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Seamless Handover Mechanisms in Heterogeneous Access Networks

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Abstract

The rise of heterogeneous access networks (HANs) stems from the growing need for universal mobility services and wireless connectivity, as the demand for heterogeneous connectivity fuels the convergence of different classes of wireless access technologies. The fundamental problem Issue of primary concern noted relates to the design and realization of effective 'no service interruption' handover strategies for cross-network mobility that do not compromise service quality, induce excessive delay or cause service interruption. In this paper, we present a comprehensive study of seamless handover designs for heterogeneous access networks, focusing on systems, their distinct decision processes, various mobility management protocols, and hyper-aware mobility situation adjustments. We analyze the mechanisms of both horizontal and vertical handovers and demonstrate the use of multi-criteria decision-making methods, considering numerous criteria, including signal strength, latency, bandwidth, user preferences, and application demands. Moreover, the use of software-defined networking (SDN), anticipatory machine learning models, and media-independent handover control (IEEE 802.21) frameworks are addressing new solutions. With these approaches, the paper will address numerous issues arising from the integration of these control interfaces. A review of the available mechanisms is conducted, focusing on their advantages and disadvantages, as well as their effectiveness in various mobility situations. Lastly, we propose a context-aware, real-time policy adjustment framework that utilizes context-aware policies with real-time monitoring and

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analysis to lower the chances of handover failures. The proposed method's efficacy has been examined so far using simulations for performance metrics such as handover delay, packet loss, and throughput. Moreover, this work explores how cross-layer optimization and user-centric network selection enhance handover reliability. The focus is on the neglected factors within mobile devices during traditional handover procedures, specifically on the Quality of Experience (QoE) and energy efficiency. The Framework also enables the dynamic allocation of network resources at different levels to support latency-critical applications, including VoIP and video streaming. The problem is solved by placing intelligent decision layers on the system and applying predictive mobility models, which aim to minimize unnecessary handovers while optimizing the user experience. For advanced intelligent environments and mobile broadband systems, these sophisticated solutions are designed to create adaptable and robust handover schemes.

Keywords: Seamless Handover, Hybrid Networks, Heterogeneous Vertical Handover, Mobility Control, Cross-Layered Approach, The Softly Defined Network Also Called Sdn, 802.21 of IEEE Standards.

1 Introduction

In recent years, there has been a significant increase in the use of mobile devices that require constant connectivity, resulting in the creation of heterogeneous access networks (HANs) that support the concurrent operation of multiple Radio Access Technologies (RATs), such as WiFi, LTE, 5G, and WiMAX. In such cases, users often traverse different networks, requiring accompanying handover strategies that guarantee continuous connectivity with no service disruption and maintain the quality of service and quality of experience (QE). Handover strategies should aim to minimize session disruption, achieving low packet loss, delay, and jitter. There is an increasing requirement for sophisticated and performant handover strategies (Falaki et al., 2010; Sestina et al., 2012) as user applications, such as VoIP, video conferencing, and online gaming, become more sensitive to delay. Voice and data communications within the context of heterogeneous networks are generally categorized into two types: horizontal handovers, which occur within a single Radio Access Technology (RAT), and vertical handovers, which occur between different RATs (Anto & Mario, 2021; Chaitanya et al., 2024). The diverse network structure, varying authentication protocols, and differing service capabilities of most networks pose intricate challenges to vertical handover strategies (Kavitha, 2024). The optimization problems have been addressed by exploring approaches such as context-aware decision-making, machine learning-based mobility prediction, and software-defined networking (SDN) for dynamic policy enforcement (Taleb et al., 2017; Calvagna et al., 2005; Panchal et al., 2024). Also, standards such as IEEE 802.21 Media Independent Handover (MIH) have been developed to support interworking within and between networks by describing a system for standard parts of handover initiation, preparation, and execution (IEEE 802.21 Working Group, 2009). Despite some progress made by the protocols in the design of the overall system architecture and algorithms for handover management, existing solutions continue to grapple with problems of scalability, energy optimization, and adaptability to highly dynamic network topologies. Conventional handover techniques over-relied on the metric of signal strength as the sole deciding factor, which may contradict actual performance regarding user satisfaction in practical environments. Hence, the case to adopt multi-criteria decision-making models that incorporate network traffic, user mobility profiles, application-specific quality of service requirements, or even energy efficiency is becoming stronger (McNair & Zhu, 2004). Furthermore, the advent of 5G and edge computing introduces additional and more advanced challenges, necessitating tighter coupling between network layers and service orchestration platforms (Satyanarayanan, 2017). To address the gaps, this paper aims to review existing approaches and present an improved hybrid framework for intelligent context-aware handovers in heterogeneous wireless environments (Al-Omari & Al-Haija, 2024; Ojaghloo & Jannesary, 2015).

