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Survey of Cross-Layering Technique in Wireless Sensor Networks (WSNs)

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***Abstract*— Wireless Sensor Networks (WSNs) have gained significant attention in recent years due to their vast applications in various fields such as environmental monitoring, healthcare, and industrial automation. However, WSNs face several challenges, including energy efficiency, latency, and reliability. Trade-off issues persist in the study results even after a great deal of research, approaches, and studies have been conducted in the subject of enhancing the quality of service in wireless sensor networks. In WSNs, cross-layer technology proved effective in meeting the demands of applications while also meeting quality of service standards. Cross-layer design has emerged as a promising approach to address these challenges by integrating and optimizing different layers of the OSI model. This survey provides a comprehensive overview of cross-layer design in WSNs, highlighting recent advancements, challenges, and future directions.**

Keywords*— Cross-Layer Design (CLD), Wireless Sensor Networks (WSNs), Energy Efficiency, Quality of Service (QoS), Scalability, Reliability, Security, Internet of Things (IoT).

I. INTRODUCTION

WSNs consist of numerous sensor nodes that communicate with each other to collect and transmit data. In both wired and wireless networks, traditional stack layer models like the OSI model and TCP/IP model have been widely employed. These models aren't ideal for WSNs, though, because to their unique requirements and resource constraints[1]. The dynamic nature of WSNs necessitates adaptable and effective communication protocols, which the conventional layered architecture is unable to provide. Cross-layer design, which involves the integration and optimization of multiple layers, has been widely adopted to improve the performance of WSNs. Cross-layer design allows for the optimization of multiple goals simultaneously, such as energy efficiency, throughput, and quality of service (QoS) [2, 3]. Optimization in one layer often requires cooperation from other layers, making cross-layer design necessary to achieve the desired performance [4]. On the other hand, different optimization goals may conflict with each other, and cross-layer design provides a means to balance these goals [5]. WSNs have been used for environmental monitoring, where cross-layer design helps optimize energy consumption and data transmission [6]. Cross-layer design has been used in healthcare applications such as wearable devices, where energy efficiency and reliability are crucial, also it can be used in industrial automation, where cross-layer design helps optimize performance and reliability [6].

Despite the advancements in cross-layer design, there are several challenges such as scalability, heterogeneity, and Security [7, 8]. Various cross-layer techniques are employed in Wireless Sensor Networks (WSNs), such as cross-layer routing, cross-layer MAC, and cross-layer energy management. These methodologies are implemented to enhance both network performance and energy efficiency [9, 10]. Cross-layer design significantly enhances Quality of Service (QoS) in wireless networks by optimizing the flow and control of information across multiple layers in the protocol stack. This approach helps to improve network performance, energy efficiency, and scalability, which are critical factors in ensuring QoS for various applications, such as real-time services like audio, video, and VoIP[11]. Cross-layer design and AI can significantly enhance the performance of wireless sensor networks (WSNs) by optimizing interactions between different layers of the protocol stack [10]. Machine learning algorithms are widely used in WSNs to eliminate unnecessary redesign or optimize network performance. Techniques like supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning can be applied to various WSN applications [12]. Cross-layering can be used ensuring security in WSNs, which are vulnerable to various threats due to their open nature and limited resources, by ensure the integrity of data collected by the network [13].

