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Software-Defined Mobility Management in Future Core Networks

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Abstract

The expected growth of IoT devices, coupled with the expected widespread adoption of 5G services, will necessitate a paradigm shift in how mobility is managed in mobile networks. Legacy mobility management approaches are often centralized and static, making them ill-suited for modern, heterogeneous networks. Software-Defined Mobility Management (SDMM) is a promising solution that applies Software-Defined Networking (SDN) concepts to provide programmable, scalable, and dynamic mobility management in future core networks. SDMM divides the mobility management unit into two distinct planes: control and data, enabling centralized control of user mobility management and dynamic resource scheduling across the access and core layers. This design improves mobility, enhances handover performance, reduces latency, and enables context-aware service-specific mobility policies. Also, the ability to integrate with Network Function Virtualization (NFV) enables the on-the-fly instantiation of lightweight distributed mobility functions. The flexibility offered by SDMM makes it well-suited to support ultra-reliable low-latency

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communications (URLLC), massive machine-type communications (mMTC), and network slicing. This study analyses SDMM's architecture and its components, speculates on the functioning of future core networks, and delves into major obstacles like scalability, interoperability, and security, while also pointing out unanswered questions in the field. The Smart Device Management Module (SDMM) enhances the intelligence and flexibility of mobile networks by viewing mobility as a software-powered function.

Keywords: Software-Defined, Mobility Management, Future Networks, 5G, Core Network, SDN, Network Virtualization.

1 Introduction

The innovative idea of Software-Defined Mobility Management (SDMM) uses the concepts of Software-Defined Networking (SDN) to revolutionize the way mobile network, radio, and core components handle user movement management. Since the entire process can now be programmed, engineers may teach the network in real time how to handle handovers, sustain data sessions, or anchor traffic (Shirmarz & Ghaffari, 2020). Instead of being stuck with predetermined hardware settings like prior systems were, SDMM can dynamically push out network rules, provide operators with a bird's-eye view of all links, and launch new activities as needed. That agility enables the system to react quickly to sudden changes by users or the network itself, opening the door to smarter, self-tuning mobility solutions (Galarza et al., 2024; Contreras et al., 2016).

As mobile networks transition to 5G and then 6G, SDMM will face new challenges regarding speed, ultra-low latency, and the massive number of devices, making flexible, code-driven control of mobility more crucial than ever. Modern mobile networks now support ultra-reliable low-latency communication, enable vast numbers of machines to communicate simultaneously, and provide super-fast broadband, all while users seamlessly roam between different technologies in crowded city grids (Siriwardhana et al., 2021). However, veteran tools like Mobile IP and 3GPP's Proxy Mobile IP fall short because they are fixed, hard to expand, and place all the load on a single central point (Surekha et al., 2024; Ali-Ahmad et al., 2013). Software-Defined Mobility Management (SDMM) introduces a fresh approach that enables engineers to modify the system through code, rather than hardware. Central SDN controllers then weigh factors like network layout, how people use their phones, and what each app needs before steering traffic to the best path (Nguyen et al., 2016). These guiding responsibilities function as lightweight virtual appliances when SDMM and Network Functions Virtualization collaborate, enhancing the utilization of spare resources and ensuring services remain available even during failures (Al-Surmi et al., 2021). These developments contribute to the future of core networks, which are anticipated to be entirely cloud-based, decentralized, and centered on on-demand services (Hoydis et al., 2020).

Part of next-gen core networks is Software-Defined Mobility Management (SDMM), as seen in Figure 1. Data and signals are sent via a combination of gNodeBs, which are first-hop base stations, through the Access Network, which User Equipment (UE) links through at the base layer. The Policy Engine and the Mobility Decision Engine, two local heroes that make lightning-fast calls, are housed in the Access slice. Those engines then communicate with an SDN Controller located in the cloud, which manages the whole setup, distributes new flow rules, and makes route decisions dynamically. Innovative, context-aware pathways, resource slicing, and bandwidth distribution are all handled by the AI Mobility Predictor and the Slice Manager, which are located in the thick Application Layer above the controller. When it comes to managing user sessions and packets, the SDN Controller has direct conversations with two essential icons: the Access and Mobility Management Function (AMF) and the User Plane Function (UPF). The combination of these features transforms disorderly traffic into orderly,

real-time mobility. They all operate in tandem to make the network flexible, scalable, open to new code, and reactive.