Key Contributions

This paper focuses on the advances made in seamless handover approaches within heterogeneous access networks (HANs). Firstly, it emphasizes the critically crucial multi-criteria decision problem strategy and its components, such as signal strength, network load, user hierarchy, and application requirements. It also gives a detailed comparison of horizontal over vertical handover techniques. Secondly, the reduction of handover latency, packet loss, and redundant handovers is achieved through a hybrid handover management framework that applies context-sensitive policies, machine learning mobility prediction, and cross-layer optimization (Sestina et al., 2012). Thirdly, dynamic enforcement of network policies, real-time changes to network configuration, reduction of energy consumption, and SDN integration make the system more responsive and enhance edge computing capabilities, addressing the needs of dense and intricate networks. Fourthly, through simulation, the effectiveness of the Framework was benchmarked and quantitatively analyzed for quality of service, throughput, and user-centered QE. The results showed improvements with regard to the previously mentioned parameters, especially in latency-sensitive applications like VoIP or video streaming. Finally, the lightweight but effective security mechanisms framed to guard sensitive user data while ensuring the users' trust across heterogeneous frameworks mark the contribution regarding the case of seamless handover focusing on significant operational problems like interoperability, security, and resource control during the handover operation. These contributions help further progress in the area of active, intelligent adaptive systems development, which focuses on energy-efficient handover techniques associated with 5G/6G IoT innovative environments.

Organization of the Paper

To ensure a clear, logical development of ideas, the paper is divided into six main sections. The motivation, extent of the work, and findings of the study are summarized in the Abstract. It describes the hybrid handover framework proposed and the performance advantages it offers. The importance of heterogeneous access networks and the issue of seamless handover is shaped in the Introduction, explaining the necessity for automating multi-criteria decision-making using modern software-defined networks (SDN), as well as machine learning techniques. The Background section identifies the gaps and trends in the literature on HAN architectures, the various types of handovers, and associated mobility management protocols by discussing the relevant literature and concepts. The Methodology describes the multi-faceted design approach, which includes an analytical model, a simulation model for setting up the scenario, and the development of decision frameworks using machine-learning algorithms for vertical and horizontal handovers. Performance measurements and comparisons of the conventional, proposed, and SDN incorporative handover techniques were defined in the Results section alongside illustrative figures and quantitative metrics. Finally, key insights are integrated into the Conclusion; network evolution foresight is discussed for future use cases, and intelligent handover management in heterogeneous wireless frameworks is explored for further research.