II. CROSS-LAYERING AND QOS IN WSNS

Cross-layer QoS implementations have become a viable method for combining the application, network, and physical layers in WSNs to improve QoS[14]. Several cross-layer QoS architectures have been released for WSNs to improve QoS in energy consumption, bandwidth, delay and data loss rates. Application-Aware cross layering approaches aim to provide enhanced QoS by considering application-layer requirements such as delay and packet loss [15]. For example, the author in [15] proposed an approach to deal with the time-slotted channel hopping mechanism in software-defined wireless sensor networks (SDWSNs) for the 4e time along with the application-aware scheduling strategy. The objective is to ensure that QoS provided by a large SDWSN network is controlled and maintained at the required level. Thus, in order to meet the requirement of QoS for the various traffic kinds, the proposed schedule is further adjusted dynamically. Cross-Layer Optimization approaches involve optimizing the parameters of multiple layers to improve the QoS [3]. For instance, the algorithms proposed by Kumar[3] performed better than the ZigBee protocol and the fundamental Distribution Grid wireless communications system, proving to provide a higher quality of service (QoS) for mission-critical traffic. Energy-Efficient Cross-Layer approaches optimize energy consumption by modifying the transmission power and data rate. A hybrid cross-layer protocol is proposed by Saritha [10] to improve layer-to-layer communication. In order to build congestion-aware routing and satisfy QoS, the parallel dual module deep Q-learning (PDMQL) and archerfish hunting optimization (AFHO) method are used which prove its efficiency in terms of energy consumption, residual energy, end-to-end delay, throughput, packet delivery rate, and accuracy [10]. Another studies in cross-layering and Quality of Service (QoS) in Wireless Sensor Networks (WSNs) include innovative approaches such as a Quality of Service Based Cross-layer (QSCL) Protocol that combines the IEEE 802.15.4-based MAC protocol with the LEACH-based routing protocol to minimize energy consumption and extend network lifetime [16]. Additionally, the use of artificial neural networks has shown promising results in improving QoS parameters like packet loss and congestion by classifying nodes and converting unqualified nodes into qualified ones, thereby enhancing network lifetime and reducing packet loss ratio [17]. Furthermore, research emphasizes the importance of intelligent WSN routing in IoT architectures to enhance QoS by forming clusters, selecting Cluster Heads (CH) using fuzzy inference systems, and optimizing data transmission routes using heuristic search algorithms like best first search, ultimately improving time complexity, packet delivery time, and energy consumption [18].

III. CROSS-LAYERING BASED AI IN WSNS

Recent studies have shown that AI approaches can be effectively implemented in WSNs to address several problems, including data distribution, routing, and energy usage [19]. For instance, a cross-layer optimization method was used to improve WSNs' energy efficiency[20]. In another approach to improve WSN routing, the author proposed a hybrid AI approach [21]. With the advent of AI in Wireless Sensor Networks (WSNs), adaptive cross-layering techniques have significantly changed. By using AI to adapt protocol behavior across several tiers of the network stack dynamically in response to shifting network conditions, these solutions maximize network performance. "On Wireless Sensor Network Models: A Cross-Layer Systematic Review," a systematic review, examines WSN modeling from an all-encompassing angle, offering a taxonomy and outlining research trends and obstacles [5]. The author of Machine learning for coverage optimization in wireless sensor networks introduce a thorough analysis of coverage optimization in wireless sensor networks (WSNs) covers the use of nature-inspired techniques and machine learning to solve coverage issues [12]. Another approaches introduce a research on cross-layer methods for energy-efficient clustering and routing assess performance according to QoS metrics [9]. The author focused on employing energy-efficient communication networks and clustering strategies to increase the lifetime and reduce power consumption in wireless sensor networks (WSNs) for a specific applications. "Energy-Efficient Routing in Wireless Sensor Networks is a Meta-Review" examines how artificial intelligence makes wireless sensor networks (WSNs) dynamic settings for environmental factor monitoring [22]. Even though cross-layer design and AI in WSNs have progressed, there are still many open research issues and possible avenues for further study.

IV. CROSS-LAYERING AND VIDEO TRANSMISSION OVER WIRELESS NETWORKS

Cross-layering design in video communications is a method that maximizes multimedia streaming performance in wireless network. It seeks to improve video quality and guarantee dependable transmission by permitting communication between various network protocol stack layers. "Cross Layer based Energy Aware and Packet Scheduling Algorithm for Wireless Multimedia Sensor Network " presents a cross-layer technique and suggests an energy-aware packet scheduling algorithm that will lessen congestion and improve link quality [23]. In order to optimize QoE1, a reinforcement learning-based ABR system that combines the transport and video application layers [24]. The ABR algorithm solves the drawbacks of the current ABR techniques, which divide network bandwidth estimation and video encoder control. The author considers video quality, and delay as the key factors affecting the QoE in RTVC

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systems. In a paper headed "Adaptive Compressed Sampling Based on EMD for Wireless Sensor Networks", In order to preserve power and minimize data transmission for wireless sensor networks (WSNs), the paper suggests a unique adaptive block compressed sampling (CS) strategy based on empirical mode decomposition (EMD) [25]. The author introduces a method to calculate an energy matrix of measurement results (EMMR) and perform 1-D EMD based on zigzag scanning to obtain an energy distribution map (EDM) of high-frequency components. The author also discusses the importance of efficient image acquisition and communication in WSNs for applications like monitoring systems and highlights the challenges in designing energy-efficient image compression transmission schemes. The significance of cross-layer architecture for dependable and effective multimedia transmission in wireless sensor networks has been shown in earlier studies. In terms of energy saving, QoS enhancement, congestion management, and robustness to wireless impairments, CLD techniques have proven to be highly beneficial. Advances in multi-objective optimization, machine learning, and adaptive coding have elevated the bar for state-of-the-art in this field of networking. There are still issues with complexity, scalability, security, and standardization, though, which opens up new avenues for investigation and advancement in the future.

