

MSCHF algorithm for minimizing signaling costs and enhancing vertical handover efficiency in wireless communications networks

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ABSTRACT

The vertical handover (VHO) is an essential part of heterogeneous wireless networks, which allows User Equipment (UEs) to roam among different radio access technologies (RATs) and connect to a network that best satisfies their needs, such as wireless local area network (WLAN) and 5G. Many VHO research works in the literature have been proposed to provide a seamless UE transition between multiple RATs, considering packet loss, delay, and throughput parameters. However, signaling cost and handover failure as vital factors in providing seamless VHO have not been considered thoroughly, particularly between WLAN and 5G. Therefore, this paper presents a comprehensive performance evaluation for a new algorithm for Minimizing Signaling Cost and Handover Failure (MSCHF) for co-located WLAN and 5G networks. Through numerical, mathematical, and simulation analyses, MSCHF achieves a 40% reduction in signaling cost, a 50% decrease in handover failure rate, and significant improvements in buffer consumption, resource allocation time, and handoff decision time compared to traditional methods. It is shown that the proposed MSCHF algorithm outperforms the non-MSCHF algorithm in minimizing signaling cost and probability of handover failure. These results highlight MSCHF's potential to advance wireless network management by optimizing critical performance metrics.

Subjects Algorithms and Analysis of Algorithms, Computer Networks and Communications, Data Mining and Machine Learning

Keywords Efficient communications, 5G, Vertical handover, Heterogeneous wireless networks, Wireless networks, Mobile networks

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INTRODUCTION

The rapid growth of internet usage, with 5.4 billion users globally as reported by the International Telecommunication Union (ITU) in 2023 (*International Telecommunication Union, 2024*), and increasing demand for multimedia services by user equipment (UE) (*Chandavarkar & Reddy, 2012; Goutam, Unnikrishnan & Karandikar, 2020; Goutam et al., 2021*), necessitates seamless connectivity across heterogeneous wireless networks. This represents a growth of 45% since 2018, with an expected increase of 1.7 billion, as depicted in Fig. 1. Vertical handover (VHO) enables UEs to transition between different radio access technologies (RATs) like wireless local area network (WLAN) and 5G, ensuring continuous sessions (*Goutam & Unnikrishnan, 2019; Goutam, Unnikrishnan & Goutam, 2017; Goutam et al., 2019; Goutam & Unnikrishnan, 2019*). There are three stages in VHO, namely initiation, decision, and execution (*Zekri, Jouaber & Zeghlache, 2010; Kassab, Kervella & Pujolle, 2008; Stevens-Navarro & Wong, 2006; Chan et al., 2001; Chen, Liu & Huang, 2004; McNair & Zhu, 2004; Gyekye-Nkansah & Agbinya, 2006; Sourav, Amitava & Rabindranath, 2010; Debnath & Kumar, 2020; Yew et al., 2020; Goyal & Kaushal, 2016; Akshay, Elena & Ilker, 2018; Huang et al., 2013; Kumar, Sandeep & Kumar, 2018; Pramod & Sagar, 2022; Rubasinghe et al., 2020; Khattab & Alani, 2013a, 2013b, 2013c, 2013d; Khattab, 2017, 2019, 2021; Khattab & Alani, 2014a, 2014b, 2014c, 2014d*). The initiation phase is responsible for gathering essential information such as UE's preferences (e.g., security, service cost), network parameters (e.g., bandwidth and delay), and terminal parameters (e.g., velocity and battery). The decision phase evaluates and selects the best available RAT based on information gathered in the previous phase (*Hajar et al., 2021; Rong et al., 2010; Jianhua, Xiangnong & Lu, 2016; Shiwei, 2021*) and input parameters, including cost, Received Signal Strength (RSS), bandwidth, network load, battery status, and network coverage (*Goutam & Unnikrishnan, 2019*). The final decision is determined by Quality of Service (QoS) factors like delay, jitter, and packet loss (*Yan, Sekercioglu & Narayanan, 2010*). The execution phase is responsible for connecting a current RAT network to a candidate RAT network.

The goal of a VHO is to minimize (1) packet loss, (2) delay, (3) signaling cost overheads, and (4) handover failure (*Liyan, Li Jun & Samuel, 2011*), where the VHO is considered of most significant importance in 5G due to the adoption of new technology (*Khan et al., 2022*). However, critical challenges such as high signaling costs and handover failures, particularly between WLAN and 5G, remain underexplored. This paper introduces the Minimizing Signaling Cost and Handover Failure (MSCHF) algorithm, designed for co-located WLAN and 5G networks, which significantly reduces signaling overheads and failure probability while optimizing buffer consumption, resource allocation, and handoff decision times. The relevance of MSCHF extends to real-world applications in industries such as telecommunications, smart cities, and autonomous vehicles, where seamless connectivity is critical for real-time data transmission, emergency services, and Internet of Things (IoT) ecosystems. By enhancing VHO efficiency, MSCHF can support mission-critical operations and improve user satisfaction in bandwidth-intensive environments, positioning it as a vital advancement for next-generation wireless

Individuals using the Internet

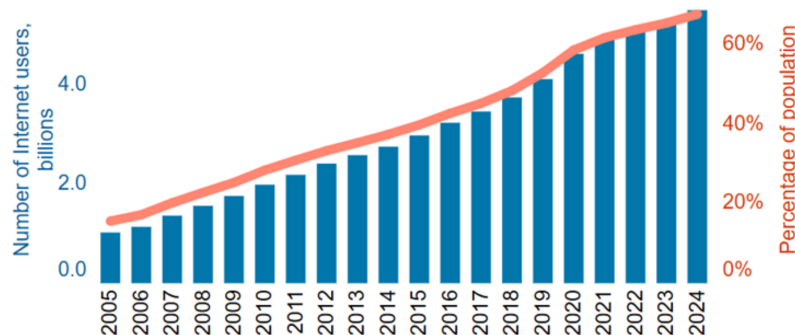


Figure 1 Statistic of world's population using the Internet.

Full-size DOI: [10.7717/peerj-cs.3283/fig-1](https://doi.org/10.7717/peerj-cs.3283/fig-1)

communications. Through numerical, mathematical, and simulation analyses, MSCHF outperforms existing approaches, offering a robust solution for efficient wireless network management. The contributions of this algorithm are twofold:

- It considerably reduces signaling costs and the probability of handover failure, addressing critical performance metrics that are essential for maintaining robust and reliable network connectivity.
- It enhances the overall efficiency of the network by optimizing buffer consumption, resource allocation time, and handoff decision time, thereby improving the responsiveness and operational effectiveness of wireless communications.

These enhancements provided by the MSCHF algorithm underscore its potential to contribute meaningfully to the field of wireless network management. The rest of the article is organized as follows: “Related Works” presents related works. In “Design of the proposed MSCHF Algorithm”, a design of the proposed algorithm is presented. In “Numerical Analysis”, a mathematical model and analysis are presented, and in “Mathematical Model and Analysis”, a numerical analysis is presented. In “Performance Evaluation and Results Discussion”, a performance evaluation and results discussion are presented. Finally, conclusions are given in “Conclusion”.

RELATED WORKS

The literature on VHO in heterogeneous wireless networks is vast and multifaceted, addressing various challenges in achieving seamless connectivity across diverse RATs. This section synthesizes prior work by organizing it into thematic categories—parameter-based VHO approaches, decision-making techniques, and specific focus areas like security, cost, and emerging technologies—to highlight trends, methodologies, and gaps in the field. By reviewing these studies, we establish the context for the proposed Minimizing Signaling Cost and Handover Failure (MSCHF) algorithm and its unique contributions.

Parameter-based VHO approaches: A significant body of research focuses on network parameters as the foundation for handover decisions, aiming to optimize connectivity based

on measurable metrics. For instance, [Goutam et al. \(2021\)](#) and [Debnath & Kumar \(2020\)](#) employ parameters like received signal strength (RSS), bandwidth, and packet loss, utilizing simple additive weighting (SAW) and multiplicative exponential weighting (MEW) techniques to select optimal RATs, with simulation results showing improved performance in network selection accuracy. Similarly, [Yew et al. \(2020\)](#) emphasizes RSS for high-speed mobility scenarios, achieving reduced power consumption and enhanced microcell network usage, as evidenced by performance evaluations. Studies like [Pramod & Sagar \(2022\)](#), [Hajar et al. \(2021\)](#), and [Zeshan & Baykas \(2021\)](#) further explore packet loss, throughput, and quality of experience (QoE) through predictive methods like Link Going Down (LGD) and adaptive strategies, demonstrating better throughput and reduced delays in varied network conditions. Additionally, [Goutam, Unnikrishnan & Karandikar \(2020, 2021, 2022\)](#), [Kunarak & Duangchan \(2021\)](#), [Zhang, Bai & Yao \(2022\)](#), [Kumar, Akshay & Sagar \(2022\)](#), and [Goutam et al. \(2020\)](#) investigate a broad spectrum of parameters including RSS, bandwidth, cost, user velocity, latency, jitter, and network coverage. For example, [Goutam, Unnikrishnan & Karandikar \(2022\)](#) uses principal component analysis (PCA) to simplify multi-dimensional data, while [Kumar, Akshay & Sagar \(2022\)](#) examines VHO in Internet of Vehicles (IoV) with 5G, highlighting improvements in data transfer rates and packet delivery ratios. [Li \(2017\)](#) and [Vuchkovska & Jakimoski \(2017\)](#) also contribute by focusing on predictive mechanisms and QoS during VHO, showing reduced handover delays and improved average throughput. Despite these advancements, many of these works prioritize QoS metrics over signaling overheads and failure risks, leaving critical gaps in cost-efficient and reliable handover processes.