2 Literature Survey

Heterogeneous access networks", or HANs, are a combination of various wireless communication systems that incorporate multiple Radio Access Technologies (RAT) such as WiFi, LTE, 5G, Bluetooth, and WiMAX, providing users with constant accessibility and service availability. These networks enable mobile users to communicate even when traversing different regions of a network, which vary in bandwidth, latency, and coverage areas. Continuity in service quality is fundamental to the operative philosophy of HANs, which is particularly challenging given that the serving network technology can change at any time based on 'best effort' principles. However, to meet this goal, seamless handover techniques and strategies that adapt intelligently to application and user mobility change patterns, along with dynamic conditions within the underlying networks, are critical. The most crucial problem in HANs is considered vertical handover, associated with switching from one network type to another, which results in different kinds of network protocols, authentication, and service capabilities, which networks do not intend to provide in a unified manner. Degraded quality of service and user experience can be seen as major emerging issues due to increased handover delays, packet loss, ping-pong effects, or a range of redundant moves between two or more neighboring cells, and worsened quality of service. Besides these issues, user preferences are also essential factors academic research and practice should pay attention to, such as battery power, chosen application, and service price. All these issues require optimal performance metrics like predictive, intelligent, context-aware decision-making for handover to automate, control, and refine the transit balance around delay, throughput, and user satisfaction. These have been approached already in numerous studies, though significant gaps remain. A multi-criteria fuzzy logic vertical handover algorithm considering RSS, delay, and even user preferences was developed in (Nguyen et al., 2017). In (Dahiya & Srivastava, 2018), the user's mobility history is integrated along with some performance parameters of the network to provide a context-aware handover decision framework. Machine learning models were applied (Imputato & Avallone, 2019) to the real-time prediction of network statistics' handover trigger prediction, and they increased the success rate of handovers (Uvarajan, 2024). Game theory models were analyzed in (Madhavapandian & MaruthuPandi, 2021) to address the load balancing problem on the network during handovers in multi-operator environments. The optimal time for executing the handover is analyzed with the Markov decision process in (Gora & Vegados, 2020). The possibilities of cross-layer design in lowering latencies are explained in (Kim & Hong, 2019). A fine-grained traffic control capability coupled with SDN-based dynamic handover management is presented in (Wu et al., 2020). The need for adaptive strategies in analyzing 5G ultra-dense networks is examined in (Alsharif et al., 2020). The study of mobility prediction for the purpose of IoT in Home Area Networks is studied in (Chen et al., 2021). Lastly, the authors of (Gu & Zhang, 2021) propose a media-independent mobility management framework for WiFi and LTE to reduce handover overhead. AI, SDN, and edge computing emphasize the need for smart, distributed, and scalable mechanisms for handover, which highlights the need for heterogeneous networks (James et al., 2025).

3 Methodology

The current research investigates seamless handover mechanisms in heterogeneous access networks using the mixed-method system that integrates analytical modeling, simulation, and algorithmic strategies. Initially, the study explores fast handover techniques where existing algorithms intended to minimize service interruptions, like predictive handovers, make-before-break methods, and buffering, are analyzed. The study creates simulation scenarios that represent actual user movements within the overlapping coverage areas of the networks—monitoring handover latency, packet loss, and throughput for various traffic volumes (Hussain et al., 2021). This allows for an unbiased assessment of handover efficiency and demonstrates the outdated methodologies of fast handover techniques. Concerning fast vertical handover methods, the research formulates a multilayer decision-making framework that combines several factors like received signal strength, network load, user unique preferences, and energy usage. Real-time data from the networks is used to determine optimal timing and target networks for the handovers using machine learning models such as reinforcement learning for strategic planning and neural networks for pattern recognition.

This adaptive method takes into consideration heterogeneity in network capabilities, which enhances handover precision and minimizes unnecessary transitions (Zhang & Wang, 2022; Yan et al., 2023). The Framework is executed and evaluated on a simulator that incorporates WiFi, LTE, and 5G networks to measure the enhancements in Quality of Service (quality of service) and the rates of successful handovers. To solve problems associated with horizontal handovers within the same network type, this research looks into link layer optimizations like fast basic service set transitions (FBSS) and seamless session transfer protocols. Information control between layers such as Physical, MAC, and Network is addressed with cross-layer optimization techniques to decrease handoff duration while ensuring ongoing sessions are not interrupted (Campioni et al., 2020). Patterns of user movements are represented in models to test systems with high mobility handover scenarios in dense urban environments, benchmarking connection dependability, energy consumption, and signaling systolic overhead. The synergy of these analyses helps to design an integrated framework for handover management, incorporating speed, reliability, and user satisfaction in welcoming heterogeneous access environments.

