

Integration of Named Data Networking (NDN) in 5G Architecture for Handover Optimization and QoS Enhancement

Ade Nurhayati ^{1,2}, Tutun Juhana ¹, and Nana Rachmana Syambas ^{1,*}

¹ School of Electrical Engineering and Informatics, Bandung Institute of Technology, Bandung, Indonesia

² School of Electrical Engineering, Telkom University, Bandung, Indonesia

Email: adenurhayati@telkomuniversity.ac.id (A.N.); tutun@stei.itb.ac.id (T.J.); nana@stei.itb.ac.id (N.R.S.)

*Corresponding author

Abstract—The increase in mobile data traffic in Fifth-Generation (5G) networks means that new handover management and content delivery solutions are needed to keep the network running smoothly and the user experience high. This paper introduces an innovative integration of Named Data Networking (NDN) into the 5G architecture, incorporating an Enhanced Popularity-Based Caching mechanism at the Multi-access Edge Computing (MEC) layer of the 5G user plane. Our design is different from previous ones because it changes how content is replicated based on how mobile and dense the User Equipment (UE) and gNB are in real time. Using Python-based models, we ran a lot of simulations to compare baseline 5G, edge-caching, and full NDN configurations. The proposed solution had a Handover Success Rate (HSR) of over 90%, a Cache Hit Ratio (CHR) of between 78% and 80%, an average latency of about 20 ms, and a packet loss rate of less than 1.0% across a wide range of network scenarios. The NDN integrated architecture cuts latency by up to 35%, boosts throughput by 40%, makes fallback efficiency improved by 36.8%, and raises average HSR by 25–40%. All of these changes improve the Quality of Experience (QoE) in environments with a lot of movement. The research we conduct aims to facilitate seamless, scalable, and resilient content delivery for next-generation 5G edge networks.

Keywords—Fifth-Generation (5G), Named Data Networking (NDN), edge caching, handover, Quality of Service (QoS), Quality of Experience (QoE)

I. INTRODUCTION

The Fifth-Generation (5G) mobile communication system is designed to connect many devices, transmit large amounts of data, and provide highly reliable, low-latency services. Ultra-Reliable Low-Latency Communication (uRLLC) is essential for 5G networks to function correctly because it ensures network management is quick, seamless, and responsive, Ali *et al.* [1]. Many applications, such as industrial automation,

holographic communication, and the Tactile Internet, require end-to-end latency of a few milliseconds or less, as discussed by Park *et al.* [2] and Osama *et al.* [3]. The study by Liu *et al.* [4], entitled M2HO: Mitigating the Adverse Effects of 5G Handovers on TCP, investigates the negative impact of 5G handover processes on Transmission Control Protocol (TCP) performance, particularly in terms of throughput degradation and increased retransmissions caused by frequent path changes during user mobility. Maleki *et al.* [5] improved the ability of 5G networks to satisfy QoS requirements is essential to address increasing network demands.

In dense 5G environments with high user mobility and numerous gNodeBs, frequent handover events may lead to packet loss, increased latency, and service interruptions. These challenges have encouraged researchers to explore new approaches for data delivery and mobility management in 5G networks. According to Haghrah *et al.* [6], the high density of users and rapid mobility in 5G environments make handover management a critical issue for maintaining reliable connectivity and service continuity. According to Ahdan and Syambas [7], Named Data Networking (NDN) is a data-centric architecture that moves communication from host-based addressing to content-based retrieval. This is a promising solution. NDN lets you send data quickly, no matter where you are, by using features like in-network caching, name-based forwarding, and content discovery. People think that the NDN architecture will change how we talk to each other now. It emphasizes that internet users need apps and content that use named data instead of IP addresses or other location-based identifiers. NDN changes data into named entities.

Combining NDN with the 5G network could speed up handovers, lower signaling overhead, and improve mobile users QoS. Named data is what NDN is all about. It communicates in a way that looks at the data and doesn't care where it is stored, just what it is. It can fix the problems that TCP/IP causes. Li *et al.* [8] stated that this novel network communication approach delivers improved handover performance amid accelerated mobile communication speeds.

Manuscript received December 3, 2025; revised December 25, 2025; accepted January 30, 2026; published May 25, 2026.

Even though 5G technology has come a long way, seamless handover and service continuity remain significant problems, especially when people are moving around a lot. Control-plane signaling and session-based routing are two essential parts of traditional handover mechanisms in 5G. These can cause problems during cell transitions. Also, the 5G user plane lacks localized caching or content awareness, leading to repeated transmission of the same data and wasted bandwidth. Because of this, we need an adaptive system that keeps connections open, reduces latency, and optimizes resource use during handover events. You can use an active caching method to reduce Interest re-transmissions during handover. This method assumes that the requested data already exists. It then proactively prefetches, or pushes, requests expected to arrive in the future into the network cache before the handover, as explained by Xing *et al.* [9].

Saoud *et al.* [10] examined several solutions to improve the reliability and efficiency of intelligent, adaptive, and sustainable mobility and handover management as a key to the success of future 5G and 6G networks for mobility prediction and proactive handover decision making. Cheng *et al.* [11] discussed Artificial Intelligence (AI)-based proactive content caching as a key solution to improve content distribution efficiency in 6G wireless edge networks. According to studies by Guduri *et al.* [12] and Deepakraj *et al.* [13], intelligent caching systems based on Reinforcement Learning and Deep Learning can predict content demand, perform proactive data retrieval, and manage cache resources in real time. These systems improve the cache hit rate by up to 50.6% and reduce latency by 30–50%, demonstrating the effectiveness of AI-based approaches for 5G and edge computing environments. Research by Khan *et al.* [14] introduces PBatch, which improves traditional VPKI by combining distributed-ledger batch authentication with caching that is based on reinforcement learning. It reduces verification time by 90%, allows for 1,000 messages per second, and greatly lowers message loss, making it a safe and scalable solution for future Cooperative Intelligent Transport Systems (C-ITS).

Pereira *et al.* [15] suggested the Vehicular Adaptation Layer (VAL) to make NDN work better in Vehicular Ad Hoc Network (VANET) while keeping the main structure of NDN. VAL uses GeoFaces, implicit ACK, and modular forwarding to cut down on broadcast storms and speed up delivery rates by as much as 87.6% when there are a lot of people. Abdullah *et al.* [16] examined the major challenges associated with mobility and content retrieval in Vehicular Named Data Networking (VNDN). The study emphasizes the need for hybrid solutions that integrate AI, SDN, and security mechanisms to develop resilient and efficient Internet of Vehicles (IoV) systems. Li *et al.* [17] presented DPN, a density-based probabilistic caching mechanism that employs NDN principles to enhance Quality of Service (QoS) in dynamic Vehicle Ad Hoc Network Traffic (VANET). Simulations show that link loads can be cut by as much as 25% and latency can be cut by as much as 35%. This

shows that it works well in crowded urban areas. Gan and Hout [18] proposed a Location-Based Clustering (LC) methodology for Vehicular Named Data Networking (VNDN) to establish dynamic clusters that mitigate broadcast storms, connection failures, and latency issues. The proposed method employs fuzzy logic for Cluster Head selection, thereby enhancing communication reliability through significant reductions in delay and packet loss.

Taki and Mastorakis [19] proposed the integration of NDN into Fog Radio Access Networks (F-RAN) to overcome the limitations of next-generation 5G/6G cellular architectures, reduce front-haul latency, optimize resource utilization, and improve caching efficiency. Simulation results indicate significant improvements in cache hit rates, front-haul load reduction, and latency performance compared with FIFO and LRU approaches. Furthermore, the study integrates NDN, 6G, and quantum cryptography to establish a secure and efficient electronic voting framework. The results show that it is very hard to listen in on and works very quickly. Ullah *et al.* [20] proposed a two-stage ICN-based MEC offloading method for 6G that reduces end-to-end latency and enhances load balancing compared to RL-only methods. Li *et al.* [21] introduced Computation and Communication Resource Allocation in Information-Centric Networks (CCR-ICN) for the distribution of shared bandwidth and CPU in 6G ICN/NDN networks. This method makes bandwidth allocation up to 66.82% better and communication overhead up to 17.51% lower. Imran *et al.* [22] suggested NDN as a fundamental framework for 5G/6G mobile networks, reducing signaling overhead, enhancing orchestration, and strengthening security. The results show that latency can be as low as 15 ms and that protection based on data is stronger.

This study aims to utilize an NDN content-based methodology to improve mobility management in 5G networks. Adding NDN as an overlay at the MEC and core layers lets data requests be handled locally, which makes end-to-end sessions less important. This method makes handover more reliable and improves QoS by lowering latency, increasing throughput, and lowering packet loss. Also, caching at the edge is a backup plan in case handovers don't work, which keeps the service going and users happy.

Combining Information-Centric Networking (ICN) and Multi-access Edge Computing (MEC) is a smart way to fix some of the biggest problems with 5G networks, like high latency, user mobility, back-haul load, and service delivery efficiency. All of these studies want to improve the Quality of Service (QoS) and the user experience (QoE), but they do it in very different ways, with different goals, and with different main contributions. Atalay *et al.* [23] identified ICN as one of the four key technologies (along with Network Functions Virtualization (NFV), SDN, and Network Slicing) for integrating MEC and IoT. It focuses more on architectural contributions than on technical implementations. Kim and Lee [24] offered a technical solution to improve cache efficiency through a Limited

Domain Caching (LdC) policy, which allows caching exclusively within the publisher domain, thereby increasing storage efficiency by up to 65%.

Xu *et al.* [25] offered a technical solution, but focuses on energy savings through the Energy-efficient Caching Algorithm (EeCA) algorithm that considers content popularity and device residual energy. Liyanage *et al.* [26] and Chhange and Patel [27] focused on standardization aspects, proposing coded delivery as a 5G MBS-based MEC service that complies with European Telecommunications Standards Institute (ETSI) and 3rd Generation Partnership Project (3GPP) specifications to improve content delivery efficiency.

Gao and Zhai [28] added a new perspective by using Uncrewed Aerial Vehicles (UAVs) as dynamic MEC nodes, optimizing cache, offloading, resource allocation, and UAV trajectories to improve the service-experience ratio. Khan and Madeira [29] related to ICN, but instead uses MEC to estimate the QoE of encrypted 360° video traffic, showing that not all MEC research is related to ICN. Some points that differentiate our research from the eight studies mentioned above are:

1) Special Focus on handover Optimization: This research concentrates solely on handover optimization as a principal issue, rather than merely an aspect of the broader mobility challenge, thereby offering analytical precision not attained by other studies.

- 2) Clear Implementation Architecture: This paper suggests a specific integrated architecture by connecting NDN parts (Forwarder, PIT, Forwarding Information Base (FIB), CS) to 5G network functions, especially User Plane Function (UPF). This shows a clear technical way for operators to implement the system.
- 3) HO Failed Fallback Mechanism: This new solution uses caching in the edge MEC and core router as a backup when a handover fails. This makes sure that service continues without having to wait for the handover process to finish. This is a very useful solution for real-time applications.
- 4) Full and Quantified Performance Evaluation: Uses Python to run simulations for three scenarios (5G baseline, edge caching, and full NDN deployment). The results are very good: latency is reduced by up to 35%, throughput is increased by up to 40%, HSR is increased by up to 40%, and fallback efficiency is increased by 36.8%.
- 5) Combined QoE Metrics: This suggests a single QoE score that combines several QoS parameters (latency, throughput, packet loss, HSR, CHR) to give a complete picture of the quality of service from the point of view of the end user.

TABLE I. COMPARISON OF ICN AND MEC INTEGRATION RESEARCH FOR 5G NETWORKS

Ref	Research Focus	Main Contributions	Relevance to ICN-MEC	Result
[23]	Shows ICN as one of the four driving technologies for MEC-IoT integration.	Positioning ICN within the broader technology ecosystem for MEC-IoT.	Demonstrates ICN as one of several core driving technologies for MEC.	Provides a holistic view of MEC-IoT integration; identifies four key enabling technologies.
[24]	Solving cache inefficiencies with Limited Domain Caching (LdC) policies.	LdC cache policy that improves storage efficiency by focusing caching	A straightforward technical solution to the cache problem in the ICN-MEC architecture.	Increase storage efficiency by up to 65%; reduce cache space waste.
[25]	Reducing energy consumption on user devices through caching strategies	Energy-saving EeCA algorithm with priority caching	A direct technical solution to energy problems in MEC offloading scenarios using ICN.	Significantly saves user device energy; increases battery life.
[26, 27]	Propose coded delivery as an MEC service for efficient content delivery.	Integrate coded delivery into standard MEC architectures (ETSI/3GPP).	Proposes a new approach to content delivery in MEC, which is philosophically aligned with ICN principles.	Improve content delivery efficiency through multicast; supported by industry standards (3GPP, ETSI).
[28]	Optimizing service experience in UAV-assisted MEC networks	Service Experience Ratio metrics and optimization algorithms for offloading, caching	Using MEC extended with UAV, not explicitly using ICN architecture.	Optimize multiple parameters at once (traffic, resources, paths); new performance metrics that take fairness into account.
[29]	QoE for encrypted 360° video streaming using MEC.	ASSESSOR 360° framework for mapping QoS to QoE	Does not directly use or discuss ICN. Focus on MEC for QoE estimation.	Capable of estimating QoE without decryption; supports various user mobility scenarios.
Our research	Optimizing handover and QoS in NDN-based 5G architecture.	Architectural Integration: Mapping NDN components to the 5G User Plane.	A live experimental study integrates NDN as an overlay on 5G architecture, actively exploiting the key features of ICN-MEC.	Focus on handover optimization; comprehensive and quantified performance evaluation; combined QoE score metrics.

