Formal Analysis of 5G Authentication

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ABSTRACT
Mobile communication networks connect much of the world’s population. The security of every user’s calls, SMSs, and mobile data, depends on the guarantees provided by the Authenticated Key Exchange protocols used. For the next-generation network (5G), the 3GPP group has standardized the 5G AKA protocol for this purpose.

We provide the first comprehensive formal model of a protocol from the AKA family: 5G AKA. We also extract precise requirements from the 3GPP standards defining 5G and we identify missing security goals. Using the security protocol verification tool Tamarin, we conduct a full, systematic, security evaluation of the model with respect to the 5G security goals. Our evaluation automatically identifies the minimal security assumptions required for each security goal and we find that some critical security goals are not met, except under additional assumptions missing from the standard. Finally, we make explicit recommendations with provably secure fixes for the attacks and weaknesses we found.

CCS CONCEPTS
• Security and privacy → Formal security models; Logic and verification; Mobile and wireless security;

KEYWORDS
5G standard, authentication protocols, AKA, symbolic verification, formal analysis

1 INTRODUCTION
Two thirds of the world’s population, roughly 5 billion people, are mobile subscribers [24]. They are connected to the mobile network via their USIM cards and are protected by security mechanisms standardized by the 3rd Generation Partnership Project (3GPP) group. Both subscribers and carriers expect security guarantees from the mechanisms used, such as the confidentiality of user data (e.g., voice and SMS) and that subscribers are billed only for the services they consume. Moreover, these properties should hold in an adversarial environment with malicious base stations and users.

One of the most important security mechanisms in place aims at mutually authenticating subscribers and their carriers and establishing a secure channel to protect subsequent communication. For network generations (3G and 4G) introduced since the year 2000, this is achieved using variants of the Authentication and Key Agreement (AKA) protocol, standardized by 3GPP. These protocols involve the subscribers, the Serving Networks (SNs) that have base stations in subscribers’ vicinity, and Home Networks (HNs) that correspond to the subscribers’ carriers. The protocols aim to enable the subscribers and the HNs to mutually authenticate each other and to let the subscribers and the SNs establish a session key.

Next-Generation (5G). Since 2016, the 3GPP group has been standardizing the next generation of mobile communication (5G), with the aim of increasing network throughput and offering an ambitious infrastructure encompassing numerous new use cases. The 5G standard will be deployed in two phases. The first phase (Release 15, expected by June 2018) will address the most critical requirements needed for commercial deployment and will be the basis for the first deployment. The second phase (Release 16, to be completed by March 2020) will address all remaining requirements.

In March 2018, 3GPP published version 1.0.0 of Release 15 of the Technical Specification (TS) defining the 5G security architecture and procedures [4]. The authentication in 5G Release 15 is based on new versions of the AKA protocols, notably the new 5G AKA protocol, which enhances the AKA protocol currently used in 4G (EPS AKA) and which supposedly provides improved security guarantees. This raises the following question: What are the security guarantees that 5G AKA provides and under which threat model and security assumptions?

Formal Methods. In this paper, we give a precise answer to the above question. Namely, we apply formal methods and automated verification in the symbolic model to determine whether precise, fine-grained security guarantees are met by 5G AKA. Formal methods have already proved extremely valuable in assessing the security of large-scale, real-world security protocols such as TLS 1.3 [10, 16, 18], messaging protocols [26], and entity authentication protocols [7]. Symbolic approaches, in particular, allow one to automate reasoning using techniques including model-checking, resolution, and rewriting. Examples of mature verification tools along these lines are TAMARIN [30], ProVerif [11], and DeepSec [14].

Unfortunately, the AKA protocols, and a fortiori 5G AKA, feature a combination of properties that are extremely challenging for state-of-the-art verification techniques and tools and, until very recently, a detailed formalization was outside of their scope. First, the flow and the state-machines of these protocols are large and complex. This is due in part to the use of sequence numbers (SQN) and the need for a re-synchronization mechanism should counters become out-of-sync. This complexity is problematic for tools that reason about a bounded number of sessions as they scale poorly here. It also eliminates the option of machine-checked manual proofs as the number of interactions is too large for humans to explore. Second, these protocols are stateful (the SQN counters are mutable and persist over multiple sessions) and have numerous loops. This makes inductive reasoning necessary and rules out fully...
We believe that our model of 5G AKA provides a valuable tool to when moving from 4G to 5G, due to the use of strong abstractions, protocol simplifications, and limitations in the analyzed properties.

Related Work. Formal methods have been applied to AKA protocols in the past, but prior work provided only weak guarantees due to the use of strong abstractions, protocol simplifications, and limitations in the analyzed properties.

The initial AKA protocol specified for 3G was manually verified by 3GPP using TLA and an enhanced BAN Logic [3]. The TLA analysis focused on functional properties, like the protocol recovers from de-synchronization. The short pen and paper proof in an enhanced BAN logic provides weak guarantees, e.g., about key agreement and confidentiality, due to the logic’s limitations. In particular, the logic does not account for, e.g., compromised agents and type-flaws, and it has had soundness issues in the past [13]. Moreover, the proof considered a simplified protocol without SQN concealment or re-synchronization as SQNs were always assumed synchronized. This misses, for example, the privacy attack based on the desynchronization error message we observed.

Other prior works have used ProVerif to formally check untraceability and basic authentication properties on simplified AKA protocols [6, 31]. These works acknowledged the challenges of formally verifying AKA protocols but only offered limited solutions. For instance, the SQN counters were abstracted away by nonces that are supposed to be initially shared by HNs and subscribers, thus reducing the protocol to a stateless protocol. The re-synchronization procedure was also omitted. The SNs and HNs were merged into a single entity. Furthermore, XOR was either not modeled or was replaced by a different construct with simpler algebraic properties.

In summary, in stark contrast to previous work, we provide the first faithful formalization of an AKA protocol. Namely, we formalize the entire protocol logic including the full protocol state machine with all message flows and symbolic abstractions of all cryptographic operators. This allows for the first comprehensive formal analysis that characterizes the properties that are achieved in different adversarial settings.

Outline. We present in Section 2 the cellular network architecture and how authentication is achieved in the 5G ecosystem using the 5G AKA protocol. We carry out a systematic formalization of the security assumptions and goals of the standard in Section 3 and highlight shortcomings. Section 4 explains the basics of the verifier TAMARIN and our modeling and design choices. We present our comprehensive security analysis of 5G AKA and our recommendations in Section 5. We draw conclusions in Section 6.
2.1 Architecture

Three main entities are involved in the cellular network architecture (see Figure 1). First, User Equipment (UE), typically smartphones or IoT devices containing a Universal Subscriber Identity Module (USIM), are carried by subscribers. We shall call a subscriber the combination of a UE with its USIM. Second, Home Networks (HNs) contain a database of their subscribers and are responsible for their authentication. However, subscribers may be in locations where their corresponding HN has no base station (i.e., antennas may connect UEs to the network), for example when roaming. Therefore, the architecture has a third entity: the Serving Networks (SNs) to which UEs may attach to. An SN provides services (e.g., call or SMS) once both the UE and the SN have mutually authenticated each other (this supports billing) and have established a secure channel with the help of the subscriber’s HN. The UE and SN communicate over the air while the SN and HN communicate on an authenticated channel (we list security assumptions later in this section).

As mentioned earlier, each subscriber has a USIM with cryptographic capabilities (e.g., symmetric encryption, MAC). Relevant for our work is that the USIM stores:

- a unique and permanent subscriber identity, called Subscription Permanent Identifier (SUPI),
- the public asymmetric key kpSN of its corresponding HN,
- a long-term symmetric key denoted as K (used as a shared secret between subscribers and their corresponding HNs),
- and a counter, called Sequence Number denoted as SQN.

The HN, associated to some subscriber, stores the same information in its database.

Simplifications. In the standard, SNs and HNs are composed of several sub-entities (e.g., HNs consist of a database, authentication server etc.). However, very few security properties require this level of granularity. We thus have chosen to consider these three larger logical entities (see Appendix A for more details).

