DTHA: A Digital Twin-Assisted Handover Authentication Scheme for 5G and Beyond

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Abstract—With the rapid development and extensive deployment of the fifth-generation wireless system (5G), it has achieved ubiquitous high-speed connectivity and improved overall communication performance. Additionally, as one of the promising technologies for integration beyond 5G, digital twin in cyberspace can interact with the core network, transmit essential information, and further enhance the wireless communication quality of the corresponding mobile device (MD). However, the utilization of millimeter-wave, terahertz band, and ultradense network technologies presents urgent challenges for MD in 5G and beyond, particularly in terms of frequent handover authentication with target base stations during faster mobility, which can cause connection interruption and incur malicious attacks. To address such challenges in 5G and beyond, in this paper, we propose a secure and efficient handover authentication scheme by utilizing digital twin. Acting as an intelligent intermediate, the authorized digital twin can handle computations and assist the corresponding MD in performing secure mutual authentication and key negotiation in advance before attaching the target base stations in both intra-domain and inter-domain scenarios. In addition, we provide the formal verification based on BAN logic, RoR model, and ProVerif, and informal analysis to demonstrate that the proposed scheme can offer diverse security functionality. Performance evaluation shows that the proposed scheme outperforms most related schemes in terms of signaling, computation, and communication overheads.

Index Terms—5G, digital twin, mobile device, handover authentication, and key agreement.

I. INTRODUCTION

O VER the past few decades, the rapid evolution of mobile devices (MDs) have transformed society, enabling unprecedented access to digital services through smartphones, wearables, and connected vehicles. The exponential growth of these devices has generated massive data traffic, creating unprecedented demands for reliable wireless communications [1]. To meet these requirements, the current fifth-generation wireless system (5G) leverages mmWave spectrum and other

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key technologies to achieve 50 Mbps data rates and offer other impressive features [2] [3]. Beyond 5G (B5G), the nextgeneration communication system is envisioned to use the ultra-wide terahertz (THz) band to further expand bandwidth and throughput for carrying the access of massive devices in the near future [4] [5]. To overcome transmission loss introduced by mmWave and THz, additional, ultra-dense networks (UDN) have been proposed by densely deploying a large number of small cells to improve spectrum efficiency [6].

While 5G and B5G can enhance the quality of communication, they also present additional mobility management challenges in high-speed mobility scenarios, such as highspeed railways and autonomous driving [7] [8]. The dense deployment of short-range base stations forces mobile devices to perform frequent handover authentication every few seconds to maintain continuous wireless connectivity. Additionally, the openness of the wireless channel makes the handover process susceptible to malicious attacks, such as eavesdropping and replay attacks [9], creating vulnerabilities that can lead to unauthorized access and compromised privacy. Although researchers have proposed various solutions leveraging advanced technologies like software-defined networks (SDN) and blockchain to enhance handover security and efficiency [10] [11], a key limitation of most existing schemes lies in adopting a reactive approach that only initiates handover authentication when mobile devices enter target base stations' coverage areas and reach the handover signal threshold. This device-initiated, network-controlled handover mechanism can lead to excessive latency and overhead, disrupting the stable and continuous connectivity of mobile devices to the network through base stations [8] [12].

As one of the promising technologies to be integrated into B5G, the emerging digital twin paradigm has garnered attention from both academia and industry [13]. A digital twin refers to the virtual agent of mobile device deployed in cyberspace [14] [15]. It receives and synchronizes multidimensional status data transmitted from mobile device, and employs artificial intelligence algorithms for process and analysis to generate decision feedback, such as providing realtime path planning and navigation for autonomous vehicles [16]. In B5G, digital twins can be used to further predict and optimize communication performance [13] [17]. By monitoring and evaluating the wireless link status, such as signal strength, the digital twin can provide feedback to the core network when detecting performance degradation through the dedicated application programming interface (API). Based on this feedback, the core network takes timely optimization measures, such as wireless resource allocation, to improve the communication quality of mobile devices [18].

This capability enables digital twin to assist mobile devices in proactive handover authentication, supporting the paradigm shift of mobility management in 5G and beyond [19]. On the one hand, the digital twin can predict and select the upcoming target base stations connections by analyzing devices' movement trajectories, especially for autonomous vehicle. On the other hand, the digital twin can act as an intelligent intermediary to access the core network as well as the predicted target base stations, transmit essential handover authentication parameters, and burden complex computation on behalf of the corresponding mobile device in advance. Builiding on this foundation, in this paper, we propose a novel Digital Twin-assisted Handover Authentication scheme (DTHA) that achieves mutual authentication and key negotiation between mobile device and target base stations for 5G and beyond wireless network. By delegating authentication tasks to digital twin, the proposed scheme ensures handover security while significantly reducing authentication overhead for mobile device. Specially, the main contributions are as follows:

- Architecture: We propose the first digital twin-assisted handover authentication architecture where the digital twin acts on behalf of the mobile device in operatorauthorized cyberspace. With authorized access to the core network and base stations, this digital twin-driven approach transforms reactive authentication patterns by enabling proactive handover management and secure authentication parameter exchange, reducing handover overhead in 5G and beyond networks.
- *Design*: We design handover authentication protocols for both intra-domain and inter-domain scenarios. The digital twin first obtains the delegation authority from the core network to act as a legitimate representative of the mobile device. Then, it proactively initiates handover authentication requests to target base stations and executes essential parameter transmission and complex computations on behalf of mobile device, enabling both the mobile device and target base stations to independently complete mutual authentication and key negotiation in advance.
- Validation: We conduct comprehensive security validation through three formal methods, Burrows-Abadi-Needham (BAN) logic, Real-or-Random (RoR) model, and ProVerif, which proves our scheme achieves mutual authentication, key negotiation and session key security. The informal analysis demonstrates that the proposed scheme can resist various attacks. Furthermore, comparative performance evaluations show that our scheme significantly outperforms most existing solutions in terms of signaling, computation, and communication overhead.

The organization of the rest of the paper is as follows. We first review the related works in section II. Then, we illustrate the system architecture, security threats and design goals in section III. We further detail the proposed scheme in section IV. Security analysis and performance evaluation of the proposed scheme are presented in section V and section VI, respectively. Finally, we draw the conclusion of the paper in section VII.

II. RELATED WORK

Handover authentication secures network access during user mobility by establishing mutual authentication between the mobile device and target access points, and negotiating session keys to protect against wireless vulnerabilities. The third generation partnership project (3GPP) has already standardized the 5G handover procedure in R16 [2]. However, it is vulnerable to suffering from different threats, such as de-synchronization attacks, replay attacks, etc [3]. Recent research has leveraged innovative technologies such as SDN, blockchain, and others to enhance the security and efficiency of handover authentication. We summarize some of these representative works as follows.

SDN separates the control plane and data plane in 5G, improving the flexibility and programmability of the network. Duan et al. [20] showed that SDN can share user-specific secure context information (SCI) with predicted cells to enable seamless handover authentication. On this basis, Cao et al. [21] proposed a pre-handover authentication mechanism where SDN forwards the device's session key and relevant information to the predicted next base station. In [7], SDN is employed to predict the moving path and inform the next base stations to initiate the handover procedure when the mobile device groups reach the signal threshold. Ma et al. [9] proposed an SDN-based 5G group handover authentication scheme that generates and distributes session keys using 5G-AKA between base stations and mobile nodes. However, the scheme [9] is limited to scenarios with fixed mobility trajectories, and the scheme [7] is vulnerable to replay attacks and man-in-themiddle attacks during the mobile device's handover request submission to the base station. In addition, these schemes [7], [9] employ aggregate message authentication codes (AMAC), which introduces susceptibility to Denial of Service (DoS) attacks during the handover process.

Blockchain is distributed ledgers that record transactions without tampering, which has been widely used in authentication management. Zhang et al. [22] and Liu et al. [23] utilized blockchain to store chameleon values of mobile devices and base stations for quick handover. However, Zhang et al.'s scheme [22] is vulnerable to tracking attack and location privacy leakage, as the chameleon value can be computed by any receiver. In response to this, Liu et al. [23] proposed periodically updating the chameleon values of mobile devices in the InterPlanetary File System (IPFS) to reduce the risk of being tracked. However, frequent handover of large-scale users could lead to excessive IPFS load, affecting data retrieval efficiency. Son et al. [24] designed a lightweight handover authentication scheme for vehicular networks where target RSUs retrieve vehicle information from the blockchain to enable efficient authentication and key agreement. Roy et al. [25] proposed utilizing RSUs as consortium blockchain nodes, storing vehicle handover authentication data as transactions on the blockchain, enabling RSUs to quickly verify vehicle identities and accomplish seamless handover authentication. Similarly,

Sanjeev et al. [26] proposed a dual-blockchain architecture to store vehicle and RSU registration information, leveraging smart contracts for cross-region handover authentication. However, in this scheme, blockchain consensus verification can introduce delays, potentially causing vehicle handover authentication failures in high-mobility scenarios. Fang et al. [12] used blockchain to protect vehicle authentication data in a zero-trust IoV environment, reducing handover authentication latency and utilizing smart contracts for reputation scoring to prevent malicious nodes from disrupting the process. However, attackers can create multiple fake ACs through Sybil attacks, enhancing the reputation of malicious nodes and allowing unauthorized vehicles to disguise themselves as legitimate to pass authentication.

In addition, several works apply digital signatures, physical layers, and other techniques to complete handover authentication. Gupta et al. [27] used proxy signature so that the base station and mobile device can mutually verify the proxy signature delegated by the core network to complete the authentication. However, it fails to effectively protect user privacy and is vulnerable to replay attacks, due to the MD information contained in the proxy certificate being publicly transmitted in communication channels. The scheme [28] introduces dynamic universal accumulators and sanitizable signatures to achieve privacy-preserving handover authentication. However, it fails to meet the requirements of Known Randomness Secrecy and Key Escrow Freeness. Yan et al. [29] employed aggregate signatures to achieve handover authentication between vehicle groups and base stations and utilized a binary search to mitigate DoS attacks. However, the scheme fails to defend against an ephemeral secret leakage attack. In [30], Cao et al. employed extended Chebyshev chaotic maps to complete access authentication for mobile devices and massive machinetype communication devices in 5G, but this scheme requires key generation center to generate keys for MD and base stations, making it impossible to achieve key escrow freedom. [31] realized handover authentication with the cooperation of least t out of n base stations based (t, n) threshold, but it fails to consider node selection criteria for optimizing threshold signature security. In [32], the authors designed a machinelearning protocol to select a target cell and guarantee both security and privacy during handovers in 5G, however, each handover authentication requires core network participation, which introduces additional communication and computation delays. Zhou et al. [33] proposed using Automatic Dependent Surveillance-Broadcast (ADS-B) to collect side information for optimizing handover decisions in Aerial-Ground Vehicular Networks. However, it is vulnerable to jamming and spoofing attacks, affecting handover reliability.

III. SYSTEM MODEL, THREAT MODEL, AND DESIGN GOALS

In this section, we first present the three-layered system model and describe the different entities that operate within each layer. We then discuss the threat model and identify the design goals in the proposed scheme.



Figure 1: System Model

A. System Model

Fig. 1 illustrates the system model in the proposed scheme, which is divided into three layers based on their practical requirements and specific functions: the 5G core network (5GC), the digital twin network (DTN), and the data plane (DP), with each layer consisting of various entities denoted in bold. The details of each layer and their corresponding entities are described below.