Previous research has laid the theoretical groundwork for the integration of ICN and MEC; however, our study differentiates itself by offering a technically viable

solution. We tackle this shortcoming with three main contributions: (1) a unified NDN-5G architectural framework, (2) a new fallback mechanism to fix

handover failures, and (3) performance data from simulations that show significant quantitative improvements. This study not only adds to what we already know, but it also makes a big step toward putting the ICN/NDN model into practice in 5G networks, which will improve service quality and mobility management. Table I shows how this study is different from studies that came before it.

NDN was made to fix the problems with IP-based design. It is a new way to connect computers that is based on content. In NDN, people look for information by its content name instead of its host address. This makes it faster and more reliable to send data. NDN also has name-based routing, in-network caching, and data replication features that help networks stay stable and make communication faster. But adding NDN to 5G networks brings up new problems, especially when it comes to handling user mobility and improving caching methods at the networks edge. When people are moving around a lot, NDN often has a lower CHR and changes in latency and throughput because the way popular content is spread out doesn't always match how people move.

This study seeks to answer the main question: How can adding an NDN architecture to a 5G system through a popularity-based caching strategy at the edge network improve the efficiency of data transmission, the reliability of handovers, and overall QoS performance in a multi-gNB setting. This paper discusses the design and performance assessment of an integrated 5G-NDN architecture, emphasizing mobility optimization and Quality of Service (QoS) improvement. In short, the main contributions of this work are:

- 1) Architecture Design: An integrated model of 5G and NDN is suggested, with NDN overlay parts (Forwarders, PIT, FIB, and Cache Store) linked to the functions of the 5G user plane.
- 2) Mechanism for handover and fallback: A mobility-aware handover model is created that uses NDN caching as a backup plan to keep content delivery going during times when there is no connection.
- 3) Framework for QoS-Aware Evaluation: We use Python to create a simulation framework that tests the proposed architectures performance using important metrics like Handover Success Rate (HSR), Fallback Efficiency, Cache Hit Ratio (CHR), and quality of service indicators like latency, throughput, and packet loss.
- 4) Performance Analysis: When comparing baseline 5G, edge caching, and full NDN deployment scenarios, we see up to a 35% decrease in latency, a 40% increase in throughput, and a better overall QoE.

The rest of this paper is set up like this: Section II talks about the work that is related and the background. In Section III, shows the proposed simulation setup and the system architecture. In Section IV, we talk about the

results and analysis of the simulation. Finally, Section V wraps up the paper and talks about where research should go next.

II. RELATED WORK

There has been a lot of research into how to make 5G networks work better because more people want fast and reliable mobile communication. Traditional 5G architectures that use IP-based transmission have trouble with dynamic mobility and keeping the same level of Quality of Service (QoS) during handover events. Several studies, as shown in Table II, have explored how to improve handover management by using improved control-plane mechanisms, predictive mobility models, and cross-layer optimization techniques. But these methods often add extra signaling overhead and don't directly fix the problems with data delivery paths during mobility transitions.

According to Zhang *et al.* [30], Information-Centric Networking (ICN) has come up as a new way to get around the inflexibility of IP-based addressing. It focuses on getting data based on content names instead of host addresses. In this context, NDN has gotten a lot of attention because it can do in-network caching, name-based routing, and data replication, it has been shown that caching data at intermediate nodes in NDN can greatly lower latency and make better use of bandwidth.

Recent studies have explored the integration of NDN with 5G architectures to improve communication efficiency and mobility support. Afanasyev *et al.* [31] proposed the use of network coding in NDN to enhance IoT communication in 5G environments. In addition, Lei *et al.* [32] and Hussaini *et al.* [33] introduced broadcasting-based handover mechanisms to reduce latency and overhead in mobile NDN networks. These approaches show that integrating NDN caching and forwarding with the 5G user plane can improve handover performance and reduce packet loss. However, most existing studies remain conceptual or focus primarily on the control layer, with limited quantitative evaluation of QoS metrics such as latency, throughput, and packet loss.

This paper offers a thorough simulation-based assessment of NDN integration within the 5G framework, concentrating on handover reliability, caching performance, and QoS enhancement, in contrast to prior studies. The suggested architecture adds NDN overlay features to both the MEC and core layers. This makes it possible to cache data in one place and use fallback methods when handover fails. This study quantitatively demonstrates how NDN-based architectures can enhance mobility resilience and user experience in next-generation mobile networks by comparing baseline 5G, edge caching, and full NDN deployment scenarios.

TABLE II. COMPARATIVE RESEARCH ON HANDOVER OPTIMIZATION IN 5G

Ref.	Research Contribution	Tools / Software Used	Measurement Metric	Result
[34]	Evaluating Conditional handover (CHO) in LEO-based Non-Terrestrial Networks (NTNs) with Earth-Moving Cells.	Proprietary dynamic system-level simulator	DL SINR, Radio Link Failure, handover Failure, Unnecessary HO, Time-of-Stay	CHO eliminates all handover and radio link failures (0%), increases the 5th percentile SINR by 4–6 dB, resulting in over 60% improvement in handover
[35]	Multi-criteria method (E-MOORA + Q-learning) to select target cells and set handover triggers, reduce unnecessary handovers, maintain throughput & QoS.	MATLAB (Simulink + Q-learning toolbox)	Number of handovers, Throughput, Probability of radio link failure, user mean throughput Latency	Reduces the number of unnecessary switches by up to 22%, while improving QoS with an average throughput increase of up to 15%.
[36, 37]	Evaluating CHO performance in 5G FR2 (28 GHz) scenarios, CHO significantly reduces mobility failures at high speeds. CHO recovery accelerates reconnection after failures.	System-level simulator (based on 3GPP TR 38.901)	HO Success (HOSucc), All Mobility Failures, Ping-Pong, CHO Recovery Rate	In 5G FR2 (28 GHz) scenarios, CHO reduces mobility failures by 3–4 times compared to baseline handover at 60 km/h, and CHO Recovery recovers more than 80% of failures.
[38]	Using deep reinforcement learning for handover optimization: selecting adaptive parameters to reduce delay, improve QoS, and reduce overhead.	Python (TensorFlow + Keras)	Number of handovers (NOH), handover Failure (HOF), Throughput, Latency, ping-pong Handover Probability (PPHP)	A 28% reduction in latency and an increase in the handover success ratio to 97.8%, with lower signaling overhead compared to traditional methods.
Our research	Optimizing handover and QoS in NDN-based 5G architecture.	Python (NDN-based 5G handover Simulation)	Comparison (Throughput, Latency, Packet Loss, Cache Hit, QoS,) on conventional network and NDN over 5G,	The proposed architecture simultaneously optimizes handover success rate (HSR > 90%), cache hit ratio (CHR: 78–80%), latency (~20 ms), and packet loss (< 1.0%) under all network conditions.

III. PROPOSED ARCHITECTURE AND SOLUTION

This chapter discusses the simulation method used to assess how well the handover process works in an NDN environment running on a 5G network. The main goal of this simulation is to see how integrating NDN affects the handover process in 5G networks.

A. Network Models and Architecture

The proposed model consists of nodes that represent the main components of the 5G communication system. The User Equipment (UE) works as both a consumer and a producer of data at the access layer. A gNodeB (gNB) is connected to each UE. The gNB is the base station that provides radio access services. After that, the gNB connects to the 5G Core Network, which includes several key functions, including the Access and Mobility Management Function (AMF), the Session Management Function (SMF), and the User Plane Function (UPF). The UPF is the data-plane anchor that connects the 5G core domain to the NDN Core Router and outside Data Networks (DN/Internet). At the edge of the network, MEC/Edge nodes are also set up. These nodes consist of NDN Forwarders with caching systems and edge apps designed to handle local content requests, as explained by Kabir [39].

According to Gürkan *et al.* [40] NDN components are distributed across several network layers. The User Equipment (UE) represents the consumer entity and sends Interest Packets to ask for content. On the other hand, the producer entity could be applications at the edge layer or Content Repositories within the NDN core

domain that give data. There are two levels of NDN Routers: The Edge Forwarder, which is located next to the gNB and helps cache popular content, and the NDN Core Router, which serves as the backbone for forwarding content between domains. Research by Nguyen *et al.* [41], The name-based forwarding mechanism works through three main components on each NDN router: the Content Store (CS), the Pending Interest Table (PIT), and the Forwarding Information Base (FIB).

The User Plane Function (UPF) maps NDN Interest Packets and Data Packets onto the 5G user plane to enable the architecture to work together. 5G has quality of service features like enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communication (URLLC), and massive Machine-Type Communication (mMTC) that can be used to meet the specific needs of NDN traffic. The AMF and SMF parts still handle mobility and session management at the control-plane layer, while NDN operates as an overlay on the user-plane. The NDN forwarding process lets UE send content requests up through the gNB and the Edge Forwarder, and finally to the NDN Core or the Data Network (DN/Internet). The corresponding Data Packets are then sent back along the paths that were recorded in the PIT. They may be cached at edge nodes, which lowers latency and better uses bandwidth, as explained by Ge *et al.* [42].

B. NDN Integration in 5G Architecture

NDN integration in 5G relies on tight coordination between the Control Plane (CP) and User Plane (UP) so that name-based communication aligns with mobility and

session management. The AMF and SMF are extended to recognize ICN/NDN PDU Sessions and manage name-prefix registration and mapping. As the UE moves, the CP updates the UP to keep NDN states such as the PIT and FIB synchronized, preventing session loss. This approach, described in the ICN-5GC architecture in the IETF Internet-Draft by, Research by Ravindran *et al.* [43], shows that the 5G CP can be extended to support name-based PDU sessions natively.

On the User Plane side, the UPF (User Plane Function) function is modified to support name-based forwarding through the integration of NDN Forwarder elements and in-network caching. After the CP establishes a PDU session for ICN/NDN, the SMF sends name-based routing rules, QoS policies, and service anchoring configurations to the UPF. With these configurations, the UPF can process Interest and Data packets based on name prefixes, not IP addresses. CP-UP synchronization occurs when the CP distributes mobility policies and forwarding rules to the UPF, while the UPF ensures that

Interest/Data processing runs according to these configurations. At the same time, MEC (Multi-access Edge Computing) nodes located on the UP path can perform NDN functions such as caching, edge computing, and service offloading, with the CP directing the traffic path to the MEC when UE mobility conditions allow. Research by Ullah *et al.* [44] showed that the integration of ICN with edge computing in 5G significantly reduces latency and back-haul load through opportunistic caching.

With this coordination, the 5G architecture not only supports location-based communications like traditional IP but also enables location-independent name-based communications. CP provides mobility and session control, while UP provides content-centric forwarding, caching, and edge processing capabilities. The result is an efficient, adaptive integration that supports future application needs that require low latency, high mobility, and efficient content distribution.

NDN over 5G : Internet vs Data Flows Control Plane and 5G Slices

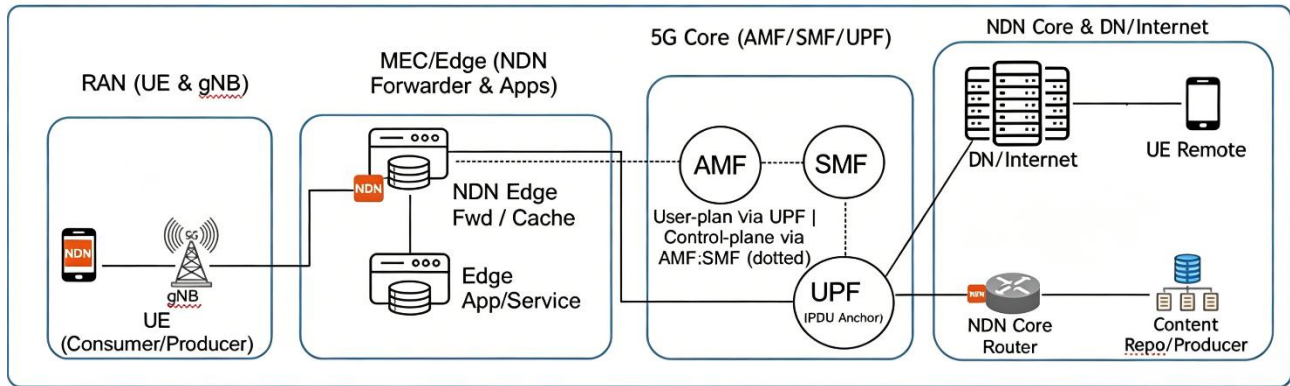


Fig. 1. Architecture NDN over 5G.

C. UE (NDN-Native)

User Equipment (UE) is a part of NDN. How UE is shown in architecture: The NDN label on the UE in Fig. 1 shows that it is a UE (Consumer/Producer). It says clearly that each UE is linked to a gNodeB. The User Equipment (UE) represents the consumer entity and sends interest packets to ask for content. This shows that the UE is the main part of the NDN model. It can be a consumer or producer of data, not just a device that talks to another device through a proxy.

User Plane NDN Integration: A modified UPF (User Plane Function) is used to integrate NDN at the User Plane. This changed UPF can then handle Interest and Data packets by name prefixes instead of IP addresses. Because the UE is the one who asked for the data (by sending Interest packets), it makes sense that it should be able to make and understand NDN packets directly in order to talk to the NDN-enabled UPF. If the UE uses a proxy, the UPF doesn't need to be changed to handle NDN packets; it just gets IP packets like it always does. UE NDN is native because it doesn't use a proxy or

translation layer on the UE side; instead, UE works in an NDN environment.

