layer sensor model designed to enhance energy efficiency in wireless sensor networks (WSNs). The model integrates the Application (APP), Network (NET), Data Link (DLL), and Physical (PHY) layers to facilitate collaborative decision-making. By utilizing received signal power estimates from the DLL and PHY layers, the network layer optimizes routing decisions to minimize energy consumption. Additionally, the DLL layer implements the Low-Traffic Aware Hybrid (LTH-MAC) protocol [1], ensuring efficient wireless medium access and improved resource utilization. The framework is evaluated through extensive simulations using OPNET, demonstrating substantial enhancements in energy efficiency, showcasing the model's superiority over conventional layered approaches. This improvement underscores its potential to optimize resource utilization and operational performance in wireless sensor networks.

The proposed model is rigorously evaluated through extensive simulations conducted using OPNET, focusing on key performance metrics such as energy consumption, latency, and throughput. The findings highlight substantial enhancements in energy efficiency, showcasing the model's superiority over conventional layered approaches. This improvement underscores its potential to optimize resource utilization and operational performance in wireless sensor networks.

The remainder of the paper is organized as follows. Section II reviews related work on cross-layer design in WSNs. Section III details our proposed cross-layer sensor model. Section IV presents simulation results using OPNET to evaluate the performance of the model in terms of energy consumption, latency, and throughput. Finally, Section V concludes the paper and discusses future research directions.

II. Related Work

Wireless Sensor Networks (WSNs) are vital for applications in fields such as environmental monitoring, healthcare, and industrial automation [2]. However, their limited energy resources, combined with the increasing demands for real-time data processing and reliability, pose significant challenges. Traditional layered architectures, though widely used, often lack the flexibility to address these issues efficiently. Cross-layer design (CLD) has emerged as a promising alternative, allowing inter-layer communication and joint optimization to enhance network performance. CLD techniques have shown potential in improving energy efficiency, reducing latency, and optimizing throughput in resource-constrained environments.

Recent studies provide a comprehensive analysis of cross-layer methodologies in WSNs, focusing on energy efficiency and protocol adaptability. For instance, Lahane and Jariwala proposed a hybrid clustering approach for secured cross-layer routing in dense WSNs, emphasizing clustering for scalability and security [4]. Similarly, Guleria et al. explored asynchronous MAC protocols coupled with cross-layer interactions to enhance energy utilization and adapt to dynamic network conditions [5]. Babber and Randhawa's comprehensive work on cross-layer designs for WSNs highlighted the versatility of such solutions in addressing energy and performance challenges [6]. Chandravathi and Mahadevan proposed a web-based cross-layer optimization technique, which optimizes energy usage by integrating network and application layer decisions [7]. Parween and Hussain provided a broad review of various cross-layer techniques for WSNs, categorizing them based on their optimization strategies and applications [3].

Expanding on these efforts, additional studies have highlighted novel methodologies in the field. Sandhiyaa and Gomathy [8] emphasized load balancing and energy-efficient QoS-based routing to improve reliability in underwater wireless sensor networks. Raj and Duraipandian [9] developed an opportunistic routing protocol paired with a sparse autoencoder to enhance energy efficiency and data transfer in dynamic WSN environments. Kumari and Yadav [10] proposed a dynamic cross-layer communication design for multi-objective optimization in WSNs, addressing scalability and energy constraints. Xu and Yuan [11] focused on multi-path transmission for event-driven WSNs, emphasizing the balance between energy efficiency and reliability.

While these contributions address various aspects of cross-layer optimization, challenges remain in achieving scalable, secure, and adaptive designs for heterogeneous and large-scale WSNs. Building on these efforts, this paper introduces a hybrid cross-layer sensor model incorporating adaptive MAC protocols and energy-aware routing algorithms. The proposed model leverages inter-layer interactions to optimize energy usage and improve key performance metrics, addressing critical challenges in WSNs.

III. Cross-Layered Models: Sensor and BS

This section describes the proposed cross-layer design framework for Wireless Sensor Networks (WSNs), focusing on energy efficiency and performance optimization. Two types of node models – sensor and base station – were developed using the OPNET simulation tool. Each model implements four interconnected layers: Application (APP), Network (NET), Data Link (DLL), and Physical (PHY). These layers work collaboratively to optimize network operations by facilitating seamless inter-layer communication and adaptive decision-making.

A. Cross-layer Interactions

The proposed model enables efficient interaction across protocol layers to address energy consumption and data transmission challenges in WSNs. Fig. 1 illustrates the inter-layer communication within the sensor model, highlighting both traditional and newly introduced interactions.

