On Post-Quantum Perfect Forward Secrecy in 6G

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Abstract—The standardized Authentication and Key Agreement protocol for 5G networks (also known as 5G AKA) has several security and privacy vulnerabilities. For example, the 5G AKA does not undertake perfect forward secrecy. In this paper, we propose a novel quantum-safe authentication and key agreement protocol for future generation of mobile communication networks (6G). Our protocol has several privacy and security properties, e.g., it is resistant against linkability attacks and it is quantum-safe. We use the Kyber algorithm, chosen by NIST to become a standard and NIST Round 4 candidate algorithms to analyze the performance of our protocol. The results for communication and computation costs show that utilizing our protocol is feasible in practice. We further prove the security of our protocol by utilizing the well-known formal verifier ProVerif.

Index Terms—6G, 5G AKA, Post-Quantum Cryptography, Privacy, Security, IMSI Catchers.

I. INTRODUCTION
The 5th generation of the mobile communication networks (5G) has several advantages over its predecessors, including lower latency and higher data rates. With 5G, more devices can connect to the mobile networks than what was possible earlier. 5G positively impacts several industries, such as healthcare, transportation and autonomous vehicles [1]. However, the emergence of 5G has increased the concerns about security and privacy of the mobile users [2].

Among other privacy and security issues in mobile networks, the authentication of subscribers is of great concern [3]. Proper authentication mechanism is needed in order to provide many services, e.g., roaming. The rise of quantum computers is one of the concerns in security. A sufficiently large quantum computer can break many currently used cryptographic algorithms. Therefore, some of the mechanisms in 5G that are still considered secure and private at the time of writing, may be broken once quantum computers are part of our reality. It is unclear when a large-scale quantum computer will be available, but it is worth mentioning that some leading companies such as Google [4] and IBM [5] are working on developing quantum computers and they are offering access to their computers over the cloud. Thus, the average attacker is expected to get access to quantum devices (over the cloud), while the average user is still using "classical" devices. Hence, the interest in a cryptography that works on classical devices with the property of resisting quantum attacks or the so called Post-Quantum Cryptography (PQC).

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In this work, we propose a novel post-quantum AKA protocol that has several security and privacy properties. Our detailed contributions and the properties of our protocol are given in Section IV.

II. PRELIMINARIES
A. 5G Terms and Acronyms
For the purposes of our discussions, there are three relevant entities in the mobile network architecture: The User Equipment (UE) which further consists of the Universal Subscriber Identity Module (USIM) and the Mobile Equipment (ME), the Home Network (HN), and the Serving Network (SN). The Home Network assigns to every subscriber a globally unique identifier that is called SUPI (Subscription Permanent Identifier). A SUPI can be concealed, resulting in SUCI (Subscription Concealed Identifier).

B. Key Encapsulation Mechanisms
A key encapsulation mechanism (KEM) is a scheme that is used in cryptographic protocols to exchange symmetric keys. A KEM is a triple of algorithms KEM = (KeyGen(), Encaps(), Decaps()) with a key space $\mathcal{K}$, where

- **KeyGen()** is a non-deterministic algorithm that generates a pair of public and secret key $(pk, sk)$.
- **Encaps**(pk) is a non-deterministic key encapsulation algorithm. The input of **Encaps**(pk) is pk and its outputs are a ciphertext $c$ and a key $k \in \mathcal{K}$.
- **Decaps**(sk, $c$) is a deterministic key decapsulation algorithm. The inputs of **Decaps**(sk, $c$) are sk and c, and the algorithm returns a key $k \in \mathcal{K}$ or $\perp$ denoting failure.

The three algorithms work together in a natural fashion, e.g., both **Encaps** and **Decaps** produce the same key $k$ when the input keys pk and sk are chosen from the same pair.

C. Post-Quantum Cryptography
The security of most practical public-key cryptography schemes is based mainly on the hardness of integer factoring and the difficulty of calculating discrete logarithms on elliptic curves. In [6] Shor showed that these two problems can be efficiently solved by a sufficiently large-scale quantum computer. On the other hand, Grover [7] proposed a quantum algorithm allowing brute-forcing an $n$-bit key in $O(2^{n/2})$ time instead of the $O(2^n)$ time required by classical computers. Consequently, primitives providing security against quantum adversaries that is equivalent to 128-bits of security against...
classical adversaries need to have a key length of at least 256 bits. For symmetric cryptography, and to resist against Grover’s algorithm, it is sufficient to consider \(2n\)–bit keys in order to ensure an \(n\)–bit quantum security level. Thus, post-quantum efforts have focused on public-key cryptography. In December 2016, the National Institute of Standards and Technology in the USA (NIST) initiated a standardization process by announcing a call for proposals for post-quantum schemes. Post-quantum cryptography inherits its security guarantees from the hardness of some well-studied mathematical problems. The current state of art suggests four types of problems, namely, problems arising from lattices, error-correcting codes, systems of multivariate polynomials, and supersingular isogeny elliptic curves. In July 2022, NIST selected CRYSTALS-KYBER which is a lattice based KEM to be the primary algorithm recommended for standardization. On the other hand, NIST also chose four algorithms for a next (4th) selection round. These four include BIKE, Classic McEliece and HQC which are all code-based schemes, as well as SIKE which is based on isogenies. We will give further details on implementing the mentioned algorithms as part of our protocol in Section VIII.