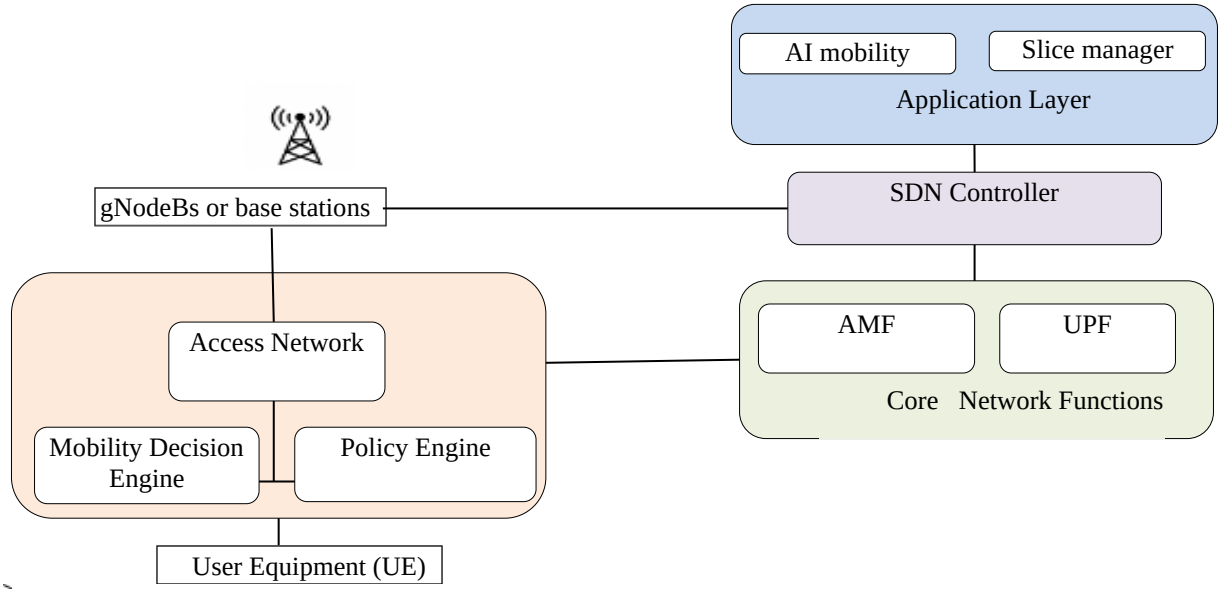

Figure 1: High-Level Architecture of Software-Defined Mobility Management (SDMM) in Future Core Networks

1.1. Research Paper Overview

Examining the architecture, operation, and implementation of Software-Defined Mobility Management inside the core networks of the future is the primary goal of this article. Separation of control and data, programmability, and abstraction are the three pillars of SDMM's architecture that set it apart from competing approaches. The following section details the whole SDMM design, which, for enhanced mobility management, uses components of software-defined networking (SDN), network functions virtualization (NFV), and edge computing. Topics covered in the article include Industry 4.0 networks, vehicle-to-everything connectivity, and smart city deployments using next-generation mobile networks. It analyzes SDMM's effects on handover delay, signaling efficiency, system scalability, and user-quality monitoring (QoE). To anchor the analysis, recent academic and industrial projects are discussed, focusing on real-world implementations and testbeds (Al-Fuqaha et al., 2015; Khan et al., 2025). Finally, the paper presents the primary research issues concerning SDMM adoption and provides suggestions for future work. These include cross-domain network interoperability, security risks due to centralized control, and AI-based controllers for mobility prediction and management (Bennis et al., 2021; Shamsudinova et al., 2025). Meeting these goals would position SDMM as an essential component enabling adaptable, robust, and smart mobile networking architectures during the 5G and 6G periods.

1.2. Problem Statement

- Scalability, latency, and adaptability issues are seen in conventional mobility management frameworks, more so in 5G and next-generation mobile networks.
- Mobile IP and Proxy Mobile IP exemplify the inefficiencies in adaptive systems, where performance is dismal due to a shifting 'target' in mobility that incorporates multi-device usage.

- The continued evolution of mobile networks, particularly the explosion of connected IoT devices and the need for ultra-low latency, posits the need for more sophisticated and intelligent solutions in mobility management.

1.3. Objective of the Study

- Investigate SDMM's capabilities as a scalable, flexible solution for dynamic mobility in the next-generation mobile network.
- Design and assess an SDMM framework that optimizes handover decisions, mitigates latency, and advances network performance through real-time mobility prediction and traffic management.
- Examine the combination of SDMM with NFV and SDN for efficient network resource use, enhanced mobility management, and a smooth user experience under varying network conditions.