- 5GC: The 5G core network serves as the management center of the wireless network and plays a crucial role in network access, connection and routing. The network functions responsible for security and authentication in the 5GC primarily include the Access and Mobility Management Function (AMF), the Authentication Server Function (AUSF), and the Unified Data Management (UDM). AUSF and UDM are responsible for initial registration, identity management, and issuance of publicprivate key pairs in the wireless system. On the other hand, AMF is responsible for mobility management and generating globe temporary identity (GUTI) for each mobile device (MD), which controls the handover of MDs between different base stations, ensuring that the 5GC provides secure and reliable wireless communication services.
- **DTN**: Digital twin network is the virtual cyberspace operated on dedicated cloud servers provided by telecom operators. Authorized MDs with service subscriptions in the 5GC can create and deploy corresponding digital twins (**DTs**) on the DTN. These DTs not only provide decision feedback for the MDs via intra-twin communication but also communicate with each other to transmit useful data via inter-twin communication. Additionally, authorized DT on DTN can obtain the access methods of 5G network functions and base stations, enabling the establishment of connections and transmitting information

through proprietary APIs, which can underpin valuable information for MD. In the proposed scheme, through trajectory analysis, the primary function of DTs is to pre-exchange essential parameters with the target base stations that the MD is expected to attach to along its route and further reduce the authentication overhead of MD during handover.

• **DP**: Data plane consists of mobile device (**MD**) and 5G base station **gNB**. In 5G, the communication between the gNB and the MD is bidirectional, with both entities transmitting and receiving data via a wireless channel. On the one hand, MD such as smartphones, wearable devices and autonomous vehicles require access to the data network through gNB. The gNB maintains the connection with the AMF and is responsible for transmitting and forwarding data to AMF-authorized MD within its signal coverage area. Furthermore, to ensure wireless connection quality before leaving the current gNB, handover authentication with the new gNB in the mobile path is necessary due to the mobility of the MD.

B. Threat Model

In this paper, we adopt the Dolev-Yao (DY), Canetti-Krawczyk (CK) and extended CK (eCK) adversary models to identify potential attacks and vulnerabilities in our proposed handover authentication scheme involving MD, DT, gNB and AMF. Data is transmitted between the MD and DT/gNB over wireless channel, while the DT and gNB/AMF communicate over wired channel. Within these threat models, an adversary possesses multiple attack capabilities. Through the vulnerable wireless channel, the adversary can perform passive and active attacks, including eavesdropping, interception, replay, and message modification of transmitted data between entities. The adversary can also execute impersonation attacks by fraudulently assuming the identity of legitimate gNBs to deceive MDs into establishing connections. Furthermore, the adversary can acquire either the long-term secrets of the MD, DT, and gNB or their ephemeral secrets during the handover authentication phase. However, the simultaneous compromise of both long-term and ephemeral secrets is infeasible under the security model.

C. Design Goals

Our goal is to utilize the digital twin to provide a secure and efficient handover authentication for MD in 5G and beyond wireless networks. In order to address the aforementioned threats, the following design goals should be met:

- Mutual Authentication: As the primary goal in the proposed scheme, mutual authentication between the MD and target gNB is essential to confirm the identity of both parties before granting handover access. In addition, acting as the representative of the MD, the DT should authenticate with the target gNBs and AMF to ensure its legitimacy and authorization.
- Key Negotiation: In the proposed scheme, to ensure the confidentiality and integrity of transmitted data over the public wireless channel, the MD and target gNB must

negotiate a temporary session key during the handover authentication process.

- Anonymity: In the handover authentication phase, only the 5GC are permitted to disclose the true identity of the MD. Otherwise, the identity should be substituted with a pseudonym or concealed in ciphertext to prevent unauthorized disclosure by malicious attackers.
- Unlinkability: It is impossible for an adversary to distinguish that two messages originate from the same MD when eavesdropping on the wireless channel in the handover phase.
- Traceability: When malicious behavior occurs during the handover authentication phase, such as an unauthorized DT attempting to gain access to the core network or the base station, it is essential to expose the true identity of the DT and the MD it represents.
- Perfect Forward/Backward Secrecy (PFS/PBS): PFS ensures that even if the private keys used by gNB and MD are compromised, an adversary cannot recover the historical temporary session keys. PBS means that the attacker cannot access future temporary session keys even if the current key is compromised.
- Key Escrow Freedom (KEF): Each member's private key is kept by itself, there is no need for trusted third parties to distribute key materials in the authentication phase. Ephemeral Secrets Leakage Resistance (ESL): Even if the ephemeral secret key is leaked to the adversary, the negotiated temporary session key between the target gNB and the MD remains confidential.
- Protocol Attack Resistance: The proposed scheme is designed to resist common protocol attacks, such as eavesdropping, forging attacks, impersonation attacks, man-in-the-middle attacks, and others.

IV. THE PROPOSED SCHEME

In this section, we review the preliminaries employed in the scheme and then detail the digital twin-assisted handover authentication scheme in 5G.

A. Preliminaries

1) Elliptic Curve Cryptography: We adopt the elliptic curve cryptosystem (ECC) to ensure the security of our proposed scheme. Let E/F_p denote an elliptic curve E defined over a prime finite field F_p , where p is a large prime number. Let P be a generator point of E with prime order q. The elliptic curve equation is defined as $E(F_p) : y^2 \equiv x^3 + ax + b \mod p$, where $a, b \in F_p$ and $4a^3 + 27b^2 \not\equiv 0 \mod p$.

2) *Mathematical Assumptions:* The security of the proposed scheme is based on the following mathematical assumptions:

- Elliptic curve discrete logarithm problem (ECDLP): Given an additive group G of prime order q with generator point P and $xP \in G$, where $x \in Z_q^*$. It is computationally infeasible to determine the value of xfrom xP.
- Elliptic curve computational Diffie-Hellman problem (ECDHP): Given an additive group G of prime order q

with P and two elements $xP, yP \in G$, where $x, y \in Z_q^*$. It is computationally infeasible to compute the xyP with any polynomial time algorithm.

• Bilinear Diffie-Hellman problem (BDHP): It is hard to distinguish between two elements (g_1, g_2, g_T) and $(g_1, g_2, e(g_1, g_2))$ in two groups G_1 and G_2 that share a bilinear pairing $e: G_1 \times G_2 \to G_T$.

B. Brief Description of the Scheme

We begin by providing a brief description of our proposed scheme, which consists of 5 phases: System Initialization, DT Creation, Access Delegation, Intra-AMF Handover and Inter-AMF Handover.

System Initialization: The 5GC is responsible for booting up and initializing the system, which includes issuing system parameters and generating partial public/private key pairs for AMF and gNB.

DT Creation: The creation of the DT on the DTN requires approval from the 5GC after the MD's request is submitted. Upon approval, the DT then has the ability to access the gNB and AMF to transmit the essential data and enable the added-value service for its MD after deployment. Additionally, to ensure secure communication, the DT and its MD should negotiate a long-term session key.

Access Delegation: In this phase, the DT applies for access delegation from the AMF using the token issued by the MD. Upon verifying the legality of the DT and the correctness of the token, the AMF issues the delegation to the DT, indicating its authorization to access all gNBs within the current domain.

Intra-AMF Handover: In this phase, DT predicts MD's movement trajectory and initiates handover requests to target gNBs via dedicated API. The process begins with mutual authentication between DT and target gNBs. DT then facilitates session key negotiation by transmitting necessary parameters between MD and target gNBs, reducing MD's authentication overhead. When MD enters the target gNB's coverage area, it can complete handover authentication and establish secure communication using the pre-computed session key.

Inter-AMF Handover: When the MD is about to move to a new gNB under another AMF control range, the DT notifies both the source AMF and MD to trigger inter-AMF handover authentication. The MD transmits the newly generated pseudonym identity to the DT through a secure wireless channel, while the source AMF sends essential security context information to the target AMF to generate new access delegation for the DT in advance. The subsequent mutual authentication and key agreement between the MD and target gNB follows the same process as intra-AMF handover.

C. The Details of Proposed Scheme

The main notations used in the proposed scheme and their corresponding descriptions are shown in Table I. The details of the scheme are as follows:

1) System Initialization: The AUSF generates the system parameters and master key pair, while the AMF and gNB generate their respective public-private key pairs and obtain certified partial private keys from AUSF.

Table I: Notations Used

Notation	Description
MD_i, DT_j	The mobile device and digital twin respectively
$SUPI_i$	The subscription permanent identifier of mobile device
$GUTI_i$	The globally unique temporary identity of mobile device
TID_i	The temporary identifier of mobile device in the gNB
N_i	The nonce number
TS_i	The current timestamp
q	The large prime number
G	The additive cyclic group
P	The generator of the additive cyclic group
$H(\cdot)$	Collision-resistant cryptographic hash function
$KDF(\cdot)$	Key derivation function
pk, Y	The public key pairs
sk, x	The private key pairs
k_{ij}	The long-term session key between MD and DT
k_{SEAF}	The security anchor key between MD and core network
k_{gNB}	The session key between MD and gNB
δ	Authorized delegation
$,\oplus$	Concatenation and bitwise XOR operations respectively

Step 1: AUSF: System Parameters

1a. AUSF initiates system initialization by taking a security parameter κ as input. Subsequently, it generates a large prime number p of κ bits in length to establish the finite field F_p .

1b. AUSF selects a generator P of prime order q on the elliptic curve $E(F_p)$. It then defines an additive cyclic group G generated by P and a multiplicative cyclic group G_T of order q in the finite field. AUSF defines a bilinear pairing map as $e: G \times G \to G_T$. 1c. AUSF selects cryptographic hash functions as $H_0: G \times \{0,1\}^* \to Z_q^*, H_1: G \to \{0,1\}^l, H_2: G \times \{0,1\}^* \to \{0,1\}^l, H_3: G \times G_T \times \{0,1\}^* \to \{0,1\}^l, H_4: \{0,1\}^* \to \{0,1\}^l$, and $H_5: \{0,1\}^* \to Z_q^*$. 1d. AUSF randomly chooses $s \in Z_q^*$ as the master private key and computes the corresponding public key $pk_{pub} = s \cdot P$. Finally, AUSF publishes the system public parameters $\{q, e, P, G, G_T, H_0, H_1, H_2, H_3, H_4, H_5, pk_{pub}\}$ while keeping s secret.

- Step 2: AMF/gNB \rightarrow AUSF: $(pk_a, ID_a)/(pk_g, ID_g)$ 2a. AMF and gNB randomly select their private keys $sk_a, sk_g \in Z_q^*$ and compute the corresponding public keys $pk_a = sk_a \cdot P$ and $pk_g = sk_g \cdot P$ separately. 2b. AMF and gNB transmit (ID_a, pk_a) and (ID_g, pk_g) to AUSF through secure communication channel, where ID_a and ID_g represent the unique identifiers of AMF and gNB respectively.
- Step 3: AUSF \rightarrow AMF/gNB: $(x_a, Y_a)/(x_g, Y_g)$ 3a. Upon receiving messages from AMF and gNB,

AUSF randomly selects $y_a, y_g \in Z_q^*$ and computes $Y_a = y_a \cdot P$ and $Y_g = y_g \cdot P$.