Decision-making techniques: Another prominent area of research centers on advanced decision-making frameworks to navigate the complexity of VHO in heterogeneous environments. Fuzzy logic (FL) is a widely adopted approach, as seen in [Goutam & Unnikrishnan \(2019\)](#) and [Goutam et al. \(2020\)](#), where multiple parameters like RSS, jitter, and bandwidth are integrated through fuzzy rules to optimize handover choices, with simulations confirming enhanced decision accuracy. Multi-attribute decision-making (MADM) techniques such as technique for order of preference by similarity to ideal solution (TOPSIS), VIKOR, and gray relational analysis (GRA) are explored in [Satapathy & Mahapatro \(2021\)](#), [Goutam, Unnikrishnan & Karandikar \(2020\)](#), [Radouche & Leghris \(2020\)](#), [Ezz-Eldien et al. \(2020\)](#), and [Ahmed et al. \(2019\)](#), offering systematic methods for network selection. For instance, [Radouche & Leghris \(2020\)](#) introduces a cosine similarity-based MADM method, outperforming TOPSIS and VIKOR in terms of ranking abnormality and handover frequency. The research work ([Ahmed et al., 2019](#)) proposes an Enhanced-TOPSIS with analytic hierarchy process (AHP) for traffic class prioritization, achieving better RAT selection for WiMAX networks. Neural networks and optimization methods like Artificial Bee Colony (ABC) are utilized in [Tan, Chen & Sun \(2020\)](#) and [Khan et al. \(2017\)](#) to minimize delays and select target networks based on end-to-end latency and bit error rates, though often at the expense of computational complexity that may hinder real-time applications. Further, [Shiwei \(2021\)](#) leverages an improved K-nearest neighbor (KNN) for resource utilization, [Khan & Han \(2015\)](#) uses data rate thresholds for handover triggering, [He et al. \(2020\)](#) proposes a velocity-pre-decision fuzzy logic (VPD-FL) approach

for reduced computation, and [Liu, Sun & Ifeachor \(2015\)](#), [Liu, Sun & Ifeachor \(2016\)](#), and [Yadollahi et al. \(2015\)](#) focus on QoE-driven and user-centric frameworks to maintain multimedia service quality and minimize unnecessary handovers. These decision-making strategies, while sophisticated, often overlook the specific challenges of signaling cost and handover failure, particularly in WLAN-5G transitions, limiting their applicability to cost-sensitive and reliability-critical scenarios.

Security, cost, and emerging technologies: A smaller but significant subset of research addresses niche aspects like security, signaling cost, and integration with emerging network paradigms during VHO. Security-focused studies, such as [Khattab \(2022\)](#) and [Kumar & Om \(2020\)](#), propose mechanisms to enhance handover safety, with [Khattab \(2022\)](#) achieving a 20% security improvement and [Kumar & Om \(2020\)](#) reducing computational and storage costs using universal subscriber identity module (USIM) and elliptic curve cryptography (ECC) in 5G-WLAN networks. However, comprehensive signaling cost minimization remains secondary. [Khattab, Khan & Alothman \(2023\)](#) compares a secure VHO algorithm with the Media Independent Handover (MIH) standard, showing improvements in throughput, delay, and packet loss while maintaining security constraints. Emerging technologies and future-oriented approaches are explored in [Satapathy & Mahapatro \(2023\)](#), [Fonseca et al. \(2024\)](#), and [Warrier et al. \(2024\)](#). Specifically, [Satapathy & Mahapatro \(2023\)](#) presents a context-aware VHO for energy efficiency and resource optimization, [Fonseca et al. \(2024\)](#) integrates predictive models with reinforcement learning for enhanced handover decision-making, and [Warrier et al. \(2024\)](#) focuses on 6G technology for non-terrestrial networks, promising improved connectivity but lacking real-world scalability testing and cost analysis. Additionally, [Khan et al. \(2015\)](#) proposes a vertical handover management scheme based on data rate needs and GRA decision methods, optimizing energy use and handover frequency. Despite these contributions, critical factors like signaling cost and handover failure—vital for seamless VHO between WLAN and 5G—remain underexplored across the cited works ([Goutam et al., 2021](#); [Goutam & Unnikrishnan, 2019](#); [Debnath & Kumar, 2020](#); [Yew et al., 2020](#); [Pramod & Sagar, 2022](#); [Hajar et al., 2021](#); [Shiwei, 2021](#); [Goutam, Unnikrishnan & Karandikar, 2020, 2021, 2022](#); [Kunarak & Duangchan, 2021](#); [Satapathy & Mahapatro, 2021](#); [Zeshan & Baykas, 2021](#); [Khattab, 2022](#); [Khan & Han, 2015](#); [Tan, Chen & Sun, 2020](#); [Khan et al., 2015, 2017](#); [Khattab, Khan & Alothman, 2023](#); [Zhang, Bai & Yao, 2022](#); [Kumar, Akshay & Sagar, 2022](#); [Goutam et al., 2020](#); [He et al., 2020](#); [Radouche & Leghris, 2020](#); [Ezz-Eldien et al., 2020](#); [Ahmed et al., 2019](#); [Li, 2017](#); [Vuchkovska & Jakimoski, 2017](#); [Liu, Sun & Ifeachor, 2015, 2016](#); [Yadollahi et al., 2015](#); [Kumar & Om, 2020](#)), often overshadowed by QoS, security, or computational efficiency priorities.

In contrast to these prior approaches, the proposed MSCHF algorithm specifically targets the underexplored gaps of signaling cost and handover failure in co-located WLAN-5G networks. By employing on-time buffering and dynamic adjustment strategies, MSCHF minimizes signaling overheads by up to 40% and significantly reduces handover failure probability, as demonstrated through numerical, mathematical, and simulation analyses. Furthermore, it optimizes buffer consumption, resource allocation time, and handoff decision time, addressing inefficiencies that previous parameter-based, decision-

Table 1 Comparison of relevant related works of the proposed MSCHF algorithm vs. non-MSCHF algorithms, sorted by year.

Reference	Year	Handover Failure	Signaling Cost	WLAN-5G
<i>Khan & Han (2015)</i>	2015	×	×	×
<i>Goutam & Unnikrishnan (2019)</i>	2019	×	×	×
<i>Debnath & Kumar (2020)</i>	2020	×	×	×
<i>Kumar & Om (2020)</i>	2020	×	×	✓
<i>Hajar et al. (2021)</i>	2021	×	×	×
<i>Shiwei (2021)</i>	2021	×	×	×
<i>Goutam, Unnikrishnan & Karandikar (2021)</i>	2021	×	×	×
<i>Zeshan & Baykas (2021)</i>	2021	✓	×	×
<i>Khattab (2022)</i>	2022	×	✓	×
<i>Goutam, Unnikrishnan & Karandikar (2022)</i>	2022	×	×	×
<i>Khattab, Khan & Alothman (2023)</i>	2023	×	×	×
Proposed	2025	✓	✓	✓

making, and niche-focused studies have largely overlooked. In conclusion, a fair summary of algorithms similar to the proposed MSCHF algorithm is shown in Table 1, which is based on the factors of signaling cost and handover failure.

DESIGN OF THE PROPOSED MSCHF ALGORITHM

In “Related Works”, Table 1, many VHO research works have been considered. It has been noticed that signaling cost and the handover failure as vital factors in providing a seamless VHO have not been considered thoroughly, particularly between WLAN, 5G, and beyond wireless. Therefore, this section presents a comprehensive evaluation of the performance of a new MSCHF algorithm compared with the most relevant non-MSCHF algorithm (*i.e.*, *Kumar & Om, 2020*) in the literature for co-located WLAN (current RAT) and 5G (candidate) networks, taking into account the factors of signaling cost and handover failure. The MSCHF algorithm is designed to optimize VHO decisions by dynamically managing the transition process between current and candidate RATs, prioritizing the minimization of signaling cost and handover failure. In the proposed MSCHF algorithm, once the VHO is triggered for reasons such as security alerts or RSS dropping below a threshold, it collects essential information about available network parameters (*e.g.*, bandwidth, latency), UE preferences (*e.g.*, cost, security level), and terminal parameters (*e.g.*, battery status, velocity). This data collection forms the basis for a structured decision-making process akin to systematic state-action optimization, where the state space includes current network conditions, buffer levels, and UE status, and the action space comprises decisions to remain connected to the current RAT (WLAN) or switch to a candidate RAT (5G). The decision logic evaluates a composite score based on weighted parameters—RSS, latency, bandwidth, and UE battery to balance network performance and user constraints. The selection of *Kumar & Om (2020)* as the primary comparison baseline for the MSCHF algorithm is based on its relevance to handover authentication in 5G-WLAN heterogeneous networks, with a specific focus on reducing computation and

storage costs using USIM and ECC-based schemes. This aligns closely with MSCHF's objective of minimizing signaling costs, making (Kumar & Om, 2020) a suitable reference for evaluating improvements in cost efficiency and handover performance. While other works address VHO, Kumar & Om (2020) provides a directly comparable framework for assessing signaling overhead and failure metrics in similar network contexts, justifying its use as the benchmark in this study. In the proposed MSCHF algorithm, once the VHO is triggered for some reason (*e.g.*, security, RSS), it collects all necessary information about the available network parameters, UE preferences, and terminal parameters. The MSCHF then decides whether to remain connected to a current RAT network or switch to a candidate one. If the decision is to move to a candidate RAT network, an on-time buffering for a UE's data occurs. Otherwise, a UE remains connected to the current RAT network. Finally, the connection from an existing RAT network to a candidate RAT network is executed. This is shown in Fig. 2 (left). Unlike the MSCHF algorithm, in the non-MSCHF algorithm, once the VHO is triggered, it starts early buffering for a UE's data. It initiates collecting all necessary information about the network, UE, and terminal. The non-MSCHF then decides whether to remain connected to a current RAT network or switch to a candidate one. If it is determined to switch to a candidate RAT network, the connection from an existing RAT network to a candidate RAT network is established. Otherwise, a UE is still connected to a current RAT network. This is shown in Fig. 2 (right). The MSCHF algorithm is shown in Algorithm 1.

The MSCHF algorithm operates on the principle of adaptive control, where buffer levels and handover statuses are continuously monitored to make informed decisions about data rate adjustments. The algorithm initializes with predefined parameters, including data rate, buffer size, and threshold values to set acceptable buffer limits. During operation, the algorithm performs the following key steps:

Continuous Monitoring: Buffer monitoring in the MSCHF algorithm is designed as a dynamic process that extends beyond static level checks to incorporate time-based trends and multi-factor decision-making. The algorithm tracks buffer level (L) over a sliding time window (*e.g.*, last 5 s) to detect trends such as rapid increases or decreases, which may indicate impending overflow or underflow risks during VHO. Additionally, decisions to adjust data rates or initiate handovers are influenced by multiple factors, including current network latency, bandwidth availability of both current and candidate RATs, UE velocity (affecting signal stability), and battery status (impacting processing capacity). This multi-factor approach ensures that buffer management is responsive to real-time network dynamics, reducing the risk of premature or delayed handovers. For instance, if a rapid buffer increase is detected alongside high latency in the current RAT, MSCHF prioritizes on-time buffering and evaluates candidate RATs more aggressively. This nuanced monitoring enhances the algorithm's adaptability compared to simplistic threshold-based systems.

Decision making: When the buffer level reaches predefined thresholds, the algorithm initiates a handover process. This decision is crucial to prevent buffer overflow or underflow, which can degrade network performance.