D. Used Symmetric Primitives

In order to be consistent with the 3GPP standardization, we use the same notations as in [3GPP TS 33.501]. In our protocol we use a Key Derivation Function (KDF) which is based on SHA256, and seven symmetric key algorithms that are denoted by \(f_1, f_2, f_3, f_4, f_5, f_1^*, \) and \(f_5^*\). Please note that although 3GPP did not fully standardized the functions \(f_1 - f_5^*\), 3GPP requires that breaking the security of these functions should require approximately \(2^{128}\) operations. The MILENAGE algorithm set [3GPP TS 35.205] provides examples of the functions \(f_1 - f_5^*\) which utilizes an AES-128 block cipher as a kernel function. Please note that an AES-256 is quantum-resistant and can be utilized as kernel function (because it has the same block size as AES-128).

III. RELATED WORK

Various works have pointed security and privacy issues in mobile networks authentication and key agreement (AKA) protocols. One of these issues is the so-called linkability attacks, such attacks consist of the attacker linking protocol executions based on the user’s behaviour to conclude some critical information about the user, for example, their identity or location. In [8], the authors described an attack where they exploited the failure messages in previous mobile AKA protocols to track the target user, the authors proposed concealing the error messages using the HN public key. In [9], Fouque et al. discovered another attack that accrues despite the fix proposed in [8]. The work in [10], described a threat where the attacker can guess the pattern of the so-called sequence number by exploiting the synchronisation failure message sent by a target UE. In our protocol, we abandon the use of sequence numbers to avoid possible de-synchronization attacks. In fact, considering the mentioned linkability attacks, became a central issue in many recent works on 5G/6G AKA protocols, see for instance [11] and the references therein. In [12], the authors provided a formal verification of 5G AKA, where they pointed further security issues in the studied protocol. In fact, they showed the lack of a session key confirmation between the UE and the SN, solutions to such an issue while considering linkability were considered in [13], [14], but these works did not consider further security problems. An example of such issues is the perfect forward secrecy. In our quantum resistance context, we expect that an attacker is currently recording the (encrypted) messages sent between the UE and the SN in the hope of compromising the long term keys of either the UE or HN by some other means, for example, a large scale quantum computer. In the standardized 5G AKA and previous generations, compromising the long term keys will imply compromising previous sessions keys. In other words, the property of perfect forward secrecy is broken, such a problem in mobile networks was considered in [15]–[17]. In both [15], [16], the perfect forward secrecy is based on the intractability of the discrete logarithm problem. Consequently, such proposals are vulnerable to quantum attacks (Shor’s algorithm), while the work in [17] uses a generic encryption in their protocol that we might assume it to be post-quantum, but their protocol lacks session key confirmation. In our work, we use quantum resistant KEMs. Implementing post-quantum KEMs in 5G was considered in [18], but the authors only consider the identification phase of the AKA protocol, thus, further security features, i.e., linkability, forward secrecy were not covered. In the next section, we list our contributions in more details.

As a side note on the work in [16], we would like to point out that the authors used ProVerif to formally verify their protocol, we remarked that the code published in [16] considers the channel between the UE and SN as secure, while the channel between the SN and the HN is insecure. In fact, it is the converse. We re-implemented the authors verification with the corrected assumptions and noted that two of the claimed properties are in fact false. However, the perfect forward secrecy still holds.

IV. CONTRIBUTIONS

We present a post-quantum authentication and key agreement protocol for 6G, where we consider various privacy and security issues from previous mobile generations, namely

- Linkability attacks.
- Key confirmation between the SN and the UE.
- Abandoning the use of sequence numbers in order to avoid potential de-synchronization attacks.
- Perfect forward and backward secrecy.

We then summarise the security properties of our protocol as follows:

1) Quantum resistance.
2) SUPI confidentiality.
3) Mutual authentication between UE and SN via the HN.
4) Confidentiality of the session key.
5) Perfect forward and backward secrecy.
6) Unlinkability.
7) Protection against replay attacks.

Moreover, we use the formal verification tool ProVerif to prove some of the above claims. Furthermore, we give an overview on practical implementation of our protocol. First by describing some backward compatibility of our protocol with previous mobile generations, see Section V-D. Second, by implementing the protocol using Kyber, the recently standardized Post-Quantum KEM by NIST and Round4 KEM NIST finalists, see Section VIII, and we further show that implementing our protocol with such KEMs and especially Kyber outperforms the use of the used public-key cryptography in 5G AKA.

V. OUR PROTOCOL

We distinguish three phases in our protocol. Phase A is the identification request phase which is performed at the UE. Phase B is the UE’s identification by the HN, and Phase C is an authentication phase, which allows both the UE and the HN to securely authenticate each other.