This document is divided into several sections. In Section II, we focus on explaining the traditional approaches to mobility management, their shortcomings, and how Software Defined Networking (SDN) helps to improve mobility solutions. In Section III, we define Software-Defined Mobility Management, explain its architecture and main constituents, discuss its advantages in operations, and propose a model that includes some mathematical formulations. In Section IV, we examine the future of core networks, the shift towards software-defined core networks, their integration with other network functions, the implementation challenges they present, relevant performance metrics, and graphical data. To wrap up, in Section V, the key points are given, the implications of SDMM on next-generation networks are analyzed, and finally, future directions towards research, business development, and policy are suggested.

2 Background Study

Core mobility management in cellular networks has typically followed specific frameworks set by 3GPP with protocols like Mobile IP (MIP), Proxy Mobile IP (PMIP), and GPRS Tunneling Protocol (GTP). The purpose of these protocols is to provide users with seamless mobility and session continuity across cells and networks (Thanoon, 2024). A central concept in such systems is the anchor-based model, which utilizes a single gateway to manage user sessions irrespective of the user’s geographical location. The previously mentioned configuration, however, results in significant latency and bottlenecks along with poor routing in densely populated, heterogeneous network scenarios (Dijana, 2023; Ali-Yahiya, 2011). In addition, traditional approaches rely on tightly coupled systems in both the control and data planes, making it very difficult to adapt to changing conditions in the network and traffic volume. Mobility anchors tend to be static and predetermined, lacking the necessary intelligence and adaptability to optimize in real-time (Akyildiz et al., 1998). Thus, the performance needs of more advanced applications like augmented reality, connected vehicles, or large-scale IoT systems is challenging to achieve with traditional mobility management solutions.

In light of 5G and the networks that will follow, existing mobility management frameworks are encountering challenges. To begin with, scalability is a significant problem. With the growing prediction of billions of connected devices, existing mobility solutions will continue to struggle due to a centralized design and excessive signaling overhead (Anusuya, 2024; Hussein et al., 2022). Furthermore, latency is crucial for use cases such as remote surgeries or autonomous driving, where traditional handover techniques pose critical delays (Taleb et al., 2017). In addition, as more and more devices switch between various Radio Access Technologies (RATs), such as 5G NR, Wi-Fi, and LTE, heterogeneity across

network devices is becoming dominant. The smooth transition between these technologies is still a challenge for older systems (Trisiana, 2024; Sofiazizi & Kianfar, 2015). Also, consumers have a poor Quality of Experience (QoE) since most mobility rules in use today are static and cannot adjust to different contexts or services (Ishaq et al., 2016; Abdullah, 2024). The security issues continue to mount. Distributed denial of service attacks and other malicious techniques can have a significant impact on the core mobility components. Even worse, users' private data can be retrieved and read since end-to-end encryption isn't locked onto the pathways users travel (Ndiaye et al., 2017; Udhayakumar et al., 2024). Smarter, more adaptable, and dispersed architectures are urgently needed for next-gen networks due to these vulnerabilities.

By decoupling the network's intelligence, or the control plane, from the hardware that transmits data, software-defined networking (SDN) enables programmers to operate the whole system from a central dashboard and view its big picture (Kreutz et al., 2015; Kamrani, 2018). Nowadays, lightning-fast connections are ideal for software-defined networking (SDN) because of this partitioning, which allows the controller to dynamically modify traffic based on top-level rules. Mobility management is based on the same principle. With a centralized control plane, SDN is able to monitor real-time network statistics, identify each device, and compare this information to promised service levels before deciding where to send a user next (Yadav, 2019; Bernardos et al., 2014). The end effect is that handoffs occur almost instantly, with no signaling or delay, which improves the experience for everyone involved in the video or conversation. In addition, telecom operators may now establish bespoke mobility controls for distinct apps, services, or even user groups thanks to Software-Defined Networking (SDN) in conjunction with Network Function Virtualisation (NFV) and network slicing (Rao & Menon, 2024; Ma et al., 2018). The 5G business women and men, or verticals, each have their own large and often chaotic traffic loads that they want the network to manage, making these adjustable controls crucial. By eliminating a centralised anchor and intelligently determining the optimal path for each user data stream, SDN may disperse mobility management throughout the system, increasing both expansion capacity and redundancy in the event of hardware failure (Malhotra & Iyer, 2024; Veerappan, 2023). Because of these reasons, SDN is currently considered by experts to be the foundation upon which tomorrow's mobile networks will build Software-Defined Mobility Management (SDMM).