D. Interest/Data Delivery on GTP Tunnel

The UE is NDN-native, but it still talks to the UPF over standard 5G infrastructure. The text and diagrams explain this process like this:

The UPF is a PDU session Anchor, which is a fixed point in the User Plane where all data traffic from the UE goes into and out of the 5G core network. GTP Tunneling: In the 5G architecture, a GPRS Tunneling Protocol (GTP) tunnel surrounds the data that is sent from the UE to the UPF and back again. This is how the standard 5G connects the RAN (gNB) to the Core Network (UPF).

The handover Process: The Control Plane (AMF/SMF) is in charge of the process when a UE hands over (moves from one gNB to another). The AMF/SMF then tells the new UPF (if the handover changes the UPF) or updates the routing information in the same UPF about the UE's new location. Then, the UPF changes its routing table so

that traffic goes to the new gNB. The gNB wraps the NDN (Interest/Data) packets made by the UE into GTP-U (User Plane) packets and sends them through the GTP tunnel to the UPF that is currently active. The UPF, which has been changed to work with NDN, then unwraps the GTP-U packets, processes the Interest or Data packets by name (not IP address), and sends them to the NDN Edge Forwarder or NDN Core Router based on the forwarding rules set up by the SMF. On the other hand, when a Data packet comes from the NDN Core or Content Repository, the UPF processes it, wraps it in a GTP-U packet, and sends it back to the UE through the right gNB, even if the UE has moved to a different gNB after the handover. No matter where the UE is, the UPF is in charge of making sure the data gets there.

To put it another way, the GTP tunnel is a straightforward way for NDN packets to get from one place to another. The UE makes the NDN Interest packet, the gNB wraps it up in GTP-U, the UPF unwraps the GTP-U packet, processes the NDN packet, and sends it to the NDN network. During handover, this process continues, and the UPF updates the GTP-U delivery destination to reflect where the UE is now. This integration lets the UE keep working as an NDN-native device without needing to learn the complex details of the 5G infrastructure.

E. Flowchart Hybrid 5G + NDN Handover

This part gives a general idea of how the Hybrid 5G+ NDN-Aware handover Simulation works. The flowchart shows how the dynamics of 5G cellular networks, such as user mobility, radio channel propagation, and RSRP/SINR measurements, work with the content-centric architecture of NDN. This hybrid approach lets handover decisions be made based on more than just signal quality. It also lets the target gNB cache hold the content that the user requested, which makes the network more efficient, lowers latency, and improves the overall user experience. The following explanation goes through each step of the flowchart in order, from the start of the simulation to the end.

The simulation begins with a simple start node—serving only as the entry point with no processing. This is followed by the initialization phase, during which gNB positions (P_{gNB}) are randomly generated within the simulation area, and each UE initial position (P_{UE}) and speed are set according to the Random Waypoint mobility model. Additionally, each gNB's cache is preloaded with content selected from a Zipf distribution, prioritizing more popular items. The NDN structures are also initialized: the FIB for content routing, the Pending Interest Table (PIT) to track outstanding requests, and the CS as a local cache managed by the LRU (Least Recently Used) policy. Finally, handover performance counters are reset to zero: $handover_attempts = 0$ and $handover_success = 0$. The next step is the simulation

loop, which iterates from $t = 1$ to T , where T represents the total number of time frames in the simulation. Each frame corresponds to one complete system update cycle. If the loop condition is satisfied (i.e., $t \leq T$), the simulation proceeds to the next processing steps; otherwise, when $t > T$, the loop terminates and the simulation moves to the finalization phase.

In process (1), mobility update, each UE moves toward its current waypoint at a randomly selected speed within a specified range $[V_{min}, V_{max}]$. If the UE reaches its destination waypoint, the system generates a new random waypoint and assigns a new random speed. This mechanism aims to realistically simulate user mobility during the simulation. In process (2), radio conditions are computed for each (UE, gNB) pair by first calculating the Euclidean distance between them. Path loss is derived using the 3GPP model at 2 GHz, then augmented with log-normal shadowing and fading—Rayleigh for Non-Line-of-Sight (NLOS) and Rician for Line-of-Sight (LOS) scenarios. These components are combined to compute the Reference Signal Received Power (RSRP) as: $RSRP_{u,g} = P_{tx} - PL_{u,g} + S_{u,g} + F_{u,g}$. where P_{tx} is the transmit power, $PL_{u,g}$ is the path loss, $S_{u,g}$ is the shadowing term, and $F_{u,g}$ represents fading. The resulting RSRP value quantifies the signal strength received by the UE from the gNB.

In process (3), interference and SINR are computed to assess connection quality and channel capacity for each UE. This involves identifying the best gNB as $g^* = \text{argmax}_{u,g} RSRP_{u,g}$ calculating inter-cell interference from all other gNB as $\sum_{g \neq g^*} 10^{RSRP_{u,g}/10}$, and then determining the SINR using the formula: $SINR_u = \frac{10^{RSRP_{u,g^*}/10}}{I_u + N_0}$ where N_0 represents the noise floor. Process (4), NDN-aware handover decision, goes beyond traditional signal-based criteria by also considering the availability of the requested content in the local cache of the target gNB g^* . For each UE, a content request is drawn from a Zipf distribution, and the system checks whether this content exists in the cache of g^* . If it does, a “cache hit” is recorded, the interest is added to the PIT if needed, and the retrieved data is stored in the CS using the LRU (Least Recently Used) policy. $g^* \neq g_{current}$ differs from the UEs current gNB $g_{current}$ the handover attempt counter is incremented; then, if a cache hit occurs and the target gNB's cache is not full, the handover is approved, the success counter is increased, and the UE-to-gNB mapping is updated. Otherwise, the handover is rejected, and communication continues over the NDN path without switching gNB.

Process (5), QoS Estimation, is performed for each UE: latency is lower in the case of a cache hit; throughput is derived by mapping the SINR to a Modulation and Coding Scheme (MCS) and then to a Transport Block Size (TBS); and packet loss is estimated based on an

SINR threshold—for example, if $\text{SINR} < 5$ dB, packet loss is considered high. All these QoS metrics are then recorded in a CSV log file for further analysis. Step 8 marks the end of frame t : once all simulation processes for the current frame are completed, the system returns to the main loop to proceed with the next time step $t+1$. Step (10) marks the end of the simulation: once the main

loop completes (i.e., when $t > T$), all collected logs are saved to a CSV file, and visual plots are generated for key performance metrics—namely RSRP, SINR, latency, throughput, packet loss, and HSR (handover Success Rate).

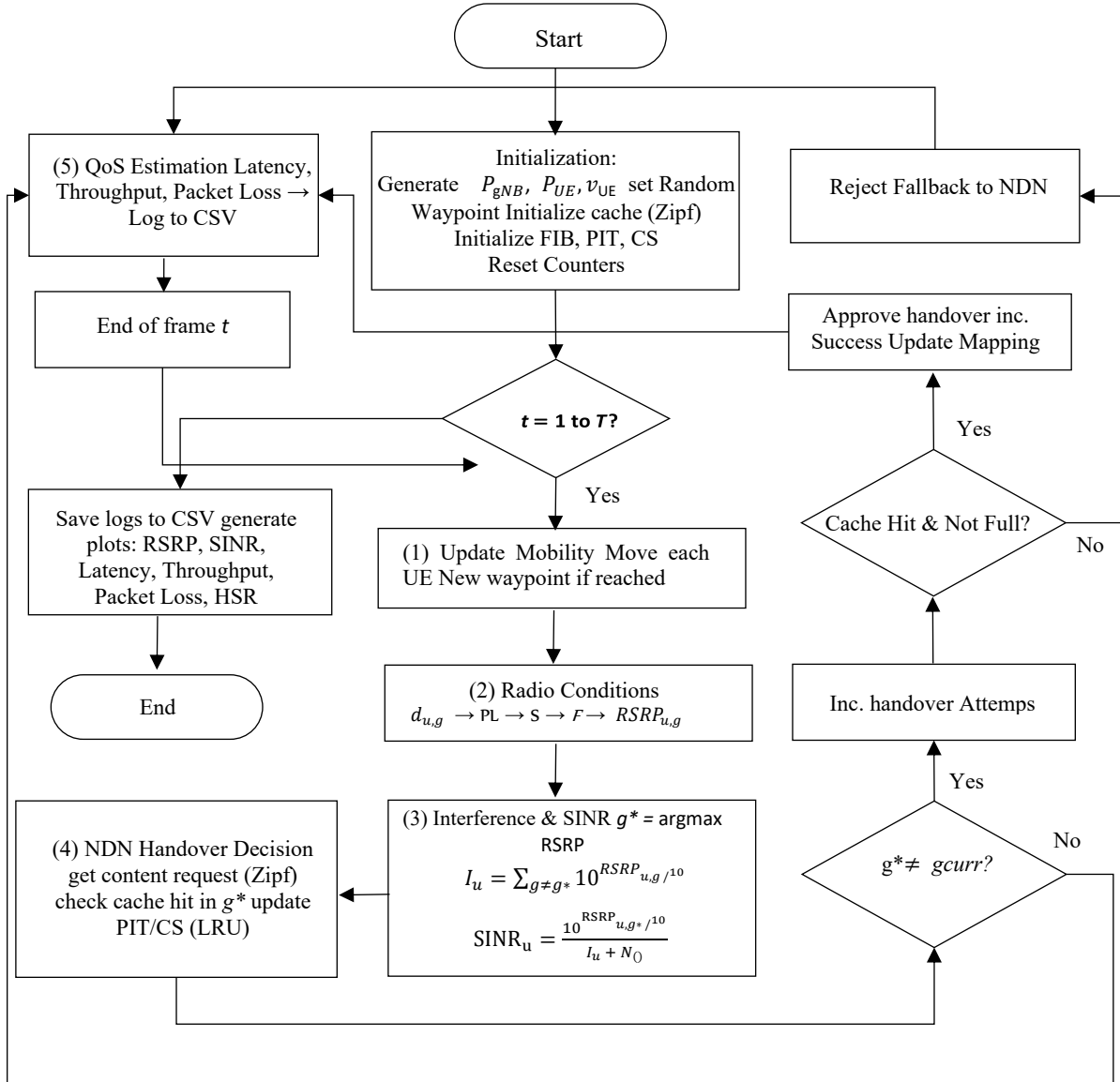


Fig. 2. Flowchart hybrid 5G + NDN handover.

F. Pseudo-Code Hybrid 5G + NDN Handover

This section presents the pseudo-code as an algorithmic framework that captures the core logic of the Hybrid 5G + NDN handover Simulation. The pseudo-code is designed to integrate two key aspects: (1) 5G cellular network dynamics—including user mobility, radio channel propagation, and the computation of RSRP and SINR, (2) NDN mechanisms, particularly the use of the CS, PIT, and FIB in handover decision-making. With this approach, handover decisions are based not only on signal quality but also on the availability of the user-requested content in the target gNB cache—aiming

to enhance network efficiency, reduce latency, and improve user experience. The following pseudo-code is structured to facilitate straightforward implementation and logical verification of the simulation.

Pseudo-code: Hybrid 5G + NDN-Aware Handover

Input: Number of UE N , number of gNB M , simulation duration T , mobility model parameters, channel parameters, NDN catalog size, cache size, Zipf α .

Output: QoS logs, RSRP/SINR, latency, throughput, packet loss, handover statistics.

- 1: Initialize gNB positions, coverage radius, transmit power, noise floor.
- 2: Initialize UE positions, speed, and random waypoint mobility

```

model.
3: Initialize NDN components: FIB, PIT, CS with LRU policy.
4: Generate content catalog of size C with Zipf popularity
distribution.
5: Assign each UE a content request from Zipf distribution.
6: Initialize log buffers: QoS log, radio log, handover log. each
simulation frame
7: For each simulation frame t = 1 to T: do
// Mobility Model
8: for each UE u do
Update position → based on Random Way-point:
9: Move UE toward next destination → at speed v u
∈ [v min, v max].
10: if UE reached waypoint, then
11: Select new random waypoint and speed.
12: end if
13: end for
// Radio Channel Model
14: for each UE → u and gNB do
15: Compute distance d = (u, g)
16: Compute path-loss using 3GPP model → example:
PL = 32.4 + 20 log10(f) + 30 log10(d)
17: Apply log-normal shadowing
18: Apply Rayleigh or Rician fading
19: Compute RSRPu,g (Reference Signal Received
Power) RSRPu,g = Ptx - PLu,g + Su,g + Fu,g
20: end for
// Interference and SINR
21: for each UE u connected to gNB g do
22: Compute received power Prx
23: Compute interference I = ∑j≠g Prx,j
24: Compute interference SINRu =  $\frac{P_{rx}}{I+N_0}$ 
25: end for

```

```

// Handover Decision
26: for each UE u do
27: Determine best gNB g* based on RSRP/SINR
28: if g* ≠ gcurrent then
29: Increment handover attempts
30: if NDN cache contains requested content then
31: Accept handover Update
32: FIB, PIT, CS.
33: Increment successful handovers
34: else
35: Reject or delay handover
36: end if
37: end if
38: end for
// QoS Computation
39: for each UE u do
40: Estimate latency using SINR-based model or random
distribution
41: Estimate throughput using MCS table or SINR
mapping
42: Estimate packet loss from SINR thresholding
43: Log all QoS metrics
44: end for
// NDN Content Handling
45: for each UE request do
46: if content in CS then
47: serve from cache (cache hit)
48: else
49: Forward request to gNB and update PIT
50: end if
51: Store response in CS using LRU
52: end for
53: end for
54: Save all logs to a CSV: radio, QoS, Handover, SINR, RSRP.
55: Plot metrics with labeled axes and units.