2.2 Authentication Protocols

In order to let SNs and subscribers establish secure channels and authenticate each other, 3GPP has specified two authentication methods: 5G AKA and EAP-AKA'. The choice between those two methods is left to the HN, once it has correctly identified the subscriber with the Initialization Protocol. We now describe these three security protocols. (All cryptographic messages are precisely described in Appendix A.)

![Overall architecture: The subscriber uses his phone (UE), equipped with a USIM, to communicate with a base station run by the SN over an insecure wireless channel. The SN communicates with the subscriber’s carrier (HN) on the right over an authenticated (wired) channel.](Image 1)

2.2.1 Initialization Protocol [TS 33.501, Sec. 6.1.2]. Figure 2 depicts the sub-protocol responsible for the subscribers’ identification and initializing the authentication. Once the SN has triggered an authentication with the subscriber, the latter sends a randomized encryption of the SUPI (for privacy reasons, as we explain in Section 3.2.3): SUCI = ⟨aenc(SUPI, R), pkHN, idHN⟩, where aenc(·) denotes asymmetric encryption, R is a random nonce, and idHN uniquely identifies an HN. The identifier idHN enables the SN to request authentication material from the appropriate HN. Upon reception of the SUCl along with the SN’s identity (referred to as SNname), the HN is able to retrieve the SUPI, the subscribers’ identity, and choose an authentication method.

2.2.2 The 5G AKA Protocol [TS 33.501, Sec. 6.1.3.2]. As mentioned before, the key K is used as a long-term shared secret, and SQN is used as a replay protection¹ for the subscriber. While SQN is expected to be synchronized between the subscriber and the HN, it may happen that they become out-of-sync (e.g., due to message loss). We thus use SQN_IDe (respectively SQN_HId) to refer to the SQN value stored in the UE (respectively HN). The 5G-AKA protocol consists of two main phases: a challenge-response and an optional re-synchronization procedure (that updates the SQN on the HN side in case the SQN is out-of-sync). The entire 5G AKA protocol flow is depicted in Figure 3.

**Challenge-Response.** Upon receiving a request for authentication material, the HN computes an authentication challenge built from:

- a random nonce R (the challenge),
- AUTN (proving the challenge’s freshness and authenticity),
- HXRES (response to the challenge that SN expects),
- K̄SEAF (key seed for the secure channel that the subscriber and SN will eventually establish).

The functions f1 – f5, used to compute the authentication parameters, are one-way keyed cryptographic functions completely unrelated, and @ denotes Exclusive-OR. Challenge(·) and KeySeed(·) are complex Key Derivation Functions (KDFs); see Appendix A for more details. AUTN contains a Message Authentication Code (MAC) of the concatenation of R with the corresponding sequence number SQN_IDe stored for this subscriber. A new sequence number is generated by incrementing the counter. The sequence number SQN_IDe allows the subscriber to verify the freshness of the authentication request to defend against replay attacks and the MAC proves the challenge’s authenticity. The HN does not send the challenge’s full response RES to the SN but only a hash thereof; the rationale being that HNs are willing to have assurance of the presence of its subscribers even with malicious SNs.

The SN stores K̄SEAF and the expected response to the challenge, and then forwards the challenge to the subscriber. Upon receiving the challenge, the subscriber first checks its authenticity and freshness. To do this, the subscriber extracts xSNQIDe and MAC from AUTN and checks that:

(i) MAC is a correct MAC value with respect to K, and replies ‘Mac_failure’ if it is not the case.

¹This design choice is for historical reasons: old USIM (e.g., in 3G and 4G) have no capability to generate random nonces.
(ii) the authentication request is fresh, i.e., SQN_{UE} < xSQN_{IN} and replies ('Sync_failurer', AUTS) otherwise (AUTS is explained in the re-synchronization procedure below).

If all checks hold then the subscriber computes the key seed K_{SEAF}-which is used to secure subsequent messages. It also computes the AKA authentication method, we do not describe those differences.

Figure 2: Initiation of Authentication

3 THREAT MODEL AND SECURITY GOALS

In this section, we derive precise, formal security goals from the informal descriptions given in the Technical Specification (TS) and Technical Requirement (TR) documents issued by the 3GPP. Our formal definitions are our interpretations of these texts. We support them with quotes from and references to relevant excerpts of the TS and TR documents. The full list of relevant excerpts along with explanations of our interpretations is given in Appendix D.

The extraction of precise properties from the standard’s informally stated goals is an important prerequisite to applying a security protocol analysis tool (like TAMARIN). It is thus a crucial step in the security analysis of a complex protocol such as 5G AKA.

3.1 Security Assumptions and Threat Model

3.1.1 Assumptions on Channels. The channel between the SN and the HN provides confidentiality, integrity, authenticity, and replay protection [TS 33.501, Sec. 5.9.3].

The channel between the subscribers and SNs is subject to eavesdropping by passive attackers and manipulation, interception, and injection of messages by active attackers. A passive attacker listens to signaling messages (i.e., messages sent on the physical layer) and can thus eavesdrop on all messages exchanged in its vicinity, but it never emits a signal. An active attacker sets up a fake base station to receive and send signaling messages, e.g., to impersonate SNs. While no 5G-specific hardware is publicly available yet, we recall that 4G base stations have been built using open-source and freely available software and hardware [23, 35]. From now on, we shall consider active attackers, except when explicitly stated otherwise.

3.1.2 Assumptions on Cryptographic Primitives. The functions f1, f1∗, f2 are message authentication functions, and f3, f4, f5, f5∗ are key derivation functions [TS 33.102, Sec. 3.2.6.3.2]. To our knowledge there is no comprehensive set of standardized security requirements for these functions. The requirements in [TS 33.105, Sec. 5] are insufficient, but we infer from the informal presentation in [TS 33.102, Sec. 3.2] and requirements in [TS 33.105, Sec. 5] that the former provide only integrity protection and the latter both integrity and confidentiality protection. However, since f1 and f1∗ are applied to data that should be secret, such as SQN (see Section 3.2.3), it is our understanding that they should also preserve the confidentiality of their inputs. We therefore assume in our analysis that all these functions protect both integrity and confidentiality, but we stress that this is either underspecified or subscribers’ privacy is put at risk (see Section 3.2.3).

3.1.3 Assumptions on Parties. To provide strong, fine-grained guarantees, we consider different compromise scenarios. First, we consider an attacker who can compromise some SNs. This means that the attacker gets access to an authenticated channel between the compromised SN and HNs, which he can use to eavesdrop on and inject messages. This is a reasonable assumption in 5G, where authentication methods should provide security guarantees even in
the presence of genuine but malicious SNs [TS 33.501, Sec. 6.1.4.1]. In such situations, the HNs may cooperate with such SNs to authenticate some subscriber. In practice, this may happen in roaming situations. Next, we consider that the attacker may have genuine USIMs and compromised USIMs under its control. For those compromised subscribers, the attacker can access all secret values stored in the USIMs; i.e., SUPI, K, and SQN. Finally, the attacker can access all long-term secrets K, sk_{HN}, and SUPI from compromised HNs.

3.1.4 Assumptions on Data Protection. The subscriber credentials, notably the key K and the identifier SUPI, shared between subscribers and HNs, should initially be secret, provided they belong to non-compromised agents [TS 33.501, Sec. 3.1].

The sequence number SQN is a 48-bit counter or a 43-bit counter [TS 33.102, Sec. 6.3.7.C.3.2] and therefore guessable with a very low probability. Note that an offline guessing attack on the sequence number counter is not possible, and online attacks on the UE first require a correct MAC (based on the shared secret K) before the UE responds whether the SQN was acceptable. We thus consider a reasonable threat model where the value of SQN is unknown to the attacker when the attack starts, but the attacker knows how it is incremented during the attack. This corresponds to an attacker who
(i) can monitor the activity of targeted subscribers in its vicinity during the attack but, (ii) can neither guess the initial value of SQN, (iii) nor can he monitor targeted subscribers all the time (i.e., from the first use of the USIM up to the attack time).