3b. AUSF uses the master private key s to compute partial private keys $x_a = y_a + s \cdot H_0(ID_a, pk_a) \mod q$ and $x_g = y_g + s \cdot H_0(ID_g, pk_g) \mod q$.

3c. AUSF securely transmits (x_a, Y_a) and (x_g, Y_g) to AMF and gNB respectively.

Step 4: AMF/gNB: $(pk_a, Y_a)/(pk_a, Y_a)$

4a. After receiving messages from AUSF, AMF verifies the correctness by checking the equation $x_a \cdot P \stackrel{?}{=} Y_a + H_0(ID_a, pk_a) \cdot pk_{pub}$. Similarly, gNB performs the corresponding verification process.

4b. Upon successful verification, AMF and gNB securely store their complete private key pairs (sk_a, x_a) and (sk_g, x_g) respectively and publish (ID_a, pk_a, Y_a) and (ID_g, pk_g, Y_g) to the network.

2) **DT Creation:** The MD generates its key pair and requests a DT creation, after which the DT is initialized with corresponding keys and establishes a secure channel with the MD. The details are as follows.

- Step 1: $MD_i \rightarrow 5GC$: Subscription Request $(SUPI_i, pk_i)$
 - 1a. The MD_i first randomly selects $sk_i \in Z_q^*$ as its private key, and calculates $pk_i = sk_i \cdot P$ as its public key.

1b. The MD_i sends subscription request $req_i = (SUPI_i, pk_i)$ to the AUSF and UDM in the 5GC, where $SUPI_i$ is the subscription permanent identifier, to apply for creating a corresponding virtual twin DT_j in the DTN.

Step 2: $DT_j \leftrightarrow MD_i$: k_{ij}

2a. After UDM verifies the request information from MD_i and confirms it meets the qualification conditions (such as completed payment), the NEF network function coordinates to allocate computing resources on dedicated cloud servers, creating and deploying its digital twin DT_i .

2b. When DT_j is successfully activated, DT_j randomly selects $sk_j \in Z_q^*$ as its private key, and calculates the corresponding public key $pk_j = sk_j \cdot P$. 2c. AUSF randomly selects $u_j \in Z_q^*$ and calculates $U_j = u_j \cdot P$. Additionally, AUSF uses the system master key to generate an anonymous identity for DT_j as $ID_j = SUPI_i \oplus H_1(sU_j)$. UDM sends (ID_j, pk_j) to AMF and gNB in the 5G network, and sends $(SUPI_i, pk_i)$ to AMF. Furthermore, UDM stores (ID_j, U_j) in the local security database for identity tracing in subsequent processes.

2d. After DT_j is successfully deployed to the DTN, it accesses 5GC and gNB through dedicated API interfaces [13]. Subsequently, DT_j negotiates a longterm session key k_{ij} with MD_i , to achieve secure data transmission via intra-twin channel [34].

3) Access Delegation: When attaching to the network for the first time, MD_i and 5GC execute the standard 5G-AKA authentication protocol based on TS 33.501, and through the root key, sequentially calculate and derive with the current AMF_1 and gNB_1 the security anchor key k_{SEAF_i} , temporary session key k_{gNB_1} , and the globally unique temporary identifier $GUTI_i$ [2]. After that, DT_j can apply the access delegation from AMF_1 for further access to the gNBs in the current domain as shown in Fig. 2.

Step 1: $MD_i \rightarrow DT_j$: Authorized Token (E_1, MAC_1)

1a. MD_i first randomly selects $a_i \in Z_q^*$ to compute $A_i = a_i \cdot pk_i$ for negotiating temporary session



Figure 2: Access Delegation Phase

keys with the gNBs that may be accessed on subsequent trips. Then, MD_i generates the nonce number N_i from the pseudo-random generator and uses the k_{SEAF_i} to compute $t_i = H_5(k_{SEAF_i} \oplus N_i)$.

1b. MD_i uses the public key of DT_j to compute $d_i = t_i \cdot pk_j$ and its private key to compute $u_i = e(sk_i \cdot d_i, P)$ separately.

1c. In order to prevent the disclosure and corruption, the MD_i computes $E_1 = Enc_{k_{ij}}(A_i, u_i, GUTI_i, N_i)$ and $MAC_1 = H_3(k_{ij}, A_i, u_i, GUTI_i, N_i)$ respectively.

1d. Finally, MD_i sends (E_1, MAC_1) as the authorized token to DT_j , so that DT_j can apply for the access delegation from AMF_1 in core network.

Step 2: $DT_j \rightarrow AMF_1$: Access Delegation Request $(GUTI_i, ID_j, w_1, z_j, d_j, N_i + 1)$

2a. Upon receiving the message from MD_i , DT_j decrypts E_1 and verifies the correctness of MAC_1 and freshness of N_i using the session key k_{ij} . If verification fails, DT_j discards the message and returns a failure response. Otherwise, DT_j randomly selects $l_j \in Z_q^*$ to compute $L_j = l_j \cdot P$.

2b. In order to protect u_i against eavesdropping, DT_j uses the public key of AMF_1 to computes $w_1 = u_i \oplus H_1(l_j \cdot pk_{a1}).$

2c. In order to prevent corruption, DT_j computes $d_j = H_0(GUTI_i, L_j, ID_j, w_1, N_i + 1)$ and uses its private key to compute $z_j = l_j + sk_j \cdot d_j \mod q$.

2d. Finally, DT_j sends $(GUTI_i, ID_j, w_1, z_j, d_j, N_i + 1)$ to AMF_1 as access delegation request.

Step 3: $AMF_1 \rightarrow DT_j$: Access Delegation Response (R_i, w_2)

3a. Upon receiving request message from DT_j ,

 AMF_1 first verifies the freshness of $N_i + 1$. If so, AMF_1 then retrieves the corresponding public key pk_j associated with ID_j from its local database, computes $L'_{j} = z_{j} \cdot P - d_{j} \cdot pk_{j}$, and verifies the correctness of $d'_i = H_0(GUTI_i, L'_j, ID_j, w_1, N_i + 1)$. If correct, AMF_1 believes the request message is from legal DT_i without attacks. Then, AMF_1 uses its private key to recover $u'_i = w_1 \oplus H_1(sk_{a1} \cdot L_i)$. 3b. Based on the received $GUTI_i$, AMF_1 can search the corresponding $SUPI_i$ and anchor key k_{SEAF_i} from local database with the help of UDM. AMF_1 then recomputes $t'_i = H_5(k_{SEAF_i} \oplus N_i)$ and verifies the correctness of $u'_i = e(t'_i \cdot pk_j, pk_i)$. If the verification is failure, AMF_1 then aborts it. Otherwise, AMF_1 trusts that DT_i has been authorized by legal MD_i and further generates access delegation for DT_i in order to prove its authority for gNBs.

3c. Subsequently, AMF_1 calculates the access delegation δ_j for DT_j as shown in equation 1 where $r_j \in Z_q^*$ and $R_j = r_j \cdot P$. In order to prevent eavesdropping, AMF_1 computes $w_2 = \delta_j \oplus H_2(r_j \cdot pk_j, N_i + 2)$. 3d. Finally, AMF_1 transmits (R_j, w_2) to DT_j as access delegation response.

$$\delta_j = sk_{a1} + x_{a1}h_1 + r_jh_2 \mod q$$

$$h_1 = H_0(GUTI_i, R_j)$$

$$h_2 = H_0(ID_j, pk_j)$$
(1)

Step 4: 4a. Upon receiving message from AMF_1 , DT_j computes $N_i + 2$ and utilizes its private key to decrypt $\delta_j = w_2 \oplus H_2(sk_j \cdot R_j, N_i + 2)$.

4b. Then, DT_j employs the public key pairs of AMF_1 to validate the correctness of $\delta_j \cdot P = h_1 \cdot bpk_{a1} + h_2 \cdot R_j + pk_{a1}$, where $bpk_{a1} = Y_{a1} + H_0(ID_{a1}, pk_{a1}) \cdot pk_{pub}$. If verification fails, DT_j aborts it and reinitiates the request.

4c. If verification succeeds, DT_j can accept δ_j as the valid access delegation and employ it to initiate the handover process with gNBs that the MD_i will connect to within the current AMF domain.

4) Intra-AMF Handover: When MD_i is within the gNB_1 's coverage area, DT_j predicts the target base station gNB_2 by analyzing MD_i 's movement trajectory in real-time. As shown in Fig. 3, DT_j initiates handover authentication with gNB_2 before MD_i enters its coverage area, completing mutual authentication and session key negotiation between MD_i and gNB_2 in advance.

Step 1: $DT_j \rightarrow gNB_2$: Handover Authentication Request: $(GUTI_i, ID_j, \lambda_j, A_i, B_j, R_j, TS_1)$

1a. DT_j randomly selects $b_j \in Z_q^*$ to compute $B_j = b_j \cdot P$.

1b. In order to prevent corruption, DT_j computes $h_3 = H_0(A_i, TS_1)$ and $h_4 = H_0(Z_j, ID_j)$, where TS_1 is current timestamp and $Z_j = (sk_j + b_j) \cdot pk_{g2}$. 1c. In order to prove the legitimacy of the identity, DT_j computes $\lambda_j = \delta_j \cdot h_3 + b_j \cdot h_4 \mod q$.

1d. Finally, DT_j transmits the handover authentication



Figure 3: Intra-AMF Handover Authentication Phase

request $(GUTI_i, ID_j, \lambda_j, A_i, B_j, R_j, TS_1)$ to gNB_2 through the dedicated API channel.

Step 2: $gNB_2 \rightarrow DT_j$: Handover Authentication Response $(ID_{q2}, C_{q2}, h_5, MAC_2, TS_2)$

2a. Upon receiving the request message, gNB_2 first checks whether the freshness of the TS'_1 is within the time threshold ΔT in order to prevent replay attacks. If $|TS'_1 - TS_1| > \Delta T$ exceeds the time threshold, gNB_2 terminates the handover process. Otherwise, gNB_2 continues to check the legitimacy of DT_j and whether it has been authorized by the AMF_1 .

2b. Based on ID_j , gNB_2 retrieves the corresponding public key pk_j from its local database and subsequently recalculates $h'_1 = H_0(GUTI'_i, R'_j)$, $h'_2 = H_0(ID'_j, pk_j)$, $h'_3 = H_0(A'_i, TS'_1)$ and $h'_4 =$ $H_0(Z'_j, ID'_j)$ using the received parameters where $Z'_i = sk_{g2} \cdot (pk_j + B_j)$.

2c. gNB_2 then verifies the correctness of $\lambda_j \cdot P \stackrel{?}{=} h'_3 \cdot (pk_{a1} + h'_1 \cdot bpk_{a1} + h'_2 \cdot R_j) + h'_4 \cdot B_j$. If the verification fails, gNB_2 aborts the handover process. Otherwise, gNB_2 considers that DT_j has been authorized by AMF_1 . In addition, gNB_2 can optimize efficiency by performing batch verification as $\sum_{j=1}^{n} (\lambda_j) \cdot P \stackrel{?}{=} \sum_{j=1}^{n} (h'_{3j}) \cdot pk_{a1} + \sum_{j=1}^{n} (h'_{1j}h'_{3j}) \cdot bpk_{a1} + \sum_{j=1}^{n} (h'_{3j}h'_{2j}) \cdot R_j + \sum_{j=1}^{n} h'_{4j} \cdot B_j$, when multiple handover requests are received.