```

G. Performance Evaluation Parameters

Several performance metrics were assessed in this simulation to evaluate the effectiveness of the proposed 5G-NDN integration model.

H. Handover Success Rate (HSR)

HSR represents the ratio between the number of successful handover processes and the total number of handovers attempts during a given simulation period. In essence, HSR quantifies the reliability of the handover mechanism in maintaining continuous connectivity as the User Equipment (UE) transitions between gNodeB.

$$HSR = \frac{NSuccess}{NAttempt} \times 100\% \quad (1)$$

where $NSuccess$ denotes the number of successful handovers, and $NAttempt$ indicates the total number of handover attempts observed during the simulation.

I. Fallback Efficiency

Fallback Efficiency (FE) is a way to see how well NDN fallback system works when handover fails because of signal loss, UPF changes, or high latency during UE mobility. When a handover fails, NDN doesn't needs to set up a new IP session like normal. Instead, it uses caching and forwarding hints in the network to get data from nearby caches (like the MEC or NDN router) so that the service can keep going without interruption.

Research Gür *et al.* [45] shows that re-issuing Interest and in-network caching cut down on packet loss and handover delay; Research by Hussaini *et al.* [33] stresses the role of forwarding hints in sending requests back to the previous node. So, FE is not just a technical sign that recovery is going well; it's also a way to measure how well the network works and how users feel about it (QoE). The network can keep service going better in places with a lot of movement if the FE value is higher; xing *et al.* [46] proposes the Dynamic Allocation of Mobile Data Flows (DAFM) method in the ICN architecture to overcome bottlenecks caused by using a single switching path for multiple data flows after handover. The method provides better performance in terms of packet delay, packet loss, and handover delay.

Based on this, Fallback Efficiency (FE) represents the percentage of handover failures that are successfully recovered by NDN fallback mechanisms, such as caches, buffers, or forwarding hints. Mathematically, FE is defined as:

$$FE = \frac{N_{Fallback}}{N_{total}} \times 100\% \quad (2)$$

FE is Fallback Efficiency — a percentage value that indicates how effective the NDN fallback mechanism is in recovering from handover failures. $N_{Fallback}$ is the number of handover failures that the NDN fallback mechanism successfully recovered from. This includes cases where: The UE temporarily loses connection during the handover, But the requested data can still be received

via the NDN cache at the edge (MEC) or core router, Without the need to wait for the handover to complete or restart the session. N_{Total} is the total number of handovers attempt during the simulation and testing period. This includes all handover attempts, whether successful, failed, or requiring a fallback.

$N_{Fallback}$ is not the total number of handover failures, but rather the number of handover failures that NDN successfully handled/recovered from. This means that if there were 100 handover failures, but only 70 were recovered by NDN, then $N_{Fallback} = 70$, not 100. See Table III.

TABLE III. INTERPRETATION OF FE VALUES

FE Value	Interpretation
FE = 0%	No handover failures were recovered successfully — the system either lacked a fallback mechanism or was ineffective. Even if a handover failure occurred, NDN was unable to mitigate it through caching.
FE = 5%	Half of the handover failures were successfully recovered — indicating the fallback mechanism is working, but there is still room for improvement.
FE=80-100%	Almost all handover failures can be recovered through the NDN fallback mechanism, indicating that the system is highly resilient and the service remains stable despite high mobility.

In NDN over 5G architectures (like in Fig. 1), 1) FE is an important measure because it shows how NDN is better than traditional IP, where service drops happen when handover fails. 2) Shows how well caching works at the MEC/edge. The higher the FE, the better the strategies for finding and caching content. 3) Helps QoE for real-time apps like gaming, video streaming, and self-driving cars, where service continuity is more important than latency. This formulation lets FE directly see how well NDN caching and alternate paths work when the conditions for handover are not stable. The better the fallback mechanism works, the better the FE and the better the user’s service quality, even when they are moving quickly or the radio is unstable.

J. Cache Hit Ratio (CHR)

CHR represents the proportion of content requests that are successfully served from the local cache (e.g., at the MEC or NDN Core Router) instead of being fetched from the original data source. It quantifies the efficiency of the in-network caching mechanism in reducing latency and bandwidth usage. The CHR is calculated as:

$$CHR = \frac{N_{hit}}{N_{total}} \times 100\% \quad (3)$$

where N_{hit} is the number of content requests satisfied from the cache, and $N_{request}$ represents the total number of content requests generated during the simulation.

K. Simulation Scenario

This simulation uses a simple topology to model the 5G network, providing clear insights into the handover process. The User Equipment (UE) acts as both a transmitter and a receiver, and the gNB is the main node. The connection status between the UE and the gNB in the

simulation shows how the handover process works. A solid line between the UE and the gNB shows that the connection is good when the UE is within the gNB coverage area. When the UE is not in the coverage area, on the other hand, the connection is shown with a dashed line. Fig. 3 shows the simulation topology. This simulation was conducted to examine how using NDN would affect 5G network performance during handover, encouraging the audience to understand the potential benefits. Python 3.11 was used to run the simulation, along with several libraries that helped, including NumPy for math and node position calculations, Pandas for data processing, Matplotlib for displaying results, and CSV and OS for writing simulation results to log files.

This simulation uses a mesh network topology, with gNB nodes ranging from 1 to 5 and UE nodes from 10 to 50, to explore various network densities. In the NDN over 5G scenario, an NDN overlay was added to the edge forwarder/MEC node, including a content store, and positioned close to the gNB to evaluate the effects of content caching on performance. The simulation scenarios are split into different groups based on the number of gNodeB (gNB) and User Equipment (UE). The goal of each scenario is to examine how changes in the number of gNB and UE affect key performance metrics, such as the HSR ratio, CHR, and handover probability. The goal of this simulation is also to test the quality of service by looking at three main metrics: throughput, latency, and packet loss. This simulation’s results give us a better idea of how NDN affects 5G network performance, especially in terms of mobility and handover efficiency.

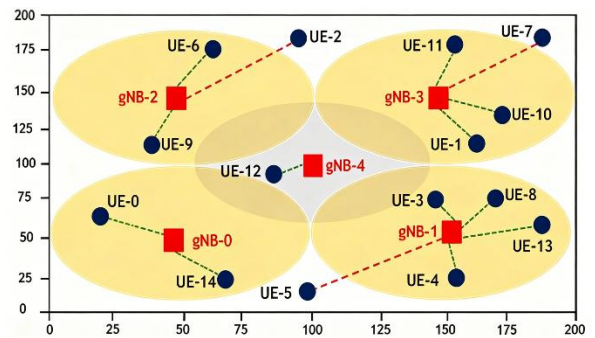


Fig. 3. Network topology NDN over 5G.

At the beginning of communication, each User Equipment (UE) connects through the gNB, and every content request (Interest Packet) is forwarded to the edge forwarder. If the requested content is available in the content store, the edge forwarder directly responds to the request. However, if the content is unavailable, the Interest Packet is forwarded to the User Plane Function (UPF) and subsequently to the Data Network (DN). In this simulation, the UE is modeled as a mobile node within a 200×200-meter simulation area. Each UE is initialized with random (x, y) coordinates and changes position in every simulation frame to emulate absolute user mobility within a cellular network. The detailed simulation scenario is shown in Table IV.

TABLE IV. NDN OVER 5G SIMULATION SCENARIO

Parameter	Symbol/Variable	Value/Description
Number of simulation runs (per gNB/UE)	num_runs	10
Simulation Frame	num_frames	120 frames
Simulation Area	area_size	500×500
Simulation frame	Area_size	50
Number of (UE), (gNB)	UE, gNB	20, 3
Number of gNB	gNB	3
Mobility parameter	Mobility Model, Vm	random_waypoint or gauss_markov
	Pedestrian fraction	50%
	Pedestrian speed,	(0.5–1.5 m/s), (8.0–15.0 m/s)
	Vehicle speed	
Radio / PHY Params:		
Transmit power gNB	tx_power_dbm	46.0 dBm
Carrier Frequency	Freq_Ghz	2.1 GHz
Bandwidth	bw_hz	10 MHz
-Noise figure	noise_Fig_dB	7.0 dB
Radio / Channel:		
Noise floor	Noise floor total	-174 dBm/Hz + 10·log ₁₀ (10 ⁷) + 7 dB ≈ -97 dBm
Model path loss	Model 3GPP	PL(d) = 128.1 + 10·3.76·log ₁₀ (d [km])
Shadowing	Log-normal sigma (dB)	Log-normal, σ = 8.0 dB
Fading Models	Rayleigh, Rician	rayleigh (default), optional rician (K = 6 dB) or none
Mobile Network		
Simulation area	Coverage_Radius	200×200
gNB capacity	UE/gNB	5 UE per gNB
- Coverage Radius	UE-Variations	50 m
gNB position	gNB	[[100, 250], [250, 250], [400, 250]]
UE Variations	UE	[10, 20, 30, 50]
Handover & Connection:		
Minimum SINR threshold	dB	-12 dB
Handover decision strategy	Comb.SINR + cache	if content is available → +10 dB
Handover rejection handling	UE/gNB	UE remains on the previous gNB if it is still (capacity coverage)
gNodeB (gNB)	RSSI Threshold	1, 2, 3, 4, 5
RSSI Threshold	SNR Threshold	-95 dBm
SNR Threshold	Threshold (dB)	5 dB, -12dB
NDN Parameter:		
Content catalog size	C	30 Chunk (video_0 to video_29)
Content requests per EU	C/UE, 1 request /s/UE	Randomly selected based on uniform distribution
Distrb.of content popularity	Zipf	with parameter α
Cache per gNB	CS	4 random contents per gNB
Cache Size	CS	Content Store (CS) Capacity on each node
Cache policy	LRU	last_used [i], timestamp [i]
NDN Component	FIB, CS, PIT	CS Hit, CSHR
QoS & Logging	Service quality metrics	RSRP (dBm), SINR (dB), Latensi (ms), Throughput (Mbps), P.loss (%)

IV. RESULT AND DISCUSSION

This part looks at how well the proposed 5G handover mechanism with NDN enhancement works. The assessment emphasizes three principal QoS metrics—latency, throughput, and packet loss—which serve as critical indicators of network efficiency and reliability in mobility contexts. A conventional IP-based 5G network and an integrated 5G–NDN architecture are compared to see how adding

content-centric features to the cellular core can help. We used a controlled environment with different numbers of gNB (2, 3, 4, 6, and 8) to see how well both network configurations could grow and stay stable. The following sections go into great detail on the results, showing how NDN integration improves data transmission efficiency, reduces handover delay, and lowers packet loss compared to the traditional method. Table V shows that the NDN-based architecture consistently outperforms the IP baseline as the number of gNB increases.

TABLE V. COMPARISON OF EFFECTS OF gNB ON PARAMETERS (NDN 5G VS BASELINE IP 5G)

Parameter	Number of gNB									
	2		3		4		6		8	
	NDN 5G	IP 5G	NDN 5G	IP 5G	NDN 5G	IP 5G	NDN 5G	IP 5G	NDN 5G	IP 5G
hsr (%)	49.80	53.35	63.88	67.65	72.96	76.37	85.62	89.54	90.73	95.21
chr (%)	56.84	0	57.62	0	57.97	0	58.03	0	59.11	0
fallback (%)	17.63	0	19.36	67.65	72.96	0	85.62	0	95.37	0
latency (ms)	4.27	6.25	3.70	4.38	2.79	3.81	2.35	3.56	1.27	2.46
throughput (mbps)	141.9	125.1	153.0	135.1	158.9	142.5	179.7	158.9	202.1	179.1
packet loss (%)	63.78	67.69	57.14	60.22	49.29	53.83	25.17	30.95	11.06	16.35

Table VI shows how the number of User Equipment (UE) in NDN and IP-based 5G networks affects key performance metrics. The numbers range from 5 to 80. This is to gauge how well the system performs with a large number of users. Both architectures perform worse as the number of UE increases due to increased competition and increased resource usage. However, the NDN-based system performs better in many ways.

To ensure the reliability and reproducibility of our performance evaluation, we complement all key metrics with rigorous statistical confidence analysis. Specifically, for each reported result derived from five independent

simulation runs per scenario—we compute both the sample standard deviation (St.Dev) and the 95% confidence interval (CI) using the Student’s t-distribution (with degrees of freedom $df=4$, since $n=5$) The 95% CI is calculated as $\bar{x} \pm t_{0.975,4} * \frac{s}{\sqrt{5}}$, where \bar{x} is the sample mean, s is the sample standard deviation, and $t_{0.975,4}=2.776$. This approach accounts for the limited number of repetitions while providing a statistically sound bound on the true population mean. \pm St. Dev and 95% CI values (e.g., “Latency = 1.27 \pm 0.20 ms, 95% CI: 1.02–1.52 ms”).

TABLE VI. COMPARISON OF EFFECTS UE ON PARAMETERS (NDN 5G VS BASELINE IP 5G)

Parameter	Number of UE									
	5		10		20		40		80	
	NDN 5G	IP 5G	NDN 5G	IP 5G	NDN 5G	IP 5G	NDN 5G	IP 5G	NDN 5G	IP 5G
HSR (%)	98.424	95.42	96.52	92.69	75.32	71.98	67.50	45.22	58.75	38.24
CHR (%)	8.664	0	22.57	0	55.35	0	78.12	0	87.22	0
Fallback (%)	6.634	0	21.53	0	22.55	0	37.03	0	44.92	0
Latency (ms)	2.66	4.77	10.73	15.42	31.39	36.56	38.68	45.89	45.01	60.75
Throughput (Mbps)	34.50	30.67	31.49	29.67	15.24	10.29	7.886	4.946	3.944	2.986
Packet Loss (%)	8.176	11.20	15.05	17.03	23.88	26.11	34.178	37.26	57.576	61.63

Example: We want to calculate the 95% confidence interval (CI) based on the data in Table VII, namely: 2 gNB: HSR = 49.80 \pm 0.30% (95% CI: 49.43 – 50.17%). from table VII, row 2 gNB on NDN 5G HSR parameters (%), the values of 5 simulations are: run 1: 49.31, run 2: 49.89, run 3: 49.64, run 4: 50.02, run 5: 50.13. from table VII, row 2 gNB on NDN 5G HSR parameters (%).