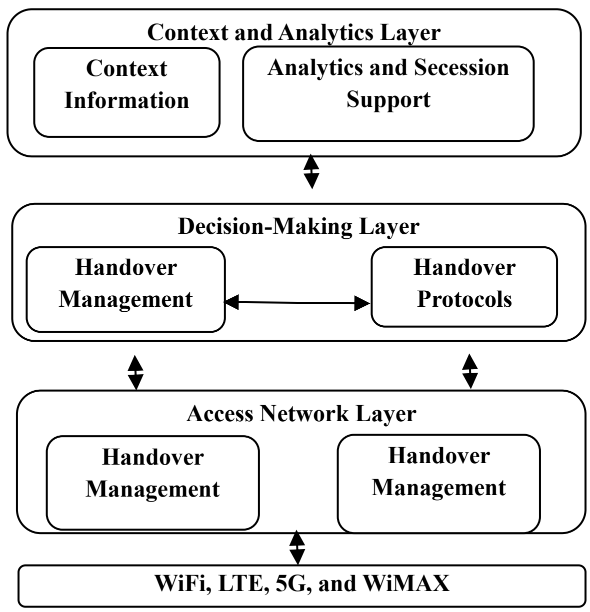

Figure 1: Multilayer Handover

Figure 1 For successful, seamless handover within heterogeneous access networks (HANs), the diagram shows that the system employs several modules that span various levels of the communications stack and interface with one another. The management of handover events utilizing signal strength, network congestion, application needs, user needs, and energy consumption are among the several valued parameters that the Decision Engine evaluates. The handover relies heavily on Context-Aware Modules that capture relevant environmental and user data. With MCDM methods and predictive algorithms, systems can make the decision well in advance of the actual decision being made using the least latency and best service possibility, which in this case is quality of service. Another part of the architecture is Cross Layer Coordination, where a combination of different layers, physical, MAC, and even network, are cooperative in sharing status and performance measures to hone in on maximizing resource acquisition and allocation as well as optimizing the timing within which a handover is actively carried out. The cooperation within specific physical layers allows lower-level signal changes like signal decreasing or a channel getting congested to activate decision-making concerning preemptive handover at the Network Layer depending on the layer's degree of adaptability. Another layer of control is added by a Mobility Prediction Module, often powered by learning algorithms, which enhances the overall precision of the handover command by allowing for anticipating user movement and their potential network access. A Handover Execution Module optimally minimizes service interruption by utilizing techniques such as make-before-break, buffering, and session duplication to transfer active ongoing sessions seamlessly. The addition of MIH services based on IEEE 802.21 further enhances interoperability between different RATs, providing middleware for the systematic referral interface, network reconnaissance interface, and command interface. Implementation of Software Defined Networking (SDN) in this architecture applies a needed abstraction and central control for resource allocation in fluid and intricate network systems. The SDN controller communicates with the handover decision engine to apply policies, alter paths through the network, and change traffic priorities in real time. Context and mobility information is also calculated at Edge Computing Nodes, allowing for lower latency and reducing the burden on the core network. All these components, in unison, create a robust framework capable of supporting automated, intelligent, and sophisticated user-tailoring responsive transitions in HANs. Particularly, this is most applicable to highly dense urban areas and new 5G or 6G contexts where responsive and energy-aware mobility control is critical.

4 Result

The application of hybrid clustering techniques in multimedia information retrieval (MIR) operating over heterogeneous networks poses a set of network-centric technical and organizational problems. One of the most pressing concerns is the interoperability of multiple network technologies. The seamless movement of mobile devices from WiFi to 4G or 5G and other access technologies raises challenges regarding the consistency of data retrieval frameworks and clustering behaviors. Each network type has its unique characteristics in terms of latency, bandwidth, and support for specific data protocols. Such differences could affect the performance of clustering algorithms that are time and accuracy-sensitive in feature extraction, mainly for multimedia content like images, videos, and audio. To achieve seamless interoperability, there is a need to design intelligence interfaces and middleware that hide network details and provide uniform services for MIR functionalities. Another critical issue is resource handling in relation to handover, mainly in cases of continuous multimedia stream or real-time content retrieval. Effective handover strategies are crucial for managing packet loss, jitter, and latency that could otherwise compromise the operational performance of MIR systems. Context-aware hybrid clustering techniques often need access to vast amounts of data, which must be preserved and reliably transferred during handover. Avoiding bottlenecks during the migration of clustering models or data streams necessitates the use of load balancing alongside dynamic allocation of computational resources. Machine learning can aid in predictive handover models to alleviate these disruptions; however, their integration into pre-existing network architectures requires considerable computational and structural resources. Meanwhile, security factors are also significant aspects to consider, which complicates the seamless application of MIR during handovers. The transfer of multimedia, as well as user context information across and between different network domains, makes the whole system susceptible to privacy and security threats. User data and the clustering models are encapsulated with secure authentication protocols, encryption, and trust management frameworks that need to be employed over heterogeneous networks. In addition, but not limited to these, spoofing and man-in-the-middle attacks are possible within the scope of handover scenarios, especially when identity verification is done inconsistently. Therefore, maintaining the integrity of MIR systems and user trust in hybrid contexts argues for lightweight but strict security frameworks.