2d. gNB_2 selects $c_{g2} \in Z_q^*$ to compute $C_{g2} = c_{g2} \cdot sk_{g2} \cdot P$ and $K_i = sk_{g2} \cdot c_{g2} \cdot A_i$. gNB_2 then generates the new temporary session key $k_{gNB}^* = H_2(K_i, GUTI_i, ID_{g2})$ and further derives encryption key $TCK_i^* = KDF(k_{gNB}^*, \text{"Enc"})$ and integrity protection key $TIK_i^* = KDF(k_{gNB}^*, \text{"Int"})$ with

 MD_i where KDF is the key derivation function defined in 3GPP R.16 [2].

2e. In order to prevent tracing on public wireless channel, gNB_2 locally generates temporary identification $TID_i = H_4(k_{gNB}^*, GUTI_i, ID_{g2}).$

2f. In order to prevent collusion, gNB_2 sequentially calculates $h_5 = H_5(TIK_i^*, TID_i, ID_j)$ and $MAC_2 = H_2(sk_{g2} \cdot h_5 \cdot B_j, C_{g2}, TS_2)$ where TS_2 is the current timestamp.

2g. Finally, gNB_2 transmits handover response $(ID_{g2}, C_{g2}, h_5, MAC_2, TS_2)$ to DT_j and retains the (TID_i, k_{gNB}^*) in its local database.

Step 3: $DT_j \rightarrow MD_i$: Handover Authentication Notification $(C_{q2}, ID_{q2}, h_6, TS_3)$

3a. Upon receiving response message from gNB_2 , the DT_j first verifies the freshness of TS_2 to prevent replay attack. If TS_2 exceeds the time threshold, DT_j aborts the handover process.

3b. DT_j utilizes the public key of gNB_2 to calculate $b_j \cdot h_5 \cdot pk_{g2}$ and subsequently validates the correctness of MAC_2 . Upon successful verification, DT_j confirms the legitimacy of gNB_2 and the correctness of the received parameters.

3c. DT_j generates the current timestamp TS_3 and computes $MAC_3 = H_2(k_{ij}, h_5 \cdot C_{g2}, ID_{g2}, TS_3)$ and $h_6 = h_5 \oplus MAC_3$.

3d. Finally, DT_j transmits $(C_{g2}, ID_{g2}, h_6, TS_3)$ to MD_i as the handover authentication notification via wireless channel.

Step 4: $MD_i \rightarrow gNB_2$: Handover Authentication Acknowledgment (TID_i, MAC_4, TS_4)

4a. Upon receiving the notification message from DT_j , MD_i first verifies the freshness of timestamp TS_3 to prevent replay attacks.

4b. MD_i computes the shared secret value $K_i = a_i \cdot x_i \cdot C_{g2}$ and subsequently generates the temporary session key $k_{gNB}^* = H_2(K_i, GUTI_i, ID_{g2})$ with gNB_2 .

4c. MD_i utilizes k_{gNB}^* to compute the temporary identity identifier $TID_i = H_4(k_{gNB}^*, GUTI_i, ID_{g2})$, and subsequently derives the temporary encryption key $TCK_i^* = KDF(k_{gNB}^*, \text{"Enc"})$ and temporary integrity protection key $TIK_i^* = KDF(k_{gNB}^*, \text{"Int"})$ with gNB_2 .

4d. MD_i computes $h'_5 = H_5(TIK_i^*, TID_i, ID_j)$ and recovers $MAC'_3 = h_6 \oplus h'_5$. Subsequently, MD_i employs k_{ij} with DT_j to verify whether $MAC'_3 \stackrel{?}{=} H_2(k_{ij}, h_5 \cdot C_{g2}, ID_{g2}, TS_3)$ is valid.

4e. Upon successful verification, when MD_i enters the signal coverage area of gNB_2 , it generates current timestamp TS_4 and computes $MAC_4 = H_4(TIK_i^*, TID_i, TS_4)$. Then, MD_i transmits (TID_i, MAC_4, TS_4) to gNB_2 as the handover authentication acknowledgment message through the open wireless channel.

4f. If any of the aforementioned verification steps fails, upon entering the coverage area of gNB_2 , MD_i



Figure 4: Inter-AMF Handover Authentication Phase

will re-execute the standard handover authentication procedure according to the 5G-AKA protocol defined in TS 33.501 to ensure the establishment of a secure access connection with gNB_2 [2].

Step 5: 5a. Upon receiving the acknowledgment message from MD_i, gNB₂ first checks the freshness of TS₄. If so, gNB₂ retrieves the k^{*}_{gNB} from the database based on the TID_i and further verifies the validity of MAC₄ = H₂(TIK^{*}_i, TID_i, TS₄).
5b. After all verifications pass, MD_i and gNB₂ complete the handover authentication protocol and establish a secure wireless communication link.

5) Inter-AMF Handover: When MD_i is about to move from gNB_2 under AMF_1 domain to gNB_3 under AMF_2 domain, based on the analysis of the movement trajectory, DT_j notifies the AMF_1 and MD_i to trigger inter-AMF handover authentication, ensuring seamless handover authentication for MD_i as shown in Fig 4. The details are as follows.

Step 1: $AMF_1 \rightarrow AMF_2$: Security Context Information $(SUPI_i, k_{SEAF_i}, ID_j, \delta_j \cdot P)$ 1a. To prepare for the inter-AMF handover, AMF_1 transmits the security context information of MD_i including $(SUPI_i, k_{SEAF_i}, ID_j, \delta_j \cdot P)$ to AMF_2 through N14 interface. 1b. AMF_2 then generates the new anchor key $k_{SEAF_i}^* = KDF(k_{SEAF_i}, SUPI_i, ID_{a2})$ and new globally unique temporary identity $GUTI_i^* = H_4(SUPI_i, k_{SEAF_i}^*)$ with MD_i . In addition, AMF_2 stores $(GUTI_i^*, ID_j, k_{SEAF_i}^*, \delta_j \cdot P)$ in the local database.

Step 2: $MD_i \rightarrow DT_j$: (E_2, MAC_5)

2a. Upon receiving notification from DT_j , MD_i first updates the new anchor key $k_{SEAF_i}^* = KDF(k_{SEAF_i}, SUPI_i, ID_{a2})$ and corresponding globally unique temporary identity $GUTI_i^* = H_4(SUPI_i, k_{SEAF_i}^*).$ 2b. MD_i employs the session key k_{ij} to calculates $E_2 = Enc_{k_{ij}}(GUTI_i^*, TS_5)$ and authentication code $MAC_5 = H_4(k_{ij}, GUTI_i^*, TS_5)$ where TS_5 is the current timestamp.

2c. Finally, MD_i transmits (E_2, MAC_5) to DT_i .

Step 3: DT_i \rightarrow AMF₂: Access Delegation Request (ID_i, v_i, μ_i, TS_6)

> 3a. Upon receiving (E_2, MAC_5) , DT_i first verifies the correctness of MAC_5 and freshness of TS_5 after decrypting E_2 . If verifications are correct, DT_j then randomly selects $l_i^* \in Z_q^*$ to compute $L_i^* = l_i^* \cdot P$.

> 3b. In order to prevent collusion, DT_i computes $\mu_{i} = H_{2}(L_{i}^{*}, ID_{i}, GUTI_{i}^{*}, TS_{6})$ and $v_{i} = \delta_{i} + l_{i}^{*} + l_{i}^{*}$ $\mu_j \cdot sk_j \mod q$, where TS_6 is current timestamp.

> 3c. DT_j submits (ID_j, v_j, μ_j, TS_6) to AMF_2 for requesting a new access delegation within the current domain.

Step 4: AMF_2 \rightarrow DT_i: Access Delegation Response (w_3, R_a^*, TS_7)

> 4a. Upon receiving the request message from DT_i , AMF_2 first verifies the freshness of TS_6 . Then, AMF_2 searches $(GUTI_i^*, ID_j, \delta_j \cdot P)$ from database. 4b. AMF_2 then computes $L_j^* \stackrel{?}{=} v_j \cdot P$ – $\delta_j \cdot P - \mu'_j \cdot pk_j$ and verifies whether $\mu'_j =$ $H_2(L_i^*, ID_j, GUTI_i^*, TS_6)$ is correct. If so, AMF_2 then can generate the new access delegation δ_i^* for DT_i to access the gNBs in the current domain as equation 1 in Section 4.3.3.

> 4c. AMF_2 computes $w_3 = \delta_i^* \oplus H_2(r_i^* \cdot pk_j, TS_7)$ and sends (w_3, R_i^*, TS_7) to the DT_j where $R_i^* = r_i^* \cdot P$ and $r_j^* \in Z_q^*$, and TS_7 is current timestamp.

Step 5: Upon receiving the message, DT_i first verifies the freshness of TS_7 . If so, DT_j then employs its private key sk_j to decrypt δ_j^* from w_3 and verifies the correctness of δ_i^* . If so, DT_j will initiate the handover procedure with the gNB_3 that the MD_i is about to connect to, as described in section 4.3.4, to assist in the mutual authentication and key negotiation between the MD_i and gNB that will be accessed in advance.

V. SECURITY ANALYSIS

In this section, we evaluate the security of the proposed scheme through formal and informal analysis. First, we use the BAN-logic, RoR model, and ProVerif to demonstrate the mutual authentication, key agreement, and session key security between MD and gNB. In addition, we also employ the informal security analysis to further analyze and prove that the proposed scheme can achieve the security goals defined in Section 3.3.

A. Formal Verification based on BAN-Logic

BAN logic is model logic based on subject knowledge and belief reasoning. We first list the common rule of BAN logic that will be used in the proof as follows:

- 1) The fresh-promotion rule: $\frac{P|\equiv \sharp(X)}{P|\equiv \sharp(X,Y)}$ 2) The nonce-verification rule: $\frac{P|\equiv \sharp(X), P|\equiv Q| \sim X}{P|\equiv Q|\equiv X}$

- 3) The decomposition rule: $\frac{P|\equiv Q|\equiv (X,Y)}{P|\equiv Q|\equiv X}$, $\frac{P|\equiv (X,Y)}{P|\equiv X}$ 4) The composition rule: $\frac{P|\equiv X, P|\equiv Y}{P|\equiv (X,Y)}$ 5) The jurisdiction rule: $\frac{P|\equiv Q|\Rightarrow X, P|\equiv Q|\equiv X}{P|\equiv X}$ $P \equiv X$
- 6) The message-meaning rule: $\frac{P|\equiv P \xleftarrow{K} Q, P\{X\}_K}{P|=Q|=X}$

Then, the basic goal of the proposed scheme is to achieve the mutual authentication and key negotiation between MD_i and gNB_2 in BAN-logic is listed as follows:

- 1) Goal 1: $MD_i \models gNB_2 \stackrel{k_{gNB}^*}{\longleftrightarrow} MD_i$
- 2) Goal 2: $gNB_2 \models gNB_2 \stackrel{k_{gNB}^*}{\longleftrightarrow} MD_i$
- 3) Goal 3: $MD_i \models gNB_2 \models gNB_2 \stackrel{k_{gNB}^*}{\longleftrightarrow} MD_i$
- 4) Goal 4: $qNB_2 \equiv MD_i \equiv MD_i \stackrel{k_{gNB}^*}{\longleftrightarrow} qNB_2$

In addition, we give the necessary assumptions as follows in order to better analyze the proposed scheme:

- 1) Assumption 1: $MD_i \models MD_i \xleftarrow{k_{ij}} DT_j$
- 2) Assumption 2: $DT_i \models MD_i \xleftarrow{k_{ij}} DT_j$
- 3) Assumption 3: $gNB_2 \equiv DT_j \Rightarrow (GUTI_i, ID_j, \lambda_j, A_i, B_j, A_i, B_j)$ R_i, TS_1
- 4) Assumption 4: $DT_i \equiv gNB_2 \Rightarrow (ID_{a2}, C_{a2}, h_5, MAC_2, h_5)$ TS_2)
- 5) Assumption 5: $MD_i \models DT_j \Rightarrow (C_{g2}, ID_{g2}, h_6, TS_3)$

Now, we prove that the proposed scheme can achieve from Goal 1 to Goal 4 as follows.