While not explicitly stated in the specification, we shall assume that the private asymmetric key s₂HN is initially secret.

### 3.2 Security Requirements

We now extract and interpret from the 5G documents the security goals that 5G AKA should achieve according to the 5G standard.

#### 3.2.1 Authentication Properties

5G specifications make claims about authentication properties at different places in the documents. We have identified relevant claims and translate them into formal security goals, indicated in purple, cursive text. We use Lowe’s taxonomy of authentication properties [28] to make the goals precise, prior to formalization. These properties are well established and understood avoiding ambiguity [8]. Moreover, there exists a formal relation between the taxonomy and mathematical definitions of security properties that can be directly modeled in Tamarin [1].

We give an overview of Lowe’s taxonomy and its relationship with formal definitions of authenticity in Appendix C. Intuitively, the taxonomy specifies, from an agent A’s point of view, four levels of authentication between two agents A and B: (i) aliveness, which only ensures that B has been running the protocol previously, but not necessarily with A; (ii) weak agreement, which ensures that B has previously been running the protocol with A, but not necessarily with the same data; (iii) non-injective agreement, which ensures that B has been running the protocol with A and both agree on the data; and (iv) injective agreement, which additionally ensures that for each run of the protocol of an agent there is a unique matching run of the other agent, and prevents replay attacks.

Note that the 5G specification considers some authentication properties to be *implicit*. This means that the guarantee is provided only after an additional *key confirmation roundtrip* (with respect to K SEAL) between the subscribers and the SN. We discuss the resulting problems and critique this design choice in Section 5.2.2. Authentication between subscribers and HNs. First, the subscribers must have the assurance that authentication can only be successful with SNs authorized by their HNs; see [TS 33.501, Sec. 6.1.1.3] and:

**[TS 33.501, Sec. 5.1.2] Serving network authorization by the home network:** Assurance [that subscriber] is connected to a serving network that is authorized by the home network. [...] This authorization is ‘implicit’ in the sense that it is implied by a successful authentication and key agreement run.

Formally, a *subscriber must obtain non-injective agreement on SNname with its HN after key confirmation.*

In 5G, the trust assumptions are different than in previous standards, like 3G or 4G. Most notably, the level of trust the system needs to put into the SNs has been reduced. One important property provided by 5G is that an SN can no longer fake authentication requests with the HNs for subscribers not attached to one of its base stations [TS 33.501, Sec. 6.1.4.1]. Formally, the *HNs obtain the aliveness of its subscribers at that SN, which is non-injective agreement on SNname from the HNs’ point of view with the subscribers.*

Authentication between subscribers and SNs. As expected, the SNs shall be able to authenticate the subscribers:

**[TS 33.501, Sec. 5.1.2] Subscription authentication:** The serving network shall authenticate the Subscription Permanent Identifier (SUPI) in the process of authentication and key agreement between UE and network.

The SNs must obtain non-injective agreement on SUPI with the subscribers. As SUPI is the subscriber’s identifier this is actually just weak agreement for the SNs with the subscribers.

Conversely, the subscribers shall be able to authenticate the SNs that are authorized by their corresponding HN:

**[TS 33.501, Sec. 5.1.2] UE authorization:** The serving network shall authorize the UE through the subscription profile obtained from the home network. UE authorization is based on the authenticated SUPI.

The SNs must obtain non-injective agreement on SUPI with the HNs.

#### 3.2.2 Confidentiality Properties

While it is not clearly specified, obviously 5G-AKA should ensure the *secrecy of K SEAL, K, and s₂HN* (see similar goals in 3G [TS 133.102, Sec. 5.1.3]).

5G-AKA should also ensure that knowing the session key K SEAL established in one session is insufficient to deduce another session key K SEAL established in either a previous session or a later session [TS 33.501, Sec. 3]. Formally, the key K SEAL established in a given session remains confidential even when the attacker learns the K SEAL keys established in all other sessions. Note that this is different from forward secrecy and post-compromise secrecy [15], which fail to hold as we shall see in Section 5.1. Forward and post-compromise secrecy require session key secrecy even in the event that long-term key material is compromised. 5G-AKA does not meet these requirements as knowledge of the key K allows an attacker to derive all past and future keys.

Finally, the same key K SEAL should never be established twice [TS 133.102, Sec. 6.2.3]. This will be analyzed as part of Inj ective agreement properties on the established key K SEAL for different pairs of parties.

#### 3.2.3 Privacy Properties

We first emphasize the importance given to privacy in 5G documentation:

**TR 33.899, Sec. 4.1.4.2** Subscription privacy deals with various aspects related to the protection of subscribers’ personal information, e.g., identifiers, location, data, etc. [...] The security mechanisms defined in NextGen shall be able to be configured to protect subscriber’s privacy.
This important role given to privacy can be explained by numerous, critical attacks that have breached privacy (e.g., with IMSI-catchers [35, 36]) in previous generations; see the survey [32]. We also recall that privacy was already a concern in 3G:

**[TR 33.899, Sec. 5.7.1]** The subscription privacy is very important area for Next Generation system as can be seen by the growing attention towards it, both inside and outside the 3GPP world. […]

Thus, 3G already had security requirements for user identity confidentiality, anonymity, and untraceability. However, these properties are required by the standard only against a passive attacker (we criticize this restriction in Section 5.2.3). We now list more precise requirements on how privacy should be protected in 5G.

In 5G, the **SUPI** is considered sensitive and must remain secret since it uniquely identifies users [TS 33. 501, Sec. 5.2.5.6.12]. Indeed, an attacker who obtains this value can identify a subscriber, leading to classical user location attacks (see [TS 133. 102, Sec. 5.1.1] above), much like IMSI-catcher attacks. Formally, the **SUPI shall remain secret in the presence of a passive attacker**.

Similarly, the **SQN** must remain secret [TS 33. 102, Sec. 6.2.3, C.3.2]. An additional reason that is not explicitly stated is that the **SQN** leaks the number of successful authentications the corresponding USIM has performed since it was manufactured, which is strongly correlated to its age and activity. This is even more critical when the attacker learns the **SQN** at different times, as this allows activity estimation for that time-period. Formally, **the SQN shall remain secret in the presence of a passive attacker**.

Preventing the attacker from learning identifying data (i.e., **SUPI, SQN**) is insufficient protection against privacy attacks such as traceability attacks (we show an example in Section 5.2.3). While no formal and explicit statement is made on the necessity of ensuring untraceability for 5G, several claims in TR and TS documents (see Appendix D.2.3) and the fact that it was required for 3G ([TS 133. 102, Sec. 5.1.1], see above), suggest that this property is relevant for 5G as well. Formally, 5G authentication methods are presumably required to provide **untraceability of the subscribers in the presence of a passive attacker**.

### 3.3 Security Goals are Underspecified

We now discuss the aforementioned standardized security goals and critique the lack of precision in the standard. We show that the requirements specified in the standard are not sufficient to provide the expected security guarantees in the context of mobile communication telephony use cases. This is completely independent of whether the proposed protocols actually fulfill these properties or not (which we examine in Section 5).

First, given that the protocol is an **Authenticated Key Exchange** protocol, we expect at least mutual authentication requirements and agreement properties on the established key. It is thus surprising that the standard does not require any agreement on **K_{SEAF}**. The different pairs of roles, especially subscribers and **SNs** should at least obtain non-injective agreement on the shared key K_{SEAF}. Moreover, the key K_{SEAF} should be different for each session. This is a critical requirement, especially for typical use cases of these protocols. Indeed, if this property is not provided, an attacker could make **UEs** and **SNs** establish a secure channel based on a key that has been previously used, and could therefore replay user data. The crucial missing requirements are **injective agreements on K_{SEAF} between pairs of parties, especially between the SNs and subscribers**.

