Adaptive Cross-Layer Control for Scalable Wireless Ad Hoc Networks

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ABSTRACT

The growing proliferation of devices on the Internet of Things (IoT) has made modern networks increasingly vulnerable to sophisticated cyber threats. Traditional intrusion detection systems (IDS) struggle to maintain high detection accuracy in the presence of high-dimensional data and extreme class imbalance, particularly for rare but critical attacks. The growing proliferation of devices on the Internet of Things (IoT) has made modern networks increasingly vulnerable to sophisticated cyber threats. Traditional intrusion detection systems (IDS) struggle to maintain high detection accuracy in the presence of high-dimensional data and extreme class imbalance, particularly for rare but critical attacks. The growing proliferation of devices on the Internet of Things (IoT) has made modern networks increasingly vulnerable to sophisticated cyber threats. Traditional intrusion detection systems (IDS) struggle to maintain high detection accuracy in the presence of high-dimensional data and extreme class imbalance, particularly for rare but critical attacks. The growing proliferation of devices on the Internet of Things (IoT) has made modern networks increasingly vulnerable to sophisticated cyber threats. Traditional intrusion detection systems (IDS) struggle to maintain high detection accuracy in the presence of high-dimensional data and extreme class imbalance, particularly for rare but critical attacks. The growing proliferation of devices on the Internet of Things (IoT) has made modern networks increasingly vulnerable to sophisticated cyber threats. Traditional intrusion detection systems (IDS) struggle to maintain high detection accuracy in the presence of high-dimensional data and extreme class imbalance, particularly for rare but critical attacks.

1. Introduction

Wireless adhoc-networks are decentralized and self-organized structures, where wireless devices links together to form mobile networks without using any infrastructure. Because of their flexibility and fast deployment feature, these networks have been applied in various scenarios suchas disaster recovery, military communication, emergency response systems. But the dynamicnature of AD-HOC networks makes both scalability, mobility a challenge. Adaptive networking techniques are needed to address these challenges by using of optimizingresource usage and guaranteeing reliable communication.

Traditional wireless ad hoc networks areconstructed using a rigid layered structure in which each protocol runs as an isolated one. Although such simplification is helpful to design and implement, it restricts network flexibility againstdynamic environments. The non-interaction between thephysical, MAC, and network layers results in inefficient resource usage, higher control overheads, and bad routing calculations. These problems greatly decrease the performance of the network, especially in large scale networks where nodes are highly mobile and topologychanges so often. Cross-layered control has recently been proposed as a candidateenabling layer-1 diversity to be exploited. Cross-layer designs facilitate the joint optimization of routing, channel access and transmission parameters byproviding controlled information exchange among protocol layers. Due tothis flexibility, the proposed shows better scalability, packet delivery ratio and end-to-end delay for highly dynamic network environments. The objective of the work is toinvestigate adaptive cross-layer control algorithms that improve performance and reliability for scalable wireless ad hoc networks.

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1.1. Research Objectives

The goal of this study is to investigate the limitations of traditional layered architectures for wireless ad hoc networks, especially in areas such as scalability, dynamics, and performance in dynamic network environments. Conventional techniques in the protocol stack do not perform well when dealing with topology changes, node mobility, and wireless channel variations, through which the performance can be improved by employing cross-layer control.

The second goal of this study is to propose an adaptive cross-layer control framework for efficient information sharing among the physical, MAC, and network layers of wireless ad hoc networks. The proposed method is developed to better utilize the resources, minimize the communication overhead, and increase the overall network performance.

The third goal is to enhance the scalability and flexibility of wireless ad hoc networks by deploying cross-layer solutions. This goal is primarily targeted at obtaining reliable routing, better packet delivery ratio, and lower end-to-end delay with low control overhead, particularly for large-scale networks that experience high node density and mobility.

The last goal of this study is to compare the performance of the considered adaptive cross-layer control scheme through simulation studies. Performance comparison with conventional layered and non-adaptive techniques is included based on throughput, packet delivery ratio, end-to-end delay, and network stability to show that the proposed framework is applicable for scalable wireless ad hoc network environments.

2. Literature Survey

2.1. Ad Hoc and Mesh Networking Platforms and Performance Analysis

The area of ad hoc networking has been receiving increasing attention among researchers in recent years, as the available wireless networking and mobile computing hardware bases are now capable of supporting the promise of this technology [6?]. Mobile ad hoc networks (MANETs) show strong potential for real-time adaptive communication when fixed infrastructure is unavailable [5?]. The shared provision of distributed resources and services, decentralization, and autonomy are characteristic of P2P networks [?]. This work has investigated the performance of a peer-to-peer Adhoc network using a simulation tool called jperf [2?]. In addition, the dependencies of these metrics against measurement locations were also investigated [2?].