Research Gap

In Software-Defined Mobility Management (SDMM), there are research gaps. To start, there hasn't been enough study into the integration of SDMM with legacy systems like Mobile IP, which has a detrimental effect on interoperability. Furthermore, rather than conducting realistic evaluations across a wide range of network ecosystems, many studies focus on theoretical frameworks and simulations. Finally, while there are studies that suggest AI-enhanced mobility, there isn't a ton of literature on how networks respond and adapt in real time to other criteria like security, load balancing, and threats. In order to improve the overall performance of research and the actual implementations of SDMM, it is crucial to close these gaps.

3 Software-Defined Mobility Management

3.1 Advantages of Software-Defined Mobility Management

The innovative Software-Defined Mobility Management (SDMM) system streamlines data transportation by centralizing management, empowering operators to define policies, and shielding end users from the underlying complexities. On top of all that smarts, SDMM also provides fast

modifications, allows networks to expand without extensive rewiring, reduces delays, and grants staff detailed control over all aspects of mobility policy. By splitting the brains of the system-the control plane-from the actual data traffic, SDMM can tweak settings the moment something changes, whether its a new device or a crowded zone. Instead of leaving handover limits, anchor points, and route maps locked in place, SDMM calculates and updates them on the fly, so users hardly notice the shift. SDMM's context-aware mobility is a prominent advantage because it facilitates the application of handover strategies based on user profiles, application types, and service level agreements. SDMM also implements resource efficiency through load-aware handovers and traffic steering, which directly improves the overall QoE. Furthermore, SDMM eliminates the single-point-of-failure problems of legacy systems, enhancing network resilience by supporting distributed or redundant control paths.

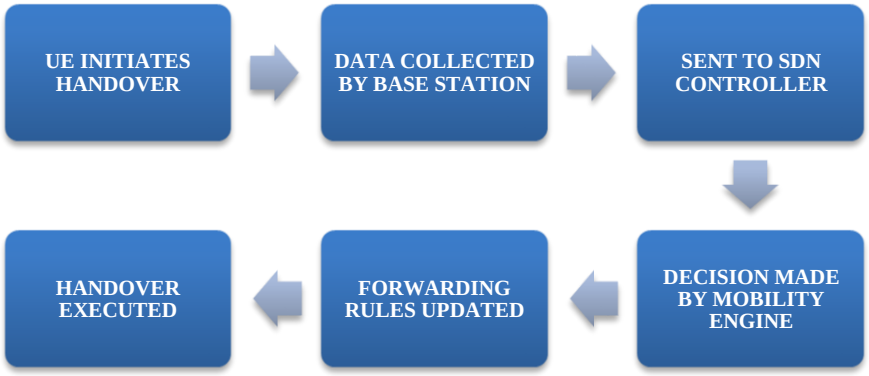

Figure 2: Flow of SDMM (Software Defined Mobility Management) Operation

The diagram (Figure 2) depicts the sequence of steps in SDMM operation, which automates the handover process in a software-defined network. It starts when the User Equipment (UE) issues a handover request and the corresponding base station begins to gather the required mobility and network data. This information is forwarded to the SDN controller, which sends it to the mobility engine. The mobility engine processes the information and, based on its analysis, makes a handover decision. After decision-making, the controller takes action to change the forwarding rules as per the decision made. At this point the handover is performed, enabling seamless transition from one base station to another for the UE.

3.2 Key Components and Architecture of Software-Defined Mobility Management

The SDMM architecture has three primary components, which include the data plane, control plane, and application layer.

- The data plane encompasses user equipment (UE), base stations, and components used for forwarding information like as switches and gateways. These components do both basic local processing and packet forwarding.
- The SDN controller, controlling mobility from a central location, oversees the whole network and is housed on the control plane. Stats including user location, connection utilisation, and signal strength are collected by the controller. Key elements include:
- Mobility Decision Engine (MDE): Determines the handover provocation and anchor shift reassignment.
- Topology Awareness Module: Tracks the dynamic state of the network and holds a current snapshot of the network topology.

- Flow Manager: Installs forwarding policies on the switches.
- Application Layer: Integrates advanced functions such as engineering the flow of traffic, enforcing security policies, and deploying prediction AI engines.

Mobility decision-making can be described by a simplified approach using a model of utility maximization. Assuming that every mobile user $u \in U$ needs to be linked to a base station $b \in B$ at every instant of time t, the total utility U(u,b,t) must be maximized.

Utility Function:

$$U(u,b,t) = \alpha R(u,b,t) - \beta L(u,b,t) \quad (1)$$

Where:

$R(u,b,t)$ captures the anticipated data rate from user u to base station b at time t.