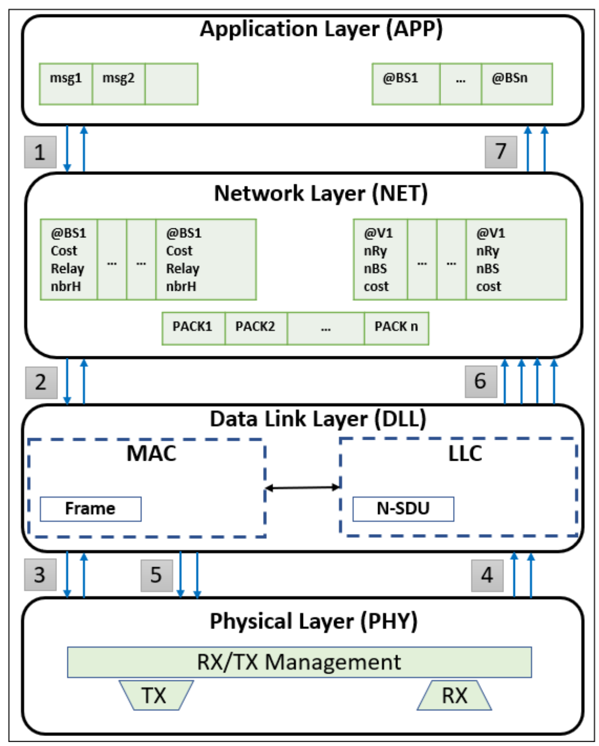

Fig. 1. Inter-layer interactions model.

Arrows (1), (2), and (3) represent the essential communication channels between adjacent layers in the network stack. These channels correspond to various service primitives defined by the traditional layered network standard, which are briefly outlined below.

- The **Network Layer (NET)** delivers critical services to ensure efficient communication. It handles address resolution, converting logical addresses (e.g. network addresses) into physical addresses (e.g. hardware addresses) for accurate packet delivery. Additionally, it performs routing, determining the most efficient paths for message transmission based on priority and current network conditions. Traffic management ensures smooth data flow by monitoring and regulating network traffic, while congestion control reduces bottlenecks and minimizes packet loss. The layer also supports packet fragmentation and reassembly, dividing large data packets into smaller fragments for efficient transmission and reassembling them at the destination.

- The **Data Link Layer (DLL)** is logically divided into two sub-layers: Logical Link Control (LLC) and Media Access Control (MAC). The LLC sub-layer provides services to the network layer, including segmentation and reassembly of data frames, flow control to regulate transmission rates and prevent overload, and error detection using mechanisms like Cyclic Redundancy Check (CRC) to identify corrupted data. The MAC sub-layer ensures efficient access to the communication medium by coordinating node access and preventing collisions.
- The **Physical Layer (PHY)** is responsible for converting digital data from higher layers into physical signals, such as analog signals, suitable for transmission through the communication medium (e.g. radio waves in wireless networks). This layer interfaces directly with the radio module in wireless systems to facilitate seamless communication.

In addition to the standard interactions between adjacent layers, the proposed model introduces novel cross-layer interactions to enhance efficiency. These new interactions are represented by additional communication channels. For example, arrow (4) indicates that the MAC layer receives signal power and channel state information (e.g. busy or idle) from the physical layer. Arrow (5) shows that the MAC layer can request the physical layer to switch channels or change its radio state (e.g. sleep or active) to optimize energy consumption.

The LLC sub-layer further interacts with the network layer. Arrow (6) signifies that the LLC provides the network layer with physical layer information, including its current state (e.g. contention, lost contention, failed reception, successful reception) and transmission-related metrics. This information helps the network layer make informed decisions, such as dropping packets if necessary. The DLL layer also communicates the remaining energy level to the network layer, which can incorporate this information into routing cost calculations. Additionally, the DLL layer provides the network layer with the received power levels of broadcast frames.

Lastly, Arrow (7) represents the communication from the network layer to the application layer. The network layer informs the application layer about the addresses of accessible base stations. This information is dynamically updated whenever a new base station becomes available or an existing one becomes inaccessible.

By incorporating these cross-layer interactions, the proposed model significantly enhances communication efficiency, optimizes energy utilization, and improves overall performance in wireless sensor networks.

B. Data Link Layer

The Data Link Layer (DLL) plays a crucial role in ensuring efficient communication and energy utilization in WSNs. It is composed of two sub-layers:

- Logical Link Control (LLC): The LLC handles data frame segmentation and reassembly, flow control, and error detection. By managing these functions, it ensures reliable communication between the network and physical layers.
- Media Access Control (MAC): The MAC sub-layer regulates access to the shared communication medium, preventing collisions and optimizing channel usage. The proposed design employs the Low-Traffic Aware Hybrid MAC (LTH-MAC) protocol [1], which adapts transmission schedules based on network traffic, node energy levels, and data priority.

The updated backoff procedure used in the LTH-MAC protocol dynamically adjusts backoff times to balance energy efficiency and low latency. The backoff time B_i is calculated using Eq. (1). This adaptive approach minimizes collisions, optimizes transmission efficiency, and extends the operational lifetime of sensor nodes.

$$B_i = \text{Min}\left(\text{round}\left(2^{\alpha \cdot T_i} \cdot \frac{1}{E_i} \cdot P_i\right), b_{\max}\right) \cdot T_{CU} \quad (1)$$

where:

- α is an exponential backoff factor (between 0 and 1).
- T_i is the traffic level at sensor node i (a measure of network contention).
- E_i is the energy level of sensor node i (a measure of the battery status between 0 and 1).
- P_i is the priority of the data being transmitted (how urgent the message is, between 0 and 1).
- $b_{\max}$ is the maximum allowed size for the backoff window.
- T_{CU} is the contention unit duration.