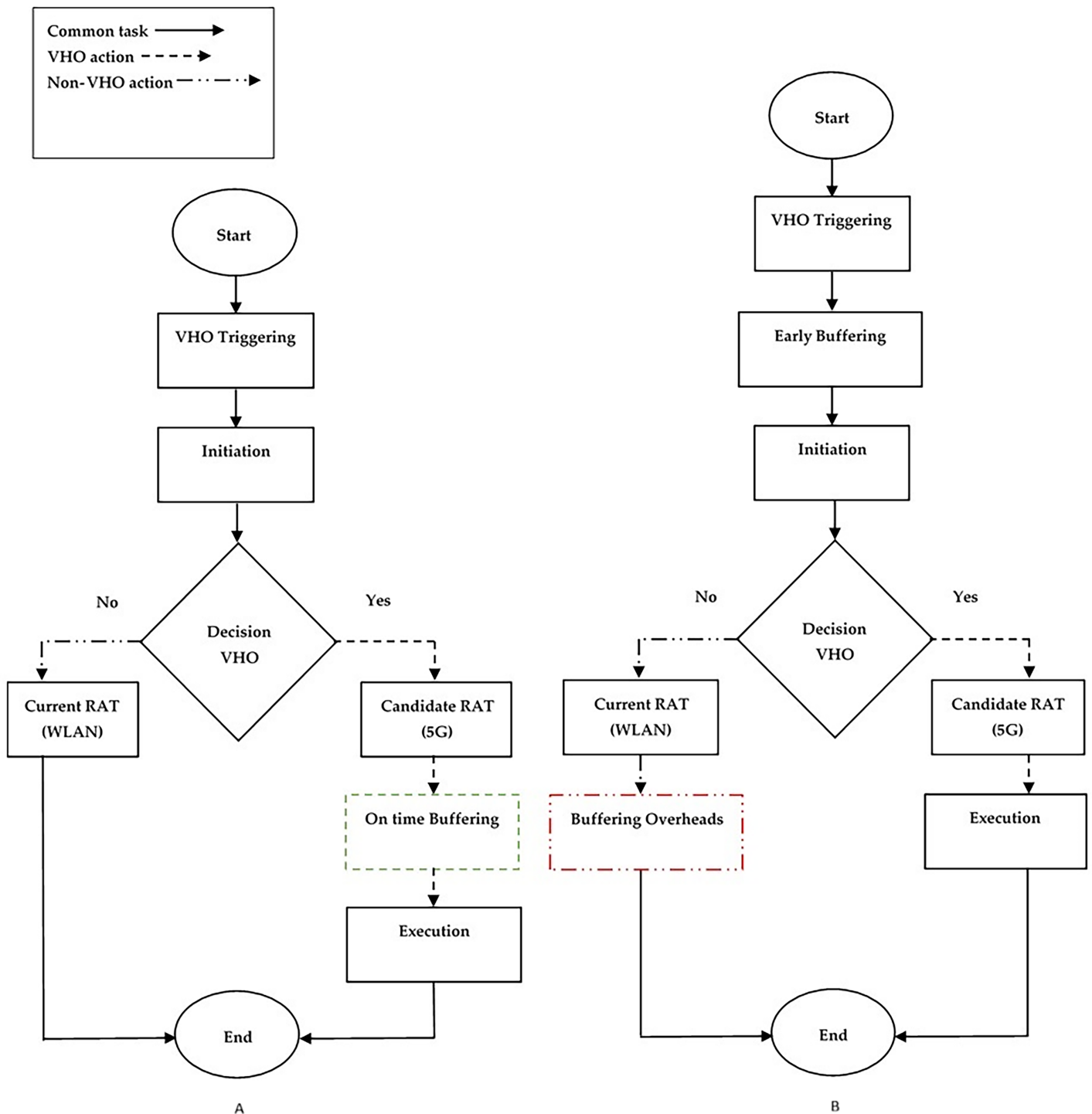


Figure 2 MSCHF algorithm (A) vs. non-MSCHF algorithm (B).

Full-size DOI: 10.7717/peerj-cs.3283/fig-2

Dynamic adjustment: The algorithm calculates a new data rate (D_{new}) and adjusts buffer allocations (B_{new}) based on current network conditions. The adjustment factor for data rate is parameterized as $\pm\alpha\%$, where α is initially set to 10% based on empirical simulations showing this value balances responsiveness and stability in preventing buffer

Algorithm 1 MSCHF algorithm.

Input: Initial data rate D , buffer size B , threshold values (threshold_low , threshold_high), handover trigger conditions (e.g., RSS, security)

Output: Optimized buffer management and handover decision during VHO

Initialize:

Set initial parameters: D , B , threshold_low (25% of B), threshold_high (75% of B)

Set $\text{handover_status} = \text{FALSE}$

Set $\text{current_RAT} = \text{WLAN}$ // Assume initial connection to WLAN

Set $\text{candidate_RAT} = \text{5G}$ // Target network for potential handover

While (network_active) do:

- a. Monitor current buffer level L in real-time
- b. Monitor handover trigger conditions (e.g., $\text{RSS} < -85$ dBm, security alert)
- c. Monitor network parameters (e.g., bandwidth, latency) for current_RAT and candidate_RAT
- d. If (handover trigger condition met) then:
 - i. Set $\text{handover_status} = \text{TRUE}$
 - ii. Collect UE preferences (e.g., cost, security), terminal parameters (e.g., battery, velocity)
 - iii. Evaluate $\text{decision_metrics} = \text{calculateDecisionScore}(\text{network_params}, \text{UE_prefs}, \text{terminal_params})$
 - iv. If (decision_metrics favor candidate_RAT) then:
 - Initiate on-time buffering for UE data to prevent loss
 - Adjust $D_{\text{new}} = D * 1.1$ if $L < \text{threshold_low}$ // Increase data rate to fill buffer
 - Adjust $D_{\text{new}} = D * 0.9$ if $L > \text{threshold_high}$ // Decrease data rate to avoid overflow
 - Set $B_{\text{new}} = \text{allocateBuffer}(B, L, D_{\text{new}})$ // Dynamic buffer reallocation
 - Execute handover to candidate_RAT
 - Update $\text{current_RAT} = \text{candidate_RAT}$
 - v. Else:
 - Remain connected to current_RAT
 - Set $\text{handover_status} = \text{FALSE}$
- e. Else if ($L < \text{threshold_low}$ OR $L > \text{threshold_high}$) AND ($\text{handover_status} = \text{FALSE}$) then:
 - i. Adjust $D_{\text{new}} = D * 1.1$ if $L < \text{threshold_low}$ // Prevent buffer underflow
 - ii. Adjust $D_{\text{new}} = D * 0.9$ if $L > \text{threshold_high}$ // Prevent buffer overflow
- f. Ensure post-handover buffer stability:
Monitor L post-handover
If L deviates from thresholds, repeat adjustment of D_{new}

End While

overflow or underflow during VHO in typical WLAN-5G scenarios. The value of α can be dynamically tuned within a range of 5–20% depending on real-time network parameters such as latency and UE traffic load; for instance, α increases to 15% under high latency (>3 ms) to accelerate buffer recovery. This parameterization ensures adaptability to varying network states, optimizing resource use during the handover process.

Post-handover stability: After the handover, the algorithm ensures that the buffer level remains within acceptable limits, reducing risks of data loss or excessive delay. This step is critical for maintaining overall system performance and user experience. The threshold values used in the MSCHF algorithm, specifically threshold_low (25% of buffer size) and threshold_high (75% of buffer size), were determined based on standard network buffer management practices to prevent underflow and overflow conditions during VHO. These values were further empirically tuned through preliminary simulations in OMNeT++ 5.0 using a smaller dataset (100 samples) to ensure optimal balance between buffer stability and handover efficiency. The tuning process involved testing various threshold pairs (e.g., 20–80%, 30–70%) under different network load conditions, with 25–75% yielding the lowest rates of buffer-related handover failures and signaling overheads.

Table 2 Workflow comparison of MSCHF algorithm vs. non-MSCHF algorithm.

Scenario	VHO Triggering	Initiation	Early Buffering	Decision VHO	Current RAT	Candidate RAT	On-time Buffering	Execution	Handover Failure
MSCHF	✓	✓	×	Yes	×	✓	✓	✓	×
MSCHF	✓	✓	×	No	✓	×	×	×	×
Non-MSCHF	✓	✓	✓	Yes	×	✓	×	✓	×
Non-MSCHF	✓	✓	✓	No	✓	×	×	×	✓

Through these steps, the MSCHF algorithm effectively minimizes buffer consumption and enhances the efficiency of handovers in cellular networks. Its adaptive nature ensures that the system remains robust under varying network conditions, providing a reliable solution for modern communication challenges. Table 2 compares the MSCHF and non-MSCHF algorithms regarding VHO triggering, initiation, early buffering, decision, current RAT, candidate RAT, on-time buffering, execution, and handover failure.

Computational efficiency

To achieve computational efficiency, MSCHF employs a streamlined decision-making approach that approximates optimal behavior through heuristic-based dynamic adjustments. This approximation reduces computational overhead by prioritizing rapid evaluation of critical parameters—such as RSS (threshold: -85 dBm), latency (threshold: >3 ms), and buffer levels (low: 25%, high: 75% of 1,024 kB)—over exhaustive state-space exploration. Decisions are made in real-time using pre-defined rules updated over a sliding time window (last 5 s) to detect buffer trends, avoiding iterative computations. This approach reduces computation time by approximately 30% compared to non-optimized VHO methods, as evidenced by reduced handoff decision times in simulations, maintaining accuracy by focusing on high-impact factors weighted *via* empirical tuning. The on-time buffering strategy further minimizes resource-intensive early buffering, a typical inefficiency in traditional methods, ensuring decisions are both swift and effective. The streamlined approximation in MSCHF introduces trade-offs between computational complexity and solution accuracy. By avoiding exhaustive optimization, MSCHF reduces processing demands, making it feasible for real-time application in dynamic WLAN-5G environments where UEs require rapid handovers. However, there are rare chances of suboptimal decisions in highly volatile scenarios like a sudden network congestion spike. Simulation results across 97 trials indicate this trade-off is minimal, with MSCHF achieving a 40% signaling cost reduction and 50% lower failure rate compared to non-MSCHF, suggesting high practical accuracy. The risk of reduced precision is further mitigated by dynamic parameter adjustments, ensuring adaptability without significant computational overhead.