$L(u,b,t)$ is the expected latency.

α, β are weighting constants defined based on the service level requirements.

Optimization Objective:

$$\max \sum_{u \in U} \sum_{b \in B} \mathrm{x_{ub}(t)} \cdot \mathrm{U(u,b,t)} \quad (2)$$

$$\mathrm{x_{ub}}(t) \in \{0,1\} \quad (3)$$

Here, $\mathrm{x_{ub}}(t)$=1 denotes that user u is linked with base station b at time t, otherwise it is 0.

This model can also be modified to incorporate multi-objective optimization criteria such as: load balancing, handover cost, and energy efficiency which can be solved by linear programming or reinforcement learning within an SDN controller.

3.3 Case Studies or Examples of Software-Defined Mobility Management Implementations

SDMM has been used in pilot projects and testbeds in different sectors, as listed below:

Smart Cities: SDMM is applied in the municipal networks for controlling the mobility of thousands of IoT devices. Based on congestion and load, the SDN controller reroutes traffic to mobile sensors dynamically.

Vehicular Networks (V2X): SDMM predictive techniques enable the handover of mobile cars to road-side units (RSUs) while providing continuous connectivity for infotainment and safety services.

Industrial IoT: In factory automation, SDMM allows mobile robots and AGVs (Automated Guided Vehicles) to sustain low-latency communication across the different regions of the factory floor.

These scenarios illustrate the versatility of SDMM and its capacity to adapt to different and ever-changing conditions, thus underscoring its potential as a fundamental technology for tomorrow's mobility systems.

Algorithm: SDMM Mobility Management

Input: UE (User Equipment), gNodeB (Base Station), Network Data (signal strength, location, etc.)

Output: Handover Decision, Updated Forwarding Rules

1. Initialize SDN controller, Mobility Decision Engine (MDE), Policy Engine, and AI Mobility Predictor.
2. UE sends handover request.
3. Collect network data (UE location, signal strength, traffic load).

4. Analyze data using AI Mobility Predictor, MDE, and Policy Engine.
5. Make handover decision:
   - If handover required:
     - Select target base station.
     - Send decision to SDN controller.
   - If no handover:
     - Continue monitoring.
6. SDN controller updates forwarding rules and calculates optimal route.
7. Perform handover:
   - Execute handover to new base station.
   - Update UE's session.
8. Monitor network status and collect feedback for real-time adjustments.
9. Repeat steps 3-8 for dynamic mobility events.

End Algorithm

3.4. Software Tool Analysis

Mobility management optimization employs various tools within the Software Defined Mobility Management (SDMM) framework. OpenFlow, ONOS, and Ryu Software defined networking (SDN) controllers support centralized control and dynamic, real-time, data-driven traffic re-routing. Mobility management performance assessment within SDN environments is facilitated by network simulators such as OMNeT++, ns-3, and Mininet. Deep learning ecosystems such as TensorFlow, Keras, and PyTorch are instrumental in the development of algorithms designed to predict mobility patterns for real-time handover decision-making. Traffic management tools like Wireshark and NetFlow provide metrics concerning network traffic and support mobility event assessment, resource re-distribution, and dynamic resource re-allocation during mobility management.

3.5. Dataset Description

Performance testing and simulation of SDMM require several datasets. For the simulation of handovers and mobility prediction, real-world data from mobility datasets like 5G-Mobility, MIT Reality Mining, and Copenhagen Suburban Mobility is useful. SDMM's dynamic load management and traffic flow optimization capabilities are evaluated using network traffic datasets from Kaggle that include internet and mobile traffic. Handover decisions are aided by insights from signal strength datasets, particularly the Kaggle Radio Signal Strength and CICIDS, which provide information about network conditions. For the analysis of SDN network dynamics and multiple mobility scenarios, SDMM evaluation and simulation data are also obtained from NS-3 mobility models and OpenFlow traffic data.

4 Results and Discussion

4.1 Evaluation Metrics

Network Reconfiguration Time:

To assess flexibility, a crucial measure is the network reconfiguration time:

$$T_r = T_d + T_c + T_p \quad (4)$$

Where:

T_d : Delay in recognizing change (e.g., user activity shift),

T_c : Delay for controller to process new configuration,

T_p : Delay in updating the data plane with new rules.

Mobility events responsiveness improves with a lower value of T_r.

Handover Success Rate (HSR):

For qualitative assessment, we propose:

$$HSR = \frac{N_s}{N_t} \quad (5)$$

Where:

N_s: Number of successful handovers,

N_t: Total handover attempts.

Higher values of HSR show better integration with other network functions during mobility events.