When multiple nodes attempt to access the medium simultaneously, a contention mechanism is employed. The Contention Unit Duration (TCU) is defined in Eq. (2):

$$T_{CU} = 2 \cdot T_{\text{MxSRT}} + T_{\text{FrmCtrl}} + T_{\text{RSSI}} \quad (2)$$

where:

- T_{MxSRT}: MAX (time to switch RX/TX and TX/RX),
- T_{FrmCtrl}: Time to send RTS frame,
- T_{RSSI}: Time for RSSI.

Fig. 2 illustrates a scenario where two nodes $n1$ and $n3$ attempt to transmit data to node $n2$. The node that wins contention transmits, while the other node defers transmission and may enter a sleep state to conserve energy. Nodes use random sub-band selection to minimize collisions during transmission. For unicast transmissions, the chosen sub-band is included in the RTS frame. Broadcast transmissions utilize an RTB-DATA frame to inform receivers of the selected sub-band.

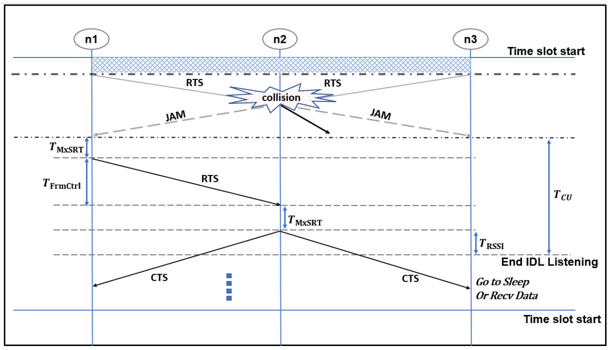

Fig. 2. Contention unit value.

The time slot duration, illustrated in Fig. 3, is calculated based on Eq. (3), considering the maximum packet size, retry limits, and synchronization times.

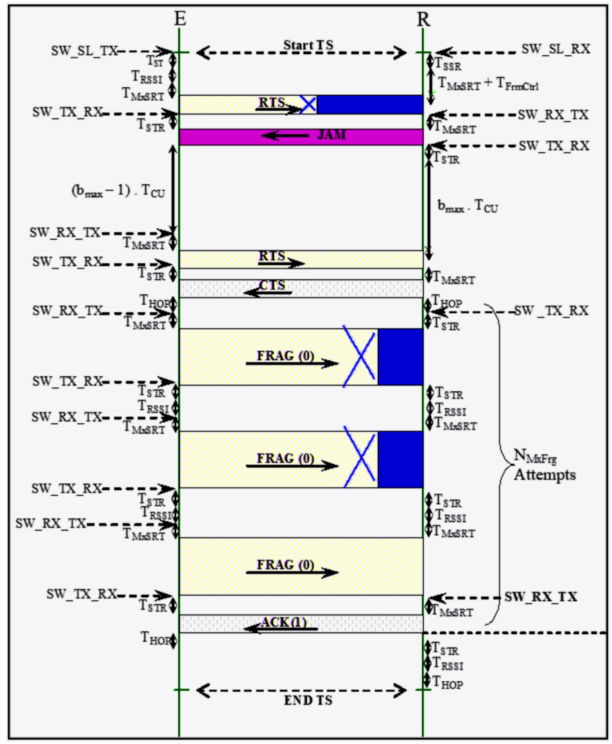

Fig. 3. Time slot duration in worst case.

$$\begin{aligned} T_{\text{slot}} = {} & T_{\text{ST}} + 2 \cdot T_{\text{RSSI}} + 3 \cdot T_{\text{MS\_RT}} + 3 \cdot T_{\text{FrmCtrl}} + T_{\text{STR}} \\ & + (b_{\text{max}} - 1) \cdot T_{CU} + 2 \cdot T_{\text{STR}} \\ & + 2 \cdot T_{\text{HOP}} + N_{\text{MxFrg}} \cdot \big(N_{\text{RtFrg}} \cdot (T_{\text{MxSRT}} + T_{\text{Frg}} + T_{\text{STR}}) \\ & + (N_{\text{RtFrg}} - 1) \cdot (T_{\text{RSSI}} + T_{\text{FrmCtrl}}) \big) \end{aligned} \quad (3)$$

where:

- $T_{\text{FrmCtrl}} = L_{\text{FrmCtrl/R}}$: Transmission time of control frame.
- L_{FrmCtrl}: Control frame length (RTS, RTB, CTS, ACK, JAM).
- R: Bit rate.
- N_{RtFrg}: MAX retry number to send the same fragment.
- $T_{\text{Frg}} = L_{\text{MxFrg/R}}$: MAX fragment transmission time.
- L_{MxFrg}: MAX data fragment length.
- $N_{\text{MxFrg}} = \text{ARROUND.SUP}\,(L_{\text{MxPk}}/(L_{\text{MxFrg}} - L_{\text{HdrFrg}}))$: MAX number of fragments in the same TS.
- L_{MxPk}: MAX NET packet length.
- L_{HdrFrg}: Header fragment length.
- b_{max}: MAX contention window length.
- SW: Switch; SL: Sleep state; RX: RX state; TX: TX state.
- T_{STR}: Switch TX/RX time.
- T_{MxSRT}: MAX switch TX/RX time.
- T_{RSSI}: RSSI time.
- T_{HOP}: Frequency hop time.
- T_{ST}: Wait to start TX from Sleep state.
- T_{SSR}: Wait to start RX from Sleep state.