The standard specifies authentication properties as weak **authorization** properties that can be formalized as non-injective agreement on the roles’ identifiers, or simply weak agreement properties (see Section 3.2.1). We discuss the standard’s restriction to “implicit authentication” in Section 5.2.2. As explained earlier, 5G requires **HNs** to have the assurance that **UEs** are attached to **SNs** [TS 33. 501, Sec. 6.1.4.1] currently. However, a non-injective agreement on **SName** from an **HN** towards a subscriber is too weak since it suffices that the subscriber has attached to the corresponding **SN** in some session in the past to fulfill the property.

It is crucial in that scenario for the **HNs** to obtain assurance that the subscriber is attached to the **SN** during the present session. The derivation of **K_{SEAF}** includes **SName** for the binding to **SN**. This derivation also includes a nonce R, due to which we obtain the desired assurance as a corollary of **injective agreement on K_{SEAF} from the HNs towards the subscribers**, which we consider instead.

Similarly, the subscribers should have the assurance that the **SNs** with which they establish secure channels are known and trusted by their **HNs** at the time of the authentication, not only in some past session. Therefore, they should obtain **injective agreement on K_{SEAF} (which is bound to SName) with the HNs**. While less critical, other pairs of roles should also have stronger assurance. We describe how the standard can be improved in this regard in Section 5.3.

### 4 FORMAL MODELS

In this section, we give a basic introduction to the symbolic model of cryptographic protocols and the tool **TAMARIN** that automates reasoning in this model (Section 4.1). Afterwards, we give an overview on how security properties can be modeled in this tool (Section 4.2). Next, after describing our modeling choices (Section 4.3), we describe the challenges associated with modeling a large, complex protocol like 5G AKA and how we overcame them (Section 4.4).
Moreover, it was recently extended with support for XOR [21], a key ingredient for faithfully analyzing 5G AKA. We chose Tamarin as it is currently the only tool that combines all these features, which are essential for a detailed analysis of 5G AKA.

In the symbolic model and a fortiori in Tamarin, messages are described as terms. For example, enc(m, k) represents the message m encrypted using the key k. The algebraic properties of the cryptographic functions are then specified using equations over terms. For example the equation dec(enc(m, k), k) = m specifies the expected semantics for symmetric encryption: the decryption using the encryption key yields the plaintext. As is common in the symbolic model, cryptographic messages do not satisfy other properties than those intended algebraic properties, yielding the so-called black box cryptography assumption (e.g., one cannot exploit potential weaknesses in cryptographic primitives).

The protocol itself is described using multi-set rewrite rules. These rules manipulate multisets of facts, which model the current state of the system with terms as arguments.

Example 4.1. The following rules describe a simple protocol that sends an encrypted message. The first rule creates a new long-term shared key k (the fact !Ltk is persistent: it can be used as a premise multiple times). The second rule describes the agent A who sends a fresh message m together with its MAC with the shared key k to B. Finally, the third rule describes B who is expecting a message and a corresponding MAC with k as input. Note that the third rule can only be triggered if the input matches the premise, i.e., if the input message is correctly MACed with k.

Create_Ltk : [Fr(k)]−→![Ltk(k)],
Send_A : ![Ltk(k),Fr(m)]−→Sent(m)−→Out((m,mac(m,k))),
Receive_B : ![Ltk(k),ln((m,mac(m,k)))]−→Received(x)−→[].

These rules yield a labeled transition system describing the possible protocol executions (see [1, 33] for the syntax and semantics). Tamarin combines the protocol semantics with a Dolev-Yao [20] style attacker. This attacker controls the entire network and can thereby intercept, delete, modify, delay, inject, and build new messages. However, he is limited by the cryptography: he cannot forge signatures or decrypt messages without knowing the key (black box cryptography assumption). He nevertheless can apply any function (e.g., hashing, XOR, encryption, pairing, ...) on messages he knows to compute new messages.

4.2 Formalizing Security Goals in Tamarin

In Tamarin, security properties are specified in two different ways. First, trace properties, such as secrecy or variants of authentication, are specified using formulas in a first-order logic with timepoints.

Example 4.2. Consider the multiset rewrite rules given in Example 4.1. The following property specifies a form of non-injective agreement on the message, i.e., that any message received by B was previously sent by A:

∀i,m. Received(m)@i ⇒ (∃j.Sent(m)@j ∧ j < i).

Since the 5G AKA protocol features multiple roles and multiple instantiations thereof, agreement properties additionally require that the views of the two partners (who is playing which role, and what is the identity of the partner) actually match; see Appendix C.

For each specified property, Tamarin checks that the property holds for all possible protocol executions, and all possible adversary behaviors. To achieve this, Tamarin explores all possible executions in a backward manner, searching for reachable attack states, which are counterexamples to the security properties.

Equivalence properties, such as unlinkability, are expressed by requiring that two instances of the protocol cannot be distinguished by the attacker. Such properties are specified using diff-terms (which take two arguments), essentially defining two different instances of the protocol that only differ in some terms. Tamarin then checks observational equivalence (see [9]), i.e., it compares the two resulting systems and checks that the attacker cannot distinguish them for any execution and for any of its behaviors.

In fully automatic mode, Tamarin either returns a proof that the property holds, or a counterexample/attack if the property is violated, or may not terminate as the underlying problem is undecidable. Tamarin can also be used in interactive mode, where the user can guide the proof search. Moreover the user can supply heuristics called oracles to guide the proof search in a sound way. We heavily rely on heuristics in our analyses as they allow us to tame the complexity of the protocol, as explained below.

4.3 Modeling Choices

To better delimit the scope of our model and our analyses, we now describe some of our modeling choices.

Architecture. We consider three roles (subscribers, SNs, and HNs) and reason with respect to unboundedly many instances of each role. As expected, each subscriber credential is stored in at most one HN. We model communication channels between these parties that provide security properties as explained in Section 3.1. Additionally, the messages exchanged are tagged on the authenticated channel between the SNs and HNs. This models the implicit assumption that the authenticated channel between an SN and an HN role instance is protected from type flaw attacks.

Modeling Cryptographic Messages. We model and treat the subscribers’ SQNs as natural numbers (using a standard encoding based on multisets [1, 34]). We assume the attacker cannot follow UEs from their creation so the SQN is not known (see Section 3.1) at first, and we thus start the sequence number with a random value. The freshness check (i.e., (ii) from Figure 3) is faithfully modelled as a natural number comparison. Since the SQN may become out-of-sync during normal protocol execution, we also consider an attacker who can arbitrarily increase SQN_{UE} (UE does not allow decrease). Note that the attacker can already increase SQN_{HN} by repeatedly triggering authentication material requests. We fully model the re-synchronization mechanism and let the HNs update their SQN_{HN} accordingly. The concealment of the SQN, using Exclusive-OR (XOR), is faithfully modeled by relying on the recent extension of Tamarin with equational theories including XOR [21].

Compromise Scenarios. We model various compromise scenarios: secret key reveals (of K or sk_{HN}), reveals of the SUPI or the initial value of SQN, and SN compromises (i.e., the attacker gains access to an authenticated channel with the HNs). This is needed mainly for two reasons. First, the specification itself considers some of those scenarios and still requires some security guarantees to hold (cf. the
compromised SNs from Section 3.1). Second, this enables a comprehensive analysis to identify the minimal assumptions required for a property to hold. For instance, if some critical authentication property were violated when the attacker could access the initial value of the SQN, this would represent a potential vulnerability in the protocol since the SQN is not a strong secret and the search space of the SQN that the attacker needs to explore could be further reduced by exploiting the meaning of this counter.

Implicit Authentication. We equip the model with an optional key-confirmation roundtrip where the subscribers and SNs confirm their key key_confirmation by MACing different constants. Our security analysis is then parametric in this roundtrip, allowing us to derive which properties already hold without key confirmation, and what is gained by this key confirmation step.