Controller Load Efficiency (CLE):

$$CLE = \frac{E_u}{E_t} \quad (6)$$

Where:

E_u : Useful controller events processed, such as successful policy updates,

E_t : Total events received.

An SDMM controller architecture with a high CLE value indicates an efficient and non-congested system.

4.2 Performance Evaluation

The shift in core networks is from a static infrastructure based on hardware components to a flexible architecture based on Software Defined Systems to meet the agile requirements of next-generation services. This transformation is a result of the adoption of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) because they separate network control from forwarding and also virtualized legacy network components such as firewalls, gateways, and mobility anchors. In this system, Core networks are also programmable, modular and service aware. Network functions may now be instantiated, scaled, or migrated on demand based on traffic and user patterns. The SDN controllers serve as centralized “brains” with a global view of the network enforcing policies at different resources which are distributed. This change also permits the inclusion of edge computing where compute resources are geographically closer to users which require ultra-low latency. In this case, mobility management needs to not only relocate sessions but also relocate contexts and service states in distributed cores.

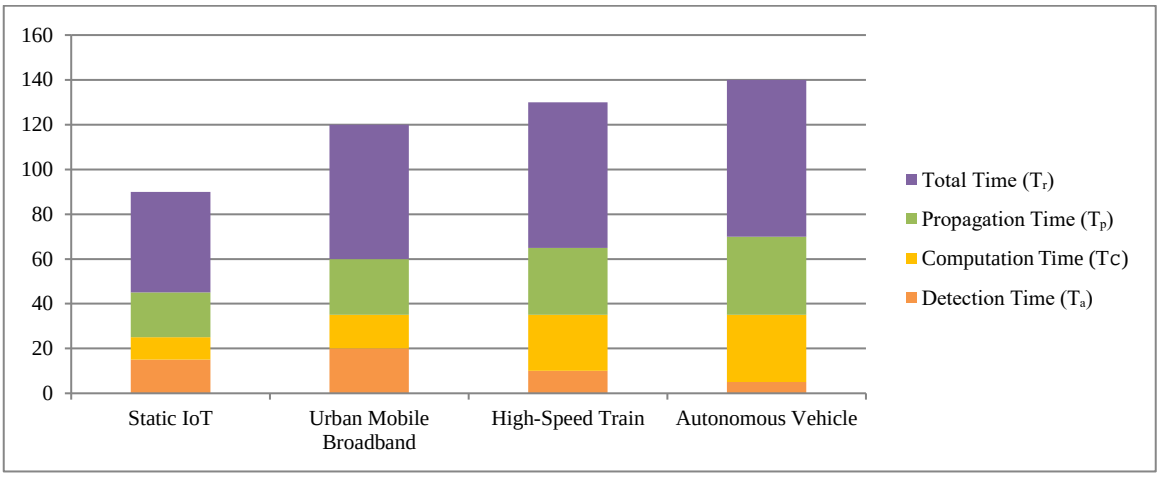

Figure 3: Network Reconfiguration Time Components

In Figure 3, the stacked bar chart shows the total network reconfiguration time alongside its core components, which are detection time, computation time, and propagation time. It also considers four scenarios: Static IoT, Urban Mobile Broadband, High-Speed Train, and Autonomous Vehicle. As noted, with an increase in mobility complexity, both computation and propagation times tend to rise. For example, in autonomous vehicle scenarios, the propagation time reaches 35 ms which is the most mobile and control update-latency sensitive environment. This visualization underscores the critical need to refine intelligent controller algorithms and improve faster mechanisms for reduced reconfiguration times in highly dynamic next-generation networks.

When Software-Defined Mobility Management (SDMM) works side by side with other software-defined tools for traffic steering, network slicing, and security, everything runs smoother. The joint setup lets SDMM change rules based on where a device is, what app it uses, how worried users are about delay, and any company policy in place. As an example, consider network slicing: a video conversation on a smartphone may rely on an Ultra-Reliable Low-Latency slice, which requires handovers that are fast and have almost no latency. Prior to the phone's actual movement, SDMM can reserve the appropriate resources along the route by communicating with the slice controller. Likewise, tying mobility rules to security fences makes sure each handover still meets log-in checks and data privacy rules. Traffic engineering modules can also dynamically reroute flows during mobility events to maintain optimal throughput.