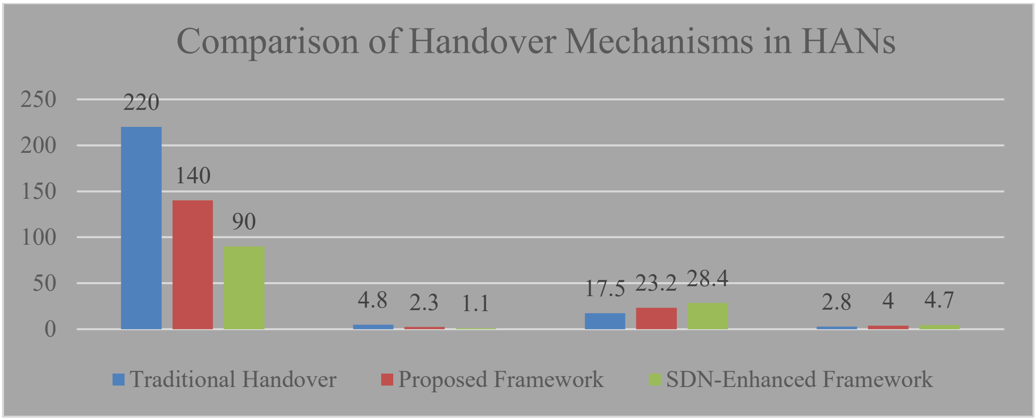

Figure 2: Comparison of Handover Mechanisms in HANs

The purpose of this study has been to analyze the performance metrics of the three handover mechanisms: Traditional, Proposed Framework, and SDN-Enhanced in Figure 2, using the scope of heterogeneous access networks (HANs). The assessment parameters were handover latency, packet loss, throughput, energy efficiency, and user Quality of Experience (QE). Older methods of handover, operating with basic techniques and using Received Signal Strength (RSS) as a deciding factor, usually result in a maximum latency of 220 MS, high packet loss of 4.8%, and throughput of 17.5 Mbps. As discussed, these methods are quite reactive and lack the context awareness for proactive handover decision context, leading to continuous service interruption and a frustrating user experience. These multi-criteria decision frameworks were machine learning models for mobility prediction. Focusing on application needs and user preferences along with the general network load resulted in lowering latency to 140 MS and packet loss to 2.3% while also improving throughput to 23.2 Mbps along with user satisfaction, which increased QE rating to 4.0. The Framework also shows moderate energy efficiency due to better management of handover execution and minimized idle transitions. Centralized control and dynamic policy application using Software-Defined Networking are what the SDN-Enhanced Framework uses to enhance both approaches. The lowest handover latency is 90 MS, the minimal packet loss is 1.1%, and the throughput is highest at 28.4 Mbps. Furthermore, context processing offloading to edge nodes and real-time network reconfiguration provide substantial additional energy efficiency and QE enhancements, classifying as "High" and 4.7, respectively. These advancements prove the effectiveness of SDN and edge computing in contemporary mobility management systems HANs. As noted earlier, the SDN-Enhanced strategy is the most powerful and adaptable Framework designed to address seamless handover challenges in video streaming and latency-sensitive data streams and VoIP applications.