Since gNB_2 receives the message $(GUTI_i, ID_j, \lambda_j, A_i)$ B_j, R_j, TS_1), we have:

S1: $gNB_2 \triangleleft (GUTI_i, ID_j, \lambda_j, A_i, B_j, R_j, TS_1)$

In the proposed scheme, gNB_2 verifies the freshness of TS_1 to prevent replay attacks. Once verification is correct, we have:

S2: $gNB_2 \equiv \sharp(TS_1)$

According to the fresh-promotion rule and S2, we have: S3: $gNB_2 \models \sharp(GUTI_i, ID_i, \lambda_i, A_i, B_i, R_i, TS_1)$

In the proposed scheme, gNB_2 verifies the correctness of $\lambda_{i}P \stackrel{?}{=} h'_{3}(pk_{a1} + h'_{1}bpk_{a1} + h'_{2}R_{i}) + h'_{4}B_{i}$. If so, according to the S3, we have:

S4: $gNB_2 \equiv DT_j \sim (GUTI_i, ID_j, \lambda_j, A_i, B_j, R_j, TS_1)$ According to the S3, S4 and nonce-verification rule, we have:

S5: $gNB_2 \equiv DT_j \equiv (GUTI_i, ID_j, \lambda_j, A_i, B_j, R_j, TS_1)$ According to the S5, Assumption 3 and the justification rule, we have:

S6: $gNB_2 \models (GUTI_i, ID_i, \lambda_i, A_i, B_i, R_i, TS_1)$ According to the S6 and decomposition rule, we have: S7: $gNB_2 \mid \equiv A_i$ And,

S8: $gNB_2 \equiv GUTI_i$

In the proposed scheme, gNB_2 has the private key sk_{q2} , we have:

S9: $gNB_2 \mid \equiv sk_{g2}$

Due to the gNB_2 randomly selects $c_{q2} \in Z_q^*$, we have S10: $gNB_2 \equiv c_{a2}$

In the proposed scheme, gNB_2 computes the secret value $K_i = c_{g2} \cdot sk_{g2} \cdot A_i$. According to the S7, S9, S10, and the composition rule, we have:

S11:
$$gNB_2 \mid \equiv K_i$$
.

Since ID_{g2} is the identification of gNB_2 , we have: S12: $gNB_2 \models ID_{g2}$.

Since $k_{gNB}^* = H_2(K_i, GUTI_i, ID_{g2})$, according to the S8, S11, S12 and the composition rule, we have:

S13: $gNB_2 \mid \equiv k_{gNB}^*$.

That is, $gNB_2 \models gNB_2 \stackrel{k_{gNB}^*}{\longleftrightarrow} MD_i$ (Goal 2) Since DT_j receives the $(ID_{g2}, C_{g2}, h_5, MAC_2, TS_2)$ from gNB_2 , we have:

S14: $DT_j \triangleleft (ID_{g2}, C_{g2}, h_5, MAC_2, TS_2)$

 DT_j checks the freshness of TS_2 to defend replay attack. If so, we have:

S15: $DT_i \mid \equiv \sharp(TS_2)$

According to the fresh-promotion rule and S15, we have: S16: $DT_j \models \sharp(ID_{g2}, C_{g2}, h_5, MAC_2, TS_2)$

In the proposed scheme, DT_j uses b_j and pk_{g2} to compute $MAC'_2 = H_2(b_j \cdot h_5 \cdot pk_{g2}, C_{g2}, TS_2)$. Then, DT_j verifies the correctness of $MAC'_2 = MAC_2$. If so, we have:

S17: $DT_j \mid \equiv gNB_2 \mid \sim (ID_{g2}, C_{g2}, h_5, MAC_2, TS_2)$

According to the S16, S17 and the nonce-verification rule, we have:

S18: $DT_j \mid \equiv gNB_2 \mid \equiv (ID_{g2}, C_{g2}, h_5, MAC_2, TS_2)$

According to the S18, Assumption 4 and the jurisdiction rule, we have:

S19: $DT_j \models (ID_{g2}, C_{g2}, h_5, MAC_2, TS_2)$ According to the S19 and the decomposition rule, we have: S20: $DT_j \models (ID_{g2}, C_{g2}, h_5)$

After receiving the $(C_{g2}, ID_{g2}, h_6, TS_3), MD_i$ first verifies the freshness of TS_3 to prevent replay attack. If so, we have: S21: $MD_i \models \sharp(TS_3)$

According to the fresh-promotion rule and S20, we have: S22: $MD_i \models \sharp(C_{q2}, ID_{q2}, h_6, TS_3)$

 MD_i first computes h'_5 , and then uses k_{ij} to verify the correctness of MAC'_3 . Since $MAC_3 = H_2(k_{ij}, h_5 \cdot C_{g2}, ID_{g2}, TS_3)$ and $h_6 = h_5 \oplus MAC_3$. If the verification is correct, we have:

S23: $MD_i \models DT_j \mid \sim (C_{g2}, ID_{g2}, h_5, TS_3)$

Since MAC_3 is composed of h_5 and TS_3 , according to the S21, we have:

S24: $MD_i \models \sharp(C_{g2}, ID_{g2}, h_5, TS_3)$ According to the S23 and S24, we have:

S25: $MD_i \mid \equiv DT_j \mid \equiv (C_{g2}, ID_{g2}, h_5, TS_3)$

According to the decomposition rule and S25, we have: S26: $MD_i |\equiv (C_{a2}, ID_{a2}, h_5, TS_3)$

According to the decomposition rule and S26, we have: S27: $MD_i |\equiv C_{g2}$

And,

S28: $MD_i \mid \equiv ID_{g2}$

Since MD_i has the private key sk_i , we have:

S29:
$$MD_i \mid \equiv sk$$

Due to the MD_i randomly selects $a_i \in Z_q^*$, we have S30: $MD_i \models a_i$

In the proposed scheme, MD_i computes the $K_i = a_i \cdot sk_i \cdot C_{g2}$. According to the S27, S29, S30 and the composition rule, we have:

S31: $MD_i \mid \equiv K_i$

Since $GUTI_i$ is the temporary identification of MD_i , we have:

S32: $MD_i \mid \equiv GUTI_i$

Since $k_{gNB}^* = H_2(K_i, GUTI_i, ID_{g2})$, according to the S28, S31, S32 and the composition rule, we have:

S33: $MD_i \mid \equiv k_{gNB}^*$

That is, $MD_i \models gNB_2 \stackrel{k_{gNB}^*}{\longleftrightarrow} MD_i$ (Goal 1) gNB_2 receives the $(GUTI_i, MAC_4, TS_4)$ from MD_i

where $MAC_4 = H_2(TIK_i^*, TID_i, TS_4)$, since TIK_i^* is derived by k_{gNB}^* , according to the S13 and the message-meaning rule, we have:

S34: $gNB_2 \mid \equiv MD_i \mid \sim (k_{gNB}^*, TID_i, TS_4)$

 gNB_2 can check the freshness of TS_4 to prevent replay attack. If so, we have:

S35: $gNB_2 \mid \equiv \sharp(TS_4)$

According to the S35 and the fresh-promotion rule, we have: S36: $gNB_2 \models \sharp(k_{aNB}^*, TID_i, TS_4)$

According to the S34, S36 and the nonce-verification rule, we have:

S37: $gNB_2 \mid \equiv MD_i \mid \equiv (k_{gNB}^*, TID_i, TS_4)$

According to the S37 and the decomposition rule, we have: S38: $gNB_2 \mid \equiv MD_i \mid \equiv k_{qNB}^*$

That is, $gNB_2 \models MD_i \models MD_i \stackrel{k_{gNB}^*}{\longleftrightarrow} gNB_2$ (Goal 4) MD_i can calculate h_5 using TIK_i^* derived by k_{gNB}^* , and

verify its correctness by checking whether MAC_3 is valid. If so, we have:

S39: $MD_i \mid \equiv gNB_2 \mid \sim h_5$

According to the S24, and the fresh-promotion rule, we have:

S40: $MD_i \mid \equiv \sharp(h_5)$

According to the S39, S40 and the nonce-verification rule, we have:

S41: $MD_i \mid \equiv gNB_2 \mid \equiv h_5$

Since $h_5 = H_2(TIK_i^*, TID_i, ID_j)$, according to the S40 and the decomposition rule, we have:

S42: $MD_i \mid \equiv gNB_2 \mid \equiv TIK_i^*$

Since TIK_i^* is directly derived by k_{gNB}^* . That is, $MD_i |\equiv gNB_2 |\equiv gNB_2 \stackrel{k_{gNB}^*}{\longleftrightarrow} MD_i$ (Goal 3)

B. Formal Analysis based on RoR Model

To validate the session key security of our proposed scheme, we then perform a formal security analysis based on the Realor-Random (RoR) model [35].

1) Participants: In the proposed scheme, three participating entities are involved in the handover authentication process: MD_i , DT_j , and gNB_2 . Let $\Pi^m_{MD_i}$, $\Pi^d_{DT_j}$, and $\Pi^g_{gNB_2}$ denote instances m, d, and g of MD_i , DT_j , and gNB_2 , respectively.

2) *Partnering:* Two instances are considered partners if and only if they simultaneously satisfy the following three conditions: (1) both instances have reached an accepted state; (2) the instances have mutually authenticated each other and share an identical session identifier; and (3) the instances have established a mutual partnership.

3) Freshness: An instance is considered fresh if its session key established with another instance has not been revealed to adversary A.

4) Adversary: Adversary A has the capability to read, modify, delete, and fabricate messages transmitted over the public communication channel. In addition, A has the attack capabilities according to the following queries:

- $Execute(\Pi^m_{MD_i}, \Pi^d_{DT_j}, \Pi^g_{gNB})$: The \mathcal{A} can obtain all messages exchanged and transmitted between MD_i , DT_j and gNB by executing this query.
- $Send(\Pi_{MD_i}^m, \Pi_{DT_j}^d, \Pi_{gNB}^g, m)$: The \mathcal{A} can launch the active attack and send the message m to the $\Pi_{MD_i}^m$ and Π_{gNB}^g . If the message m passes the verification from the instance, \mathcal{A} will receive a valid response. Otherwise, the query will abort.
- Reveal(Π^t): In this query, the \mathcal{A} can obtain the current specific state information created by the $\Pi^m_{MD_i}$ and its partner Π^g_{aNB} in the current session.
- $Corrupt(\Pi^t)$: Upon executing this query, the instances $\Pi^m_{MD_i}$ and Π^g_{gNB} can be compromised, and its long-term secret keys can be leaked to the \mathcal{A} .
- $Test(\Pi_{MD_i}^m, b)$: This query verifies the semantic security of the temporary session key between $\Pi_{MD_i}^t$ and Π_{gNB}^u . The output is determined by flipping a uniformly random coin b. For an established and fresh session key, the query returns the real session key if b = 1, and a random string of equal length if b = 0. The \mathcal{A} 's goal is to guess the hidden bit b. If \mathcal{A} can guess b correctly, it breaks the semantic security of the session key.