A. Phase A: The Identification Request at the UE

The UE starts the identification request phase by freshly generating a pair of public/private KEM keys: \((pk_U, sk_U)\). Then the UE conceals both the SUPI and \(pk_U\). The concealment that we denote by \(\text{SUPI}_{\text{conc}}\) is done by symmetric encryption \(\text{Enc}_{K_s}\) using the key, \(K_s\), resulting from an encapsulation based on the HN public key, \(pk_{H,N}\), which is stored at the USIM. Finally, the UE computes a MAC tag using the function \(f_1\) with \(\text{SUPI}_{\text{conc}}, K_s\), and \(K\). Please note that the asymmetric encryption (encapsulation) is the most costly computation in the above process. According to [3GPP TS 33.501], the SUPI encryption can be performed by a next generation SIM card [3GPP TS 3.102], or outside of the SIM, namely, by the ME. In our design we consider the latter case as we intend to further precise the operations performed by the USIM and ME.

First, the ME generates a pair of KEM public/private keys:

\[(pk_U, sk_U) \leftarrow \text{KeyGen}()\].

The ME stores \(sk_U\), then the USIM computes a hash \(K' = f_1(pk_U, K)\) and hands \(K'\) to the ME. This last performs the following operations to generate the authentication request material at UE.

| **Identification Request** \((K', \text{SUPI}, \text{ID}_{SN}, \text{ID}_{HN})\): |
|---------------------------------------------------------------|
| 1) \((pk_U, sk_U) \leftarrow \text{KeyGen}()\). |
| 2) \((c_1, K_s) \leftarrow \text{Encaps}(sk_{HN}).\) |
| 3) \(\text{SUPI}_{\text{conc}} \leftarrow \text{Enc}_{K_s}(\text{SUPI}|pk_U, \text{ID}_{SN}).\) |
| 4) \(\text{MAC}_U = f_1(\text{SUPI}_{\text{conc}}, K_s, K')\). |
| 5) \(\text{Send} (c_1, \text{SUPI}_{\text{conc}}, \text{MAC}_U, \text{ID}_{HN})\) to SN. |

Note that the use of \(K'\) in the MAC in Identification Request helps in authenticating the UE identification request by the HN. This is to protect against an attacker who has somehow obtained victim’s SUPI. One way of compromising the SUPI in the quantum era is via a downgrade attack, where the attacker forces the UE to use 5G AKA. In this case, the SUPI is encrypted using ECIES which is vulnerable to Shor’s algorithm. If the key \(K'\) was not used in the MAC derivation, then the attacker can perform all the operations in Identification Request including generating its own key pair \(pk_U / sk_U\) and consequently the attacker could keep requesting legit authentication vectors from the HN which might result in a Denial of Service (DoS) attack. Please note that replaying a recorded SUPI will not be detected by the HN as there is no mechanism to check freshness of the first message sent by the UE to the HN. Such an attack scenario (replaying recorded SUCIs) could be prevented by the HN by remarking arrival of multiple identical SUCIs during a (short) period of time. Then the replays could be detected as all SUCIs are expected to be different which is due to the use of a randomized encryption. It is unlikely that an attacker is able to collect a big number of different valid SUCIs before it launches the DoS attack.

B. Phase B: The UE Identification at the HN

Once the SN receives \((c_1, \text{SUPI}_{\text{conc}}, \text{MAC}_U, \text{ID}_{HN})\), it generates a random 256 bit string \(R_{SN}\), and then forwards \((c_1, \text{SUPI}_{\text{conc}}, \text{MAC}_U, R_{SN})\) to the HN.

| **Identification at HN** \((sk_{HN}, \text{ID}_{SN}, c_1, \text{SUPI}_{\text{conc}}, \text{MAC}_U)\): |
|---------------------------------------------------------------|
| 1) \(K_s \leftarrow \text{Decaps}(c_1, sk_{HN}).\) |
| 2) \((\text{SUPI}, pk_U) \leftarrow \text{Dec}_{K_s}(\text{SUPI}_{\text{conc}})\). |
| 3) Use SUPI to retrieve \(K\). |
| 4) Compute \(K' = f(pk_U, K)\). |
| 5) \(\text{MAC}'_U = f_1(\text{SUPI}_{\text{conc}}, K_s, K')\). |
| 6) \(\text{If } \text{MAC}_U \neq \text{MAC}'_U \text{ abort.}\) |
| 7) \(\text{Else } (c_2, K_s) \leftarrow \text{Encaps}(sk_U)\). |

The next step consists of the generation of an authentication challenge for the UE by the HN.

C. Phase C: The Authentication Phase

Once the MAC check passes at the HN, it derives the key \(K_{s2}\) and the ciphertext \(c_2\) using the post-Quantum KEM and \(pk_{U}\). Next, the HN proceeds on computing an authentication vector using the \(\text{Auth}_{\text{Vector}}(K, K_{s2}, R_{SN}, \text{ID}_{SN})\) algorithm.