Simplifications made. As usual in the symbolic model, we omit message bit lengths. Some key derivation functions also take the length of their arguments to prevent type flaws. This is covered in our model as such length-based misinterpretation cannot happen. The protocols under study feature sub-messages that are publicly known constants, for example, fixed strings like AMF or ‘MAC_Failure’. We mostly omit such sub-messages, unless they are useful as tags. We do not model the optional, non-normative protection against wrapping around the SQN [TS 33.102, Sec. C]. Note that this is in line with our modeling of the SQN as a natural number for which no wrapping can occur. The 5G AKA protocol establishes a session key, to which a key identifier is associated (the key set identifier ngKSI). Such identifiers are needed for subsequent procedures only and do not interact with the authentication methods and hence we omit them. An SN may create a pseudonym, called 5G-SNU, associated with the SUPI of a subscriber who is visiting this SN, in order to recognize this subscriber in a subsequent session. We omit this optional mechanism. Authentication tokens do not expire in our model as is usual in symbolic models. However, since such mechanisms are never clearly specified in normative documents, we emphasize that critical security properties should not rely on them.

4.4 Tamarin Models of 5G AKA

We have built a Tamarin model for the 5G AKA authentication method which enables automated security analyses. Our models and associated documentation are available [5], and use Tamarin v1.4.0 [2], which includes XOR support.

Writing a formal model of such a substantial real-world protocol is challenging. However, the real difficulty is doing this in a way that enables effective reasoning about the models, i.e., is amenable to automation. We now describe this modeling as well as the proof strategies we have developed, and argue why this can serve as a basis for future analyses of protocols in the AKA family.

4.4.1 Challenges. The 5G AKA protocol uses a combination of features that make reasoning about these models highly complex. First, 5G AKA is a stateful protocol, i.e., it relies on internal states (the SQNs) that are persistent across sessions and that are mutable. In the symbolic model, the set of values these states can take — all natural numbers — is unbounded. This feature alone excludes most verification tools, leaving only the verifier Tamarin. Verifiers for a bounded number of sessions are not a viable choice, simply due to the size of a single session. Moreover, the sequence numbers are not only internal counters, they are also used for comparison on input. This requires the ability to compare two values (see Section 4.3) in the chosen representation of natural numbers. This is demanding in terms of proof efforts: to the best of our knowledge, this is the first time a complete, real-world protocol relying on natural numbers and comparisons is analyzed with a formal verifier. Previous examples are limited to the case of just an internal counter for a TPM [29] or small examples, like simplified Yubikey [27].

Second, 5G AKA heavily relies on XOR to conceal the value of SQNs. Reasoning about XOR in the symbolic model is challenging and its integration in Tamarin is recent [21]. Intuitively, this is because there are numerous ways to obtain a given term when one can exploit the algebraic properties of XOR (i.e., associativity, commutativity, cancellation, and neutral element). These different options must be explored separately and considerably increase the search space when proving properties. Again, in the symbolic model, we are not aware of any formal analysis of such a large-scale real-world protocol featuring XOR.

Finally, the state-machine of the 5G AKA protocol is large and complex. Role instantiations can be in 14 different states. Evolution between these states includes numerous loops, notably because of the persistent and mutable states’ SQNs, e.g., sessions can be repeated while using a given SQN.

4.4.2 Proof Strategies. The way SQNs are updated on the subscribers’ and HN’s sides, notably with the re-synchronization procedure, induces complex state-change that must be tackled by our proof strategies. Manual proofs are not feasible due to the size of the search space one would have to explore. In contrast, Tamarin’s fully automatic mode fails to prove relevant security properties and even extremely weak properties such as the full executability of the protocols. Our work straddles this divide: we developed a proof structure based on intermediate lemmas (called helping lemmas) as well as proof strategies for proving these lemmas and the security properties. Proof strategies are implemented through oracles that offer a light-weight tactic language, implemented in Python, to guide the proof search in Tamarin.

The key helping lemmas we prove state that the SQN associated to a subscriber stored on his side (respectively on its HN’s side) is strictly increasing (respectively monotonically increasing). Thanks to our chosen modeling of the states’ SQNs as multisets and the comparisons of SQNs based on pattern-matching, we were able to prove the aforementioned lemmas by induction with a simple, general proof strategy. The security properties, however, require dedicated and involved proof strategies (~1000 LoC of Python).

4.4.3 Our models. Based on our modeling choices, we built a complete model of 5G AKA (preceded by the initialization protocol) that is amenable to automation. We model fully parametric compromise scenarios that enables one to easily choose what kind of reveals or compromises are considered when proving properties. We also implement the key confirmation roundtrip in a modular way: one can consider authentication properties after or without the re-synchronization procedure, induces complex state-change that must be tackled by our proof strategies. Manual proofs are not feasible due to the size of the search space one would have to explore. In contrast, Tamarin’s fully automatic mode fails to prove relevant security properties and even extremely weak properties such as the full executability of the protocols. Our work straddles this divide: we developed a proof structure based on intermediate lemmas (called helping lemmas) as well as proof strategies for proving these lemmas and the security properties. Proof strategies are implemented through oracles that offer a light-weight tactic language, implemented in Python, to guide the proof search in Tamarin.

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Our models include all the necessary lemmas: helping lemmas, sanity check lemmas, and the lemmas we eventually use to check the relevant security properties against the 5G AKA protocol. Since
we aim at identifying the minimal assumptions required for the stated properties to hold, we prove several lemmas for each security property. First, we state a lemma showing that the property holds under a certain set of assumptions. Second, we show the minimality of this set of assumptions. We do this by disproving all versions of the previous lemma where the set of assumptions has been reduced by just one assumption. This represents ~1000 LoC.

Our model of 5G AKA is general in that it can be used to model different protocols from the AKA family with localized modifications. Part of the model (creation or role instantiations, reveal and compromise modelings, etc.) would not change, but the roughly 300 LoC defining the main flow of the protocol would have to be adapted. The size of this change depends on how different the chosen protocol is to 5G AKA. We expect our oracle to be still valid, at least after minor modifications to the model. Furthermore, given that our analysis is fully automatic (thanks to our proof strategies), our model can be easily kept up-to-date with future evolutions of the standard and any change in terms of provided security guarantees can then be automatically identified by the tool.

5 SECURITY ANALYSIS

5.1 Results

We present the results of our comprehensive analysis of the 5G AKA protocol. We emphasize that we automatically analyze the formal security guarantees that the protocol provides for an unbounded number of sessions executed by subscribers, SNs, and HNs when used in combination with the initiation protocol. Thus, our analyses account for all potential unintended interactions an attacker could exploit between these sub-protocols run by all three roles we consider.

We depict the outcome of our analysis of authentication properties in Table 1. For each pair of parties, we present the minimal assumptions required to achieve authentication properties: i.e., weak agreement, non-injective agreement, and injective agreement. We only consider agreement on relevant data (i.e., $K_{SEAF}$, the $SUPI$, and $SNname$). The assumptions are minimal in that strengthening the attacker’s capabilities in any direction violates the property. The symbol $\oplus$ denotes that the property is violated for the weakest threat model we consider (i.e., no compromised agents and an active subscriber but is unable to learn the key the subscriber has computed). We present our results concerning secrecy properties in Table 2.

5.2 Discussion

Table 1 clearly shows the extent that the 5G standard underspecifies authentication requirements (recall that [ ] denotes explicit goals): see Section 3.3. We also indicate a number of properties that are violated even in the weakest threat model where all participants are honest ( $\oplus$). We discuss why in Section 5.2.1. Afterwards, we explain and critique the use of key-confirmation in Section 5.2.2. We discuss privacy properties in Section 5.2.3. Finally, our results concerning secrecy properties are as expected and are not discussed further. Also, perfect forward secrecy of $K_{SEAF}$ is violated as expected.

5.2.1 Missing Security Assumption. The 5G AKA protocol fails to meet several security goals that are explicitly required as well as other critical security properties. This is still true under the assumptions specified in the standard, even after a successful key-confirmation phase (see Table 1). More specifically, the agreement properties on $K_{SEAF}$ between the subscribers and SNs are violated. So is weak agreement from the subscribers towards the SNs. This is caused by the lack of a binding assumption on the channel between SNs and HNs and because the $SUPI$ is sent to the SN in a different message than the message containing $K_{SEAF}$, which is sent earlier. Therefore, as soon as a pair of a SN and a HN runs two sessions concurrently, there is no assurance that the $SUPI$ sent to the SN is received at the end of the protocol actually corresponds to the $K_{SEAF}$ it has received earlier (it could correspond to another concurrent session).