In the proposed scheme, the cryptographic hash function $h(\cdot)$ is accessible to all participants and adversary \mathcal{A} , and is modeled as a random oracle \mathcal{HO} , where hash query returns a fixed but unpredictable value for each unique input.

5) Semantic security: Let Succ be the event that \mathcal{A} win the game, and Pr[Succ] denote its probability. We use the $Adv_{\mathcal{A}}^{P} = |2Pr[Succ] - 1|$ to represent the advantage of \mathcal{A} that can break the semantic security of the proposed scheme. If the advantage $Adv_{\mathcal{A}}^{P}$ is bounded by a negligible value ϵ , we consider the proposed scheme secure against polynomial-time adversaries.

Theorem 1: Let \mathcal{A} be a t-polynomial time adversary against the semantic security of our proposed scheme. q_s , q_e and q_h represent the number of Send queries, Execute queries and Hash queries respectively. |Hash| denotes the bit lengths of the hash function. $Adv_{\mathcal{A}}^{ECDHP}$ is the advantage of adversary in breaking the ECDH problem in upper-bound time t. The advantage of \mathcal{A} in breaching the session key security of our proposed scheme is estimated as:

$$Adv_{\mathcal{A}}^{P} \leq \frac{q_{h}^{2}}{|Hash|} + \frac{(q_{s}+q_{e})^{2}}{|Hash|} + 2q_{h}Adv_{\mathcal{A}}^{ECDHP} \tag{2}$$

Proof: We define the four games $Game_i$ to verify the semantic security of the proposed scheme, where i = [0, 3].

 $Game_0$: This game directly simulates the real attack scenario where A attempts to determine the hidden bit b chosen at the game's initialization. According to the semantic security of the session key, we have:

$$Adv_{\mathcal{A}}^{P} = |2Pr[Succ_{0}] - 1| \tag{3}$$

 $Game_1$: This game represents an eavesdropping attack where the A can intercept messages transmitted between DT_j , MD_i and gNB over the public channel by executing *Execute* query. The \mathcal{A} subsequently uses the *Test* query to distinguish whether the output key is real or random. The temporary session key between MD_i and gNB_2 is computed as $k_{gNB}^* = H_2(K_i, GUTI_i, ID_{g2})$, where $K_i = a_i \cdot sk_i \cdot C_{g2} = c_{g2} \cdot sk_{g2} \cdot A_i$. To obtain the k_{gNB}^* , the \mathcal{A} would need to acquire the secret values a_i and c_{g2} as well as the private keys sk_i and sk_{g2} . However, these values cannot be extracted from the messages captured over the channel. That is, the adversary's advantage in winning $Game_1$ does not increase. Therefore, we have:

$$Pr[Succ_1] = Pr[Succ_0] \tag{4}$$

Game₂: Based on Game₁, Game₂ adds send query and hash query. This game simulates that the adversary \mathcal{A} can launch active attacks through forging messages that can be accepted and verified by receivers. \mathcal{A} can intercept all exchanged messages $\langle GUTI_i, ID_j, \lambda_j, A_i, B_j, R_j, TS_1 \rangle$, $\langle ID_{g2}, C_{g2}, h_5, MAC_2, TS_2 \rangle$, $\langle C_{g2}, ID_{g2}, h_6, TS_3 \rangle$ and $\langle TID_i, MAC_4, TS_4 \rangle$ to continuously execute hash query to find the message collisions. In addition, \mathcal{A} can embed the timestamp from intercepted messages into forged messages and search for collisions through hash query. According to the birthday paradox, we have:

$$|Pr[Succ_{2}] - Pr[Succ_{1}]| \le \frac{q_{h}^{2} + (q_{e} + q_{s})^{2}}{2|Hash|}$$
(5)

 $Game_3$: In this game, the adversary can launch the $Corrupt(\Pi^t)$ and $Reveal(\Pi^t)$ to compromise the temporary session key k_{gNB}^* between gNB and MD_i . \mathcal{A} can execute Exectute, Hash queries, while leveraging combinations of Reveal and Corrupt queries. This game occurs on three occasions:

- Reveal(Π^t): This query is to prove the ephemeral secret leakage. By executing this query, the \mathcal{A} can obtain the state information (a_i, A_i) of the instance $\Pi^m_{MD_i}$ and (c_{g2}, C_{g2}) of the instance Π^g_{gNB} . To compute the temporary session key k^*_{gNB} , the \mathcal{A} needs to acquire both sk_i and sk_{g2} .
- $Corrupt(\Pi^t)$: This query is to prove the perfect forward secrecy. By executing this query, the \mathcal{A} can obtain the (sk_i, A_i) of the instance $\Pi^m_{MD_i}$ and (sk_{g2}, C_{g2}) of the instance Π^g_{gNB} . To compute the temporary session key k^*_{gNB} , the \mathcal{A} needs to acquire both a_i and c_{g2} .
- $Corrupt(\Pi^t)$ and $Reveal(\Pi^t)$: By executing these queries, the adversary \mathcal{A} can obtain either the secret key sk_i from instance $\Pi^m_{MD_i}$ and the state information (c_{g2}, C_{g2}) from instance Π^g_{gNB} , or the state information (a_i, A_i) from instance $\Pi^m_{MD_i}$ and the secret key sk_{g2} from instance Π^g_{gNB} . To compute the temporary session key k^*_{gNB} , \mathcal{A} must obtain either the pair (a_i, sk_{g2}) or the pair (c_{g2}, sk_i) .

The probability for \mathcal{A} to distinguish between $Game_2$ and $Game_3$ and derive the shared session key k_{gNB}^* is negligible without breaking the hash function or solving the ECDHP. Therefore, we have:

$$|Pr[Succ_3] - Pr[Succ_2]| \le q_h A dv_{\mathcal{A}}^{ECDHP} \tag{6}$$

After exhausting all query options and implementing various attacks against the proposed scheme, the adversary \mathcal{A} can only guess the bit b to win the game through the $Test(\Pi_{MD_i}^m, b)$ query. Therefore, we have:

$$Pr[Succ_3]| = \frac{1}{2} \tag{7}$$

According to the triangle inequality $|a \pm b| \le |a| + |b|$, we have:

$$\frac{1}{2}Adv_{\mathcal{A}}^{P} = \left| Pr[Succ_{0}] - \frac{1}{2} \right| \\
= \left| Pr[Succ_{0}] - Pr[Succ_{3}] \right| \\
\leq \frac{q_{h}^{2}}{2|Hash|} + \frac{(q_{s} + q_{e})^{2}}{2|Hash|} + q_{h}Adv_{\mathcal{A}}^{ECDHP}$$
(8)

That is $Adv_{\mathcal{A}}^P \leq \frac{q_h^2}{|Hash|} + \frac{(q_s+q_e)^2}{|Hash|} + 2q_hAdv_{\mathcal{A}}^{ECDHP}$. Given that $|Hash| = 2^q$, where q represents the output bit length of the hash function, and $Adv_{\mathcal{A}}^{ECDHP}$ denotes the probability of successfully solving the ECDH problem (which is negligibly small under reasonable security assumptions), we can conclude that $Adv_{\mathcal{A}}$ is negligible. Consequently, the proposed scheme achieves semantic security of session keys under the RoR model.

C. Formal Analysis based on ProVerif

ProVerif is an automated cryptographic protocol verification tool widely used to examine whether protocols satisfy specific security properties based on the Dolev-Yao attack model [36]. We continue to use ProVerif to demonstrate that the proposed scheme can achieve mutual authentication, key agreement, and data confidentiality between gNB and MD with the assistance of DT during the handover. For space conservation, the complete verification code for the proposed scheme is presented in [37].

In order to verify that the proposed scheme can achieve the security objectives, we have declared the necessary events and defined corresponding queries as shown in Fig 5(a). query attacker(Msq MD) and query attacker (Msq qNB) describe the confidentiality of transmitted messages encrypted by the negotiated session key between gNB and MD, inj - event(termMD(x, y, z)) = =>inj - event(acceptsgNB(x, y, z)) describes the authentication of MD to gNB, inj - event(termgNB(x, y, z)) = >inj-event(acceptsMD(x, y, z)) describes the authentication of gNB to MD similarly. Furthermore, the last query event(termgNB(x, y, k)) & event(acceptsMD(x, y, k'))=> k = k' describes that gNB and MD can negotiate the same session key after completing mutual authentication. Fig. 5(b) presents the simulation results of the proposed scheme under ProVerif, it demonstrates that the proposed scheme has successfully achieved mutual authentication, key negotiation as well as data confidentiality.

D. Further Security Analysis

We further demonstrate that the proposed scheme can achieve the design goals against various attacks.



(a) Events and Queries

Verification summary:
Query not attacker(Msg_MD[]) is true.
Query not attacker(Msg_gNB[]) is true.
<pre>Query inj-event(termMD(x,y,z_1)) ==> inj-event(acceptsgNB(x,y,z_1)) is true.</pre>
<pre>Query inj-event(termgNB(x,y,z_1)) ==> inj-event(acceptsMD(x,y,z_1)) is true.</pre>
<pre>Query event(termgNB(x,y,k_3)) && event(acceptsMD(x,y,k')) ==> k_3 = k' is true.</pre>

(b) Simulation Results



1) Mutual Authentication: During the access delegation phase, MD_i generates an authorized token d_i for DT_j using DT's public key and k_{SEAF_i} (shared between MD_i and AMF). MD_i signs d_i as u_i and encrypts it with k_{ij} before sending to DT_j . DT_j then signs u_i and encrypts it using AMF_1 's public key. This ensures only the legitimate AMF_1 can decrypt u_i . If u_i is compromised, AMF_1 can detect this by recomputing $t_i = H_5(k_{SEAF_i} \oplus N_i)$ using the received $GUTI_i$ and verifying that $u_i = e(sk_i \cdot d_i, P) = e(sk_i \cdot P, d_i) = e(pk_i, t_i \cdot pk_j)$ fails with an attacker's public key. This allows AMF_1 to authenticate DT_j . Additionally, DT_j verifies AMF_1 's legitimacy and the access delegation δ_j by computing $\delta_j P = h_1 \cdot bpk_{a1} + h_2 \cdot R_j + pk_{a1}$.