The HN sends AUTN, HXRES* and \(c_2\) to the SN and this last forwards both AUTN and \(c_2\) to the UE. At the UE side, the ME first obtains \(K_{s2}\) using the decapsulation algorithm with the stored secret key \(sk_{U}\).

\(K_{s2} \leftarrow \text{Decaps}(c_2, sk_{U})\).

At its turn the USIM receives \(K_{s2}\) and proceeds on computing the response to the challenge.

In the case of a successful run of USIM Resp, the ME generates RES* and the key material using ME Resp.
Auth\_Vector\((K, K_{s_2}, R_{SN}, ID_{SN})\):
1) Compute \(MAC = f_1(K, K_{s_2}, R_{SN})\).
2) \(XRES = f_2(K, K_{s_2}), CONC = f_3(K, K_{s_2}) \oplus R_{SN}\).
3) \(AUTN = (CONC, MAC)\).
4) \(CK = f_4(K, K_{s_2}), IK = f_4(K, K_{s_2})\).
5) \(XRES^* = KDF(CK, IK, K_{s_2}, XRES, ID_{SN})\).
6) \(HXRES^* = SHA256(R_{SN}, XRES^*)\).
7) \(K_{ausf} = KDF(CK, IK, K_{s_2}, CONC, ID_{SN})\).
8) \(K_{sea} = KDF(K_{ausf}, ID_{SN})\).
9) Set \(K_3 = XRES^* \oplus f_5(K, K_{s_2})\).
10) Compute the symmetric encryption \(M = SEnc_{K_3}(K_{sea}, SUPI)\).
11) Return \((AUTN, HXRES^*, M)\).

USIM\_Resp\((K_{s_2}, AUTN, K)\):
1) Parse \(AUTN\) as \(AK \oplus R_{SN}, MAC\).
2) \(AK = f_5(K, K_{s_2})\).
3) Compute \(R_{SN}\) from \(AK \oplus R_{SN}\).
4) Check \(f_1(K, K_{s_2}, R_{SN}) = MAC\). If this check does not pass, Return \(\perp\).
5) \(RES = f_2(K, K_{s_2})\).
6) \(CK = f_3(K, K_{s_2}), IK = f_4(K, K_{s_2})\).
7) Return \((RES, CK, IK)\).

ME\_Resp\((K_{s_2}, CK, IK, AUTN, ID_{SN}, RES)\):
1) \(RES^* = KDF(CK, IK, K_{s_2}, RES, ID_{SN})\).
2) Get \(CONC\) from \(AUTN\).
3) \(K_{ausf} = KDF(CK, IK, K_{s_2}, CONC, ID_{SN})\).
4) \(K_{sea} = KDF(K_{ausf}, ID_{SN})\).
5) Return \((K_{sea}, RES^*)\).

Finally, the ME forwards \(RES^*\) the SN, the SN receives the value of \(RES^*\) from the UE and then compares \(SHA256(RES^*, R_{SN})\) with \(HXRES^*\). If the two values are equal, the SN uses \(R_{SN}\) to obtain \(f_5(K, K_{s_2})\) from \(CONC\) and computes:

\[ K_3 = RES^* \oplus f_5(K, K_{s_2}). \]

Finally, the SN obtains the \(SUPI\) and \(K_{sea}\) by decrypting \(M\) using \(K_3\). Finally, the SN sends a confirmation message.

D. Remark on Backward Compatibility of our Protocol

In 5G AKA, the UE and the HN store sequence numbers that we denote by \(SQN_U\) and \(SQN_H\) respectively. These numbers are supposed to match as the sequence number is used to check synchronization and detect replay attacks. Consequently, unsynchronized \(SQN\) might cause a communication interruption. An attacker can force such unsynchronization by a DoS attack. Moreover, and for generating the UE challenge at the HN, the HN generates a random bit string denoted RAND. The freshly generated RAND is a part of the authentication vector sent by the HN to the UE and it is sent as a plain text to allow the UE to derive the challenge response. In [11], the authors remarked that known linkability attacks might be avoided by masking RAND, to do so they re-used the shared key between the HN and the UE that was initially used for encrypting the \(SUPI\). In our protocol, to avoid potential unsynchronization attacks we replaced the sequence number by \(R_{SN}\), the randomness generated at the SN. Furthermore, the RAND in 5G AKA is replaced by \(K_{s_2}\), the key that is encapsulated by the HN using the freshly generated public key of the UE. In fact, with this two modification we kept the same algorithm as in 5G AKA for deriving the authentication vector at the HN. Similarly, the response at the USIM uses the same algorithm as in 5G AKA but again by replacing \(SQN\) by \(R_{SN}\) and RAND by \(K_{s_2}\), which provides a USIM compatibility with the standardized 5G AKA.