V. CROSS-LAYERING DESIGN AND IoT

The application of The Internet of Things (IoT) has revolutionalized the world by allowing a variety of physical devices and sensors to connect seamlessly [26]. IoT systems contend with particular difficulties such fluctuating network topologies, energy limitations, and disparate communication protocols. Cross-layer design techniques have become a viable remedy for these issues, enabling the simultaneous optimization of several network levels [27].

IoT networks are dynamic and heterogeneous, necessitating the need for adaptive routing techniques that can adjust to shifting network conditions. Intelligent routing algorithms that take into account variables like link quality, node energy, and application-level needs have been developed using cross-layer design techniques.

Energy is a critical factor of concern in the IoT because of the many low-energy devices connected to the Internet including those with battery-only power. Cross-layer design techniques have been employed to optimize energy consumption by jointly considering factors such as channel conditions, node mobility, and application requirements.

A cross-layer optimization case study discussed a Radio-in-the-Loop (RIL) simulation and emulation model for energy-efficient and cognitive IoT networks in smart cities [28]. The authors introduced a methodology that integrates real wireless hardware and radio environments into the simulation of communication protocols and algorithms. The proposed approach concentrates on optimizing wireless sensor networks for better energy efficiency and network performance to meet Internet of Things (IoT) applications requirements.

A hybrid AI-based cross-layer routing protocol that surpassed conventional routing algorithms in Internet of Things networks was presented to minimize lengthy routing discovery latencies, the strategy makes use of two proactive and reactive routing strategies [29]. The research did not indicate the effectiveness of the proposed model with regard to the network power consumption.

A novel routing model for opportunistic networks that routes packets dynamically based on the meeting probability of nodes [30]. Extensive simulations demonstrate the model's effectiveness, showing improved message delivery probability with reasonable overhead and latency. As mentioned previously, cross-layering in IoT offers a number of significant benefits that enhance network performance and efficiency. Cross-layer design maximizes collaboration across several network layers by standardizing communication settings across multiple layers, such as MAC, network, and transport, hence improving capacity, power efficiency, and network scalability[31, 32]. The authors suggested utilizing the IEEE 802.15.4 standard, a novel cross-layer protocols for the MAC and routing layers is suggested to improve mesh network scalability, dependability, and energy efficiency.

In comparison to other protocols such as RPL and the suggested protocols exhibits enhanced dependability, decreased end-to-end latency, and superior energy efficiency. With the help of this method, IoT environments can become self-configuring and self-organizing, guaranteeing effective data transfer and service continuity—particularly for delicate applications like e-health—while accepting communication outages or device malfunctions [32, 33]. Furthermore, by addressing the high heterogeneity of hardware and software capabilities in the Internet of Things, cross-layer techniques improve wireless network characteristics like bandwidth and energy consumption and offer creative solutions to security problems through machine learning-based protocols [33]. Improving energy efficiency, dependency of data, and network throughput are some effects caused by cross-layering in Internet of Things data transmission. A significant number of research works support the use of multiple layers to enhance various aspects in the Internet of Things networks. For instance, in CLEERDTS model transmission modes at the physical layer are chosen, location information is placed at the network layer, while transmit power is estimated at the MAC layer to optimize energy utilization and reliable data transfer [34]. The 2SAEC-IoT technique also emphasizes that in IoT contexts, devices are self-organizing and self-configuring improve QoS and energy efficiency in consideration of communication characteristics in MAC/NWK/TRAN layers [34, 35]. In addition, there are

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cross-layer designs such as CoCoA3+-TCP that provide optimum TCP performance of IoT networks through packet scheduling, congestion control, and dynamic retransmission timeouts, thus increasing the throughput, goodput, and decreasing transmission delay [32]. The combined result of these studies shows that cross-layering has a significant impact on enhancing the IoT data communication procedure in terms of energy, reliability, QoS, and the efficiency of the network.

VI. CROSS-LAYER DESIGN FOR NETWORK SECURITY ENHANCEMENT

The capacity of CLD to maximize network security by overcoming conventional layer boundaries has drawn a lot of attention in recent years. Information sharing between layers is made possible by this method, and this can enhance network performance in terms of security and energy efficiency. When resources are scarce and network circumstances are very dynamic, CLD is especially helpful in wireless networks [6]. Cross-layer design, which overcomes the drawbacks of conventional layered techniques, is essential to improving network security. By integrating information from multiple protocol layers, cross-layer designs can improve system performance and security effectiveness [8].