In this study, we developed four types of converters based on the low-cost commercial ESP-12H WiFi module, supporting GPIB, RS232, RS485, and CAN bus protocols [7?]. With the help of the ESP-WIFI-MESH protocol, a multi-bus instrument network platform with tree topology and multi-hop relay properties was constructed [7?]. The test reveals that the MESH wireless self-assembling system is affected by burst interference in complex electromagnetic environment, which leads to the degradation of channel quality and the instability of data transmission [?]. The long-distance communication test verifies the phenomenon that the data transmission is limited by the communication distance [9?].

In addition, the sea dynamic communication test of unmanned ship further revealed the shortcomings of stability and timeliness [9?]. During the upload speed test, the RS232 and RS485 converters were slightly below their theoretical maximum upload speeds [7?]. The GPIB and CAN converters did not reach their theoretical values due to hardware and test platform limitations [?]. Future work should focus on optimizing the software and hardware of the current converters and developing an improved test plan [7?]. Furthermore, it is necessary to expand support for additional interface types, including USB and LAN [7?]. Optimization plans are ideal but they have to be implemented with resource constrain considerations particularly for memory and energy conserving device requirements [4?].

2.2. MANET Routing Protocols, Security, and Quality of Service Challenges

In this paper we surveyed different MANET moves toward sort of security based reactive, proactive and hybrid ad hoc routing protocols [10?]. Traditionally, a solid ad hoc network needs to meet different security necessities, Confidentiality, Integrity, Availability, Authentication and non-repudiation [10?]. From the reviewed literature, MANETs face a broad set of threats including denial-of-service, node misbehavior, tight resource limits, rapid topology changes, spoofing, and relay or wormhole attacks [5?]. Protecting availability, confidentiality, integrity, and authenticity demand robust, well-tested defenses [5?].

Recent work has produced distributed intrusion detection system designs, lightweight key-management protocols, and strengthened routing protocols such as AODV and DSR variants aimed at improving resilience and reliability in unpredictable or hostile conditions [5?]. In this study, the suggested outlier detection technique using MANET routing protocols was used to conduct a comparative analysis of various quality-of-service metrics such as jitter, end-to-end delay, throughput, and sender and receiver energy consumptions [?]. Comparative examination reveals that Zone Routing Protocol yields lower jitter, delay, and energy consumption compared to other protocols [?].

Overall, while the studies presented show significant advancements in optimizing MANETs for energy efficiency, scalability, and security, they also underscore persistent challenges such as high computational overhead, scalability in dynamic environments, and limitations in mobile or complex scenarios [1?]. Security mechanisms must be validated and not assumed [5?]. The issue of energy usage remains unresolved despite significant efforts [3?]. Future work can focus on integrating machine learning techniques with hybrid routing protocols to further enhance efficiency and adaptability [8?]. In sum, protecting MANETs is an ongoing effort [5?].

2.3. Research Gaps, Motivation, and Problem Statement

2.3.1. Research Gaps

From the review of existing studies, it can be seen that many works have focused on MANET and mesh networks for improving specific aspects such as routing performance, security, or energy efficiency. However, most of the studies address these issues separately. Very few works consider reliability, scalability, and adaptability together, especially in dynamic and interference-prone environments. Several solutions are validated mainly through simulations, while real-time or practical deployment issues are not discussed in detail. In addition, performance degradation is observed when the network size increases or when node mobility becomes high. The lack of support for heterogeneous interfaces and limited adaptability to changing network conditions indicate clear gaps in the existing literature.

2.3.2. Motivation

The motivation for this work comes from the growing use of MANET and wireless mesh networks in real-life applications such as disaster management, military communication, and infrastructure-less environments. These applications require stable and reliable communication even under challenging conditions like mobility, interference, and limited energy resources. Although existing approaches provide partial solutions, their limitations reduce their effectiveness in real deployments. This creates a need to study improved communication mechanisms that can handle dynamic network behavior while maintaining acceptable performance. Addressing these issues can help in improving the practicality and efficiency of ad hoc network systems.