In LTH-MAC protocol [1], transmissions were initiated at the start of each time slot without channel contention. However, this approach is unsuitable for networks with multiple broadcast data transmissions. The proposed design simplifies synchronization by assigning synchronization responsibility solely to the time slot owner node. Key improvements include:

- New Node Integration: A newly joined node only needs to determine the beginning of the current time slot, eliminating the need for complex synchronization algorithms, as required in traditional TDMA protocols like SMAC.
- Distributed Synchronization: Initiated by a base station, the synchronization process stabilizes as synchronized nodes assist in synchronizing new neighbors.
- Desynchronization Recovery: If a node remains without neighbors for a defined period, it is flagged as desynchronized at the MAC layer and must reinitiate synchronization. Nodes also remove unresponsive neighbors after repeated failed connection attempts and inform the network layer.

To maintain synchronization, Synchronized nodes periodically broadcast SYNC frames over a dedicated synchronization channel. SYNC frames, sent after data transmission, reception, or idle periods, include the remaining time until the next time slot begins. This mechanism reduces overhead by forgoing periodic maintenance phases and facilitates efficient network operation.

C. Network Layer

The network layer in the proposed framework incorporates two energy-aware routing algorithms, tailored for sensor nodes and the base station (Fig. 4). These algorithms are designed to optimize energy utilization and ensure efficient data transmission across the network. The sensor node routing algorithm employs a decentralized approach, constructing routing trees based on local neighbor information. These trees facilitate data transmission from sensors to base stations by dynamically evaluating routing costs.

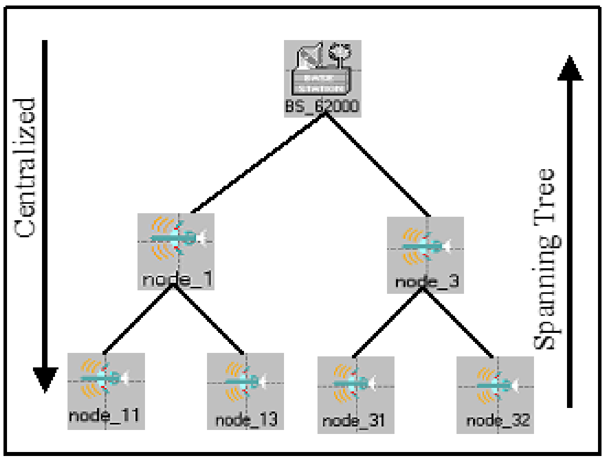

Fig. 4. Routing algorithms.

Each sensor node broadcasts a Cost Packet (COST) to its immediate neighbors, containing information about accessible base stations, the associated route costs, and the number of hops to each base station (see Fig. 5). Upon receiving a COST packet, the MAC layer computes a preliminary link cost based on metrics like signal quality and the receiver's sensitivity threshold. This link cost is calculated using Eq. (4).

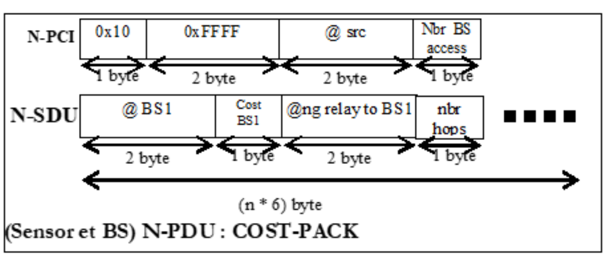

Fig. 5. Cost packet.

$$\text{Cost\_Link} = \frac{\text{Cst}}{\text{Signal Quality}} \tag{4}$$

where:

- Cst: A constant factor representing the cost.
- Signal Quality: A measure of the signal strength or quality.

Where Cst is a simulation-derived constant influenced by network density and signal quality. Lower link costs indicate higher link quality. The network layer refines this value and updates the relay lists of neighboring nodes. Nodes prioritize neighbors with the lowest costs, and if multiple neighbors have identical costs, they select those with fewer relay operations or make a random selection in case of ties.

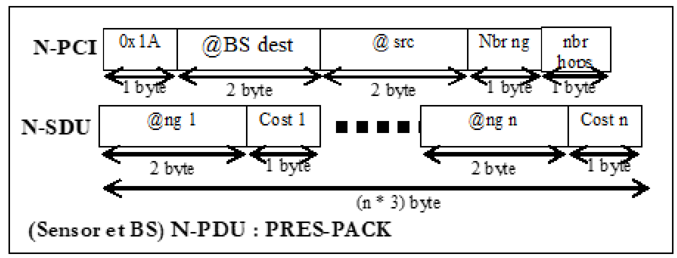

Fig. 6. Presentation packet.