The values of 5 simulations are: run 1: 49.31, run 2: 49.89, run 3: 49.64, run 4: 50.02, run 5: 50.13.

So the number of samples: $n = 5$. then we calculate the average value (mean), by adding the values of runs 1 to 5 then divided by the number of simulations, resulting in a value of 49.789, see (1), and the results match the average value in the table. The standard deviation (St.Dev) value has been obtained in the table, so we only need to determine the t value for the 95% CI. Since $n = 5$ (small), we use a distribution with: degrees of freedom for a 95% confidence level, critical value: 2,776. Next, we calculate the Standard Error (SE) by:

$$SE = \frac{s}{\sqrt{n}} = \frac{0.30}{\sqrt{5}} = \frac{0.30}{2.2361} \approx 0.1342$$

Then the margin of error (ME) is calculated based on

$$ME = t \times SE = 2.776 \times 0.1342 \approx 0.3725$$

So the 95% Confidence Interval (CI) is calculated based on the Lower bound and Upper Bound. So 95% CI = [49.43%, 50.17%]

$$(LB) = \bar{x} - ME = 49.80 - 0.3725 = 49.4275 \approx 49.43$$

$$(UB) = \bar{x} + ME = 49.80 + 0.3725 = 50.1725 \approx 50.17$$

A. The Effect of gNB on HSR and CHR

The handover Success Rate (HSR) changes across two network architectures as the number of gNB increases: NDN 5G (red bars) and Baseline (IP) 5G (blue bars). As the number of gNB goes up, the figure shows that both systems have different trends in HSR. The HSR for NDN

5G starts high at about 95.37% with two gNB, stays steady at about 95.01% with three gNB and 94.99% with four gNB, then drops to 85.62% with six gNB and rises slightly again to 90.73% with eight gNB. The Baseline (IP) 5G starts lower, at 53.35% with two gNB. It then slowly rises to 67.65% with three gNB, 76.43% with four gNB, 89.54% with six gNB, and finally reaches 95.21% with eight gNB. This data shows that NDN 5G has a higher HSR on average across different numbers of gNB, but Baseline (IP) 5G gets better as more gNB are added. The NDN architecture provides more consistent and reliable handover performance, which helps keep the network stable, especially when many devices are switching between gNB. Adding NDN to a network makes mobility support more stable and predictable as the network gets more complicated. See Fig. 4 and Table VII for a comparison of (HSR), This is better than traditional IP-based 5G.

Fig. 5 and Table VII shows how the Cache Hit Ratio (CHR) changes when the number of UE goes up for two types of networks: NDN 5G (red bars) and Baseline (IP) 5G (blue bars). With 2 UE, the NDN 5G architecture keeps a CHR of about 56.84%. With 3 UE, it goes up to 57.62%, with 4 UE, it goes up to 57.97%, with 6 UE, it goes up to 58.03%, and with 8 UE, it goes up to 59.11%. The Baseline (IP) 5G, on the other hand, has a CHR of 0% for all UE counts. This shows one of the main benefits of NDN: its content-centric design lets data be cached locally and stored on the network, so that frequently requested data can be served directly from the nearest node instead of a remote server. The NDN 5G network’s steady CHR values show that caching is working well, even as the number of UE grows. On the other hand, the IP-based baseline doesn’t has this scalable caching feature, so there are no cache hits. This makes it less efficient for delivering content in dense mobile network environments.

Table VII shows the Handover Success Rate (HSR) for various gNB number configurations (2–8). Each value is accompanied by a standard deviation (St. Dev) and a 95% Confidence Interval (CI) based on five independent simulations. The results show that although the HSR increases with the addition of gNBs in both architectures, 5G NDN exhibits better stability in medium-density scenarios, while the quantitative comparison claim is supported by narrow averages and CIs.

Table VII compares the Cache Hit Ratio (CHR) between NDN 5G and Baseline IP 5G. As expected, the IP-based architecture does not generate any cache hits (0% in all scenarios), while NDN 5G records a stable CHR between 56.84% to 59.11%, with a standard deviation ≤ 0.4 and tight confidence intervals, proving the effectiveness of content-based caching in a multi-gNB environment.

TABLE VII. COMPARISON OF 95% CONFIDENCE INTERVAL (CI) ON THE EFFECTS OF gNB ON HSR AND CHR (NDN 5G vs BASELINE IP 5G)

Effect	gNB	NDN 5G				BASELINE IP 5G			
		Total	Avg	St. Dev	95% CI	Total	Avg	St. Dev	95% CI
HSR%	2	248.0	49.80	0.3	49.80 ± 0.30% (95% CI: 49.43 – 50.17%)	0.3	52.98	0.3	53.35 ± 0.30% (95% CI: 52.98 – 53.72%)
	3	64.15	63.88	0.3	63.88 ± 0.30% (95% CI: 63.51 – 64.25%)	0.3	67.21	0.3	67.65 ± 0.30% (95% CI: 67.28 – 68.02%)
	4	364.8	72.96	0.3	72.96 ± 0.30% (95% CI: 72.59 – 73.33%)	0.3	76.85	0.4	76.43 ± 0.40% (95% CI: 75.93 – 76.93%)
	6	428.1	85.62	0.4	85.62 ± 0.40% (95% CI: 85.12 – 86.12%)	0.4	89.78	0.4	89.54 ± 0.40% (95% CI: 89.04 – 90.04%)
	8	453.6	90.73	0.4	90.73 ± 0.40% (95% CI: 90.23 – 91.23%)	0.4	95.37	0.4	95.21 ± 0.40% (95% CI: 94.71 – 95.71%)
CHR%	2	284.2	56.84	0.2	56.84 ± 0.20% (95% CI: 56.59 – 57.09%)	0	0	0	0.00 ± 0.00% (95% CI: 0.00 – 0.00%)
	3	64.15	57.62	0.4	57.62 ± 0.40% (95% CI: 57.12 – 58.12%)	0	0	0	0.00 ± 0.00% (95% CI: 0.00 – 0.00%)
	4	288.1	57.97	0.2	57.97 ± 0.20% (95% CI: 57.72 – 58.22%)	0	0	0	0.00 ± 0.00% (95% CI: 0.00 – 0.00%)
	6	290.2	58.03	0.2	58.03 ± 0.20% (95% CI: 57.78 – 58.28%)	0	0	0	0.00 ± 0.00% (95% CI: 0.00 – 0.00%)
	8	295.6	59.11	0.3	59.11 ± 0.30% (95% CI: 58.74 – 59.48%)	0	0	0	0.00 ± 0.00% (95% CI: 0.00 – 0.00%)

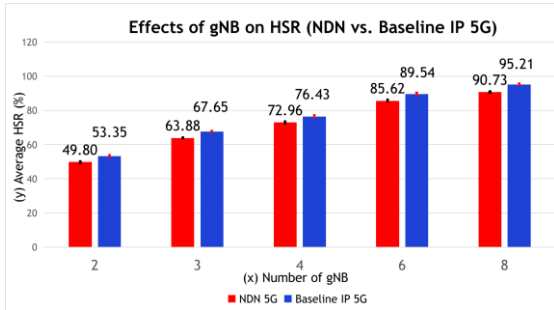


Fig. 4. Effects of gNB on HSR (NDN vs. Baseline IP 5G).

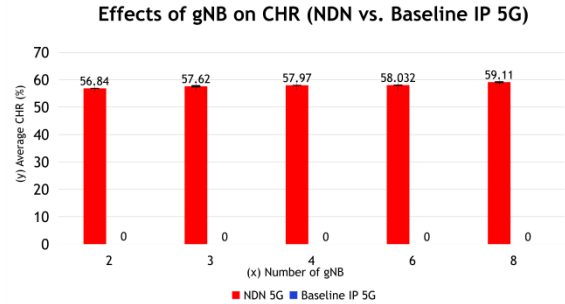


Fig. 5. Effects of gNB on CHR (NDN vs. Baseline IP 5G).

B. The Effect of gNB on Fallback Efficiency and Latency

Fig. 6 and Table VIII shows how the number of gNB affects the Average Fallback Efficiency in two types of networks: NDN 5G (red bars) and Baseline (IP) 5G (blue bars). In the NDN 5G environment, the fallback efficiency goes up from 17.63% with two gNB to 19.36% with three gNB, 26.00% with four gNB, 31.21% with six gNB, and 35.24% with eight gNB. The Baseline (IP) 5G, on the other hand, always shows a fallback efficiency of 0% no matter how many gNB there are. The fact that fallback efficiency for NDN is going up means that as the network gets denser, the NDN architecture uses more adaptive fallback mechanisms to keep connections going smoothly during handover failures or network instability. On the other hand, the IP-based baseline doesn't have an active, scalable fallback mechanism, so handover failures probably mean that the connection is lost right away and there are no attempts to get it back. This big difference shows one of NDNs best features: it can handle mobility problems well with context-aware fallback strategies,

which makes it more stable and reliable in fast-moving, high-density 5G environments.

Fig. 7 and Table VIII shows how adding gNB changes the average end-to-end latency in both the NDN-enhanced architecture (red bars) and the standard IP-based baseline (blue bars). Both architectures show a general trend toward lower latency as the network gets busier, but they work and are more efficient in very different ways. In the NDN environment, latency starts at 4.27 ms with two gNB. It then drops to 3.70 ms with three gNB, 2.79 ms with four gNB, 2.35 ms with six gNB, and finally 1.27 ms with eight gNB. The IP-based baseline also shows a drop in latency, starting at 6.25 ms with two gNB, dropping to 4.38 ms with three gNB, going up a little to 3.81 ms with four gNB, then dropping to 3.56 ms with six gNB, and finally reaching 2.46 ms with eight gNB. Both systems work better with more gNB, but the NDN architecture always works better than the IP baseline, no matter how many gNB there are. As the number of gNB in the NDN network goes up, latency goes down by almost 50%. Because NDN is content-centric, it uses in-network caching and

name-based routing to speed up the process of sending data to and from remote servers. The results show that NDN not only reduces latency more effectively than traditional IP, but it also works better as the network gets denser. This makes it a good choice for 5G applications that need very low latency, like real-time gaming, self-driving cars, and remote surgery.

Table VIII quantifies the systems ability to recover service when a handover fails. 5G NDN shows a consistently increasing Fallback Efficiency from 17.63% (2 gNB) to 35.24% (8 gNB), with a narrow CI, while the

5G IP Baseline remains at 0%, confirming that only the NDN architecture provides a cache-based fallback mechanism.

Table VIII shows that end-to-end latency decreases with increasing number of gNBs in both architectures, but 5G NDN consistently outperforms—for example, 1.27 ± 0.20 ms at 8 gNBs compared to 2.46 ± 0.20 ms at the baseline. All values are accompanied by St. Dev and 95% CI, indicating that the NDN performance improvement is statistically significant and reproducible.

TABLE VIII. COMPARISON OF 95% CONFIDENCE INTERVAL (CI) ON THE EFFECTS OF GNB ON FALLBACK EFFICIENCY (FE) AND LATENCY (NDN 5G VS BASELINE IP 5G)

Effect	gNB	NDN 5G				BASELINE IP 5G			
		Total	Avg	St. Dev	95% CI	Total	Avg	St. Dev	95% CI
Fallbac Efficiency (%)	2	88.15	17.63	0.2	$17.63 \pm 0.20\%$ (95% CI: 17.38 – 17.88%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	3	96.80	19.36	0.2	$19.36 \pm 0.20\%$ (95% CI: 19.11 – 19.61%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	4	30.00	26.00	0.4	$26.00 \pm 0.40\%$ (95% CI: 25.50 – 26.50%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	6	156.06	31.21	0.2	$31.21 \pm 0.20\%$ (95% CI: 30.96 – 31.46%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	8	176.19	35.24	0.2	$35.24 \pm 0.20\%$ (95% CI: 34.99 – 35.49%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
Latency (ms)	2	21.37	4.27	0.3	4.27 ± 0.30 ms (95% CI: 3.89 – 4.65 ms)	31.25	6.25	0.2	6.25 ± 0.20 ms (95% CI: 6.00 – 6.50 ms)
	3	64.15	3.70	0.2	3.70 ± 0.20 ms (95% CI: 3.45 – 3.95 ms)	21.9	4.38	0.2	4.38 ± 0.20 ms (95% CI: 4.13 – 4.63 ms)
	4	13.93	2.79	0.1	2.79 ± 0.10 ms (95% CI: 2.67 – 2.91 ms)	19.05	3.81	0.1	3.81 ± 0.10 ms (95% CI: 3.69 – 3.93 ms)
	6	11.77	2.35	0.1	2.35 ± 0.10 ms (95% CI: 2.23 – 2.47 ms)	17.79	3.56	0.1	3.56 ± 0.10 ms (95% CI: 3.44 – 3.68 ms)
	8	6.36	1.27	0.2	1.27 ± 0.20 ms (95% CI: 1.02 – 1.52 ms)	12.3	2.46	0.2	2.46 ± 0.20 ms (95% CI: 2.21 – 2.71 ms)

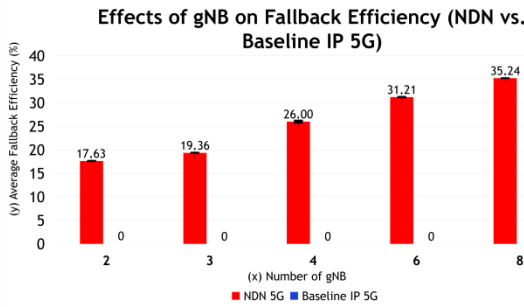


Fig. 6. Effects of gNB on fallback efficiency (NDN vs. baseline IP 5G).