VI. THE CASE OF GUTI

In the above we only covered the case where the identification is based on the permanent identifier \(SUPI\). However, the much more frequent case is when the Global Unique Temporary Identifier (GUTI) is used. The use of GUTI is favoured over the use of \(SUPI\) in 5G (and also in earlier generations) because it is a frequently changing identifier which is chosen independently of \(SUPI\). It is transferred to the UE over encrypted channel. Therefore, GUTI provides identity confidentiality against passive attackers. When GUTI is used as an identifier, no (asymmetric) encryption is required. In the best case, after every successful communication, the SN assigns a new GUTI to the UE over the pre-established secure channel. As in the case of \(SUPI\), the identification request can be initiated either by the UE or the SN. In the rest of this section, we assume that the identification is based on GUTI, where the UE sends its GUTI to the SN. Next, the SN either chooses to continue using the shared session keys from the previous connection or starts a fresh authentication via the HN. Note that in both cases a new GUTI can be allocated to the UE. In the latter case, the authentication (in 5G AKA) is similar to the \(SUPI\) case. Hence, the resulting session key \(K_{sea}\) will suffer from the mentioned security issues, namely, the lack of forward secrecy and key confirmation. In this section, we equip our protocol by a mechanism covering the GUTI case.

We recall that after a successful run of our protocol, both the UE and the HN will share the key \(K_{s_2}\) and the random bit string \(R_{SN}\) generated by the SN. We further require that after each key confirmation, both the UE and the HN store a hash value:

\[ K_S = h(K_{s_2}, R_{SN}) , \]

where \(h\) is some hash function that is agreed globally. Moreover, we require that with every GUTI assignment, the SN
generates and sends a random bitstring $R'_SN$ attached to the GUTI to the UE over the established secure channel. The idea behind our solution for the GUTI case is to replace $K_{s2}$ with $K_S$ and $R'_SN$ with $R_SN$ in our SUPI-based protocol. More precisely, the procedure goes as follows

1) The UE sends an identification request to the SN by sending GUTI.
2) The SN resolves the SUPI from GUTI and forwards the SUPI with the stored $R'_SN$ to the HN.
3) The HN runs Auth_Vector with $K_S$ instead of $K_{s2}$ and $R_SN$ instead of $R_SN$.
4) Similarly, the UE runs ATME and USIN_Resp with $K_S$ instead of $K_{s2}$ and $R'_SN$ instead of $R_SN$.

Note that the HN is able to distinguish the GUTI case from the SUPI case. Please remark also that the forward security in the case of SUPI (resp. GUTI) is based on the shared $K_{s2}$ (resp. $K_S$), while the key confirmation follows from the contribution of the SN, that is $R_SN$ in the SUPI identification and $R'_SN$ in the GUTI case. By assumption, the parameters $K_{s2}$, $K_S$ are shared only between the UE and the HN, while $R_SN$ and $R'_SN$ are shared by the UE, SN and HN. Moreover, the SUPI and GUTI protocols are similar, and the only difference consists of replacing $K_{s2}$ by $K_S$ and $R_SN$ by $R'_SN$. Furthermore, and thanks to the hash function $h$, it is practically impossible to link $K_{s2}$ to $K_S$. The same is true for $R_SN$ and $R'_SN$ as they are randomly generated separately. Consequently, a SUPI based protocol execution and a subsequent GUTI based protocol execution cannot be linked to each other. Due to the similarity between the GUTI and SUPI cases, we mainly focus on the security analysis of the SUPI based protocol.

VII. SECURITY ANALYSIS

We prove the security of our protocol by utilizing ProVerif [19], which is one of the well-know formal verification tools.

A. The ProVerif Code

Our verification consists of four major parts. The process at the UE, the process at the SN, the process at the HN, denoted by UE, SN, HN respectively, and a main process to conclude to proof. Our ProVerif code with implementation details and design choices on the chosen primitives, i.e., XOR, KEM, is available in our repository at https://github.com/Secure-Systems-Group/ProVerif-AKA-6G.

B. Verification Results and Security Analysis

In this section, we show our results on the executability of our protocol by showing that each pair of successive messages is executed in sequence. We further prove the secrecy of the protocol long term parameters, namely, $K$ the long term key at the UE/HN, $sk_{HN}$, the secret key at the HN and the long term identifier SUPI. Moreover, the authentication of the UE by the SN by the help of the HN is proved.

1) Query not attacker($sk_{HN}$) is true.
2) Query not attacker($k$) is true.
3) Query not attacker(SUPI[]) is true.
4) Query event($HNRecRegSN(a)$) ==> event($SNSendReqHN(b)$) is true.
5) Query event($SNRecResHN(a)$) ==> event($HNSendResSN(b)$) is true.
6) Query event($UERecResSN(a)$) ==> event($SNSendResUE(b)$) is true.
7) Query event($SNRecConUE(a)$) ==> event($UESendConSN(b)$) is true.
8) Query event($HNRecConSN(a)$) ==> event($SNSendConHN(b)$) is true.

The first three items of the above verification result shows respectively, the secrecy of

1) The HN secret key $sk_{HN}$.
2) The secrecy of the long term key $K$
3) The SUPI confidentiality.