When a sensor node discovers a new base station, it sends a Presentation Packet (PRES) to the base station, as depicted in Fig. 6. This packet contains the hop count to the base station, a list of neighbors, and their respective link costs. Base stations analyze these packets to construct a global view of the network. Each PRES packet is acknowledged by the base station with an ACK-PRES message to confirm successful reception. Data packets from sensors that have not sent PRES packets are rejected, ensuring accurate routing and network integrity. The base station employs a centralized routing algorithm, which uses the information from PRES packets to calculate the shortest paths to all nodes in the network. This centralized approach complements the decentralized algorithm of sensor nodes, ensuring optimized data routing and energy efficiency.

To evaluate route costs, the framework employs three metrics. The first metric calculates the total sum of link costs along the route. The second metric adjusts link costs based on the residual energy levels of nodes. Nodes with lower energy levels increase their link costs to discourage routing through them, while nodes with higher energy levels reduce their link costs to encourage traffic. The third metric, which combines link costs and the number of hops, is defined in Eq. (5).

$$f_3(\text{route}_k) = \text{nbr\_hops}(\text{route}_k) \cdot \sum_{ij \in \text{route}_k} \text{Cost\_link}_{ij} \tag{5}$$

where:

- $route_k$: The path or $route_k$ in the network.
- nbr_hops(route_k): Number of hops in the $route_k$.
- Cost_link$_{ij}$: Cost of the direct link between nodes i and j.

Queue management at the network layer ensures efficient data handling. A single packet queue is maintained, prioritizing control packets over data packets. Control packets are placed at the head of the queue, replacing any existing control packets destined for the same location. Data packets are aggregated with existing packets when their combined size does not exceed the maximum packet length. Otherwise, they are added to the tail of the queue.

By integrating decentralized and centralized routing algorithms with adaptive metrics and efficient queue management, the proposed framework achieves reliable data transmission, minimizes energy consumption, and extends the operational lifetime of the network.

IV. Performance Evaluation

This section evaluates the performance of the proposed Cross-layer model against the traditional Layered model. The evaluation focuses on key metrics under various network conditions, highlighting the impact of the Cross-layer model's energy-aware protocol and enhancements to the LTH-MAC protocol. Simulations were conducted using the OPNET simulator across 20 runs with different seed values to ensure reliability, achieving a 95% confidence level. The simulation parameters are provided in Table I.

TABLE I. Simulation Parameters

MAC Protocol Parameters		Energy Model	
Parameters [units]	**Values**	**Parameters [units]**	**Values**
L_{FrmCtrl} [Byte]	14	Battery [J]	1000
L_{MxFrg} [Byte]	40	Tx [mW]	31.2
L_{HdrFrg} [Byte]	14	Rx [mW]	24.5
N_{RtFrg}	3	Idle [mW]	10.5
T_{STR} [μs]	850	Sleep [mW]	1
T_{STS} [μs]	10	**Radio Module**	
T_{SRT} [μs]	850	**Parameters [units]**	**Values**
T_{RSSI} [μs]	12	Modulation	BPSK
b_{max}	7	Bandwidth [bps]	19200
T_{ST} [μs]	851.2	Sensitivity [nW]	0.3652
T_{HOP} [μs]	200	Maximal range [m]	100
E_{STR} [μJ]	21.4	TX power [mW]	31.2
T_{STS} [μs]	10	**Network**	
T_{SRT} [μs]	850	**Parameters [units]**	**Values**
T_{RSSI} [μs]	12	Topology [1000 m × 1000 m]	Random
b_{max}	7	Mobility [m/s]	5

The following metrics were analyzed:

- Energy Consumption: Total energy consumed by all sensor nodes in the network. Energy consumption measures the total energy used by all nodes in the network during the simulation.
- Network Lifetime: Time duration until the first node in the network runs out of energy. The remaining lifetime is calculated by evaluating the rate of energy consumption and the remaining energy at different points during the simulation.
- End-to-End delay is defined as the time it takes for a data packet to travel from the source to the destination. The average delay is computed by averaging the delay for all successfully delivered packets during the simulation.
- Throughput: Total data transmitted successfully from source nodes to the base station per unit of time. Throughput is calculated as the total amount of data successfully delivered to the destination divided by the total time.
- Packet Delivery Ratio (PDR): Ratio of successfully delivered packets to the total packets sent. PDR is calculated by dividing the number of successfully delivered packets by the total packets sent, then multiplying by 100 to obtain a percentage.

A. Performance Under Low Traffic Conditions

This subsection presents the performance evaluation of the proposed Cross-layer framework and the Layered model over time. The simulation features a network topology consisting of 100 sensor nodes randomly distributed over a 1000 m × 1000 m area, with a single static base station located at the center. Sensor nodes communicate in a multi-hop mode, relying on intermediate relay nodes to reach the base station. Nodes exhibit random mobility at speeds of up to 5 m/s to simulate real-world scenarios, while the base station remains stationary. The performance was assessed under low traffic conditions to measure efficiency.