In the handover authentication phase, gNB_2 verifies DT_j 's legitimacy using its public key to check signature λ_j (equation 9). Upon verification, gNB_2 accepts that DT_j is authorized by AMF_1 . gNB_2 then generates MAC_2 using sk_{g2} and h_5 using TIK_i^* (derived from k_{gNB}^*). DT_j verifies MAC_2 using gNB_2 's public key pk_{g2} , confirming gNB_2 's legitimacy and the correctness of C_{g2} and h_5 . DT_j then encrypts h_5 in MAC_3 using k_{ij} and sends it to MD_i . After verifying MAC_3 , MD_i accepts C_{g2} and h_5 as legitimate and authenticates gNB_2 by validating h_5 . Finally, gNB_2 verifies MD_i by checking MAC_4 , which is possible because only legitimate MD_i and gNB_2 can compute K_i and k_{qNB}^* .

$$\lambda_j P = (\delta_j \cdot h_3 + b_j \cdot h_4) \cdot P$$

= $\delta_j \cdot h_3 \cdot P + h_4 \cdot B_j$
= $h_3 \cdot (pk_{a1} + h_1 \cdot x_{a1} \cdot P + h_2 \cdot R_j) + h_4 \cdot B_j$
= $h_3 \cdot pk_{a1} + h_1 h_3 \cdot bpk_{a1} + h_2 h_3 \cdot R_j + h_4 \cdot B_j$ (9)

2) Key Negotiation: In the proposed scheme, MD_i transmits A_i to gNB_2 , and gNB_2 delivers C_{g2} to MD_i via DT_j . Subsequently, they can individually calculate the secret value K_i and derive the temporary session key k_{gNB}^* . It is infeasible for any attackers or even DT_j to compute K_i without knowing

Table II: Functionality Comparison

Functionality	MAKA	Anonymity	Unlinkability	Traceability	Key Confirmation	PFS	PBS	KEF	ELS
5G-AKA [2]	\checkmark	\checkmark	×	\checkmark	×	×	×	×	×
Lai et al.'s [7]	\checkmark	\checkmark	×	\checkmark	×	\checkmark	\checkmark	×	×
Ma et al.'s (I) [9]	\checkmark	\checkmark	×	\checkmark	×	×	×	×	×
Ma et al.'s (II) [9]	\checkmark	\checkmark	×	\checkmark	×	\checkmark	\checkmark	×	×
Cao et al.'s [21]	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	×	×	×	×
Zhang et al.'s [22]	\checkmark	\checkmark	×	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark
Yan et al.'s [29]	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark	\checkmark	\checkmark	×
Gupta et al.'s [27]	\checkmark	\checkmark	×	×	\checkmark	\checkmark	\checkmark	\checkmark	×
He et al.'s [38]	\checkmark	\checkmark	×	\checkmark	×	\checkmark	×	×	×
Wang et al.'s [39]	\checkmark	\checkmark	×	\checkmark	×	\checkmark	\checkmark	\checkmark	×
Li et al.'s [34]	\checkmark	\checkmark	×	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	×
Ours	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark

1. MAKA: MD and base station achieve mutual authentication and key agreement; 2. Anonymity: MD's true identity should be protected from base stations and adversaries; 3. Unlinkability: The adversary cannot distinguish that more different messages originate from the same MD. 4. Traceability: The true identity of MD should be revealed when misbehavior happens; 5. Key Confirmation: MD and base station should confirm that each other has generated the secret key successfully; 6. PFS: Perfect Forward Secrecy; 7. PBS: Perfect Backward Secrecy; 8: KEF: Key Errow Freshness; 9: ESL: Ephemeral Secret Leakage.

2. \checkmark represents the functionality is achieved; \times represents the functionality is not achieved.

the secret values a_i , sk_i , c_{g2} , and sk_{g2} , even if A_i and C_{g2} have been intercepted according to ECDLP and ECDHP. The correctness of K_i is shown in equation 10.

$$K_{i} = a_{i} \cdot sk_{i} \cdot C_{g2}$$

$$= a_{i} \cdot sk_{i} \cdot c_{g2} \cdot sk_{g2} \cdot P$$

$$= c_{g2} \cdot sk_{g2} \cdot a_{i} \cdot sk_{i} \cdot P$$

$$= c_{g2} \cdot sk_{g2} \cdot a_{i} \cdot pk_{i}$$

$$= c_{g2} \cdot sk_{g2} \cdot A_{i}$$
(10)

3) Anonymity and Unlinkability: In the proposed scheme, true identity of the MD_i is hidden in temporary value $GUTI_i$, which is used by DT_j to initiate the handover authentication with gNBs. Only the 5GC can reveal the true identity $SUPI_i$ of MD_i . In addition, MD_i generates different TID_i with gNBs in intra-domain handover and updates the $GUTI_i$ with AMFs in inter-domain handover. It is difficult for an adversary to determine that the two temporary identities belong to the same MD_i when eavesdropping on the wireless channel.

4) **Traceability**: There are malicious MD_i that can apply and deploy the corresponding compromised digital twin, using intercepted information such as u_i , to engage in unauthorized access delegation with AMFs or initiate handover processes with gNBs. During the verification phase, if any suspicious behavior is detected, traceability measures can be activated through UDM and AUSF. Using the ID_j identifier, UDMcan search the corresponding U_j , enabling AUSF to compute the $SUPI_i = ID_j \oplus H_1(sU_j)$ to reveal the true identity of MD_i . AUSF and UDM can further revoke the public key of DT_j and imposing the application of MD_i in the network.

5) **Perfect Forward/Backward Secrecy (PFS/PBS)**: In the proposed scheme, the secret value $K_i = a_i \cdot sk_i \cdot C_{g2}$ or $K_i = c_{g2} \cdot sk_{g2} \cdot A_i$ and temporary session key $k_{gNB}^* = H_2(K_i, GUTI_i, ID_{g2})$. Since a_i and c_{g2} are chosen randomly in each session, even if the attacker can obtain the long-term keys sk_i and sk_{g2} , it is difficult to derive the previous secret value K_i and session key k_{gNB}^* , thus achieving PFS. Moreover, since future sessions will use new random values

 a_i and c_{g2} that are independent of previous sessions, even if an attacker obtains previous session keys k_{gNB}^* , they cannot derive or compromise the keys for subsequent sessions, thus achieving PBS.

6) Key Escrow Freeness (KEF): In the system initialization phase, MD_i , DT_j , gNB independently generate their private key. In addition, although AUSF generates partial secret key x_a for AMF, which generates its own private key sk_a and introduces random number r_j in each access delegation so that AUSF cannot derive δ_j with x_a alone. Therefore, the proposed scheme is a key escrow-free handover authentication protocol.

7) Ephemeral Secret Leakage (ESL) Resistance: In the proposed scheme, the session key $k_{gNB}^* = H_2(a_i \cdot sk_i \cdot c_{g2} \cdot sk_{g2} \cdot P, GUTI_i, ID_{g2})$ is derived from combination of ephemeral secrets (a_i, c_{g2}) and long-term keys (sk_i, sk_{g2}) . If an adversary attempts to compute the k_{gNB}^* , it requires that both ephemeral and long-term secrets must be leaked simultaneously, which is highly unlikely in practice. Therefore, our proposed scheme is resistant to ephemeral secret leakage.

8) **Protocol Attack Resistance:** In the proposed scheme, the confidential data including u_i is encrypted by the k_{ij} between MD_i and DT_j and the access delegation δ_j and u_i is encrypted by the each other's public key between DT_j and AMF_1 to resist **eavesdropping**. The random session number N_i generated by MD_i and the timestamp TS added in each session is to defend the replay attack from the malicious attacker who intercepts the previous data. The hash function, message authentication code, and digital signature are employed in each session to resist **impersonation attack** and **man-in-the-middle attack**. In addition, our scheme supports batch verification which can alleviate the **DoS attacks** for gNBs.

VI. PERFORMANCE EVALUATION

In this section, we analyze the security functionality and performance including signaling, communication, and computation overheads of the proposed scheme between MD and gNB in the intra-domain handover authentication phase, and compare it with other related handover authentication schemes.

A. Security Functionality

Table II presents the comparison of the security functionalities between our proposed scheme and other relevant handover authentication schemes. 5G-AKA [2] is standard scheme as defined by 3GPP, Lai et al.'s scheme [7], Ma et al.'s scheme I and scheme II [9], Cao et al.'s scheme [21], Zhang et al.'s scheme [22] and Yan et al.'s scheme [29] are handover scheme in 5G related scenarios; Gupta et al.'s scheme [27], He et al.'s scheme [38], Wang et al.'s scheme [39] and Li et al.'s scheme [34] are handover scheme in other wireless network scenarios. Through the analysis, all schemes can achieve the basic goal of mutual authentication and key agreement between MD and base station. Regarding identity privacy preservation, all schemes support the anonymity of the MD and the traceability of the central server or core network, except for schemes [27]. However, only Ma et al.'s scheme II [9], Cao et al.'s scheme [21], Yan et al.'s scheme [29] and ours support unlinkability to prevent tracking by adversaries on the wireless channel. Cao et al.'s scheme [21], Zhang et al.'s scheme [22], Gupta et al.'s scheme [27], Li et al.'s scheme [34], and ours support key confirmation. In the context of secret key security, 5G-AKA [2], Ma et al.'s scheme I [9] and Cao et al.'s scheme [21] fail to achieve PFS, PBS and KEF. He et al.'s scheme [38] can not achieve PBS and KEF. Ma et al.'s scheme II [9] and Lai et al.'s scheme [7] can not achieve KEF. Additionally, only Zhang et al.'s scheme [22] and ours can resist ESL attack.

B. Signaling Overhead

Signaling overhead refers to the costs of transmitting signaling messages to achieve handover authentication between the MD and the base station. We use a to represent the overhead of transmitting a signaling message between the MD and the base station and n to represent the number of MDs. As shown in Table III, we compare the signaling overheads with other 5G-related schemes and illustrate this comparison in Fig. 6. By comparison, our scheme demonstrates lower signaling overhead compared to most existing schemes, except for Ma et al.'s scheme [9] and Lai et al.'s scheme [7], which utilize a group leader to generate aggregated authentication codes for base stations on behalf of other MDs. In our proposed scheme, digital twin have replaced MD to transmit some necessary messages to the base station through dedicated API wired channels. This not only saves wireless resources but also reduces the signaling overhead. The MD only needs to send one message to the base station to complete authentication. In fact, this message serves as the key confirmation to complete the entire handover authentication procedure between the MD and the target base station.

C. Computation Overhead

We present the main computation costs of cryptographic operations for both the MD and base station in Table IV. Testing was performed on an Intel i5-2500 @ 3.30 GHz (MD)

Table III: Comparison of Signaling Overhead

Schemes	Signaling Overhead
5G-AKA [2]	5an
Lai et al.'s [7]	2a
Ma et al.'s [9]	2a
Cao et al.'s [21]	3an
Zhang et al.'s [22]	3an
Yan et al.'s [29]	2an + 4a
Gupta et al.'s [27]	3an
He et al.'s [38]	3an
Wang et al.'s [39]	3an
Li et al.'s [34]	3an
Ours	an



Figure 6: Signaling Overhead in Handover Authentication

and Intel i7-6600U @ 2.60 GHz (base station, including gNB, eNB, and other access points) [39]. The operations are denoted as T_p for pairing operation, T_e for modular exponentiation, T_m for elliptic curve scalar multiplication, T_r for RSA signature verification, and T_h for hash operation. Lightweight operations (symmetric encryption, XOR, point addition) are omitted due to negligible costs. We analyze computation overhead in two scenarios: the normal scenario considers all computations during handover authentication, and the optimized scenario only considers computations after MD enters the target base station's coverage area.