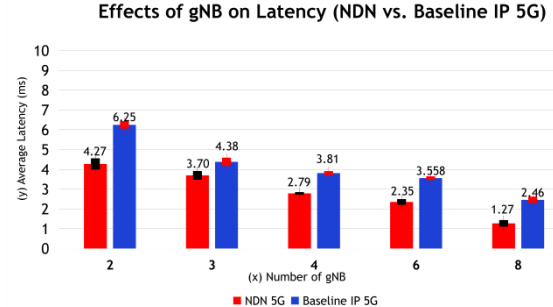


Fig. 7. Effects of gNB on latency (NDN vs. baseline IP 5G).

A. The Effect of gNB on Throughput and Packet Loss

The number of gNB affects the average throughput of the NDN-enhanced architecture (red bars) and the baseline IP architecture (blue bars). This is shown in Fig. 8 and Table IX As the number of gNB increases from 2 to 8, both systems exhibit higher throughput. This is because more resources are available and spatial reuse is better. In all setups, the NDN architecture always beats the IP baseline. When there are two gNB, the NDN throughput is 141.9 Mbps. With three gNB, it reaches 153.0 Mbps. When there are four gNB, it reaches 158.9 Mbps. When there are six gNB, it reaches 179.7 Mbps, and when there are eight gNB, it reaches 202.1 Mbps. With two gNB, the IP-based baseline starts at 125.1 Mbps. With three gNB, it reaches 135.1 Mbps; with four gNB, 142.5 Mbps; with six gNB, 158.9 Mbps; and with eight gNB, 179.1 Mbps. Both architectures can handle more traffic, but NDN scales more smoothly and

achieves better peak performance, with a maximum throughput about 23 Mbps higher than the IP baseline at full density.

These improvements are possible because NDN uses in-network caching and content-aware routing to reduce unnecessary data transfers and improve path selection. These results show that adding NDN to 5G networks not only increases throughput but also improves performance stability and traffic handling as the network grows.

Fig. 9 and Table IX shows how adding more gNB changes the average packet loss for both the NDN-enhanced architecture (red bars) and the standard IP-based baseline (blue bars). As the number of gNB goes up from 2 to 8, both systems show a clear drop in packet loss. This means that connections are more stable and resources are more available. In every configuration, the NDN architecture always beats the IP baseline. With two gNB, NDN starts with 63.78% packet loss and goes

down steadily to 57.14% with three gNB, 49.29% with four gNB, and then drops sharply to 25.17% with six gNB and finally to 11.06% with eight gNB. The IP baseline starts at 67.69% with two gNB, goes down to 60.22% with three gNB, stays around 53.83% with four gNB, drops to 30.95% with six gNB, and ends at 16.35% with eight gNB. Both architectures work better with denser deployments, but NDN gets lower packet loss faster, especially when there are more than four gNB.

The fact that NDN is content-centric makes it possible to use intelligent caching, which cuts down on the need for remote servers and makes routing more stable during mobility events. These results show that NDN is better at keeping data safe when network conditions change. This

makes it a great choice for 5G applications that need low latency and high mission-critical reliability.

Table IX shows that throughput increases with gNB density, with 5G NDN achieving 202.1 ± 0.1 Mbps at 8 gNBs, or ~13% higher than the baseline. The very small standard deviation (≤ 0.3 Mbps) and narrow CI (± 0.2 Mbps) indicate high consistency in high-speed data delivery. Table IX shows that packet loss decreases drastically with the addition of gNBs, with 5G NDN reaching $11.06 \pm 0.20\%$ at 8 gNBs, lower than the baseline ($16.35 \pm 0.20\%$). The narrow confidence interval indicates that the benefit of NDN in reducing packet loss is robust and non-random.

TABLE IX. COMPARISON OF 95% CONFIDENCE INTERVAL (CI) ON THE EFFECTS OF gNB ON THROUGHPUT AND PACKET LOSS (NDN 5G vs BASELINE IP 5G)

Effect	gNB	NDN 5G				BASELINE IP 5G			
		Total	Avg	St. Dev	95% CI	Total	Avg	St. Dev	95% CI
Throughput (%)	2	709.6	141.9	0.3	141.9 ± 0.3 (95% CI: 141.5 – 142.3 Mbps)	625.4	125.1	0.3	125.1 ± 0.3 (95% CI: 124.7 – 125.5 Mbps)
	3	64.2	153.0	0.2	153.0 ± 0.2 (95% CI: 152.8 – 153.2 Mbps)	675.6	135.1	0.2	135.1 ± 0.2 (95% CI: 134.9 – 135.3 Mbps)
	4	794.7	158.9	0.2	158.9 ± 0.2 (95% CI: 158.7 – 159.1 Mbps)	712.3	142.5	0.2	142.5 ± 0.2 (95% CI: 142.3 – 142.7 Mbps)
	6	898.6	179.7	0.2	179.7 ± 0.2 (95% CI: 179.5 – 179.9 Mbps)	794.5	158.9	0.2	158.9 ± 0.2 (95% CI: 158.7 – 159.1 Mbps)
	8	1011	202.1	0.1	202.1 ± 0.1 (95% CI: 202.0 – 202.2 Mbps)	895.5	179.1	0.1	179.1 ± 0.1 (95% CI: 179.0 – 179.2 Mbps)
Packet Loss (%)	2	319	63.78	0.2	63.78 ± 0.20% (95% CI: 63.53 – 64.03%)	338	67.69	0.2	67.69 ± 0.20% (95% CI: 67.44 – 67.94%)
	3	64	57.14	0.2	57.14 ± 0.20% (95% CI: 56.89 – 57.39%)	301	60.22	0.2	60.22 ± 0.20% (95% CI: 59.97 – 60.47%)
	4	246	49.29	0.2	49.29 ± 0.20% (95% CI: 49.04 – 49.54%)	269	53.83	0.2	53.83 ± 0.20% (95% CI: 53.58 – 54.08%)
	6	126	25.17	0.2	25.17 ± 0.20% (95% CI: 24.92 – 25.42%)	155	30.95	0.1	30.95 ± 0.10% (95% CI: 30.83 – 31.07%)
	8	55	11.06	0.2	11.06 ± 0.20% (95% CI: 10.81 – 11.31%)	82	16.35	0.2	16.35 ± 0.20% (95% CI: 16.10 – 16.60%)

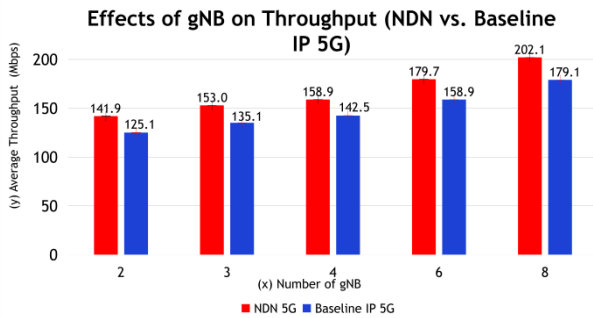


Fig. 8. Effects of gNB on throughput (NDN vs. baseline IP 5G).

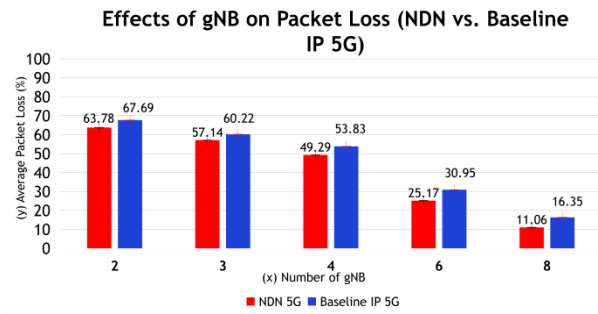


Fig. 9. Effects of gNB on packet loss (NDN vs. baseline IP 5G).

B. The Effect of UE on HSR and CHR

The handover Success Rate (HSR) is greatly affected by the number of User Equipment (UE) in both 5G NDN and 5G Baseline (IP) settings. The graph in Fig. 10 and Table X shows that both architectures keep HSR close to 100% with only a few UE (5–10). This means that the network is stable and not too crowded. As the number of UE grows, both systems HSR goes down, but at different rates. 5G NDN has a slightly higher HSR of 75.32% at 20 UE than 5G IPs 71.98%, which shows that NDN handles handover performance better when mobility increases. 5G NDN does much better than 5G IP at 40 UE, with an HSR of 67.50% compared to 45.22%. This suggests that NDN is better at handling heavy network loads. Even with a huge number of UE (80), NDN still has a clear edge with an HSR of 58.75%, while 5G IP drops to 38.24%. In general, these results show that increasing the

UE count has a negative effect on HSR in both architectures. However, 5G NDN is always more competitive and works better than traditional IP-based methods in different load situations.

The impact of increased User Equipment (UE) on the Cache Hit Ratio (CHR) distinctly illustrates the disparities between 5G NDN and 5G Baseline IP architectures. Fig.11 and Table X shows that 5G Baseline IP always has a CHR of 0% across all UE scenarios. This means that it can't keep sessions going when people move around. The CHR for 5G NDN, on the other hand, gets a lot better as the number of UE goes up. The CHR starts at 8.66% with 5 UE and goes up to 22.57% with 10 UE. This shows how the network is adjusting to the load. As the network density increases, 5G NDNs performance improves significantly, reaching 55.35% at 20 UE, 78.12% at 40 UE, and its highest CHR of 87.22% at 80 UE. These results show that name-based communication

and caching in NDN networks make them more resilient to mobility and congestion. They can keep sessions going and even improve them when traffic is heavy, which is something that traditional IP-based 5G systems can't do.

Table X shows the HSR degradation as user load increases (5–80 UEs). 5G NDN maintains an HSR of $58.75 \pm 0.30\%$ at 80 UEs, significantly above the baseline

($38.24 \pm 0.40\%$), with non-overlapping CIs—confirming NDNs superiority in dense user scenarios.

Table X shows that the CHR on 5G NDN increases with the number of UEs, reaching $87.22 \pm 0.90\%$ at 80 UEs, indicating that caching becomes more effective under high content demand conditions. In contrast, the baseline remains at 0%, confirming the reliance of IP on the end-to-end path without local caching support.

TABLE X. COMPARISON OF 95% CONFIDENCE INTERVAL (CI) ON THE EFFECTS OF UE ON HSR AND CHR (NDN 5G vs BASELINE IP 5G)

Effect	UE	NDN 5G				BASELINE IP 5G			
		Total	Avg	St. Dev	95% CI	Total	Avg	St. Dev	95% CI
HSR%	5	492.1	98.42	0.4	$98.42 \pm 0.40\%$ (95% CI: 97.92 – 98.92%)	477.1	95.42	0.4	$95.42 \pm 0.40\%$ (95% CI: 94.92 – 95.92%)
	10	482.6	96.52	0.3	$96.52 \pm 0.30\%$ (95% CI: 96.15 – 96.89%)	463.4	92.69	0.4	$92.69 \pm 0.40\%$ (95% CI: 92.19 – 93.19%)
	20	376.6	75.32	0.4	$75.32 \pm 0.40\%$ (95% CI: 74.82 – 75.82%)	359.9	71.98	0.4	$71.98 \pm 0.40\%$ (95% CI: 71.48 – 72.48%)
	40	337.5	67.50	0.1	$67.50 \pm 0.10\%$ (95% CI: 67.38 – 67.62%)	226.1	45.22	0.1	$45.22 \pm 0.10\%$ (95% CI: 45.10 – 45.34%)
	80	293.8	58.75	0.3	$58.75 \pm 0.30\%$ (95% CI: 58.38 – 59.12%)	191.2	38.24	0.4	$38.24 \pm 0.40\%$ (95% CI: 37.74 – 38.74%)
CHR%	5	43.3	8.66	0.4	$8.66 \pm 0.40\%$ (95% CI: 8.16 – 9.16%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	10	112.8	22.57	0.6	$22.57 \pm 0.60\%$ (95% CI: 21.83 – 23.31%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	20	276.8	55.35	0.8	$55.35 \pm 0.80\%$ (95% CI: 54.36 – 56.34%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	40	312.5	78.12	0.7	$78.12 \pm 0.70\%$ (95% CI: 77.25 – 78.99%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)
	80	436.1	87.22	0.9	$87.22 \pm 0.90\%$ (95% CI: 86.11 – 88.33%)	0	0	0	$0.00 \pm 0.00\%$ (95% CI: 0.00 – 0.00%)

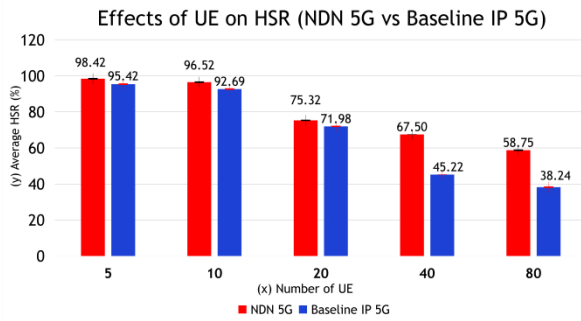


Fig. 10. Effects of UE on HSR (NDN 5G vs baseline IP 5G).