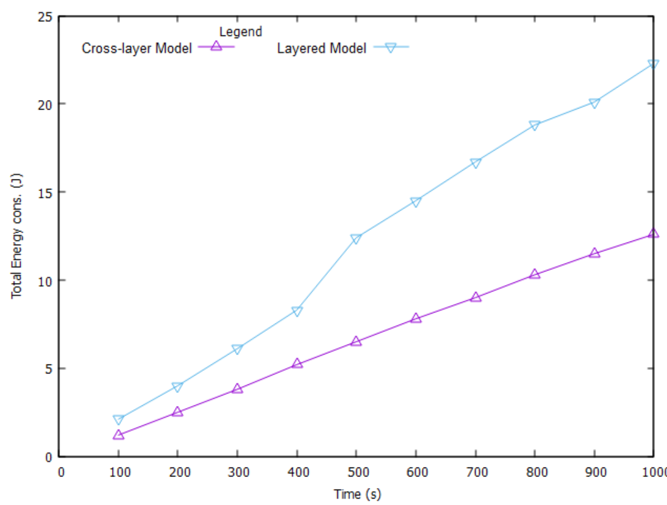

Fig. 7. Total energy used by the network during the simulation.

The Cross-layer model demonstrated a significant reduction in energy consumption compared to the Layered model across all time points (Fig. 7). It exhibited a significant 43% average reduction in energy consumption compared to the Layered model. This improvement results from the dynamic energy-aware protocol, which optimizes transmission rates and power usage based on real-time conditions, and the LTH-MAC protocol, which minimizes unnecessary energy expenditure by adjusting schedules and power levels.

As shown in Fig. 8, the Cross-layer model significantly extends network lifetime. It extended network lifetime by an

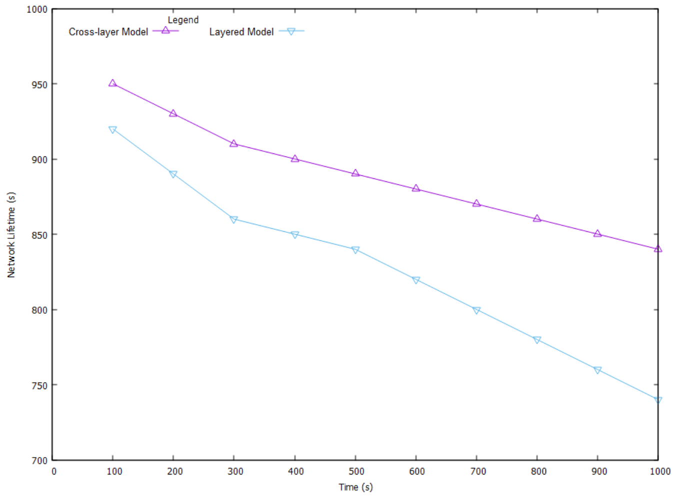

Fig. 8. Network remaining Lifetime calculated during the simulation.

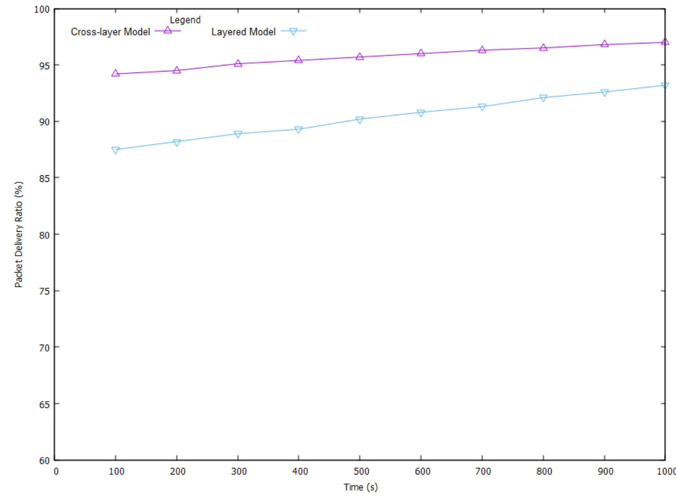

Fig. 10. Packet delivery ratio calculated during the simulation.

average of 8%, effectively delaying the depletion of the first node's battery. This improvement is critical for sustaining network operations in energy-constrained environments.

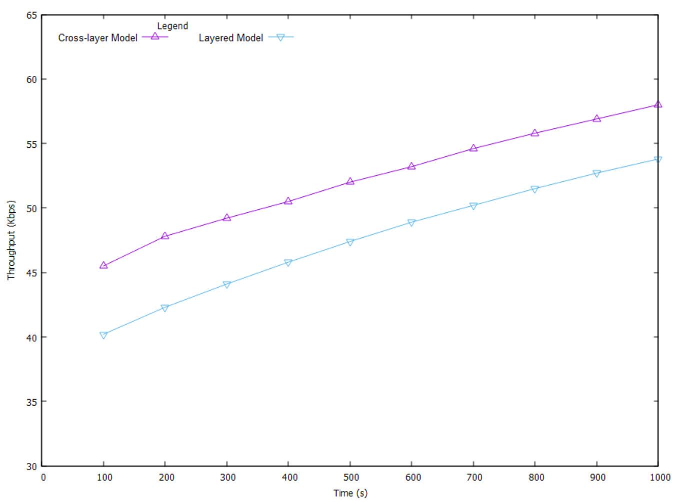

Fig. 9. Throughput calculated during the simulation.