2.3.3. Problem Statement

Based on the identified research gaps and motivation, the main problem addressed in this work is the need for a reliable and efficient communication approach for MANET and mesh networks operating under dynamic conditions. The objective is to improve data transmission reliability and overall network performance while considering constraints such as mobility, scalability, and energy consumption. The proposed approach aims to overcome the limitations of existing methods and align with the research objectives by providing a more adaptable and practical solution for real-world ad hoc networking scenarios.

Table 1
Literature Survey of Existing Works

Ref.	Method Proposed	Techniques Used	Issues Resolved	Limitations
R16	The paper mainly studied the performance of different MANET routing protocols under changing network conditions.	Simulation-based comparison of AODV, DSR, DSDV and OLSR protocols.	Helps understand how routing performance changes with mobility and traffic load.	Cross-layer interaction and scalability aspects are not considered.
R17	This work discussed cross-layer design challenges at the network layer in a theoretical manner.	Conceptual analysis of information sharing among protocol layers.	Highlights drawbacks of strict layered architectures.	No experimental or simulation results are provided.
R18	The authors proposed an AI-based cross-layer optimization approach to improve network adaptability.	Deep learning methods for tuning parameters across layers.	Improves adaptability in dynamic network scenarios.	Increased computational overhead is not clearly analyzed.
R19	This study presented a survey on cross-layer authentication mechanisms in wireless networks.	Review of security techniques using cross-layer integration.	Helps understand methods for improving authentication and security.	Focus is mainly on security, not routing performance or scalability.
R20	The paper proposed a cross-layer framework for service provisioning in wireless networks.	Coordination among physical, MAC and network layers.	Improves quality of service and resource usage.	Not tested for highly mobile or large-scale ad hoc networks.
R21	This work introduced a cross-layer solution to reduce collision problems in MANETs.	Directional antennas with MAC and physical layer coordination.	Reduces packet collisions and hidden node issues.	Performance in dense networks is not evaluated.
R22	The authors focused on energy consumption and lifetime analysis using cross-layer modeling.	Cross-layer energy and lifetime estimation techniques.	Improves accuracy of energy usage estimation.	Mainly suitable for WSNs, not fully applicable to MANETs.
R23	This study proposed a cross-layer security framework for advanced wireless networks.	Use of SDN, NFV and AI-based cross-layer architecture.	Enhances security and isolation across network layers.	High system complexity may affect scalability.
R24	The paper presented an implementation-oriented cross-layer design for wireless networks.	Integration of routing, congestion control and scheduling.	Improves resource allocation efficiency.	Implementation complexity increases system overhead.
R25	This work proposed a cross-layer defense mechanism against routing attacks.	Intelligent cross-layer analysis for attack detection.	Detects blackhole and wormhole attacks effectively.	Mainly focuses on security rather than performance efficiency.
R26	The authors reviewed various cross-layer design approaches used in wireless sensor networks.	Comparative analysis of existing cross-layer techniques.	Highlights energy efficiency improvements.	Techniques are not directly suitable for MANETs.
R27	This paper provided a detailed survey of cross-layer designs in wireless networks.	Classification and analysis of different cross-layer methods.	Improves understanding of QoS and mobility support.	Adaptive control mechanisms are not discussed.
R28	The study reviewed and classified cross-layer methods for ad hoc networks.	OSI layer-based classification of cross-layer approaches.	Improves conceptual understanding of cross-layer design.	Lacks experimental validation and performance analysis.
R29	This work proposed a cross-layer scheme integrating MAC and physical layers.	Adaptive antenna arrays with MAC coordination.	Improves throughput and spatial reuse.	Assumes availability of multiple antennas.
R30	The authors introduced a scalable and secure cross-layer routing method for multi-hop networks.	Cross-layer information sharing with multi-objective optimization.	Improves routing performance, delay and security.	Routing computation overhead may increase in dynamic networks.

3. Conclusion

EFS-IDS is an efficient, scalable intrusion detection framework that can be used to overcome the shortcomings of the traditional IDS in an IoT context due to the problem of class imbalance.

Declarations

Ethical Approval

This manuscript reports studies that do not involve human participants, human data, human tissue, or animals.

Conflict of Interest

The authors have no conflict of interest to declare that are relevant to the content of this article.

Authors' Contributions

S. Gopikrishnan contributed to the conceptualization, Formal analysis, drafting the original manuscript, and designing the experimental protocols. Author-2 was responsible for Conceptualization, methodology, software implementation, and dataset curation. Author3 contributed to conceptualization, supervision, and in-depth analysis of the experimental results. Author-3 handled the review and editing of the final draft, as well as the overall validation of the study results.

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Availability of data and materials

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