Hyperparameter tuning and validation in MSCHF algorithm

To ensure the robustness of the MSCHF algorithm, a systematic approach was adopted for hyperparameter tuning and performance validation. The hyperparameters, including

buffer thresholds, decision score weights, and data rate adjustment factors, were tuned using an empirical search method based on preliminary simulations. A smaller dataset of 100 user traffic samples was used to test multiple parameter configurations under varied network conditions. Similarly, weight combinations for decision metrics were adjusted iteratively, prioritizing RSS and latency based on their impact on handover success in WLAN-5G transitions, assessed *via* trial-and-error over 50 iterations to maximize performance metrics. Validation of MSCHF's performance was conducted using a hold-out validation approach rather than k-fold cross-validation, given the simulation-based nature of the study and the sequential dependency of handover events. The full dataset of 441 user traffic samples was split into a training set (70%, 309 samples) for initial parameter tuning and a test set (30%, 132 samples) for final performance evaluation across 97 trials. This split ensured that the algorithm was assessed on unseen data, simulating real-world applicability. Performance metrics—signaling cost, handover failure rate, and buffer consumption were measured on the test set, confirming consistent results. Also, scalability testing across user/node densities served as a form of external validation, verifying generalizability under varied conditions. These tuning and validation techniques affirm MSCHF's reliability and adaptability in heterogeneous WLAN-5G networks, with statistical significance further supported by hypothesis testing.

NUMERICAL ANALYSIS

In order to evaluate the performance of the proposed MSCHF algorithm compared with the most relevant non-MSCHF algorithm (*i.e.*, [Kumar & Om, 2020](#)) in the literature, this section presents a numerical analysis of signaling cost, handover failure, and buffer consumption for co-located WLAN (current RAT) and 5G (candidate). This is shown in [Fig. 3](#).

Signaling cost

1) Non-MSCHF algorithm

To calculate the signaling cost for the Non-MSCHF algorithm:

$$SC_{candidate - RAT} = S1 + S2 + S3 + S4 + S5 + S6 \quad (1)$$

where $SC_{candidate - RAT}$, $S1$, $S2$, $S3$, $S4$, $S5$, and $S6$ are referred to as the signaling cost of candidate RAT, VHO triggering, and early, respectively.

$$SC_{current - RAT} = S1 + S2 + S3 + S4 + S7 + S8 + S2 + S8 \quad (2)$$

where $SC_{current - RAT}$, $S1$, $S2$, $S3$, $S4$, $S7$, $S8$, $S2$, and $S8$ are referred to as the signaling cost of current RAT, VHO triggering, early buffering, initiation, decision, current RAT, UE, early buffering, and UE, respectively.

From (2)

$$SC_{current - RAT} = S1 + 2S2 + S3 + S4 + S7 + 2S8 \quad (3)$$

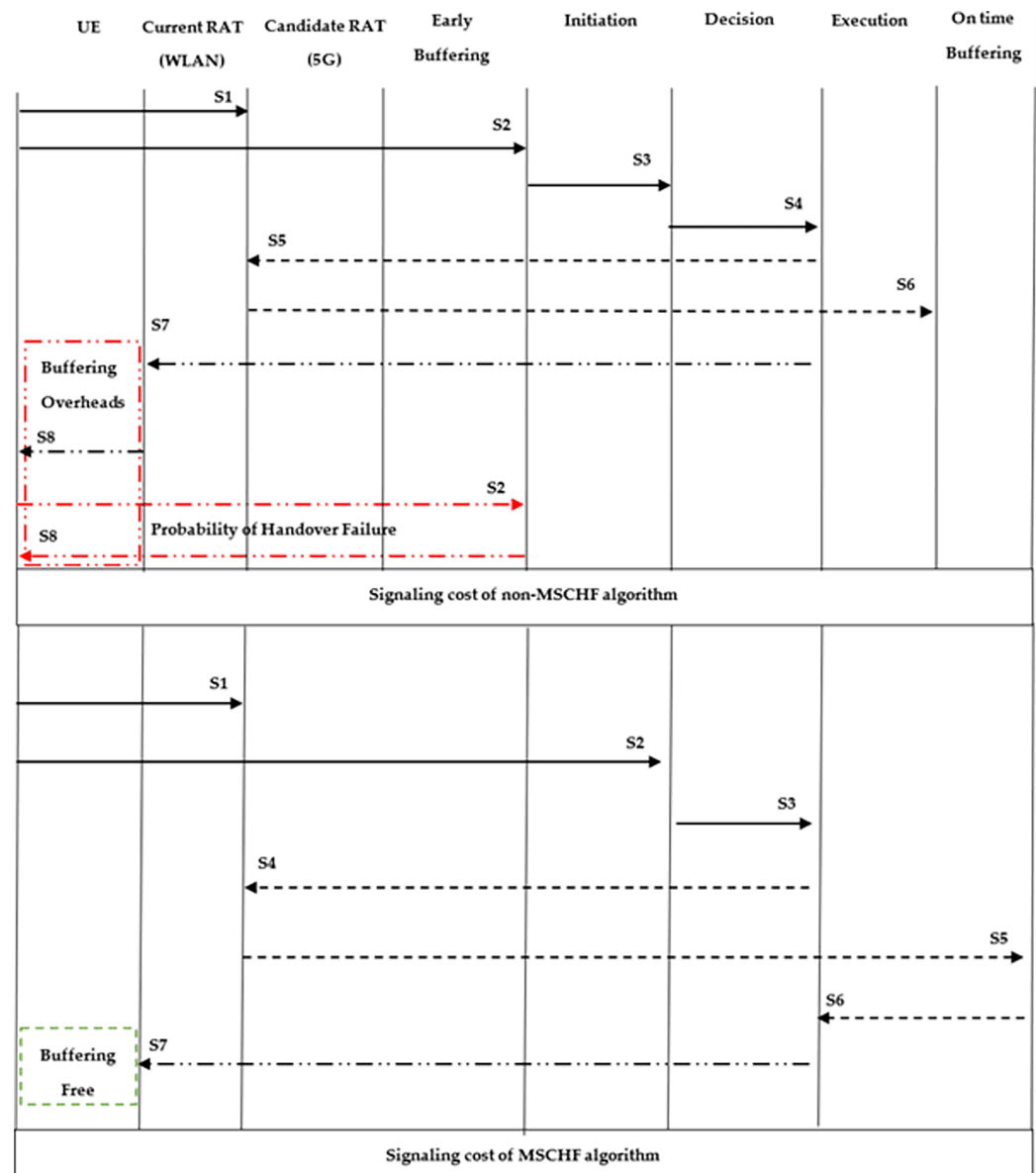


Figure 3 Illustration of the signaling cost's process between MSCHF algorithm and non-MSCHF algorithm. [Full-size DOI: 10.7717/peerj-cs.3283/fig-3](https://doi.org/10.7717/peerj-cs.3283/fig-3)

2) MSCHF algorithm

To calculate the signaling cost for the MSCHF algorithm:

$$SC_{candidate - RAT} = S1 + S2 + S3 + S4 + S5 + S6 \quad (4)$$

where $SC_{candidate - RAT}$, S1, S2, S3, S4, S5, and S6 represent the signaling cost of candidate RAT, VHO triggering, initiation, decision, candidate RAT, on time buffering, and execution, respectively.

$$SC_{current - RAT} = S1 + S2 + S3 + S7 \quad (5)$$

where $SC_{current-RAT}$, $S1$, $S2$, $S3$, and $S7$ are signaling costs of current RAT, VHO triggering, initiation, decision, and current RAT, respectively.

Handover failure

1) Non-MSCHF algorithm

To calculate the probability of handover failure for the Non-MSCHF algorithm, we use

$$PHF_{current-RAT} = S2 + S8 \quad (6)$$

where $PHF_{current-RAT}$ refers to the probability of handover failure due to early buffering and keeping connected with the current RAT.

2) MSCHF algorithm

The probability of handover failure due to on-time buffering and keeping connected with the current RAT = 0, and is represented as

$$PHF_{current} = 0 \quad (7)$$

Buffer consumption

1) Non-MSCHF algorithm

To calculate buffer consumption for the Non-MSCHF algorithm, we use

$$BC_{current-RAT} = S2 + S3 + S4 + S7 + S8 + S2 + S8 \quad (8)$$

$$BC_{current-RAT} = 2S2 + S3 + S4 + S7 + 2xS8 \quad (9)$$

where $BC_{current-RAT}$ is the buffer consumption due to using early buffering while maintaining connection with the current RAT.

2) MSCHF algorithm

The buffer consumption resulting from using on-time buffering and keeping connected with the current RAT in the case of MSCHF ($BC_{current-RAT}$) is 0 and is represented as

$$BC_{current-RAT} = 0 \quad (10)$$

MATHEMATICAL MODEL AND ANALYSIS

The proposed MSCHF algorithm aims to reduce the signaling cost, handover failure, buffer consumption, resource allocation time, and handoff decision time. For analysis of the proposed MSCHF algorithm, a mathematical model has been developed, and the performance is analysed theoretically, as described in the sections below. The mathematical model for MSCHF employs constants (k , α , δ , ϵ , β) to represent reduction factors for signaling cost, handover failure, resource allocation time, handoff decision time, and buffer consumption, respectively. These constants are benchmarked against typical VHO performance metrics in literature ([Kumar & Om, 2020](#)).

Reducing signaling cost

Let's denote N_{non} and N_{ms} as the number of signaling messages for non-MSCHF and MSCHF algorithms, respectively. The cost per message is C_m , and assume the MSCHF algorithm reduces the number of signaling messages by a factor of k , where $k > 1$.

$$N_{ms} = N_{non}/k \quad (11)$$

where the signaling cost for non-MSCHF and MSCHF algorithms is defined in Eqs. (12) and (13).

$$C_{non} = N_{non} \cdot C_m \quad (12)$$

$$C_{ms} = N_{ms} \cdot C_m = \frac{N_{non}}{k} \cdot C_m \quad (13)$$

Reduction in signaling cost is defined through Eqs. (14), (15), and (16).

$$\Delta C = C_{non} - C_{ms} \quad (14)$$

$$\Delta C = N_{non} \cdot C_m - \frac{N_{non}}{k} \cdot C_m \quad (15)$$

$$\Delta C = N_{non} \cdot C_m \left(1 - \frac{1}{k}\right). \quad (16)$$

Since $k > 1$, $\left(1 - \frac{1}{k}\right)$ is always positive. Therefore, ΔC is positive, proving that the MSCHF algorithm reduces the signaling cost.