The throughput results, illustrated in Fig. 9, reveal that the Cross-layer model consistently outperforms the Layered model. It achieved an average throughput improvement of 10% over the Layered model. This is due to the dynamic adjustments in data rates and transmission power provided by the LTH-MAC protocol, which reduces collisions and retransmissions, ensuring faster data delivery.

As shown in Fig. 10, the Cross-layer model achieves a higher PDR than the Layered model across all simulation intervals. It demonstrated superior reliability with an average PDR improvement of 6% over the Layered model. The energy-aware protocol prioritizes energy-efficient transmissions, while the LTH-MAC protocol reduces dropped packets, even under varying network conditions.

The Cross-layer model also demonstrates lower average delay compared to the Layered model, as depicted in Fig. 11.

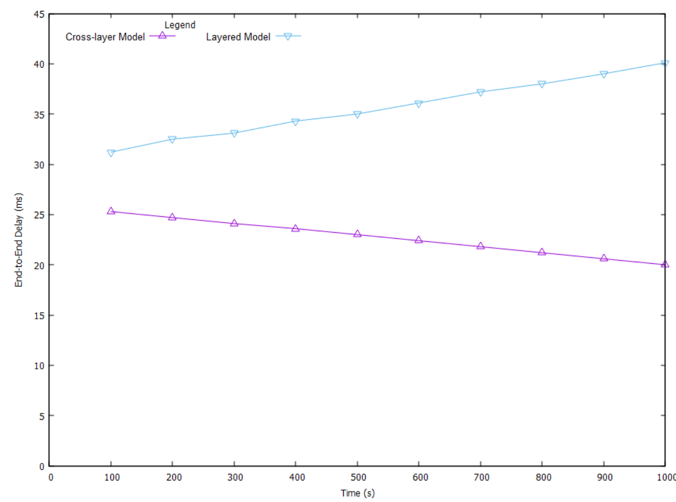

Fig. 11. End-to-end delay calculated during the simulation.

It reduced delay by an average of 36%, ensuring faster packet delivery. The synergy between the energy-aware protocol and LTH-MAC protocol minimizes queuing and processing delays while preventing retransmissions.

B. Performance Under High Traffic Conditions

To assess the scalability and robustness of the Cross-Layer model under heavy load, we extended our evaluation to include high traffic scenarios. These simulations maintained the same network topology and parameters as the low traffic experiments, but the data generation rate of each sensor node was significantly increased. This resulted in a substantial increase in network congestion and contention for the wireless medium. The key performance metrics were evaluated under varying node densities, and the results are summarized in Table II.

The results indicate that while the Cross-Layer model's performance is still favorable, the performance gap between it and the Layered model narrows under high traffic conditions. Specifically:

TABLE II. Performance Comparison of Cross-Layer and Layered Models (High Traffic)

	Cross-Layer Model (High Traffic)					Layered Model (High Traffic)				
	Node Density					Node Density				
Performance Metric	**50**	**75**	**100**	**125**	**150**	**50**	**75**	**100**	**125**	**150**
Energy (J)	7.0	9.5	16.0	20.0	24.0	10.5	14.8	28.0	35.0	42.0
Throughput (Kbps)	50.0	53.0	62.0	64.0	65.0	44.0	46.0	57.0	58.0	59.0
Delay (ms)	22.0	24.0	26.0	28.0	30.0	30.0	38.0	48.0	53.0	58.0
PDR (%)	95.0	94.0	95.0	94.0	93.0	90.0	89.0	90.0	89.5	88.5
Lifetime (s)	850	800	740	680	600	800	700	640	580	500

- Energy Consumption: The Cross-Layer model still consumes less energy, but the reduction is not as significant as in the low traffic scenario. The increased number of retransmissions and control packet overhead contribute to higher energy usage in both models.
- Network Lifetime: The network lifetime advantage of the Cross-Layer model is reduced due to the faster energy depletion of all nodes under heavy load.
- Throughput: The Cross-Layer model maintains a higher throughput, but the improvement is less pronounced. Both models experience increased packet collisions and queuing delays, limiting the maximum achievable throughput.
- Packet Delivery Ratio (PDR): PDR decreases for both models in high traffic conditions, but the Cross-Layer model exhibits a slightly better PDR. The LTH-MAC protocol's adaptive backoff mechanism helps to mitigate packet loss to some extent.
- End-to-End Delay: End-to-End delay increases significantly for both models. However, the Cross-Layer model's ability to prioritize critical traffic and optimize routing contributes to a slightly lower delay.