In Table V, we compare our scheme with other handover authentication schemes and visualize the total computation overhead comparison in Fig. 7. Through comprehensive analysis, our results reveal that in normal scenarios, our scheme exhibits slightly higher computation overhead compared to 5G-AKA [2], Ma et al.'s scheme (I) [9], and Cao et al.'s scheme [21]. This increased overhead stems from two primary factors: these existing schemes utilize lightweight symmetric encryption for handover authentication, while our scheme requires the target base station to perform additional multiplication operations to verify the digital twin's legitimacy. However, in optimized scenarios, our scheme demonstrates significantly lower computation overhead than all other com-

Table IV: Computation Costs of the Primitive Cryptography Operations (ms)

	T_p	T_e	T_m	T_r	T_h
MD	2.87	0.225	0.203	0.127	0.0013
Base Station	0.762	0.034	0.03	0.019	0.0008

Schemes	T_{MD}	T_{BS}	T_{tot}	T_{MD-opt}	T_{BS-opt}	$T_{tot-opt}$
5G-AKA [2]	$4nT_h$	$2nT_h$	0.016n	$4nT_h$	$2nT_h$	0.016n
Lai et al.'s [7]	$2T_m + T_h + nT_r + 2nT_p$	$3T_e + nT_m$	5.897n + 0.509	$nT_r + 2nT_p$	$nT_m + 3T_e$	5.897n + 0.102
Ma et al.'s (I) [9]	$5nT_h$	nT_h	0.007n	$5nT_h$	nT_h	0.007n
Ma et al.'s (II) [9]	$3nT_m + 4nT_h$	$2nT_m + nT_h$	0.675n	$3nT_m + 4nT_h$	$2nT_m + nT_h$	0.675n
Cao et al.'s [21]	$4nT_h$	$5nT_h$	0.0092n	$3nT_h$	$3nT_h$	0.0063n
Zhang et al.'s [22]	$6nT_m + 4nT_h$	$6nT_m + 5nT_h$	2.001n	$3nT_m + 2nT_h$	$3nT_m + 6nT_h$	1.067n
Yan et al.'s [29]	$5nT_p + 7nT_m + 8nT_h$	$(2n+9)T_m + 4(n+1)T_h + 5T_p$	15.781n + 0.063	$2nT_h$	$2nT_h$	0.004n
Gupta et al.'s [27]	$7nT_m + 7nT_h$	$12nT_m + 7nT_h$	1.878n	$3nT_m + 4nT_h$	$3nT_m + 4nT_h$	0.754n
He et al.'s [38]	$3nT_e + 4nT_m$	$3nT_p + nT_e + 2T_m$	3.64n	nT_e	$3nT_p + nT_m$	2.541n
Wang et al.'s [39]	$2nT_m + 2nT_h$	$7nT_m + 5nT_h$	0.623n	$2nT_m + 2nT_h$	nT_h	0.409n
Li et al.'s [34]	$14nT_m + 5nT_h$	$8nT_m + 5nT_h$	3.093n	$4nT_m + 3nT_h$	$7nT_m + 4nT_h$	1.029n
Ours	$nT_m + 7nT_h$	$(5n+3)T_m + 11nT_h$	0.372n + 0.09	nT_h	nT_h	0.002n





Figure 7: Computation Overhead in Handover Authentication

pared schemes. The MD and target base station each only need to perform a single hash operation to complete the entire handover authentication process. This remarkable efficiency is achieved because the digital twin proactively completes most computational tasks while the MD remains within the source base station's coverage, pre-establishing authentication and key agreement with the target base station.

D. Communication Overhead

We further analyze the communication overhead, which includes the size of the necessary parameters forwarded between the MD and the target base station during the handover authentication process. In order to achieve the same security level of key strength, it is assumed that the encryption and decryption key length of AES is 128 bits, according to the National Institute of Standards and Technology (NIST) standard. In addition, we assume the sizes of the elements in the cycle group G is 256 bits, and the key size is 3072 bits for both RSA (integer-factorization cryptography) and finite-field cryptography-based public keys. The output size is 128 bits for hash values, message authentication codes, random numbers, and identities. The MD's capability and proxy warrant are 80 bits each, the timestamp is 32 bits and the sequence number is 48 bits. Considering that the Lai et al.'s scheme [7], Ma et al.'s scheme [9], and Yan et al.'s scheme [29] are group-based handover authentication, we have disregarded the communication overhead within the group.

As shown in Table VI, for the standard 5G-AKA [2], the total communication overhead is 512n bits, where n

represents the number of MDs. This overhead comprises a 128-bit random number RAND, 128-bit authentication token AUTN, 128-bit concealed subscriber identity SUCI, and 128-bit response value RES^* . In Lai et al.'s scheme [7], the total communication overhead is 3328n + 9728 bits which is based on finite-field cryptography. In Ma et al.'s (I) [9], the total communication overhead is 128n + 768 and in Ma et al.'s (II) [9] is 384n+976 where the latter uses the ECC encryption. In Cao et al.'s [21], the total communication overhead is 1184nincluding the necessary capability generated by AHM. In Zhang et al.'s [22], the total communication overhead is 1856nbits. In Yan et al.'s [29], the total communication overhead is 320n + 1024 bits including the pre-handover messages, and the handover authentication executed between each vehicle and the target base station. In our scheme, on the one hand, the essential parameters from the MD to the target base station for authentication are transmitted by digital twin using wired communication. On the other hand, the DT transmits the essential 544 bits pre-handover parameters from source base station to the MD for authentication via the data plane. This approach conserves wireless resources at the control plane, requiring the MD to send only a 288-bit key confirmation to complete the handover authentication process with the target base station. As shown in Fig. 8, it can be observed that our scheme has higher communication overhead compared to Ma et al.'s (I) [9] but is better than other schemes, which helps in saving more wireless resources.

Table VI: Communication Overhead in Handover Authentication (bits)

Schemes	Uplink	Downlink	Total	
5G-AKA [2]	256n	256n	512n	
Lai et al.'s [7]	3328n + 3328	6400	3328n + 9728	
Ma et al.'s (I) [9]	128n + 384	384	128n + 768	
Ma et al.'s (II) [9]	384n + 464	512	384n + 976	
Cao et al.'s [21]	640n	424n	1184n	
Zhang et al.'s [22]	928n	928n	1856n	
Yan et al.'s [29]	288n + 512	32n + 512	320n + 1024	
Gupta et al.'s [27]	1104n	1104n	2208n	
He et al.'s [38]	1128n	384n	1512n	
Wang et al.'s [39]	672n	832n	1504n	
Li et al.'s [34]	1712n	1008n	2720n	
Ours	288n	_	288n	



Figure 8: Communication Overhead in Handover Authentication

E. Performance with Unknown Attacks

Although our scheme can resist common attacks discussed in Section V, unknown attacks may still occur unpredictably [9]. In our scheme, these unknown attacks could disrupt DT operation and data transmission to the MD, preventing advance handover authentication and key negotiation between the MD and base station. We analyze our protocol's performance against unknown attacks in terms of signaling, computational, and communication overhead [21]. This includes analyzing DT's computation overhead for parameter processing and communication overhead for data transmission to MD through the data plane. Focusing on communication overhead analysis, we express the average communication overhead Com_{avg} under attacks in equation 11, where Com_{fail} represents unsuccessful authentication overhead under unknown attacks and Com_{succ} represents successful authentication overhead under known attacks [9]. We use p_{fail} to denote the probability of an unknown attack occurring and $p_{succ} = 1 - p_{fail}$ for success probability. Additionally, $Com_{fail} = \sum_{i=1}^{N} Com_i \times q$ where N is the total number of authentication messages, q = 1/Nis the probability of an unknown attack at step i, and Com_i is the total communication overhead before an attack occurs at step *i*.

$$Com_{avg} = \frac{Com_{fail} \times p_{fail} + Com_{succ} \times p_{succ}}{p_{succ}}$$
(11)

As shown in Fig. 9, we compare average signaling, computation, and communication overhead with other 5G handover authentication schemes under unknown attacks. For groupbased schemes [7], [9], [29], we assume 20 MDs per group and consider unknown attacks affecting wireless communication between group members. We also assume DT has equivalent computation capability to the base station (Table III). In Fig. 9(a), our scheme's signaling overhead under unknown attacks is higher than [9] and [7] but lower than other schemes. As attack probability increases, our scheme's signaling overhead converges with [29]. Fig. 9(b) shows our scheme's average computation overhead under normal scenarios exceeds [9], [21], and [2] but remains lower than other schemes, primarily due to DT's role in generating and verifying handover requests. Fig. 9(c) demonstrates our scheme achieves better average computation overhead in optimal scenarios compared to other schemes, benefiting from DT's advanced processing of complex calculations. Fig. 9(d) reveals that our scheme maintains superior average communication overhead even when accounting for encrypted data and message authentication code transmission from DT to MD via the data plane.

F. Comprehensive Discussion

Our scheme shows slightly higher signaling overheads compared to Lai et al.'s scheme [7] and Ma et al.'s scheme [9], and higher computation overhead compared to standard 5G-AKA [2], Ma et al.'s scheme (I) [9], and Cao et al.'s scheme [21]. However, it achieves better communication overhead, conserving wireless channel resources. While Ma et al.'s scheme [9] is limited to predictable railway scenarios, our scheme adapts to complex urban environments, enabling proactive session key negotiation with future base stations through realtime trajectory analysis, suitable for various mobile scenarios and reducing authentication computational burden regardless of base station distribution patterns. Moreover, our scheme provides enhanced security functionality while maintaining lower overheads between MD and gNB.

Although DT is crucial in our scheme, it faces various potential attacks in real-world scenarios that could impact handover authentication efficiency. While DT can be deployed in TEE on operator-provided dedicated servers [14], it remains vulnerable to DoS and side-channel attacks. Despite authentication parameters being encrypted by k_{ij} , wireless communication faces potential disruption attacks between MD and DT. Even secure interfaces between DT and the base station/core network aren't immune to unauthorized access attempts. Beyond analyzing authentication overhead under unknown attacks, we recommend: periodic k_{ij} updates with continuous authentication between MD and DT, implementing DoS defense and enhanced DT environment security, and regular security audits with improved defensive measures. While these aspects extend beyond our paper's scope, such additional security measures are essential for achieving secure and efficient DT-assisted handover authentication in 5G and beyond.

VII. CONCLUSION

In this paper, we propose a novel handover authentication scheme that both supports 5G Intra-AMF and Inter-AMF scenarios with the assistance of digital twin. By our proposed scheme, the digital twin first obtains the delegation from AMF, then it replaces the MD to initiate handover authentication request to the target base station by analyzing the real-time path so that the mobile device and the MD can accomplish mutual authentication and key agreement before attaching. The proposed scheme is analyzed by BAN logic, ProVerif and informal analysis to prove it can achieve several security functionalities. Additionally, our scheme demonstrates better signaling, computation, or communication overhead, attributed to the incorporation of digital twin, in comparison to the majority of existing related schemes. Despite our scheme being slightly higher than a few schemes in performance, we possess significant in terms of security functionality, features support, and application scenarios. In future work, we will analyze and





Figure 9: Comparison of the Performance under Unknown Attacks.

explore employing the digital twin to support massive mobile device access authentication in 5G and beyond.

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