As a consequence, a SN may associate the session key $K_{SEAF}$ to the correct subscriber (a necessary condition for the key confirmation to be successful), but to the wrong $SUPI$, violating the aforementioned properties. Thus, the binding property for the channel between the SNs and HNs appears to be a critical security assumption, and should be explicitly mentioned in the standard. This weakness has been introduced in the last version of the standard. In the previous version (v0.7.1), the $SUPI$ was sent by the $HN$ to the SN together with the challenge, thus preventing the aforementioned attack and therefore making the binding assumption unnecessary.

However, the new version of the standard requires this additional assumption. A similar looking issue, but between two parts of the $HN$ has been previously observed by [19], but it is an entirely independent concern of the one we describe.

Table 3 depicts additional security properties the 5G AKA protocol provides when the channel between the SNs and HNs is assumed to be binding. Under this assumption, the previously violated properties are now satisfied under reasonable threat models. We only show results for UEs and SNs to show how their guarantees change.

5.2.2 Implicit Authentication. A successful key-confirmation roundtrip is required to obtain crucial security guarantees. More precisely, this roundtrip is required for all agreement properties from the subscribers’ point of view except weak agreement towards the HNs. Indeed, an attacker can impersonate a SN towards a subscriber but is unable to learn the $K_{SEAF}$ key the subscriber has computed.

[Ts 33.501, Sec. 5.1.2] The meaning of ‘implicit key authentication’ here is that authentication is provided through the successful use of keys resulting from authentication and key agreement in subsequent procedures.

The 5G standard only requires implicit authentication properties for the subscribers. However, the standard neither specifies that subscribers must wait for this key confirmation to be successful before continuing nor does it specify this additional roundtrip as part of the authentication method. As a consequence, the standard makes a choice that we consider risky: it postpones the handling and the verification of the additional key confirmation roundtrip to all possible subsequent procedures (e.g., NAS security mode command procedure [Ts 33.501, Sec. 6.7.2]). The standard fails to specify a standalone authentication protocol that provides a reasonable set
Agreements on

Table 3: Minimal assumptions required for 5G AKA to achieve authentication properties. We denote subscribers by $UE$, non-injective by NI and injective by I. Assumptions are expressed in terms of forbidden reveals (e.g., $\neg K$, meaning the property only holds when $K$ is not revealed). We also indicate whether a key confirmation phase is needed with $\neg \text{k-c}$ while $\neg \text{ch}$ denotes an uncompromised channel between $SN$ and $HN$. $\times$: the property is violated by definition (e.g., because $SUPI$ is constant). wa: the property coincides with weak agreement and requires same assumptions. The explicit goals given in the specification are denoted by [ ] around them.

<table>
<thead>
<tr>
<th>Partner</th>
<th>$UE$</th>
<th>$SN$</th>
<th>$HN$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agreement</td>
<td>NI</td>
<td>I</td>
<td>NI</td>
</tr>
<tr>
<td>on $K_{SEAF}$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\neg K \land \neg \text{k-c}$</td>
</tr>
<tr>
<td>on $SUPI$</td>
<td>$wa \times$</td>
<td>$wa \times$</td>
<td>$\neg \text{ch}$</td>
</tr>
<tr>
<td>on $SN\text{name}$</td>
<td>$wa \times$</td>
<td>$[\neg K \land \neg \text{k-c}] \times$</td>
<td>$wa \times$</td>
</tr>
<tr>
<td>Weak agreement</td>
<td>[ ]</td>
<td>$\neg K$</td>
<td>$[\neg K \land \neg \text{ch}]$</td>
</tr>
</tbody>
</table>

Table 2: Minimal assumptions for 5G AKA to achieve secrecy properties. We omit the assumption that data that is supposed to be secret is not revealed. See Table 1 for the legend. The symbol * indicates that there is no dishonest $SN$s at all and the underlying property is always violated otherwise.

<table>
<thead>
<tr>
<th>Point of view</th>
<th>$UE$</th>
<th>$SN$</th>
<th>$HN$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{SEAF}$</td>
<td>$\neg K \land \neg \text{ch}$</td>
<td>$\neg K \land \neg \text{ch}$</td>
<td>$\neg K \land \neg \text{ch}$</td>
</tr>
<tr>
<td>$PFS(K_{SEAF})$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$SUPI$</td>
<td>$\neg s_{K_{HN}} \land \neg \text{ch}^*$</td>
<td>$\neg \text{ch}$</td>
<td>$\neg \text{ch}$</td>
</tr>
<tr>
<td>$K$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Minimal assumptions required for 5G AKA to achieve authentication properties between $UE$s and $SN$s, assuming that the channel between $HN$s and $SN$s is binding. Agreements on $SUPI$ and $SN\text{name}$ are not impacted.

<table>
<thead>
<tr>
<th>P.o.V.</th>
<th>$UE$</th>
<th>$SN$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partner</td>
<td>$SN$</td>
<td>$UE$</td>
</tr>
<tr>
<td>Agr.</td>
<td>NI</td>
<td>I</td>
</tr>
<tr>
<td>on $K_{SEAF}$</td>
<td>$\neg K \land \neg \text{k-c}$</td>
<td>$\neg K \land \neg \text{k-c}$</td>
</tr>
<tr>
<td>Weak agre.</td>
<td>$[\neg K \land \neg \text{k-c} \land \neg \text{ch}]$</td>
<td>$[\neg K \land \neg \text{ch}]$</td>
</tr>
</tbody>
</table>

of security guarantees since some critical properties are provided only when the protocol is used in specific, appropriate contexts.

More importantly, since the standard makes the overall security of the authentication rest on subsequent procedures, it is very challenging, and out of the scope of the present paper, to assess if all currently specified subsequent procedures (as well as future ones that may be added) either correctly mandate the use of this key confirmation roundtrip or do not require authentication properties from the subscribers’ point of view towards the $SN$s. We believe that there are at least two potential use cases where the above weakness represents a vulnerability. First, the standard specifies that $SN$s can initiate key change on-the-fly [TS 33.591, Sec. 6.9.4.1] as well as switch security contexts [TS 33.591, Sec. 6.8], including keys, parameters, etc. This raises the question whether a malicious $SN$ or a

fake base station could not fully impersonate a genuine $SN$ towards the subscribers by changing the session key immediately after 5G AKA. Second, in a scenario where subscribers use the presence of $SN$s for geo-localization or for making sensitive decisions (related to e.g., emergency calls), an active attacker could impersonate an $SN$ since the (mismatched) $K_{SEAF}$ key may not be needed or used.

Finally, the key confirmation roundtrip is not the only option to achieve the aforementioned missing security guarantees. We provide and discuss in Section 5.3.3 two alternative solutions that fix this issue while reducing necessary communications.

5.2.3 On Privacy. As mentioned in Section 3.2.3, the 5G standard aims to protect privacy against passive attackers only. 5G AKA provides an identifier hiding mechanism and sends the $SUPI$ only in a randomized public key encryption (the Subscription Concealed Identifier, $SUCl$). We show with Tamarin that the $SUPI$ indeed remains confidential, even against active attackers (see Table 2), hence also against passive attackers. 5G AKA defeats thus previous IMSI-catcher attacks$^4$ [32]. We also have modelled a weak, passive attacker and have automatically proven that he cannot trace subscribers.

We believe that active attackers are realistic threats for most use cases. Moreover, since privacy is a real concern to 3GPP, 5G AKA should protect subscribers’ privacy also against active attackers. Unfortunately, we have found that this is not the case as the 5G AKA protocol suffers from a traceability attack.