Items 4-8 shows that the following events are executed in the following order

4) The HN received the identification request from the SN (sent by the UE) after the request being sent by SN.
5) The SN received the authentication response for the UE after the response being sent by SN (which accrues once the HN confirmed the identity of UE using MAC1).
6) The UE received the response from the SN (sent by the HN) after the UE being identified by the HN.
7) The UE received the authentication request from the SN (sent by the HN) after the request being forwarded by SN.
8) The SN received the authentication confirmation of the HN from the UE when this last has sent the authentication response, which happens after authenticating the HN by the UE using MAC2.
9) The HN received the session key confirmation from the SN when the SN sends the confirmation message to the HN.

C. Properties of the Session Key $K_{sea}$

We recall that the session key $K_{sea}$ is derived from $K$, $K_{s1}$, $K_{s2}$, $R_SN$ and $ID_SN$, where $K$ is the long term key residing at the temper resistant part of the USIM and the HN. The key $K_{s1}$ is shared between the UE and the HN as is a result of an encapsulation at the UE using the HN public key $pk_{HN}$ and recovered by the HN after decapsulation of a post-quantum cipher text $c_1$ using the secret key $sk_{HN}$ stored at the HN. The key $K_{s2}$ is freshly generated during every session as the KEM used to generate it is a probabilistic encryption depending on a freshly generated randomness at the UE. Similarly, the key $K_{s3}$ is encapsulated at the HN and it is freshly generated as it depends on a newly generated randomness at the HN during encapsulation and the fresh UE public key $pk_{UE}$ sent to the HN in an encrypted form with the SUCI using $K_{s1}$. The bitstring $R_SN$ is generated by the SN during every session and sent to the HN by the SN over a secure channel, then the HN includes $R_SN$, $K$ and $K_{s2}$ in the MAC tag sent the UE with a cipher $c_2$, which allow the UE to decapsulate $K_{s2}$ and authenticate the SN and check that the used $R_SN$ is issued by the legit SN. The identity of $SN$, $ID_SN$ is used to bound the key to the SN contributing to the session. In summary, to obtain $K_{sea}$ an attacker should compromise the long term key $K$, the HN secret key $sk_{HN}$, etc.
the freshly generated randomnesses at the HN (encapsulation) and the SN, which is only possible when the UE, SN and HN are all compromised. From the above we also conclude further properties on $K_{sea f}$, namely, perfect forward secrecy and backward secrecy.

**D. Perfect Forward Secrecy:**

Assuming that an attacker has a recording of some past (encrypted) sessions. Forward secrecy ensures that past recorded encrypted messages will remain protected, despite the long term keys being compromised at some point. Similarly, backward secrecy assumes that if the long term keys leaked, then future sessions (keys) are protected. In 5G AKA, the long term parameters at the UE are the SUPI, and the key $K$ which is stored at the tamper resistant part of the USIM, while the HN has the SUPI and two keys $K$ and $sk_H$. Additionally, and as mentioned previously, the UE and HN shares the sequence numbers $SQN_H$ and $SQN_E$. The session key in the 5G AKA protocol, depends on $K$, RAND and the sequence number SQN. We recall that RAND and the authentication token in 5G are sent over the insecure channel. Moreover, SQN can be obtained from the authentication token using RAND and $K$. Hence, if the key $K$ leaked (from UE or HN), then both forward and backward secretcies for the session key are broken.

The perfect forward secrecy property in mobile networks has been considered in [15] and more recently in [16]. In both works, this property follows from the intractability of the discrete logarithm problem which is vulnerable to quantum attacks. We argue that perfect forward secrecy should be considered in the post-quantum context to prevent the case where an attacker is recording current sessions in the hope of getting access to large scale quantum computer that will allow them to break the recorded ciphers. In our protocol, and as mentioned above, the session key depends on $K$, $K_{s_1}$, $K_{s_2}$, $R_{SN}$ and $ID_{SN}$. Thus, compromising the long term parameters at the UE and HN, i.e., $K$, $sk_{HN}$ and SUPI, will not reveal previous session keys. In fact, compromising the key $sk_{HN}$ would imply revealing the key $K_{s_1}$ and the public key $pk_{U}$, which is send with the SUCI, but the key $K_{s_2}$ and $R_{SN}$ are ephemera. Please note that the encapsulation algorithm that is used to generate $K_{s_2}$ is a probabilistic algorithm that takes an input $pk_{U}$. Hence, re-using the same encapsulation algorithm with the same $pk_{U}$ would result in a key that is different from $K_{s_2}$. Moreover, $R_{SN}$ being ephemeral adds more complexity to the exhaustive key search attack including quantum search attacks (using Grover’s algorithm).

**E. Key Confirmation**

The 5G AKA protocol lacks of a session key confirmation between the UE and the SN. The key $K_{sea f}$ is computed by the UE, while the SN gets the session key from the HN. In fact, there is no confirmation round between the SN and the UE to ensure that they share the same key. However, the key confirmation is considered implicit, that is because if the SN and the UE don’t share the same key, then clearly this would result in a non-reliable communication. In [?], the authors led a formal verification of the 5G AKA protocol using Tamarin, thus, such a problem is worth considering in future designs.