Enhancing network security requires reducing vulnerabilities and maximizing efficiency, which is achieved through the integration of many protocol layers through cross-layer architecture. By breaking down the silos between traditional networking layers, cross-layer design makes it easier to optimize protocols simultaneously, improving overall network performance and energy efficiency [14]. Through encryption methods like Elgamal cryptosystem and Elliptic Curve Cryptography, it enables the creation of secure cross-layer protocols that use routing parameters from the MAC layer to make the best routing decisions, taking into account variables like energy, distance, and risk [36]. Furthermore, by combining encryption and modulation methods, cross-layer solutions can improve reliability and secrecy capacity in data transmission by using neural networks to create secure waveforms that are difficult for adversaries to decrypt [37]. Cross-layer design can also be used in wireless sensor networks to increase network lifetime and guarantee secure data delivery by preventing packet collisions during transmission [38]. Cross-layer security in optical code division multiple access systems augments information security by merging algorithmic encryption with physical-layer security, therefore increasing the difficulty of data interception by eavesdroppers, particularly in asynchronous transmission systems [39]. The latest advancements in the Internet of Things (IoT) and wireless sensor networks (WSNs) have had a significant impact on WSN security [40]. More security measures are needed as WSNs become more embedded in the IoT ecosystem due to the vast range of application domains, which include industry, finance, and health [40]. Innovative security techniques like Digital Signature and Private Key Cryptography (DSPKC) have been developed in response to the changing environment to strengthen node authentication and thwart eavesdropping threats in WSNs [41]. Furthermore, to ensure optimal secure pathways and node security for effective routing operations in WSN communications, the introduction of Enhanced Security Models with Improved Defensive Routing Mechanisms (IDRM) has addressed the need for complete defense against various malicious assaults [42].

VII. CONCLUSION

The cross-layer approach in WSNs is more useful, energy-efficient, scalable, and secure as compared to the traditional approaches. The difference in cross layer design is that the protocol stack is viewed as a system and not as separate individual layers. This makes it possible for the information from the various layers to be utilized in order to achieve the best possible aims. Cross layer techniques also help in sharing data between different layers thus helping in reducing the transfer overhead and increasing the overall performance of the network. These approaches are still under investigation and development by researchers to cope up with the various issues associated with WSNs. In conclusion, cross layer design is central in controlling the behavior of WSN and achieving optimal network communication.

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استعراض لتقنيات الطبقات المتقاطعة في شبكات الاستشعار اللاسلكية (WSNs)

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الملخص:

شبكات الاستشعار اللاسلكية (WSNs) قد حظيت باهتمام كبير في السنوات الأخيرة بسبب تطبيقاتها الواسعة في مجالات متنوعة مثل مراقبة البيئة ،الرعاية الصحية ،والأتمتة الصناعية. ومع ذلك ،تواجه شبكات الاستشعار اللاسلكية عدة تحديات ،بما في ذلك كفاءة الطاقة ،التأخير ،والموثوقية. تستمر مشكلات المقايضات في نتائج الدراسات حتى بعد الكثير من الأبحاث ،والأساليب ،والدراسات التي أجريت في موضوع تحسين جودة الخدمة في شبكات الاستشعار اللاسلكية. في شبكات الاستشعار اللاسلكية ،أثبتت تقنية الطبقات المتقاطعة فعاليتها في تلبية متطلبات التطبيقات مع تلبية معايير جودة الخدمة أيضًا. لقد برز تصميم الطبقات المتقاطعة كنهج واعد لمعالجة هذه التحديات من خلال دمج وتحسين الطبقات المختلفة لنموذج OSI. تقدم هذه الدراسة استعراضًا شاملاً لتصميم الطبقات المتقاطعة في شبكات الاستشعار اللاسلكية ،مسلطين الضوء على التطورات الأخيرة ،التحديات ، والاتجاهات المستقبلية.

الكلمات المفتاحية:

تصميم الطبقات المتقاطعة(CLD) ،شبكات الاستشعار اللاسلكية(WSNs) ،كفاءة الطاقة ،جودة الخدمة(QoS) ،القابلية للتوسع ،الموثوقية ،الأمن ،إنترنت الأشياء.(IoT)