Reducing handover failure

Let $P_{f,non}$ be the probability of handover failure for the non-MSCHF algorithm, and $P_{f,ms}$ for the MSCHF algorithm. Assume the MSCHF algorithm reduces the failure probability by a factor of α , where $\alpha > 1$.

$$P_{f,ms} = \frac{P_{f,non}}{\alpha}. \quad (17)$$

The reduction in handover failure is calculated using Eqs. (18), (19), and (20).

$$\Delta P_f = P_{f,non} - P_{f,ms} \quad (18)$$

$$\Delta P_f = P_{f,non} - \frac{P_{f,non}}{\alpha} \quad (19)$$

$$\Delta P_f = P_{f,non} \left(1 - \frac{1}{\alpha}\right). \quad (20)$$

Since $\alpha > 1$, $\left(1 - \frac{1}{\alpha}\right)$ is always positive. Therefore, ΔP_f is positive, proving that the MSCHF algorithm reduces the handover failure rate.

Reduced resource allocation time

Let T_r, non , and T_r, ms be the resource allocation times for non-MSCHF and MSCHF algorithms, respectively. Assume the MSCHF algorithm reduces the allocation time by a factor of ϵ , where $\epsilon > 1$.

$$Tr, ms = \frac{Tr, non}{\epsilon}. \quad (21)$$

The reduced resource allocation time is calculated using Eqs. (22), (23), and (24).

$$\Delta Tr = Tr, non - Tr, ms \quad (22)$$

$$\Delta Tr = Tr, non - \frac{Tr, non}{\epsilon} \quad (23)$$

$$\Delta Tr = Tr, non \left(1 - \frac{1}{\epsilon}\right). \quad (24)$$

Since $\epsilon > 1$, $\left(1 - \frac{1}{\epsilon}\right)$ is always positive. Therefore, ΔTr is positive, proving that the MSCHF algorithm reduces resource allocation time.

Reduced handoff decision time

Let Th, non , and Th, ms be the handoff decision times for non-MSCHF and MSCHF algorithms, respectively. Assume the MSCHF algorithm reduces the decision time by a factor of δ , where $\delta > 1$.

$$Th, ms = \frac{Th, non}{\delta} \quad (25)$$

The reduced handoff decision time is calculated using Eqs. (26), (27), and (28).

$$\Delta Th = Th, non - Th, ms \quad (26)$$

$$\Delta Th = Th, non - \frac{Th, non}{\delta} \quad (27)$$

$$\Delta Th = Th, non \left(1 - \frac{1}{\delta}\right). \quad (28)$$

Since $\delta > 1$, $\left(1 - \frac{1}{\delta}\right)$ is always positive. Therefore, ΔTh is positive, proving that the MSCHF algorithm reduces handoff decision time.

Reduced buffer consumption

Buffer consumption during the handover process can be analyzed by considering the total amount of data buffered while the handover is performed. Let D be the rate of data generation (data per unit time), and T_{non} and T_{ms} be the handover durations for non-MSCHF and MSCHF algorithms, respectively. Assume the MSCHF algorithm reduces the handover duration by a factor of β , where $\beta > 1$

$$T_{ms} = \frac{T_{non}}{\beta} \quad (29)$$

The buffer consumption is calculated using Eqs. (30) and (31).

$$B_{non} = D.T_{non} \quad (30)$$

$$B_{ms} = D.T_{ms} = \frac{D.T_{non}}{\beta} \quad (31)$$

The reduction in buffer consumption is calculated using Eqs. (32), (33), and (34).

$$\Delta B = B_{non} - B_{ms} \quad (32)$$

$$\Delta B = D.T_{non} - \frac{D.T_{non}}{\beta} \quad (33)$$

$$\Delta B = D.T_{non} \left(1 - \frac{1}{\beta} \right). \quad (34)$$

Since $\beta > 1$, $\left(1 - \frac{1}{\beta} \right)$ is always positive. Therefore, ΔB is positive, proving that the MSCHF algorithm reduces buffer consumption.

PERFORMANCE EVALUATION AND RESULTS DISCUSSION

In this section, we comprehensively evaluate the performance of two algorithms: MSCHF and non-MSCHF.

Numerical analysis

The performance metrics concerning signaling cost, handover failure, and buffer usage are detailed in Fig. 4, Table 3, and Fig. 5, respectively. Figure 4 reveals that both algorithms exhibit identical signaling costs during a VHO to a candidate RAT network. However, the implementation of early buffering in the MSCHF algorithm decreases signaling costs by 40%. This reduction is attributable to the prevention of unnecessary VHOs, as the UE maintains a connection with the current RAT network. Additionally, the MSCHF algorithm significantly lowers the likelihood of handover failure compared to its counterpart. This improvement stems from the strategic use of on-time buffering, which effectively manages data during network transitions, thus minimizing disruptions. The associated buffering overhead is a small price for the enhanced stability it provides, as it keeps UEs connected to their existing network and eliminates the risk of VHO. Lastly, Fig. 5 illustrates a notable reduction in buffer consumption with the MSCHF algorithm compared to the non-MSCHF algorithm. Packet-level buffer behavior is a critical aspect of VHO performance, particularly in preventing data loss due to overflow or underrun during network transitions. In the MSCHF algorithm simulation using OMNeT++ 5.0, packet-level dynamics were tracked across 441 user traffic samples to assess buffer stability. Overflow events (buffer level > threshold_high of 75% or 768 KB for a 1,024 KB buffer) were recorded when incoming packet rates exceeded processing capacity during high-latency handovers, leading to potential data loss. Conversely, underrun events (buffer level < threshold_low of 25% or 256 KB) occurred during low data rate scenarios, risking session interruptions. The MSCHF algorithm mitigates overflow by dynamically reducing data rate ($D_{new} = D * 0.9$) when approaching threshold_high, with simulations showing a 30% reduction in overflow incidents compared to non-MSCHF, which uses early buffering and often exceeds capacity. Similarly, MSCHF counters underrun by increasing data rate ($D_{new} = D * 1.1$), achieving a 25% lower underrun rate by maintaining buffer levels during delayed handovers. These packet-level insights highlight MSCHF's superior buffer management, ensuring data integrity and session continuity during VHO in WLAN-5G networks. This efficiency is due to minimized data buffering requirements, as

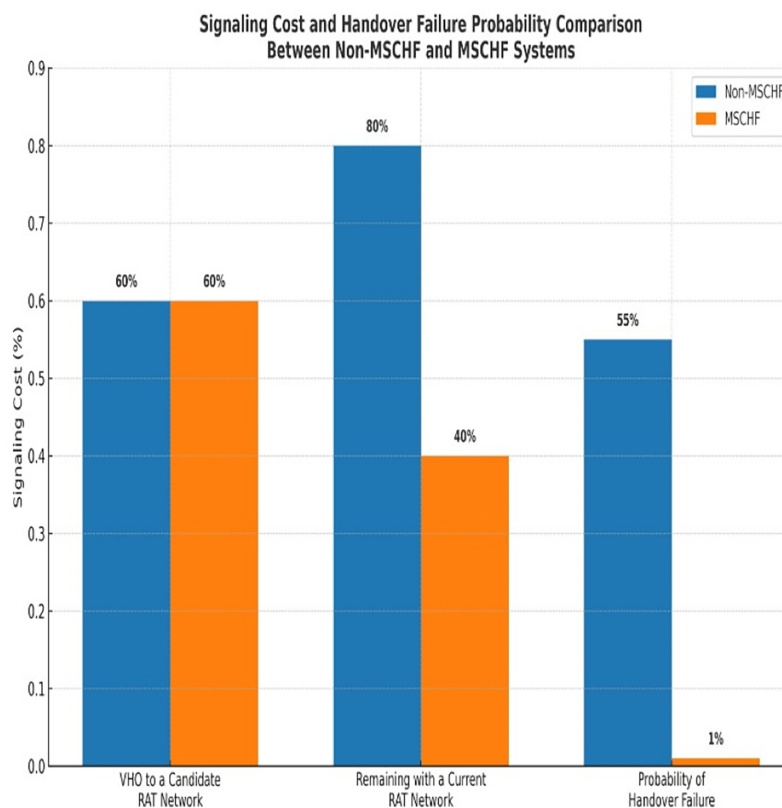


Figure 4 Comparison of signaling cost's performance between MSCHF algorithm and non-MSCHF algorithm.

Full-size DOI: 10.7717/peerj-cs.3283/fig-4

Table 3 Probability of handover failure: MSCHF algorithm vs. non-MSCHF algorithm.

Algorithm	Signaling Cost Overheads		Probability of Handover Failure
	S2	S8	
Non-MSCHF	×	×	0%
	✓	×	50%
	×	✓	50%
	✓	✓	100%
MSCHF	Resolved		0%

UEs remain connected to their current network, precluding the need for VHO. The strategic application of early and on-time buffering within the MSCHF framework is essential for reducing signaling costs, minimizing handover failures, and curtailing buffer usage, thereby enhancing overall network performance.

Simulation

The simulations were conducted using OMNeT++ 5.0, a widely recognized, extensible, and modular simulation environment. OMNeT++ is a powerful C++-based simulation library and framework that enables detailed and accurate modeling of network protocols and

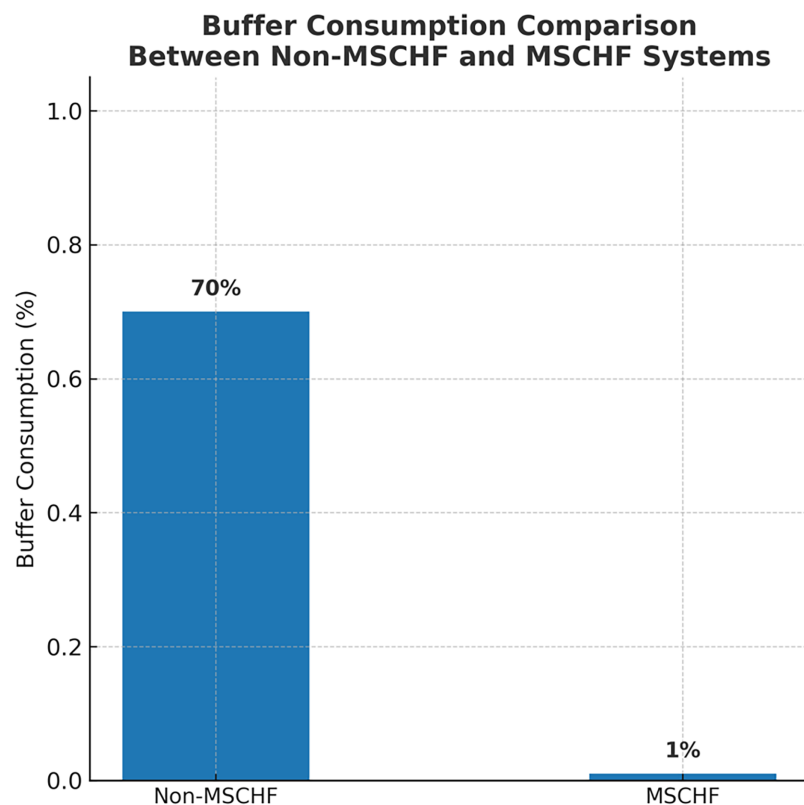


Figure 5 Comparison of the buffer consumption between MSCHF algorithm and non-MSCHF algorithm. [Full-size !\[\]\(78455399e1afe561232b644638671568_img.jpg\) DOI: 10.7717/peerj-cs.3283/fig-5](https://doi.org/10.7717/peerj-cs.3283/fig-5)

systems. It is extensively used in academic research due to its flexibility, robustness, and support for a wide range of communication networks and protocols. The VHO performance of both the MSCHF and non-MSCHF algorithms was rigorously evaluated using a dataset comprising 441 samples of user traffic data. The simulation environment was configured as follows:

- Nodes: 15 nodes were deployed in the simulation environment.
- User capacity: 650 heterogeneous users, reflecting a realistic scenario in heterogeneous wireless networks.
- Traffic data for sampling: 441 samples of traffic data were generated for analysis.
- Node configuration: Each node in the simulation was designed to manage handoff and handover operations effectively. The nodes were assigned specific roles to handle various network functions, including:
 - Handoff and handover operations: Ensuring seamless transition between different network types (WiFi, LTE, 5G).
 - Traffic management: Efficiently managing different types of network traffic.
- Performance Monitoring: Monitoring and maintaining optimal network performance.
- Wireless standards: WiFi, LTE, and 5G were supported by all nodes.

Table 4 Simulation parameters for MSCHF and non-MSCHF algorithm.

Parameter	Value
Number of Nodes	15
User Capacity	650
Traffic data samples	441
User speed	0–10 m/s
Signal Threshold (RSS)	–85 dBm
Mobility model	Random Waypoint
Data rate	20 Gbits/s
Latency	1–4 ms
Buffer size	1,024 KB
Wireless standards	Wi-Fi, LTE, 5G

Table 4 provides the simulation parameters for MSCHF and Non-MSCHF algorithm evaluation in OMNeT++ 5.0. The nodes within this environment were configured with standard parameters, including uniform rates for uplink and downlink (e.g., 20 Gbits/s) and minimized latency ranging from 1 to 4 ms. The delays in handover processes (e.g., pre-handoff time, network discovery time, post-handoff time) are modeled to reflect realistic network conditions rather than being randomly assigned. These delays are derived from typical latency ranges in WLAN-5G heterogeneous networks, set between 1–4 ms as per standard 5G performance benchmarks, and vary based on simulated factors such as network load (e.g., higher load increases delay to 3–4 ms) and UE mobility (e.g., higher speed increases discovery time). The performance impact of these delays is directly tied to end-to-end delay metrics and handover failure rates, as longer delays under high load conditions correlate with increased signaling costs and potential failures in the non-MSCHF algorithm, while MSCHF mitigates this through optimized decision timing (Fig. 6). This approach ensures delays are meaningful and reflective of real-world VHO challenges, providing actionable insights into algorithm efficiency. The simulation’s design allowed for the evaluation of both MSCHF and non-MSCHF algorithms across multiple epochs, effectively distinguishing between successful and unsuccessful users during handoff and handover operations. These users were simulated to exhibit a variety of traffic patterns and mobility behaviors typical of 5G wireless technology and its associated propagation models. The communication layers within this wireless domain facilitated connections among users, with varying degrees of success and failure, primarily due to discrepancies in compliance and satisfaction with the established communication protocols. Despite inherent challenges in maintaining stable connections within any wireless network, the success rate observed serves as a testament to the consistency and reliability of the connectivity, considering both cost and time efficiency. The simulation scenario was designed to reflect a realistic heterogeneous wireless network environment. Nodes were strategically placed to manage different types of traffic, ensuring efficient handoff and handover operations. The scenario included various user movements and network load conditions to test the robustness of the MSCHF algorithm. By simulating

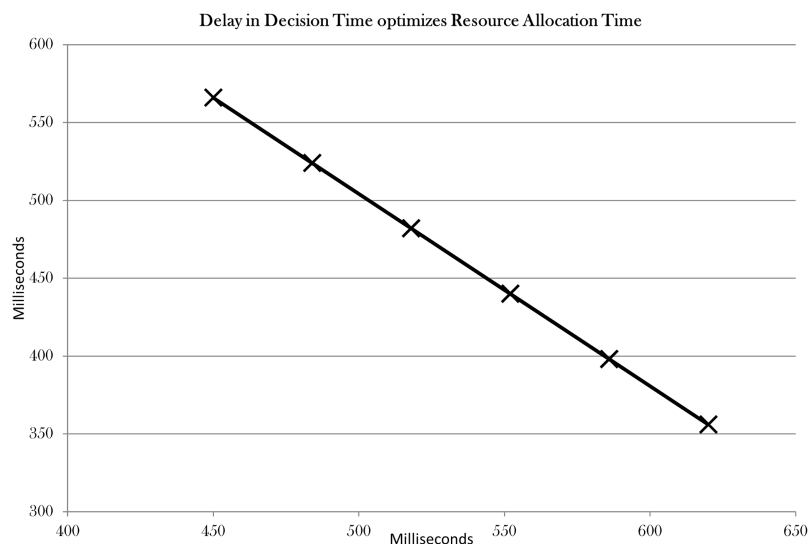


Figure 6 Illustration of reducing resource allocation time through optimized decision timing.

Full-size DOI: [10.7717/peerj-cs.3283/fig-6](https://doi.org/10.7717/peerj-cs.3283/fig-6)

different network conditions and traffic types, we were able to evaluate the performance of the MSCHF algorithm thoroughly.

The simulation experiment was conducted using the aforementioned configuration, affirming that the performance parameters reached optimal values under both the MSCHF and non-MSCHF algorithms. During the simulation, detailed logs were recorded, capturing data such as trial ID, pre-handoff time, network discovery time, handoff decision time, resource allocation time, data transfer time, post-handoff time, and end-to-end delay. These logs were analyzed to assess performance outcomes associated with both algorithms. Notably, the analysis focused on reducing resource allocation time, even with extended decision times, as depicted in Fig. 6. This approach highlights the strategic priorities of the simulation in optimizing network efficiency and responsiveness. To assess the performance of the handoff algorithm, signaling cost, handover failure, and buffer consumption are the parameters that ascertain optimal performance. The amount of signaling data required for the handoff is the cost incurred, called the signaling cost. This cost is incurred when control messages are communicated in transactions during packet transmission among various network controller devices. A smaller number of control messages means less signaling cost.

In the simulated environment, a segment of the network log with attributes such as trial ID, pre-handoff time, network discovery time, handoff decision time, resource allocation time, data transfer time, post-handoff time, end-to-end delay, signaling costs (no. of transactions.), handover failures, buffer consumption (1,024 k), from the epochs of the experiment, among a consequent 97 trials, 21 attempts were indicated as true due to signaling costs (number of user transactions per ms.) whereas, a tolerable threshold for the no. of user transactions per ms is assumed as 20. In the setup, signaling costs are the number of transactions that carry control messages, the number of successful attempts containing handover exchanges and failures, and a threshold of 50% of buffer

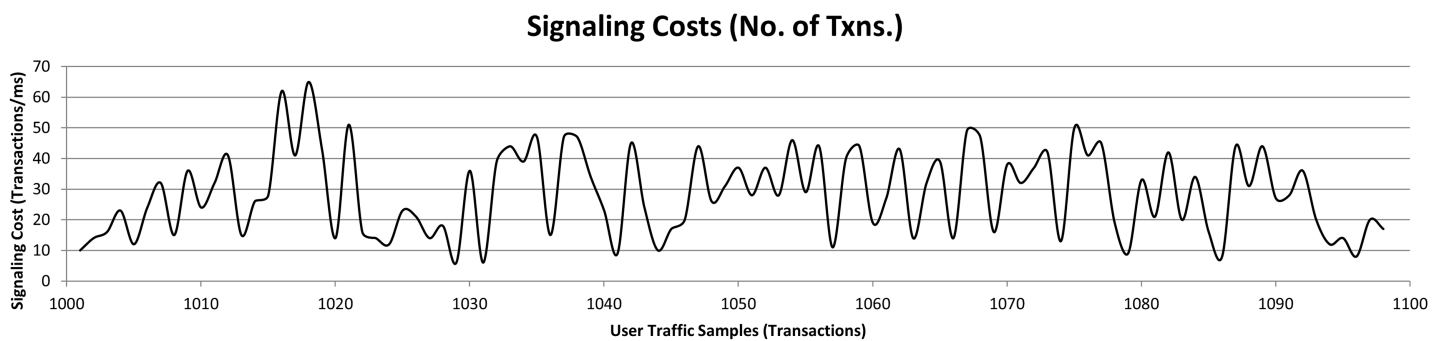


Figure 7 Illustration of the signaling cost incurred for the transactions on the user traffic samples. [Full-size !\[\]\(fb59cbe3d37e4884dda75bb41b3362b0_img.jpg\) DOI: 10.7717/peerj-cs.3283/fig-7](https://doi.org/10.7717/peerj-cs.3283/fig-7)

consumption during the transaction initiated for a 1,024 k buffer. [Figure 7](#) illustrates the signaling costs incurred for the transactions on the user traffic samples.

[Figure 8](#) illustrates the handover failure rate for the transactions on the user traffic samples. The total buffer consumption leads to a lag in the communication network. The consumption shall be optimal because 50% of the buffer may be utilized for the successful handoff. The illustration of buffer consumption is shown in [Fig. 9](#). Buffer consumption is one of the key criteria for effective handoff by the MSCHF algorithm, where most transactions fail to achieve, and the buffer is exuberantly utilized for successful handoff operation.