A comprehensive comparative analysis with other WSN protocols is challenging due to the difficulty in replicating identical simulation environments and parameters. However, the LTH-MAC protocol, a key component of the proposed cross-layer model, has been thoroughly evaluated and compared against other MAC protocols in the literature [1]. In that work, the author demonstrated that LTH-MAC outperforms traditional MAC protocols in terms of energy efficiency and adaptability to varying traffic conditions. The proposed cross-layer framework builds upon the strengths of LTH-MAC by integrating it with an energy-aware routing algorithm and enabling cross-layer interactions. While a full comparative simulation of the entire framework against other cross-layer designs is beyond the scope of this paper, the obtained simulation results demonstrate the significant performance improvements achieved by the proposed framework compared to a traditional layered WSN architecture. These improvements highlight the effectiveness of the cross-layer design and the benefits of the LTH-MAC protocol within this integrated framework.

In summary, under high traffic loads, the Cross-Layer model demonstrates graceful degradation. While the performance gains are less dramatic compared to low traffic scenarios, the Cross-Layer model maintains advantages in energy efficiency, throughput, and packet delivery. These improvements are primarily due to the integration of the energy-aware protocol in the network layer and the enhanced LTH-MAC protocol in the Data Link Layer (DLL). The energy-aware protocol dynamically adjusts transmission rates, routes, and energy consumption strategies based on real-time network conditions, ensuring efficient resource utilization and avoiding unnecessary energy depletion. Simultaneously, the enhanced LTH-MAC protocol optimizes medium access, minimizes packet collisions, and adapts transmission power levels to reduce overhead and improve packet delivery reliability. By adopting a Cross-layer design, the proposed model enables seamless communication and cooperation between protocol layers, breaking the traditional boundaries that often hinder efficiency. This integrated approach allows each layer to leverage real-time feedback from others, fostering adaptability and resilience to changing network conditions. Consequently, the Cross-Layer model not only enhances network performance across key metrics but also ensures prolonged operational lifetimes, reduced latency, and reliable data delivery, making it a robust solution for energy-constrained and performance-critical WSN applications. This highlights the importance of adaptive mechanisms, such as those in the LTH-MAC protocol and the energy-aware routing algorithm, for maintaining acceptable performance under varying network conditions.

V. Conclusion

This paper introduced a novel cross-layer design framework for Wireless Sensor Networks (WSNs), addressing critical challenges of energy efficiency, latency, and throughput. By integrating an energy-aware protocol at the network layer and enhancing the Low-Traffic Aware Hybrid MAC (LTH-MAC) protocol at the Data Link layer, the proposed framework facilitates dynamic inter-layer interactions, resulting in optimized resource utilization and robust network performance. The LTH-MAC protocol's ability to adapt transmission schedules based on network traffic, node energy levels, and data priority plays a crucial role in the improved performance of the Cross-layer model. Although the simulations presented here were conducted under low traffic conditions, the adaptive nature of LTH-MAC makes it well suited to handle varying traffic loads. However, it is important to note that the performance improvements of LTH-MAC, and consequently the overall cross-layer framework, may be less pronounced in very high traffic scenarios, where contention and collision rates increase significantly. The dynamic backoff procedure allows the protocol to adjust backoff times to balance energy efficiency and low latency, minimizing collisions and optimizing transmission efficiency.

Simulation results demonstrate that the cross-layer model consistently outperforms the traditional layered approach across key metrics, including a 43% reduction in energy consumption, an 8% extension in network lifetime, and enhanced throughput, packet delivery ratio, and reduced latency. These findings highlight the ability of the framework to support efficient and reliable communication in energy-constrained and dynamic WSN environments.

The proposed cross-layer framework offers several advantages, including improved energy efficiency, extended network lifetime, enhanced throughput, reduced latency, and increased reliability. These benefits translate to significant real-world implications for WSN applications. For instance, in environmental monitoring, the extended network lifetime allows for longer deployment times and reduced maintenance costs. In healthcare, the reduced latency and increased reliability ensure timely delivery of critical patient data, enabling more effective remote patient monitoring and potentially life-saving interventions. In industrial automation, the enhanced throughput and reduced latency facilitate the collection of large volumes of sensor data for predictive maintenance, optimizing operations, and minimizing downtime.

However, the proposed framework also has some limitations. The cross-layer design introduces additional complexity compared to traditional layered architectures, which could increase the implementation and management overhead. The performance of the framework may also depend on specific network conditions and application requirements. As mentioned earlier, while LTH-MAC is designed to handle varying traffic, its effectiveness in very high traffic scenarios may be limited.

Future research will focus on several key areas. First, we aim to integrate machine learning techniques to enhance the framework's adaptability and predictive capabilities. This includes exploring the use of machine learning for predictive maintenance, enabling proactive network management and optimization. Second, we will investigate security considerations in cross-layer WSNs, developing mechanisms to protect data transmission and prevent malicious attacks. Third, we plan to extend the framework to support diverse Quality of Service (QoS) requirements, enabling the prioritization of different types of data traffic and ensuring optimal performance for a wider range of applications. Finally, we will address the challenges of deploying the framework in heterogeneous WSNs and real-world environments, including issues such as scalability, deployment complexity, and environmental factors.

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