In our protocol, and during the authentication vector generation by the HN, this last generates XRES, the expected response from the UE which will be received by the SN once the UE authenticates the SN and the SN, then computes $HXRES^* = SHA256(R_{SN}, XRES^*)$, and the symmetric encryption

$$M = SEnc_{K_3}(K_{sea f}, SUPI),$$

where the key $K_3$ is derived as follows

$$K_3 = XRES \oplus f_5(K, K_{s_2}),$$

Next, the SN receives $CONC = f_5(K, K_{s_2}) \oplus R_{SN}$, a MAC for authenticating the HN by the UE, the message $M$ and a ciphertext $c_2$ which will allow the UE to decapsulate the key $K_{s_2}$, and $HXRES^*$ (but not XRES). Recalling that $R_{SN}$ is generated and stored by the SN, thus, the SN is able to retrieve $f_5(K, K_{s_2})$ from $CONC$ by a simple XOR operation. Consequently, and to get the key $K_3$, the SN needs the XRES which will be received from the UE after authentication both the HN and also the SN by computing $R_{SN}$ from the authentication vector and using it in the MAC check. Once the SN receives the UE expected response $RES^*$, then the SN checks if

$$HXRES^* = SHA256(R_{SN}, RES^*).$$

This last check confirms that the UE and the SN share the same session key material. The last step consists of the SN decrypting the SUPI and $K_{sea f}$ using the received $RES^*$ and sending a confirmation message to the HN.

**F. Preventing Linkability and Replay attacks**

A linkability attack is a type of attack where the attacker is able to link a user different sessions based on observing the behaviour of the target. One classical way to perform such attacks is where the attacker records messages from an honest execution of a protocol by a target user, replays later the recorded messages in an attack area, then based on the received answers from users in the attack area, the attacker is able to distinguish if the target user is in the area or not. Examples of linkability attacks on mobile networks protocols includes failure message linkability attack [8], encrypted SUPI replay attack [9] and sequence number inference attack [10]. Our protocol prevents such a type of attacks by providing resistance to reply attacks. Assuming that the channel between the SN and the HN is secure, then the message flow of our protocol reduces to the messages sent between the UE and the SN. There is only one message from the SN to the UE consisting of the ciphertext $c_2$ resulting from an encapsulating using the freshly generated UE public key and

$$AUTN = \{f_5(K, K_{s_2}) \oplus R_{SN}, MAC = f_5(K, K_{s_2}, R_{SN})\}.$$
schemes have at least the **Indistinguishability under Chosen Plaintext Attack** (IND-CPA). In particular, any replied cipher \( c_2 \) in our protocol will be detected by the UE, that is assuming that our protocol was implemented using NIST finalists or any IND-CPA KEM. Moreover, the MAC in AUTN depends on the freshly generated key \( K_{s_2} \) and randomness \( R_{SN} \). \( K_{s_2} \) is protected by the freshly generated secret key \( sk_{U} \) of the UE, while \( R_{SN} \) is obtained using \( K \) and \( K_{s_2} \). Consequently, replied or handcrafted \( c_2 \), AUTN or both will be detected by the UE via the MAC check.

### G. Summary and Comparison with Previous Works

Table I compares the security and privacy properties of our protocol with those properties of several recent works.

### VIII. PRACTICAL IMPLEMENTATIONS OF OUR PROTOCOL

In this section, we discuss possible implementations of our protocol. As in the case of 5G AKA, the protocol can be split to an asymmetric part, where KEMs are used and a symmetric part consisting of the SUCI encryption and the authentication procedure. Our aim is to compare our protocol with the standardized 5G AKA. In fact, we use the same symmetric primitives as in 5G AKA plus one hash. We use the standardized post-quantum KEMs instead of just Encaps in the case of 5G AKA, the recently standardized post-quantum KEM Kyber outperforms the current ECIES profiles in 5G AKA defined by the curve S256r1 and Curve25519. The most significant computational cost comes from Classic McEliece. It is worth mentioning that the heaviest operation in Classic McEliece is the KeyGen as it takes 14 ms. We conclude that despite considering the three operations KeyGen, Encaps and Decaps for post-quantum KEMs instead of just Encaps in the case of 5G AKA, the recently standardized post-quantum KEM Kyber still outperform the used ECIES profiles. Next we will evaluate the operations at the HN using a similar approach to the operations at the UE. Compared to 5G AKA, which requires only one ECIES decapsulation at the HN, our protocol uses one Decaps and one Encaps at the HN (plus one hash and one symmetric encryption). Table II summarizes the computational time of such operations.