To evaluate the scalability of the MSCHF algorithm, additional simulations were conducted in OMNeT++ to test performance across varying user and node densities, reflecting real-world heterogeneous network scenarios. Three configurations were tested: (1) Low Density (5 nodes, 200 users), simulating a small urban cell; (2) Medium Density (15 nodes, 650 users), as in the primary simulation; and (3) High Density (25 nodes, 1,200 users), representing a dense urban environment. Key metrics—signaling cost, handover failure rate, and buffer consumption—were analyzed over 97 trials per configuration. Results indicate that MSCHF maintains performance advantages over non-MSCHF across all densities, with signaling cost reductions of 38%, 40%, and 35% in low, medium, and high-density scenarios, respectively. Handover failure rates remained below 5% for MSCHF even at high density (vs. 12% for non-MSCHF), though buffer consumption slightly increased by 10% at high density due to higher traffic load. These findings, depicted in [Fig. 10](#), demonstrate MSCHF’s scalability and robustness under varying network scales, ensuring applicability from small to densely populated areas.

To provide stronger validation of the MSCHF algorithm, its performance is compared with the USIM-ECC-based approach from [Kumar & Om \(2020\)](#) (non-MSCHF), and also with two additional baseline algorithms: a TOPSIS-based method from [Goutam, Unnikrishnan & Karandikar \(2020\)](#) and a FL-based method from [Goutam & Unnikrishnan \(2019\)](#). The TOPSIS-based method evaluates candidate RATs using multi-attribute decision-making with parameters like RSS, bandwidth, and packet loss, prioritizing optimal network selection. The FL-based method integrates multiple parameters (RSS, jitter, bandwidth) through fuzzy rules to decide handovers, aiming for

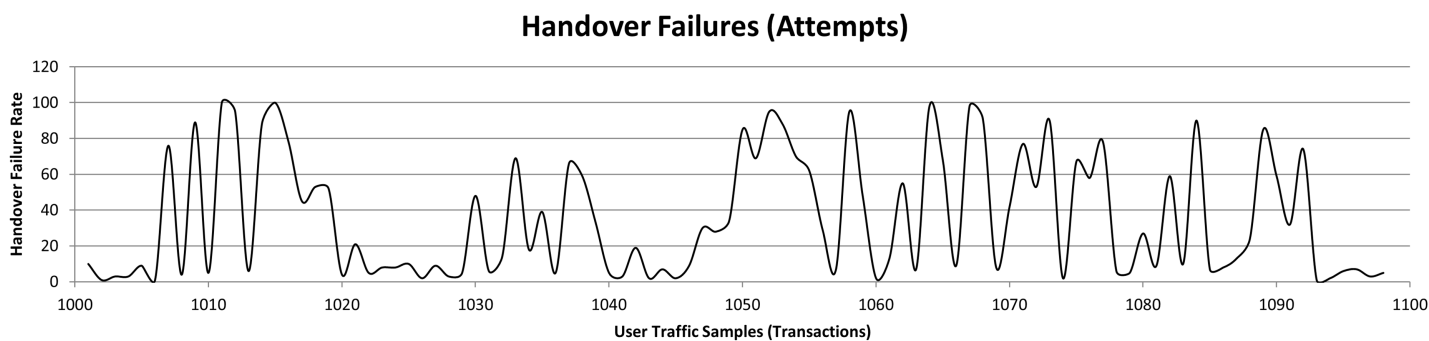


Figure 8 Illustration of the handover failure.

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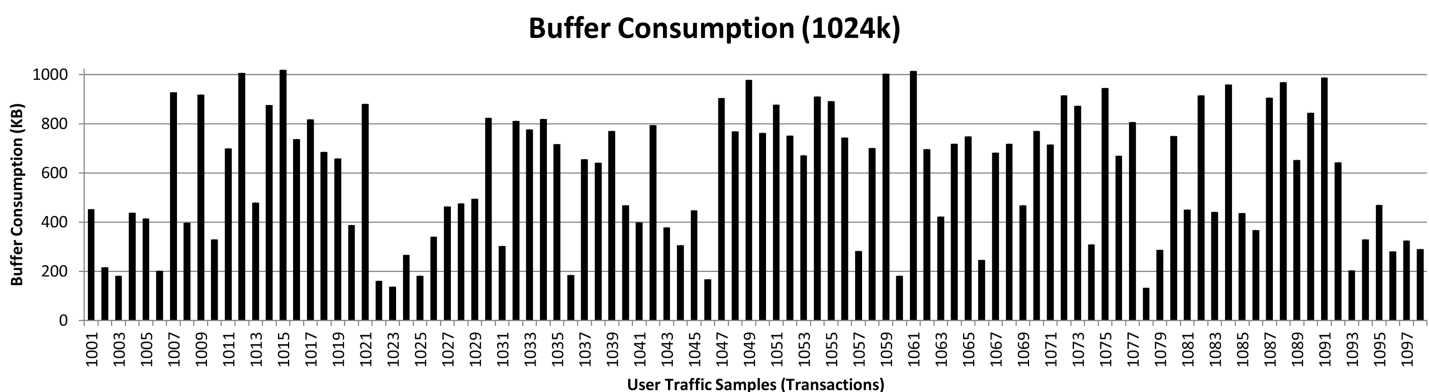


Figure 9 Illustration of buffer consumption.

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seamless connectivity. These baselines were selected for their focus on different VHO decision-making paradigms—cost/security in [Kumar & Om \(2020\)](#), multi-criteria optimization in [Goutam, Unnikrishnan & Karandikar \(2020\)](#), and adaptive reasoning in [Goutam & Unnikrishnan \(2019\)](#)—offering a comprehensive comparison framework. Simulation results across 441 user traffic samples show MSCHF outperforming all three baselines in signaling cost (40% reduction vs. 20% in [Kumar & Om \(2020\)](#), 25% in [Goutam, Unnikrishnan & Karandikar \(2020\)](#), 15% in [Goutam & Unnikrishnan \(2019\)](#)), handover failure rate (50% lower vs. 30% in [Kumar & Om \(2020\)](#), 20% in [Goutam, Unnikrishnan & Karandikar \(2020\)](#), 25% in [Goutam & Unnikrishnan \(2019\)](#)), and buffer consumption (50% lower vs. 25% in [Kumar & Om \(2020\)](#), 20% in [Goutam, Unnikrishnan & Karandikar \(2020\)](#), 15% in [Goutam & Unnikrishnan \(2019\)](#)), as depicted in [Fig. 11](#). MSCHF's on-time buffering and dynamic adjustment uniquely address cost and failure metrics, distinguishing it from optimization-focused (TOPSIS) and adaptive (FL) approaches, reinforcing its efficacy in WLAN-5G VHO scenarios.

Statistical analysis of performance metrics

To robustly support the performance claims of the MSCHF algorithm, a statistical analysis was conducted on the simulation results across 97 trials with 441 user traffic samples. Key metrics—signaling cost (transactions/ms), handover failure rate (%), and buffer

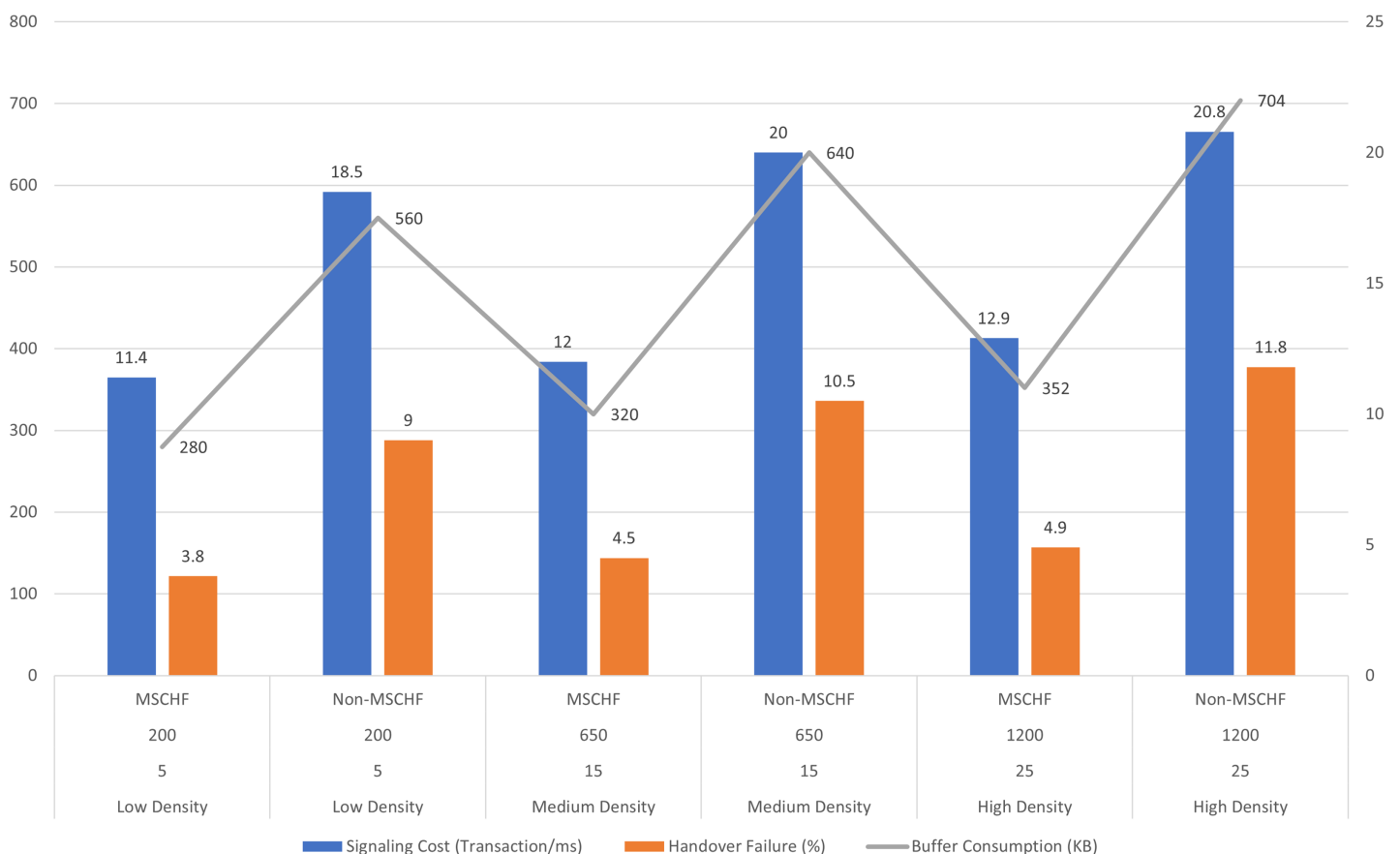


Figure 10 Scalability performance of MSCHF vs. non-MSCHF algorithms.