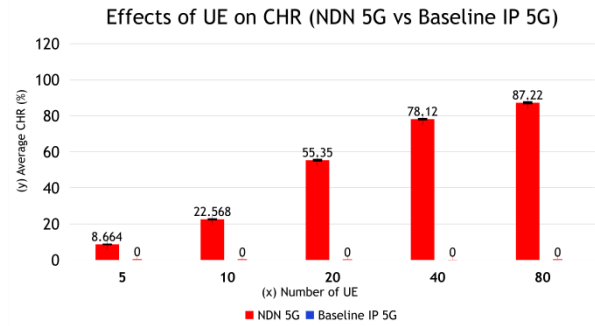


Fig. 11. Effects of UE on CHR (NDN 5G vs baseline IP 5G).

C. The Effect of UE on Fallback Efficiency and Latency

The effect of more User Equipment (UE) on Fallback Efficiency shows the significant performance difference between the 5G NDN and Baseline 5G IP architectures. The graph in Fig. 12 and Table XI shows that Baseline 5G IP always has a Fallback Efficiency of 0% across all UE scenarios. This means that there is no way to recover interrupted sessions during mobility events. In contrast, 5G NDN clearly shows that it can maintain the fallback operation, with efficiency increasing as the number of UE increases. 5G NDN has a fallback efficiency of 6.63% when there are 5 UE, 21.53% when there are 10 UE, and 22.55% when there are 20 UE. At higher loads, efficiency continues to increase, reaching 37.03% at 40 UE and peaking at 44.92% at 80 UE. These results show that 5G NDN has a strong and scalable fallback mechanism that works even when the network is bustling. This resilience stems from its use of name-based communication and multipath data retrieval, which enable it to recover from service outages. Traditional IP-based 5G architectures don't have these features.

As more User Equipment (UE) connect to the network, the difference in performance between 5G NDN and

Baseline 5G IP architectures becomes clear. The graph in Fig. 13 and Table XI shows that both systems keep their latency low when there are only a few UE (5–10). 5G NDN shows latencies of 2.66 ms and 10.73 ms at 5 and 10 UE, respectively. 5G IP shows higher latencies of 4.77 ms and 15.42 ms. Latency goes up in both networks as the number of UE goes up because of more traffic and signaling overhead from mobility. But as the number of UE goes up, the latency gap between the two architectures gets bigger. 5G NDN has a latency of 31.39 ms at 20 UE, which is better than 5G IPs 36.56 ms. At 40 UE, NDN has a latency of 38.68 ms, and IP has a latency of 45.89 ms. This trend continues, and it becomes even clearer at 80 UE, where NDN has a latency of 45.01 ms, and IP has a latency of 60.75 ms. These results show that 5G NDN can handle more network traffic more efficiently by speeding up retrieval times with in-network caching and name-based forwarding. On the other hand, IP-based architectures see a bigger rise in latency as the number of UE grows. Table XI shows that the 5G NDN Fallback Efficiency increases from 6.63% (5 EUs) to 44.92% (80 EUs), indicating that the fallback mechanism is increasingly relevant in dense scenarios. All values are

accompanied by St. Dev and 95% CI, validating the claim that NDN provides scalable service resilience. In Table XI, latency increases with UE load, but 5G NDN remains

lower—e.g., 45.01 ± 0.60 ms at 80 UEs vs. 60.75 ± 0.60 ms at baseline. Non-overlapping CI between the two architectures indicate a statistically significant difference.

TABLE XI. COMPARISON OF 95% CONFIDENCE INTERVAL (CI) ON THE EFFECTS OF UE ON FALLBACK EFFICIENCY (FE) AND LATENCY (NDN 5G VS BASELINE IP 5G)

Effect	UE	NDN 5G				BASELINE IP 5G			
		Total	Avg	St. Dev	95% CI	Total	Avg	St. Dev	95% CI
FE %	5	33.2	6.634	0.8	6.63 ± 0.80 (95% CI: 5.64 – 7.62%)	0	0	0	0.00 ± 0.00 (95% CI: 0.00 – 0.00%)
	10	107.7	21.53	0.3	21.53 ± 0.30 (95% CI: 21.16 – 21.90%)	0	0	0	0.00 ± 0.00 (95% CI: 0.00 – 0.00%)
	20	112.8	22.55	0.4	22.55 ± 0.40 (95% CI: 22.05 – 23.05%)	0	0	0	0.00 ± 0.00 (95% CI: 0.00 – 0.00%)
	40	185.1	37.03	0.5	37.03 ± 0.50 (95% CI: 36.41 – 37.65%)	0	0	0	0.00 ± 0.00 (95% CI: 0.00 – 0.00%)
	80	224.6	44.92	0.5	44.92 ± 0.50 (95% CI: 44.30 – 45.54%)	0	0	0	0.00 ± 0.00 (95% CI: 0.00 – 0.00%)
Latency %	5	13.3	2.66	0.6	2.66 ± 0.60 (95% CI: 1.92 – 3.40 ms)	23.9	4.77	0.6	4.77 ± 0.60 (95% CI: 4.03 – 5.51 ms)
	10	53.7	10.73	0.4	10.73 ± 0.40 (95% CI: 10.23 – 11.23 ms)	77.1	15.42	0.4	15.42 ± 0.40 (95% CI: 14.92 – 15.92 ms)
	20	157.0	31.39	0.8	31.39 ± 0.80 (95% CI: 30.40 – 32.38 ms)	182.8	36.56	0.8	36.56 ± 0.80 (95% CI: 35.57 – 37.55 ms)
	40	193.4	38.68	0.8	38.68 ± 0.80 (95% CI: 37.69 – 39.67 ms)	229.5	45.89	0.8	45.89 ± 0.80 (95% CI: 44.90 – 46.88 ms)
	80	225.0	45.01	0.6	45.01 ± 0.60 (95% CI: 44.27 – 45.75 ms)	303.8	60.75	0.6	60.75 ± 0.60 (95% CI: 60.01 – 61.49 ms)

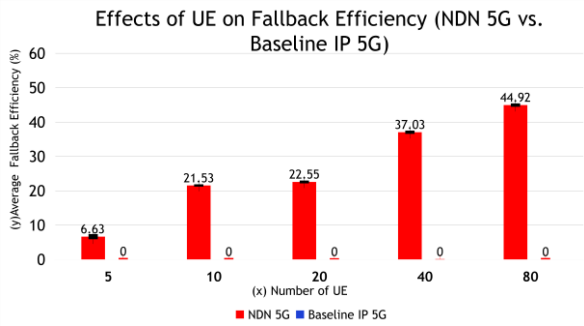


Fig.12. Effects of UE on fallback efficiency (NDN 5G vs. baseline IP 5G).

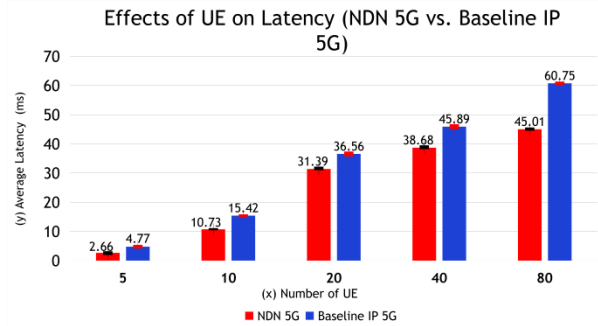


Fig.13. Effects of UE on latency (NDN 5G vs. baseline IP 5G).

D. The Effect of UE on Throughput and Packet Loss

Increasing the number of UEs reduces throughput in both 5G NDN and 5G IP due to mobility-related congestion, resource competition, and signaling overhead. However, 5G NDN consistently outperforms 5G IP. With 5–10 UEs, NDN achieves 35.42–32.65 Mbps versus IPs 30.14–24.7 Mbps. Even at 20 UEs, NDN maintains a higher throughput (12.07 Mbps) compared to IP (10.5 Mbps), as shown in Fig. 14 and Table XII.

This pattern continues even when the network is busier. For example, 5G NDN can send data at 5.81 Mbps with 40 UE and 3.17 Mbps with 80 UE. IP-based systems can only send data at speeds of 4.63 Mbps and 3.03 Mbps. The results show that name-based communication and caching in NDN networks make it easier to get data and cheaper to send it. This means that the network can still handle more data even if the number of UE grows. On the other hand, IP-based 5G architectures exhibit a larger throughput drop under the same conditions.

Fig. 15 and Table XII shows how the number of User Equipment (UE) affects the packet loss rate in two different network environments: 5G NDN and 5G IP

Baseline. The average packet loss in both cases increases significantly as the number of UE increases. When there is only a few UE, like 5, 5G NDN experiences slightly more packet loss than 5G IP Baseline. But as the number of UE grows, 5G IP Baseline tends to have more packet loss than 5G NDN. For instance, the 5G IP Baseline has a packet loss rate of 65.15% at 80 UE, while NDN 5G has a rate of only 56.76%. This means that 5G NDN can handle more UE more effectively than regular 5G IP networks, thereby better preventing data packet loss. So, 5G NDN has a better chance of maintaining high communication quality as more people use it.

Table XII Despite the throughput decrease due to resource competition, 5G NDN consistently outperforms the baseline in all scenarios (e.g., 3.94 ± 0.40 Mbps vs 2.99 ± 0.40 Mbps at 80 UEs), with CI supporting the claimed performance improvement.

Table XII, packet loss increases with UEs, but 5G NDN is consistently lower—especially at high load ($57.58 \pm 0.40\%$ vs. $61.63 \pm 0.40\%$ at 80 UEs). The small standard deviation and consistent CIs indicate the reliability of the simulation results.

TABLE XII COMPARISON OF 95% CONFIDENCE INTERVAL (CI) ON THE EFFECTS OF UE ON THROUGHPUT AND PACKET LOSS (NDN 5G VS BASELINE IP 5G)

Effect	UE	NDN 5G				BASELINE IP 5G			
		Total	Avg	St. Dev	95% CI	Total	Avg	St. Dev	95% CI
Throughput (Mbps)	5	709.6	141.9	0.3	34.5 ± 0.3 (95% CI: 34.1 – 34.9 Mbps)	625.4	125.1	0.3	30.67 ± 0.30 (95% CI: 30.30 – 31.04 Mbps)
	10	64.2	153.0	0.2	31.5 ± 0.2 (95% CI: 31.3 – 31.7 Mbps)	675.6	135.1	0.2	29.67 ± 0.20 (95% CI: 29.42 – 29.92 Mbps)
	20	794.7	158.9	0.2	15.2 ± 0.5 (95% CI: 14.6 – 15.8 Mbps)	712.3	142.5	0.2	10.29 ± 0.50 (95% CI: 9.67 – 10.91 Mbps)
	40	898.6	179.7	0.2	7.9 ± 0.3 (95% CI: 7.5 – 8.3 Mbps)	794.5	158.9	0.2	4.95 ± 0.40 (95% CI: 4.46 – 5.44 Mbps)
	80	1011	202.1	0.1	3.9 ± 0.4 (95% CI: 3.4 – 4.4 Mbps)	895.5	179.1	0.1	2.99 ± 0.40 (95% CI: 2.50 – 3.48 Mbps)
Packet Loss %	5	40.9	8.176	0.4	8.18 ± 0.40% (95% CI: 7.68 – 8.68%)	56.0	11.20	0.4	11.20 ± 0.40% (95% CI: 10.70 – 11.70%)
	10	75.3	15.05	0.2	15.05 ± 0.20% (95% CI: 14.80 – 15.30%)	85.2	17.03	0.3	17.03 ± 0.30% (95% CI: 16.66 – 17.40%)
	20	123.4	23.88	0.4	23.88 ± 0.40% (95% CI: 23.38 – 24.38%)	131	26.11	0.4	26.11 ± 0.40% (95% CI: 25.61 – 26.61%)
	40	163.5	34.18	0.3	34.18 ± 0.30% (95% CI: 33.81 – 34.55%)	186	37.26	0.3	37.26 ± 0.30% (95% CI: 36.89 – 37.63%)
	80	259.7	57.58	0.4	57.58 ± 0.40% (95% CI: 57.08 – 58.08%)	308	61.63	0.4	61.63 ± 0.40% (95% CI: 61.13 – 62.13%)

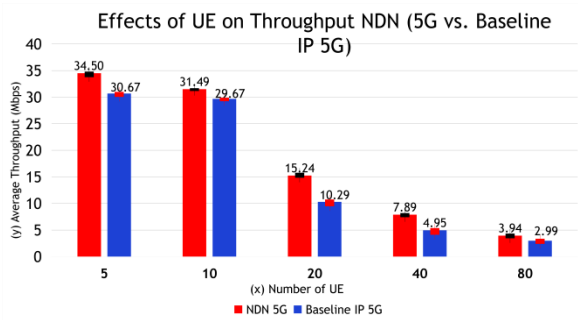


Fig. 14. Effects of UE on throughput NDN (5G vs. baseline IP 5G).

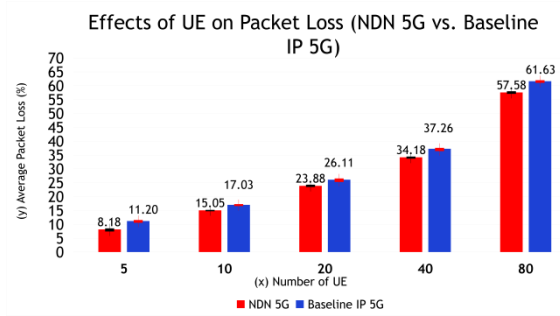


Fig. 15. Effects of UE on packet loss (NDN 5G vs. baseline IP 5G).