Using Tamarin (see our model [5]), we automatically find the following attack in 5G AKA. In this attack, the attacker observes one 5G AKA authentication session and later replays the $SN$’s message to some subscriber. From the subscriber’s answer (MAC failure or Synchronization failure), the attacker can distinguish between the subscriber observed earlier (in case of Synchronization failure) and a different subscriber (in case of MAC failure). This attack can be exploited to track subscribers over time. A variant of this attack was first described in [6] for the AKA protocol as used in 3G.

5.3 Recommendations

Throughout the paper, we have highlighted weaknesses in the standard and suggested improvements and refinements. We now

$^4$Those attacks relied on the subscribers sending IMSI (matching $SUPI$ in 5G) in the clear.
summarize some of them and propose more precise, provably secure fixes as a replacement for the key-confirmation and the binding channel assumptions. Again, we emphasize the critical role played here by our formal interpretation of the standard and our formal analysis of the described 5G AKA protocol.

5.3.1 Explicit Requirements. As shown in Table 1 and discussed in Section 5.3, the standard underspecifies security requirements for the 5G AKA protocol. We suggest that the standard explicitly requires the missing intended security properties. In particular, it should be clear that 5G AKA aims at achieving injective agreement on $K_{SEAF}$ between the subscribers and the HNs which is central to the protocol’s purpose. The subscribers should obtain injective agreement on $K_{SEAF}$ with the HNs; they are thereby assured the HNs recently authorized this session, since $K_{SEAF}$ derives from the random $R$. Finally, the HNs should have injective agreement on $K_{SEAF}$ with the subscribers, obtaining recent aliveness as a consequence.

5.3.2 Binding Channel. As discussed in Section 5.2.1, the last version of the standard introduced attacks under the given security assumptions. There are two solutions to fix this: either the standard explicitly states an additional security assumption (i.e., the channel between the SNs and HNs must be binding), or alternatively the 5G AKA protocol is fixed (without the need for a new assumption) using the following minor modification: $(SUPI, SUCI)$ is sent instead of $SUPI$ in the final message from $HN$ to $SN$. However, it is our understanding that the binding assumption is a property that is required for other reasons anyway, such as reliability.

5.3.3 On the Key-Confirmation. We already have discussed the danger of missing key-confirmation in 5G AKA in Section 5.2.2. We now propose two simple modifications to the protocol that would make key-confirmation redundant and unnecessary, therefore reducing the number of roundtrips that are needed to achieve intended security guarantees. Before explaining our fix, note that the key-confirmation was necessary in the first place because the HNs never commit to a specific $SNname$ when computing the challenge $R, AUTN$. Only the key $K_{SEAF}$ is bound to $SNname$, but the challenge itself is not.

Our first fix consists of binding $AUTN$ to $SNname$ so that subscribers directly have the proof the $HN$ has committed to a specific $SNname$, without even using $K_{SEAF}$. Formally, $AUTN$ currently refers to $(SQN_{HN} \otimes AK, MAC)$ where $MAC = t1(K, (SQN_{HN}, R))$. In our fix, $MAC$ is replaced by $t1(K, (SQN_{HN}, R, SNname))$. Therefore, the subscribers can verify the authenticity of the challenge that commits to a specific $SNname$. We have formally verified [5] that a key-confirmation roundtrip is no longer necessary with this fix.

Our second, alternative, fix consists in replacing the full key-confirmation roundtrip by an unidirectional key-confirmation from the $SN$ only. More precisely, we could add (any) message MACed with a key derived from $K_{SEAF}$, sent by the $SN$s to the subscribers, at the very end of the protocol. We have proven with Tamarin that no further guarantees are provided by a full key-confirmation, compared to our (less costly) unidirectional key-confirmation.

5.3.4 On Privacy. We recall that the functions $f1$ and $f1^*$ are not explicitly required to protect the confidentiality of their inputs (see Section 3.1.2). This is however necessary for privacy as these MAC functions take $SQN$ as input, among others. If these functions were not confidentiality-preserving, a passive attacker could learn the subscribers’ $SQNs$ and perform location attacks [32] by tracking nearby $SQNs$ over time or perform activity monitoring attacks [12].

We also recommend for the standard to explicitly aim at protecting privacy against active attackers and take steps in this direction. Unfortunately, this would involve significant modifications to the protocol since at least the failure reasons (MAC/Synchronization failure) must be hidden from the attacker [6, 22] and the $SQN$ concealment mechanism should be strengthened against active attackers [12], possibly by using proper encryption or using an anonymity key $AK$ based on subscriber-generated randomness. We leave a complete evaluation of possible solutions for future work and we expect our model to be valuable in this process.

5.3.5 Redundancies. A close look at the cryptographic messages (see detailed list in Appendix A) and their purposes shows many redundancies. For instance, in $RES^*$, the proof of possession of $K$ is in $CK, IK$, and $RES$. $R$ appears to be redundant as well. Similarly, $SNname$ is redundant in the key derivation of $K_{SEAF}$. Legacy reasons may explain these redundancies, but these design choices could be questioned and the protocol simplified.

5.3.6 On the role of $SQN$. The purpose of the $SQN$ counters is to provide replay protection for the subscribers. This mechanism was introduced in 3G, when the USIM was incapable of generating good randomness. This is no longer the case in 5G, where USIMs can perform randomized asymmetric encryption (required to compute $SUCI$ from $SUPP$). Therefore, authentication protocols should be rethought and more standard challenge-response mechanisms could be used to replace the $SQN$ counters. This would benefit the current authentication methods, which can suffer from de-synchronization and must keep the privacy sensitive $SQNs$ up-to-date and sometimes fail to protect them against attackers (see Section 5.3.4).

5.3.7 On the benefits of Formal Methods. As argued throughout this section, the standard could be simplified and improved in various directions. We recall that formal models, such as our model of the 5G AKA protocol, have proven to be extremely valuable to quickly assess the security of such modifications and simplifications. Our model can serve as a basis to accompany the future evolution of the standard and can be used as a tool to quickly evaluate the security of modification proposals.

6 CONCLUSION

We have formally analyzed one of the two authentication methods in 5G, the one which enhances the previous variant currently used in 4G. This included a detailed analysis of the standard to identify all assumptions and security goals, a formal model of the protocol and security goals as specified in the standard, the automated security analysis using the Tamarin prover, and a detailed discussion of our findings. Our models are substantially more detailed than those of previous work and account for detail of the state machine, counters, the re-synchronization procedures, and the XOR operations.

While analyzing the standard we discovered that security goals and assumptions are underspecified or missing in the standard, including central goals like agreement on the session key. Moreover, our analysis in Tamarin shows that some properties are violated
without further assumptions, which is notably the case for agreement properties on the session key. We also critique the standard’s choice of implicit authentication and the lack of key confirmation as this introduces weaknesses if the protocol is used incorrectly. Finally, our privacy analysis shows that the 5G version of AKA still fails to ensure unlinkability against an active attacker; this scenario is, in our opinion, completely realistic.

As future work, we intend to analyze other variants of the AKA protocol, notably those used in 3G and 4G networks, to see which security guarantees they provide compared to 5G AKA. We also plan to follow the future development of the 5G standard as it can serve as the basis for improving the protocol’s design, in particular to evaluate ideas and avoid regressions. For example, we identified one weakness that was introduced in revision v1.0.0, which was not present in v0.7.1. This is a major benefit of tool-based analysis of protocol design: once the model is constructed, one can quickly test changes and evaluate different design options.

REFERENCES

A NOTATIONS AND ACRONYMS
We list all the acronyms we introduced throughout the paper in Table 4 and give a correspondence table between our simplified terminology and the 3GPP terminology in Table 5.