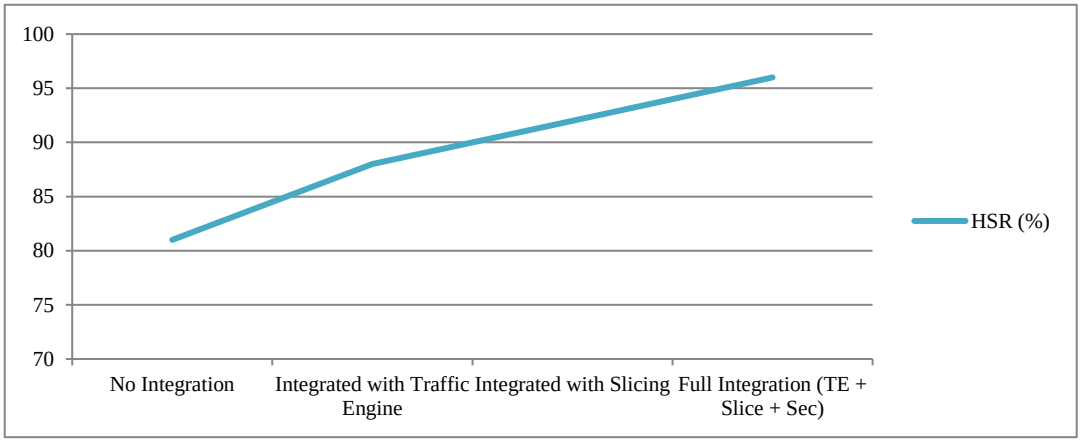

Figure 4: Handover Success Rate by Integration Type

Figure 4 presents a line chart where the handover success rate (HSR) is tracked with an increasing level of integration of software-defined mobility management (SDMM) with other network functions. HSR starts at 81% with no integration and increases significantly as SDMM is integrated with traffic engineering providing 88%, network slicing at 92%, and finally full integration at 96%. Increased dependability and smooth handovers are suggested by the outcomes of a holistic strategy that incorporates mobility decisions with slicing policies, traffic optimisation, and security. The significance of software-defined core network inter-domain cross-functional orchestration is emphasised by this reason.

The deployment of SDMM presents a multitude of obstacles. Controller scalability is of the utmost importance as the number of mobile users and base stations grows. The need for a distributed or tiered control strategy on the control plane may arise from the fact that controllers must handle several streams of events or data from various sources within a specific time constraints. Mobile users experience significant lag while accessing navigation applications on vehicles, meaning the delay in control messages will affect mobility performance. These control messages lattency or reliability will equally affect the overall mobility performance. Interoperability concerns also arise. The future core networks will most likely contain equipment from multiple different vendors as well as from older legacy vendors. A seamless interface between the SDMM modules and traditional mobility functions will necessitate protocol commons for design and standards for mobility APIs. Since SDMM employs centralized intelligence, preserving security and privacy makes SDMM intelligence enforcement vulnerable to attacks. The design must embed controller redundancy and encryption alongside strict access control frameworks.