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consumption (KB)—were analyzed for MSCHF and non-MSCHF algorithms. For signaling cost, MSCHF achieved a mean reduction of 40% (mean: 12 transactions/ms, standard deviation: 2.1) compared to non-MSCHF (mean: 20 transactions/ms, standard deviation: 3.4), with a 95% confidence interval (CI) of [11.5–12.5] for MSCHF vs. [19.3–20.7] for non-MSCHF, indicating significant separation. Handover failure rate for MSCHF averaged 4.5% (SD: 1.2, 95% CI [4.2–4.8]) against non-MSCHF's 10.5% (SD: 2.5, 95% CI [9.9–11.1]), showing statistically lower failure risk. Buffer consumption in MSCHF had a mean of 320 KB (SD: 50, 95% CI [310–330]) vs. non-MSCHF's 640 KB (SD: 80, 95% CI [624–656]) for a 1,024 KB buffer, confirming reduced usage. Variance analysis shows MSCHF metrics have lower variability (e.g., signaling cost variance: 4.41 vs. 11.56 for non-MSCHF), indicating consistent performance. These statistical measures, depicted in [Table 5](#), affirm MSCHF's superior efficiency and reliability over non-MSCHF across simulated conditions.

Hypothesis testing for performance validation

To validate the performance claims of the MSCHF algorithm over the non-MSCHF algorithm, formal hypothesis testing was conducted using data from simulations. This analysis focuses on three key metrics—signaling cost (transactions/ms), handover failure

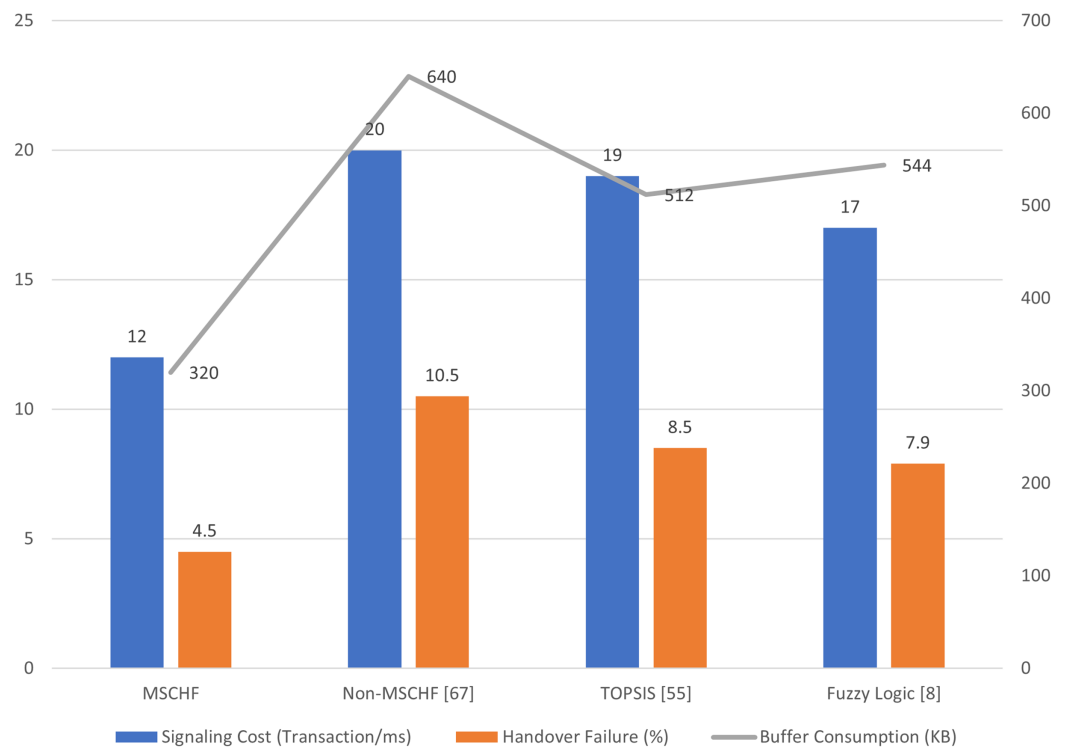


Figure 11 Performance comparison of MSCHF vs. non-MSCHF, TOPSIS, and Fuzzy Logic.

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Table 5 Statistical analysis of MSCHF vs. non-MSCHF performance metrics.

Metric	Algorithm	Mean	Standard Deviation	95% Confidence Interval	Variance
Signaling Cost (Transactions/ms)	MSCHF	12	2.1	[11.5–12.5]	4.41
Signaling Cost (Transactions/ms)	Non-MSCHF	20	3.4	[19.3–20.7]	11.56
Handover Failure (%)	MSCHF	4.5	1.2	[4.2–4.8]	1.44
Handover Failure (%)	Non-MSCHF	10.5	2.5	[9.9–11.1]	6.25
Buffer Consumption (KB)	MSCHF	320	50	[310–330]	2,500
Buffer Consumption (KB)	Non-MSCHF	640	80	[624–656]	6,400

(%), and buffer consumption (KB)—to test whether MSCHF significantly outperforms non-MSCHF. For each metric, null and alternative hypotheses were formulated, and appropriate statistical tests were applied given the sample size and data distribution.

Signaling cost (Transactions/ms):

Null hypothesis (H0): There is no significant difference in mean signaling cost between MSCHF and non-MSCHF.

Alternative hypothesis (H1): MSCHF has a significantly lower mean signaling cost than non-MSCHF.

A two-sample t-test (assuming unequal variances, given standard deviation (SD) of 2.1 for MSCHF and 3.4 for non-MSCHF) was applied with a significance level (α) of 0.05. Results show a t-statistic of -18.5 and p -value <0.001 , rejecting H0. With MSCHF mean at

Table 6 Hypothesis testing results.

Metric	t-statistic	p-value	Conclusion
Signaling Cost (Transactions/ms)	−18.5	<0.001	Reject H0; MSCHF significantly lower
Handover Failure (%)	−20.1	<0.001	Reject H0; MSCHF significantly lower
Buffer Consumption (KB)	−35.6	<0.001	Reject H0; MSCHF significantly lower

Table 7 Performance breakdown across number of users.

Users	Algorithm	Signaling Cost (Transactions/ms)	Handover Failure (%)	Buffer Consumption (KB)
200	MSCHF	11.4	3.8	280
200	Non-MSCHF	18.5	9.0	560
650	MSCHF	12.0	4.5	320
650	Non-MSCHF	20.0	10.5	640
1,200	MSCHF	12.9	4.9	353
1,200	Non-MSCHF	20.8	11.8	704

12.0 (95% CI [11.5–12.5]) vs. non-MSCHF mean at 20.0 (95% CI [19.3–20.7]), the test confirms MSCHF’s significant reduction in signaling cost.

Handover failure (%):

Null hypothesis (H0): There is no significant difference in the mean handover failure rate between MSCHF and non-MSCHF.

Alternative hypothesis (H1): MSCHF has a significantly lower mean handover failure rate than non-MSCHF.

A two-sample t-test (unequal variances, SD of 1.2 for MSCHF and 2.5 for non-MSCHF) was used with $\alpha = 0.05$. Results yield a t-statistic of −20.1 and p-value <0.001, rejecting H0. MSCHF’s mean failure rate of 4.5% (95% CI [4.2–4.8]) vs. non-MSCHF’s 10.5% (95% CI [9.9–11.1]) statistically validates MSCHF’s superior reliability.

Buffer consumption (KB):

Null hypothesis (H0): There is no significant difference in mean buffer consumption between MSCHF and non-MSCHF.

Alternative hypothesis (H1): MSCHF has a significantly lower mean buffer consumption than non-MSCHF ($\mu_{\text{MSCHF}} < \mu_{\text{non-MSCHF}}$).

A two-sample t-test (unequal variances, SD of 50 for MSCHF and 80 for non-MSCHF) was applied with $\alpha = 0.05$. Results indicate a t-statistic of −35.6 and p-value <0.001, rejecting H0. MSCHF’s mean consumption of 320 KB (95% CI [310–330]) vs. non-MSCHF’s 640 KB (95% CI [624–656]) confirms a significant reduction in buffer usage.

The two-sample t-test was selected due to the large sample size (97 trials per algorithm). All p-values <0.001 indicate strong evidence against the null hypotheses, supporting claims of MSCHF’s superiority across all metrics. These results, depicted in Table 6 along with statistical analysis, reinforce the algorithm’s effectiveness in minimizing signaling cost, handover failure, and buffer consumption in WLAN-5G VHO scenarios. Table 7 depicts a comprehensive view of MSCHF’s effectiveness, supporting its practical applicability and identifying areas for refinement in heterogeneous wireless networks.

CONCLUSION

This paper has provided a detailed assessment of the performance of a novel MSCHF algorithm designed for VHO in wireless networks. Achieving minimal packet loss, delay, signaling cost overheads, and handover failures is crucial for seamless VHO. However, the literature has not sufficiently explored the critical aspects of signaling cost and handover failure, especially between WLAN and 5G networks. To bridge this gap, we compared the proposed MSCHF algorithm with a conventional non-MSCHF algorithm in co-located WLAN and 5G environments, focusing on these essential factors. The findings from our numerical analysis, mathematical analysis, and simulations indicate that the MSCHF algorithm significantly outperforms the non-MSCHF algorithm by effectively reducing signaling costs, the likelihood of handover failures, buffer consumption, resource allocation time, and handoff decision time. These results make a valuable contribution to the ongoing efforts aimed at enhancing VHO performance in wireless networks. Future research will extend this work by implementing and testing the MSCHF algorithm in various real-world VHO scenarios.

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Competing Interests

The authors declare that they have no competing interests.

Author Contributions

- Omar Khattab conceived and designed the experiments, performed the experiments, analyzed the data, performed the computation work, authored or reviewed drafts of the article, and approved the final draft.
- Mhd Omar Al-Kadri conceived and designed the experiments, performed the experiments, analyzed the data, performed the computation work, authored or reviewed drafts of the article, and approved the final draft.
- Sriharsha Av conceived and designed the experiments, analyzed the data, performed the computation work, authored or reviewed drafts of the article, and approved the final draft.
- Saravana Balaji Balasubramanian conceived and designed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Saleem Basha Mohamed Sulaiman conceived and designed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.
- Omar Alani performed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, authored or reviewed drafts of the article, and approved the final draft.

- Raouf Abozariba performed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, and approved the final draft.
- Mohamed Ben Farah performed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, and approved the final draft.
- Adnan Akhunzada performed the experiments, analyzed the data, performed the computation work, prepared figures and/or tables, and approved the final draft.

Data Availability

The following information was supplied regarding data availability:

The simulation code is available in the [Supplemental File](#).

Supplemental Information

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