V. CONCLUSION

Our study shows that adding NDN to 5G architecture makes the network work much better during handover. This is especially true when there are a lot of gNB and people are moving around a lot. This is because it lowers latency, raises throughput, and lowers packet loss more than traditional IP-based methods. These benefits come from NDN built-in support for stateful forwarding, localized caching, and content-centric communication. These features work together to make it easy to connect and keep a high level of service in changing situations.

This research has implications: NDN can be a critical part of latency-sensitive 5G applications such as driverless cars, immersive AR/VR, and real-time industrial automation, which require constant data delivery. Our results show that the NDN architecture is naturally suited to the edge computing model, making it easy to use with distributed caching and content-based routing, and improving handover.

To further advance this direction, future research should focus on three key areas: (1) developing AI-based adaptive caching strategies that dynamically optimize content placement based on user mobility patterns and demand forecasts; (2) integrating NDN with 6G technologies, which includes support for terahertz frequencies, intelligent reflecting surfaces, and the requirements for ultra-reliable low-latency communication (URLLC); and (3) conducting experimental validation through real-world test beds or simulated large-scale deployments to evaluate scalability, security, and interoperability under diverse network conditions. It will also be important to look into hybrid

architectures that combine NDN with AI-driven network slicing and federated edge intelligence in order to fully realize the potential of next-generation mobile networks.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Ade Nurhayati defined the research problem, created a model for the proposed solution, tested the model, looked at the results, wrote the research report, and wrote the manuscript for publication; Tutun Juhana helped Ade Nurhayati oversee and guide the research process and helped set up the experimental environment by putting the system model into the NDN architecture, which focused on integrating 5G networks; Nana Rachmana Syambas set the overall research direction, oversaw all of the research activities, and made sure that Ade Nurhayati manuscript writing process was in line with academic standards; all authors had approved the final version.

ACKNOWLEDGMENT

The author would like to thank the NDN Research Team from the STEI ITB Telematics Lab, who provided initial ideas and suggestions for the writing structure of this paper from start to finish.

REFERENCES

[1] R. Ali, Y. B. Zikria, A. K. Bashir, S. Garg, and H. S. Kim. "URLLC for 5G and beyond: Requirements, enabling incumbent technologies and network intelligence," *IEEE Access*. vol. 9, pp. 67064–67095, 2021.

- [2] J. Park *et al.*, “Extreme ultra-reliable and low-latency communication,” *Nat Electron*, vol. 5, pp. 133–141, 2022.
- [3] M. Osama, A. A. Ateya, and A. Muthanna, “Ultra-reliable low-latency communications: Unmanned aerial vehicles assisted systems,” *Information*, vol. 13, no. 9, p. 430, 2022.
- [4] Z. Liu, Q. Deng, Z. Tan, Z. Qian, X. Zhang, A. Swami, and S. V. Krishnamurthy, “M2HO: Mitigating the adverse effects of 5G handovers on TCP,” in *Proc. 30th Ann. International Conference on Mobile Computing and Networking*, 2024, pp. 1089–1103. doi: 10.1145/3636534.3690680
- [5] E. F. Maleki, W. Ma, and L. Mashayekhy, “QoS-aware content delivery in 5G-enabled edge computing: Learning-based approaches,” *IEEE Transactions on Mobile Computing*, vol. 23, no. 10, pp. 9324–9336, 2024.
- [6] A. Haghrah *et al.*, “A survey on the handover management in 5G-NR cellular networks: aspects, approaches and challenges,” *J. Wireless Com Network*, vol. 52, 2023.
- [7] S. Ahdan and N. R. Syambas, “Towards efficient data communication in vehicular NDN: The superiority of Adaptive SRTT-Based Forwarding (ASF),” *Journal of Communications*, vol. 20, no. 4, pp. 415–435, 2025.
- [8] Z. Li, Y. Chen, and H. Shi, “NDN-GSM-R: A novel high-speed railway communication system via named data networking,” *J. Wireless Com Network*, vol. 48, 2016.
- [9] M. Xing, H. Deng, and R. Han. “A method for 5G – ICN seamless mobility support based on router buffered data,” *Future Internet*, vol. 16, no. 3, p. 96, 2024.
- [10] B. Saoud, I. Shayea, M. A. Alnakhli, and H. Mohamad, “Mobility and handover management in 5G/6G networks: Challenges, innovations, and sustainable solutions,” *Technologies*, vol. 13, no. 8, p. 352, 2025.
- [11] G. Cheng, C. Jiang, B. Yue, R. Wang, B. Alzahrani, and Y. Zhang, “AI-driven proactive content caching for 6G,” *IEEE Wireless Communications*, vol. 30, no. 3, pp. 180–188, 2023.
- [12] N. V. R. Guduri *et al.*, “Intelligent caching strategies for 5G edge networks using machine learning,” in *Proc. 4th International Conference on Smart Electronics and Communication*, 2023, pp. 44–49.
- [13] J. Deepakraj, P. Thangavel, and D. Deepa, “AI-driven smart caching for optimized web performance and reduced latency,” in *Proc. Fourth International Conference on Smart Technologies, Communication and Robotics (STCR)*, 2025, pp. 1–5.
- [14] S. Khan *et al.*, “PBatch: Pseudonym certificate batch authentication with generative AI-based cache for cooperative intelligent transportation systems,” *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–16, 2025.
- [15] J. F. Pereira, M. J. Nicolau and A. D. Costa, “VAL – Vehicular adaptation layer, for NDN,” *IEEE Access*, vol. 11, pp. 50064–50074, 2023.
- [16] M. Abdullah, A. Kiran, and U. Azam, “Mobility and content retrieval in vehicular named data network: Challenges and countermeasures,” in *Proc. 4th International Conference on Advancements in Computational Sciences (ICACS)*, Pakistan, 2023, pp. 1–8.
- [17] Y. Li, L. Guan, Z. Zhang, and G. Vogiatzis, “DPN: Density-based probability VANET caching method leveraging with NDN concept,” in *Proc. 2024 IEEE 21st International Conference on Mobile Ad-Hoc and Smart Systems (MASS)*, Seoul, Korea, 2024, pp. 557–562.
- [18] Y. Gan and R. Hou, “Location-based clustering for data transmission in vehicular named data networking,” in *Proc. 2024 IEEE/CIC International Conference on Communications in China (ICCC)*, Hangzhou, China, 2024, pp. 173–178.
- [19] S. U. Taki and S. Mastorakis, “An NDN-enabled fog radio access network architecture with distributed in-network caching,” in *Proc. IEEE International Conference on Communications*, Rome, Italy, 2023, pp. 5291–5296.
- [20] S. S. Ullah, S. Hussain, I. Ali, and S. Mastorakis, “A secure NDN-based architecture for electronic voting in 6G,” *IEEE Communications Standards Magazine*, vol. 7, no. 4, pp. 20–26, 2023.
- [21] J. Li *et al.*, “Two-stage optimization of computation offloading for ICN-assisted mobile edge computing in 6G network,” *ICT Express*, vol. 11, no. 1, pp. 26–33, 2025.
- [22] M. Imran *et al.*, “An efficient communication and computation resources sharing in information-centric 6G networks,” *IEEE Internet of Things Journal*, vol. 11, no. 16, pp. 27275–27294, 2024.
- [23] T. O. Atalay, A. Stavrou, and L. Zhang, “Envisioning the next-generation cellular architecture with named data networking,” *Computer*, vol. 58, no. 8, pp. 20–29, 2025.
- [24] D. Kim and J. Lee, “An NDN cache management for MEC,” *Applied Sciences*, vol. 10, no. 3, p. 896, 2020.
- [25] J. Xu, H. Shi, H. Chu and W. Zhang, “EeCA: A novel approach for energy conservation in MEC via NDN-based content caching,” in *Proc. 2023 24th Asia-Pacific Network Operations and Management Symposium (APNOMS)*, 2023, pp. 349–352.
- [26] M. Liyanage, P. Porambage, A. Y. Ding, and A. Kalla, “Driving forces for Multi-Access Edge Computing (MEC) IoT integration in 5G,” *ICT Express*, vol. 7, no. 2, pp. 127–137, 2021.
- [27] L. Chhangte and A. S. Patel, “Standardization aspects of caching and coded delivery in MEC integrated 5G system,” in *Proc. 2024 16th International Conference on Communication Systems and Networks (COMSNETS)*, 2024, pp. 1135–1138.
- [28] X. Gao and L. Zhai, “Service experience oriented cooperative computing in cache-enabled UAVs assisted MEC networks,” *IEEE Transactions on Mobile Computing*, vol. 23, no. 10, pp. 9721–9736, 2024.
- [29] M. M. Khan and E. R. M. Madeira, “ASSESSOR 360°: A MPEG-DASH based framework to estimate QoE for encrypted 360° video traffic with Multi-Access Edge Computing (MEC) over 5G,” in *Proc. 2025 12th International Conference on Future Internet of Things and Cloud (FiCloud)*, Istanbul, Turkiye, 2025, pp. 257–264.
- [30] L. Zhang, A. Afanasyev, J. Burke, V. Jacobson, K. C. Claffy, P. Crowley, C. Papadopoulos, L. Wang, and B. Zhang, “Named data networking,” *ACM Sigcomm Computer Communication Review*, vol. 44, no. 3, pp. 66–73, 2012.
- [31] A. Afanasyev, J. Burke, T. Refaei, L. Wang, B. Zhang and L. Zhang, “A brief introduction to named data networking,” in *Proc. 2018 IEEE Military Communications Conference (MILCOM)*, Los Angeles, CA, USA, 2018, pp. 1–6.
- [32] K. Lei, S. Zhong, F. Zhu, K. Xu, and H. Zhang, “An NDN IoT content distribution model with network coding enhanced forwarding strategy for 5G,” *IEEE Transactions on Industrial Informatics*, vol. 14, no. 6, pp. 2725–2735, 2017.
- [33] M. Hussaini, S. A. Nor, H. B. Salau, H. J. Hadi, A. A. Gumel, and K. A. Jahun, “Mobility support challenges for the integration of 5G and IoT in named data networking,” in *Proc. 2019 2nd International Conference of the IEEE Nigeria Computer Chapter (NigeriaComputConf)*, Zaria, Nigeria, 2019, pp. 1–7.
- [34] E. Juan, M. Lauridsen, J. Wigard, and P. Mogensen, “Performance evaluation of the 5G NR conditional handover in LEO-based non-terrestrial networks,” in *Proc. 2022 IEEE Wireless Communications and Networking Conference*, TX, USA, 2022, pp. 2488–2493.
- [35] M. R. Palas *et al.*, “Multi-criteria handover mobility management in 5G cellular network,” *Computer Communications*, vol. 174, pp. 81–91, 2021.
- [36] S. Bin Iqbal, A. Awada, U. Karabulut, I. Viering, P. Schulz, and G. P. Fettweis, “On the modeling and analysis of fast conditional handover for 5G-advanced,” in *Proc. 2022 IEEE 33rd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Kyoto, Japan, 2022, pp. 595–601.
- [37] J. Stanczak, U. Karabulut and A. Awada, “Conditional handover in 5G – Principles, future use cases and FR2 performance,” in *Proc. 2022 International Wireless Communications and Mobile Computing (IWCMC)*, Dubrovnik, Croatia, 2022, pp. 660–665.
- [38] T. S. Kumar *et al.*, “Advanced Handover Optimization (AHO) using deep reinforcement learning in 5G Networks,” *J. King Saud Univ. Comput. Inf. Sci.*, vol. 37, no. 115, 2025.
- [39] S. Kabir, “Study on 5G network architecture, research challenges, and existing solutions,” 2024.
- [40] G. Gur *et al.*, “Convergence of ICN and MEC for 5G: Opportunities and challenges,” *IEEE Communications Standards Magazine*, vol. 4, no. 4, pp. 64–71, 2021.
- [41] Q. N. Nguyen *et al.*, “A context-aware green information-centric networking model for future wireless communications,” *IEEE Access*, vol. 6, pp. 22804–22816, 2018.

- [42] L. Ge, J. Zhou, and Z. Zheng, "Dynamic hierarchical caching resource allocation for 5G-ICN slice," *IEEE Access*, vol. 9, pp. 134972–134983, 2021.
- [43] R. Ravindran, P. Suthar, A. Chakraborti, S. O. Amin, A. Azgin and G. Wang, "Deploying ICN in 3GPP's 5G nextgen core architecture," in *Proc. 2018 IEEE 5G World Forum (5GWF)*, Silicon Valley, CA, USA, 2018, pp. 26–32.
- [44] R. Ullah *et al.*, "ICN with edge for 5G: Exploiting in-network caching in ICN-based edge computing for 5G networks," *Future Generation Computer Systems*, no. 111, pp. 159–174, 2020.
- [45] G. Gür *et al.*, "Integration of ICN and MEC in 5G and beyond networks: Mutual benefits, use cases, challenges, standardization, and future research," *IEEE Open Journal of the Communications Society*, vol. 3, pp. 1382–1412, 2022.
- [46] M. Xing, H. Deng, and R. Han, "ICN-oriented mobility support method for dynamic allocation of mobile data flows," *Electronics*, vol. 12, no. 7, p. 1701, 2023.

Copyright © 2026 by the authors. This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited ([CC BY 4.0](https://creativecommons.org/licenses/by/4.0/)).