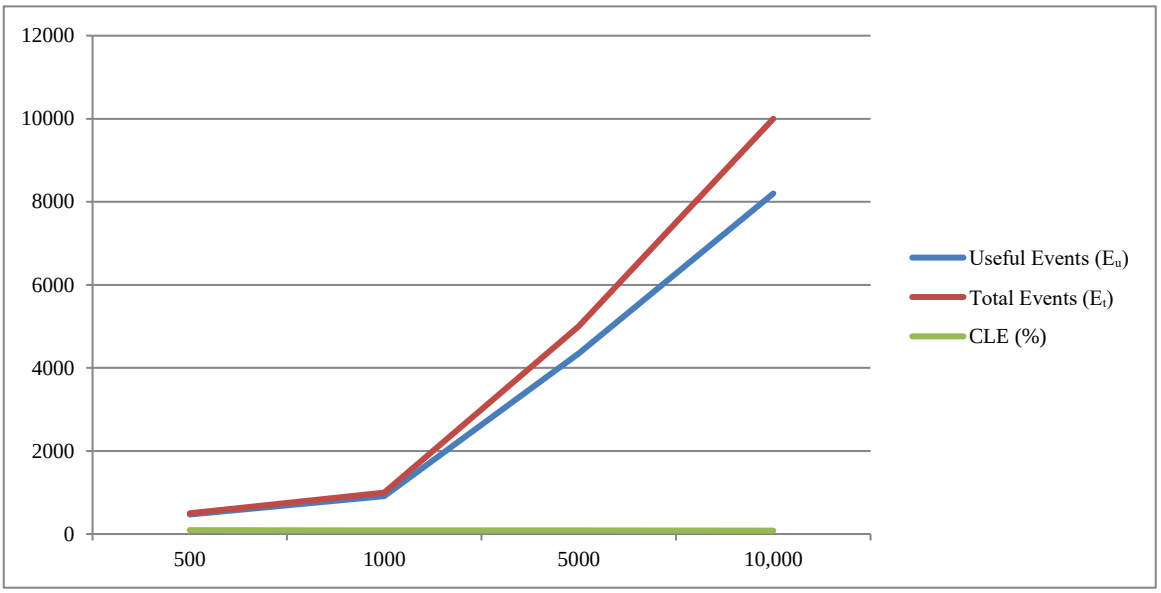

Figure 5: Controller Load Efficiency vs. Network Size

The line chart (Figure 5) shows the controller load efficiency (CLE) versus the number of active mobile users. As the user count increases from 500 to 10,000, CLE decreases from 94% to 82%. This reduction shows the extent to which the network scaling affects the controller's efficiency in processing pertinent mobility events. Although the drop is gradual, it highlights the centralized control scalability limitations. The trend may be offset by the distributed or hierarchical SDN controller architectures that are likely needed for large-scale deployments.

4.3 Performance Comparison

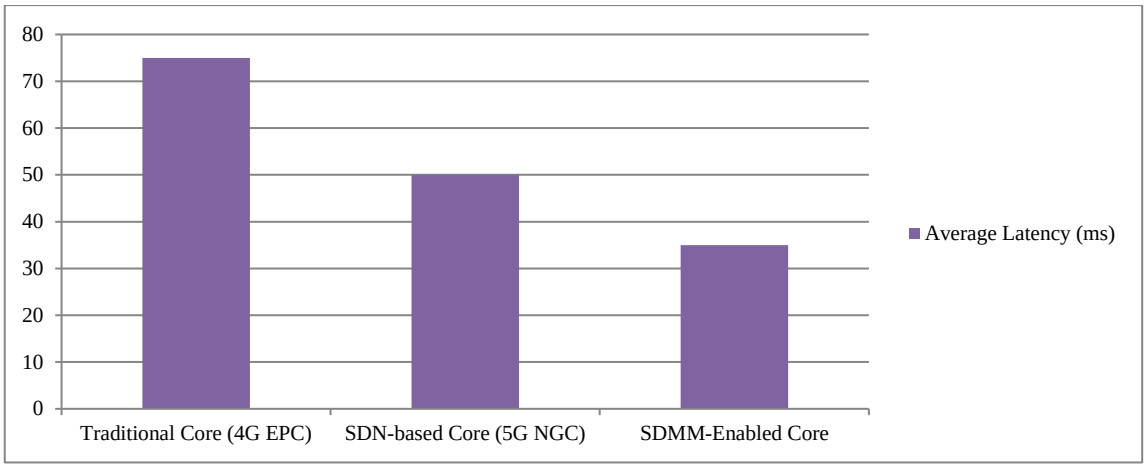

Figure 6: Latency Comparison Across Core Architectures

This bar chart (Figure 6) illustrates the average end-to-end latency for the three core network architectures: Traditional Core (e.g., 4G EPC), SDN-based Core (e.g., 5G NGC), and SDMM-Enabled Core. The traditional core has the highest latency of 75 ms, with rigid anchoring and inflexible routing as the primary contributors. The SDN-based core decreases this to 50 ms with the addition of programmability and central control. The SDMM-enabled architecture achieves the lowest at 35 ms with real-time traffic redirection, optimized anchor selection, and adaptive mobility decision. The graph clearly demonstrates the performance enhancement with the SDMM enabled ultra-low latency targeted for future networks.

5 Conclusion

This research has examined the impact of Software-Defined Mobility Management (SDMM) on future core networks, particularly its transformative prospects. SDMM approaches mobility management on a more traditional level with its programmable, flexible, scalable, centralized intelligence, and separated control and data planes. Its advantages include better handover success rates, lower latency, dynamic resource allocation, integration with traffic engineering, and network slicing. Mathematical models and performance measurements help support the SDMM architecture's real-time flexibility through the Mobility Decision Engine and Topology Awareness Layer modules, which are operationally efficient. The requirements of next-generation applications such as autonomous driving, vast IoT, and immersive AR/VR will be met in large part by SDMM, as core networks move towards completely virtualised and cloud-native components. However, prior to that, we need to address the issues of security, interoperability, and controller scalability. Some areas that might use more investigation include large-scale testbed validation, standardised interfaces, multi-controller coordination, and mobility prediction using AI. When it comes to 5G and core network mobility management, SDMM is and will remain a game-changer for more responsiveness, intelligence, and resilience.

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