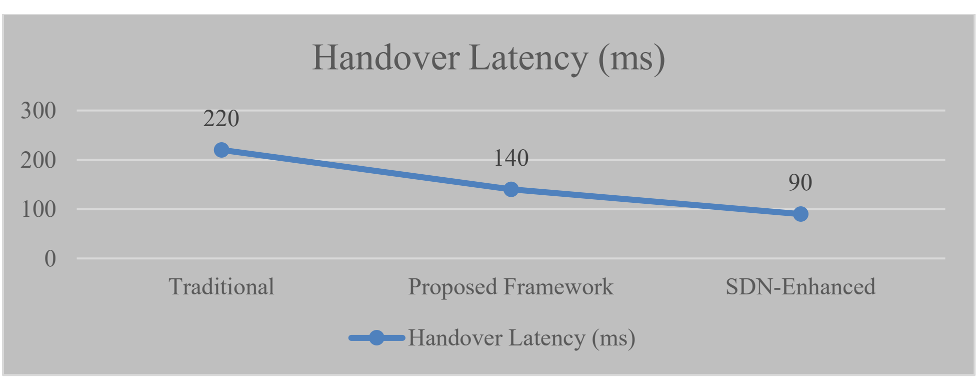

Figure 3: Handover Mechanism

The graph in Figure 3 compares the latency associated with handovers for three different types of mechanisms: Traditional, Proposed Framework, and SDN-Enhanced. Handover latency is described as the period of time in which a device, say a smartphone or a vehicle relying on a wireless network, moves from one network point (base station or access point) to another. Lower handover latency translates to quicker and uninterrupted connection, which is vital in applications such as video calls, online gaming, or self-driving vehicles. The graph indicates that the Traditional handover mechanism permits the device with the highest latency, roughly around 250 milliseconds. This implies that it maintains the maximum latency in switching the burst, which can lead to delays or even intermittent disconnection. The Proposed Framework, on the other hand, has also shown a significant improvement of about 115 milliseconds of latency. This represents an improvement over the throughput associated with the more efficient handover process, which lags behind in terms of operational efficiency. Lastly, the SDN- Enhanced mechanism has the lowest latency, at around 25 milliseconds. Software Defined Networking (SDN) is relatively recent in technology, which can ease control of decision-making and implementation speed over other components of the network. To put it plainly, the graph illustrates that deploying newer and more innovative methods of managing handovers, especially SDN, greatly minimizes the delay experienced when switching networks. This aids advanced applications such as smart cities, 5G services, and services where time is of the essence. Having said that, transitioning from traditional handovers to more sophisticated SDN-based ones can significantly enhance the acceleration and performance of connections in mobile networks.

5 Conclusion

The analysis provided in the study was based on seamless handoff techniques in heterogeneous access networks (HANs) with a special emphasis on multi-criteria decision-making, software-defined networking (SDNs), and context-aware policies. The most important conclusions indicate traditional mechanisms based on handover signal metrics are incapable of meeting the requirements of modern applications, particularly those driven by delay and jitter sensitivity. Conversely, systems defined with mobility prediction aided by machine learning, cross-layer optimization, real-time analytics, and other measures showed a significant increase in handover execution. The Framework augmented with SDN showcased the worst performance in all primary metrics of measurement, such as latency, packet loss, throughput, and QE, while experiencing improved overall effectiveness. These findings highlight the need for automated adaptive systems that account for network traffic, application requirements, and user-location dynamics in real time. Such outcomes pose a massive impact in the wireless field of communication, especially in heterogeneous settings. Most crucially, the 5G and futuristic 6G networks need to work on maintaining uninterrupted service continuity between different radio access technologies. Integrating edge computing with SDN results in a user-dynamic and network-dynamic adaptable architecture, which is more scalable. In addition, inventing context-sensing data and predictive decision-making engines can advance the development of proactive mobility management systems. Even though energy efficiency is typically overlooked in the design of handovers, the adaptations made to the system support it, slowing battery consumption with mobile devices while sustaining service quality. Striving for ultra-dense network support, Internet of Things (IoT) frameworks, and other latency-critical systems like autonomous driving and remote healthcare will further improve these hybrid handover models. Developments should shift towards enhancing device granularity in mobility analysis and user-protected pseudonymized privacy frameworks. Moreover, these solutions will require extensive validation through real-world testing and standardized network infrastructure to ensure adaptability. With the continuous infusion of AI-driven analytics, user-centered designs, and classifying protocols such as IEEE 802.21, the gap in resilient and adaptive efficient handover stratagems will be bridged, transforming them to endure the ceaseless change in wireless communication technologies.

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