| Property                     | [15] | [16] | [13] | [14] | 5G AKA | [11] | [17] | Ours |
|------------------------------|------|------|------|------|-------|------|------|------|
| Unlinkability                | ✗    | ✓    | ✓    | ✓    | ✗     | ✓    | ✓    | ✓    |
| Perfect Forward Secrecy      | ✓    | ✓    | ✗    | ✗    | ✗     | ✓    | ✓    | ✓    |
| Session Key Confirmation     | ✗    | ✓    | ✓    | ✓    | ✓     | ✗    | ✗    | ✓    |
| Quantum-Safe                 | ✗    | ✗    | ✗    | ✗    | ✗     | ✓    | ✗    | ✓    |
| Coverage over GUTI           | ✓    | ✗    | ✗    | ✓    | ✓     | ✗    | ✗    | ✓    |

**TABLE I**

**Comparison of the Security and Privacy Properties of Our Protocol with the Prior Art.**

| Algorithm        | At UE | At HN |
|------------------|------|------|
| ECIES Curve25519 | 0.040| 0.040|
| ECIES Secp256r1  | 0.180| 0.180|
| Kyber            | 0.026| 0.019|
| Classic McEliece | 14.047| 0.047|
| BIKE             | 0.862| 0.672|
| HQC              | 0.421| 0.331|
| SIKE             | 7.000| 5.398|

**TABLE II**

**Running Time of the Asymmetric Primitives at the UE and HN (milliseconds).**

We remark that the standardized Kyber outperforms the currently used ECIES profiles in 5G AKA defined by the curve S256r1 and Curve25519. The most significant computational cost comes from Classic McEliece. It is worth mentioning that the heaviest operation in Classic McEliece is the KeyGen as it takes 14 ms. We conclude that despite considering the three operations KeyGen, Encaps and Decaps for post-quantum KEMs instead of just Encaps in the case of 5G AKA, the recently standardized post-quantum KEM Kyber still outperform the used ECIES profiles. Next we will evaluate the operations at the HN using a similar approach to the operations at the UE. Compared to 5G AKA, which requires only one ECIES decapsulation at the HN, our protocol uses one Decaps and one Encaps at the HN (plus one hash and one symmetric encryption). Table II summarizes the computational time of such operations.

Similarly to the case of UE, the lattice based schemes
outperform both ECIES profiles, and as noted in the UE case, the use of Classic McEliece at the HN is faster than ECIES Secp256r1 as the KeyGen is not used at the HN. For the SN, our protocol is only required to perform a random number generation, a symmetric decryption and an XOR operation compared to 5G AKA. For the communication cost we recall that in our protocol an encryption of a pk, is sent over the radio channel from the UE to the SN. An extra 256 bit string R_{SN} is sent by the SN to the HN. The HN is sending a symmetric encryption of the SUPI and the session key, which happens also in 5G AKA but in the final state. A KEM ciphertext is also sent by the HN to the SN, then by the SN to the UE. Table III illustrate the parameters sizes of the used schemes.

| Algorithm        | sk  | pk  | Ciphertext | Shared secret |
|------------------|-----|-----|------------|--------------|
| ECIES Curve25519 | 32  | 32  | 32         | 32           |
| ECIES Secp256r1  | 32  | 32  | 32         | 32           |
| Kyber            | 1632| 800 | 768        | 32           |
| Classic McEliece | 6452| 201120 | 128        | 32           |
| BIKE             | 5223| 1541| 1373       | 32           |
| HQC              | 2289| 2240| 4481       | 64           |
| SIKE             | 28  | 330 | 330        | 110          |

TABLE III COMMUNICATION COST (BYTES)

In 5G AKA, the UE sends a KEM cipher over the radio channel to the SN and this last forwards it to the HN which results in a total of 32 bytes, that is under the assumption of ignoring the SUCI and other authentication parameters. With the same assumption, in our protocol, the UE sends a symmetric encryption of a KEM public key and a KEM ciphertext, while the HN responds with a ciphertext to the UE. From Table III we clearly see that ECIES provides a small communication cost compared to post-quantum KEMs, while Classic McEliece has to most significant communication cost due to the size of the public key. We note that the standardized Kyber offers the best communication cost among the studied post-quantum KEMs.

IX. CONCLUSION

In the present paper, we presented a quantum resistant authentication and key agreement protocol for 6G with further securities and privacy features that are not offered by the standardized 5G AKA, such features includes resistance to known linkability attacks, perfect forward secrecy, key confirmation between the UE and the SN. Moreover, in our protocol, we abandoned the use of sequence numbers to avoid possible desynchronization attacks, and we equipped the identification process by a further mechanism to protect against some type of DoS attacks. Furthermore, our protocol covers the case of GUTI which is usually not covered in similar works. We used Proverif to formally verify some of our security claims. Furthermore, we gave an overview of possible practical implementations of the protocol using the recently standardized KEM Kyber, we also considered NIST round4 finalists and we concluded that Kyber out performs computationally the currently used ECIES profiles, which proves the practicality of our protocol despite the post-quantum feature. In summary, we illustrated a theoretical and practical implementation of a quantum safe AKA protocol for 6G and presented supporting argument for its security features using both formal and classical methods.

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