B THE EAP-AKA’ PROTOCOL
We depict the core flow of the EAP-AKA’ protocol in Figure 4. We omit the MAC failure and Re-synchronization failure phases that are the same as for 5G-AKA (see Section 2.2.2 and Figure 3). We also omit the message headers specific to the EAP framework such as ‘EAP Request’ and ‘EAP Success’. The key derivation is a bit different compared to 5G-AKA. K_{SEAF} is derived from K_{AUSF} exactly as in 5G-AKA:

\[ K_{SEAF} = KDF(K_{AUSF}, SNname) \]

but K_{AUSF} is derived differently: K_{AUSF} = MK[1152...1407] (we write [x...y] for the substring from bit x to y) where the master key MK is:

\[ KDF((KDF(JK, SNname), KDF(CK, SNname)), (EAP-AKA, SUPI)). \]

Therefore,

\[ K_{SEAF} = KeySeed(K, R, SQN_{HN}, SNname, SUPI) = KDF(KDF((KDF(JK, SNname), KDF(CK, SNname)), (EAP-AKA, SUPI))[512..767], SNname). \]

The messages AT_MAC are MAC messages over the other sub-messages as part of the same message. The key in use is K_{aut} = MK[1152...1407].

Conceptually, the main difference of EAP-AKA’ compared to 5G AKA are as follows:

- the challenge xRES does not directly bind the SN’s identity SNname. However, since the challenge is MACed (with the session key K_{aut}) together with SNname, both are de facto bound together.
- SN serves as a pass-through until the authentication is considered successful by the HN. Only at this time SN obtains SUPI and K_{SEAF} from the HN, while it obtains K_{SEAF} already in the first message in 5G AKA.

C LOWE’S TAXONOMY AND TAMARIN MODELING
Lowe’s Taxonomy [28] notably defines aliveness, recent aliveness, weak agreement, non-injective agreement, and injective agreement. After an introductory example showing how properties are typically modelled in TAMARIN, we show how aliveness and non-injective agreement properties are modelled. The process for the other properties is similar.

C.1 Introductory Example: Secrecy
As an introductory example, let us see how secrecy properties are modelled in TAMARIN. For instance, we model the property that the SUPI of subscribers is never revealed to the attacker. Formally, such a property is formalized in TAMARIN using the formula defined below, where facts Claim_Secret(a, k) are produced for each rule of agent a (some subscriber or some HN) who accesses or stores the identifier SUPI. Note that K(t) denotes the fact that t is in the attacker’s Knowledge.

Definition C.1. Secrecy is modeled via the following formula:

\[ \forall a \; \#i. \; \text{Claim}_\text{secret}(a, t)@i \Rightarrow \neg(\exists j. \; K(t)@j). \]

C.2 Aliveness
Lowe defines aliveness as follows (excerpt from [28]):

We say that a protocol guarantees to an initiator A aliveness of another agent B if, whenever A (acting as initiator) completes a run of the protocol, apparently with responder B, then B has previously been running the protocol.

Let us see how this property is mathematically modelled in TAMARIN. We assume that the TAMARIN model is equipped with facts Claim_commit(a, b, (A, B)) (i.e., an agent a of role A claims it has established aliveness of b whose role is B) and Claim_running(b, B) (i.e., an agent b of role B claims it has run the protocol).

Definition C.2. Aliveness of a role A towards a role B is modeled via the following formula:

\[ \forall a \; b \; \#i. \; \text{Claim}_\text{commit}(a, b, (A, B))@i \Rightarrow (\exists j. \; \text{Claim}_\text{running}(b, B)@j). \]

Note that we do not restrict the timestamp #j to be before the timestamp #i (e.g., with a constraint #i < #j) since the trace semantics of TAMARIN already accounts for this constraint. More precisely, if, for some execution, there was a fact Claim_running(b, B)@i but only after the fact Claim_commit(a, b, (A, B))@i (i.e., #i < #j), then it would suffice, for falsifying the property, to consider a prefix of the considered execution that contains Claim_commit(a, b, (A, B))@i but not Claim_running(b, B)@j.

C.3 Non-injective Agreement
Another example is the non-injective agreement property, defined as follows (excerpt from [28]):

We say that a protocol guarantees to an initiator A non-injective agreement with a responder B on a set of data items t_s (where t_s is a set of free variables appearing in the protocol description) if, whenever A (acting as initiator) completes a run of the protocol, apparently with responder B, then B has previously been running the protocol, apparently with A, and was acting as responder in his run, and the two agents agreed on the data values corresponding to all the variables in t_s.

We assume that the TAMARIN model is equipped with facts Claim_commitngr(a, b, (A, B, t_s)) (i.e., an agent a of role A claims it has established agreement on data t with b whose role is B) and Claim_runninggr(b, a, (A, B, t_s)) (i.e., an agent b of role B claims it tries to establish agreement on data t with a whose role is A). The above property is modelled as follows.
Table 4: Acronyms and abbreviations (mostly from [TS 33.501, Sec. 3.2])

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full name</th>
<th>Reference</th>
<th>Description (if needed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AK</td>
<td>Anonymity Key</td>
<td>Section 2.2</td>
<td></td>
</tr>
<tr>
<td>AMF</td>
<td>Authentication Management Field</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>AMF(*)</td>
<td>Access and Mobility Management Function</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>ARPF</td>
<td>Authentication credential Repository and Processing Function</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>AUSF</td>
<td>Authentication Server Function</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>EAP</td>
<td>Extensible Authentication Protocol</td>
<td>Section 2.2</td>
<td></td>
</tr>
<tr>
<td>IMSI</td>
<td>International Mobile Subscriber Identity</td>
<td>Section 2.1</td>
<td>Uniquely identity subscribers</td>
</tr>
<tr>
<td>gNB</td>
<td>NR Node B</td>
<td>Appendix A</td>
<td>new generation base station</td>
</tr>
<tr>
<td>GUTI</td>
<td>Globally Unique Temporary UE Identity</td>
<td>Section 4.3</td>
<td></td>
</tr>
<tr>
<td>ME</td>
<td>Mobile Equipment</td>
<td>Section 2.1</td>
<td></td>
</tr>
<tr>
<td>MNC</td>
<td>Mobile Country Code</td>
<td>Appendix A</td>
<td>Uniquely identify HNs’ countries</td>
</tr>
<tr>
<td>MNC</td>
<td>Mobile Network Code</td>
<td>Appendix A</td>
<td>Uniquely identity HNs in a country</td>
</tr>
<tr>
<td>RAND (R)</td>
<td>Random Challenge</td>
<td>Section 2.2</td>
<td></td>
</tr>
<tr>
<td>RES</td>
<td>REsponse</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>SEAF</td>
<td>SEcurity Anchor Function</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>SUCI</td>
<td>Subscription Concealed Identifier</td>
<td>Section 2.2</td>
<td></td>
</tr>
<tr>
<td>SUPI</td>
<td>Subscription Permanent Identifier</td>
<td>Section 2.1</td>
<td></td>
</tr>
<tr>
<td>SQN</td>
<td>SeQuence Number</td>
<td>Section 2.1</td>
<td></td>
</tr>
<tr>
<td>UDM</td>
<td>Unified Data Management</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>USIM</td>
<td>Universal Subscriber Identity Module</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>XRES</td>
<td>eXpected REsponse</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>SIDF</td>
<td>Subscription Identifier De-concealing Function</td>
<td>Appendix A</td>
<td></td>
</tr>
<tr>
<td>SUPI</td>
<td>Subscription Concealed Identifier</td>
<td>Section 2.1</td>
<td></td>
</tr>
<tr>
<td>SUCI</td>
<td>Subscription Permanent Identifier</td>
<td>Section 2.2</td>
<td>Randomized encryption of SUPI</td>
</tr>
<tr>
<td>SNd</td>
<td>SN identity (?)</td>
<td>Appendix A</td>
<td>Uniquely identity SNs</td>
</tr>
</tbody>
</table>

Table 5: Correspondence between our terminology with the one of TS33.501

<table>
<thead>
<tr>
<th>Our notion</th>
<th>Correspondent notion in TS33.501</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serving Network</td>
<td>Combination of SEAF, AMF(*) and gNB</td>
</tr>
<tr>
<td>Home Network</td>
<td>Combination of AUSF, ARPF, UDM and SIDF</td>
</tr>
</tbody>
</table>

Definition C.3. Non-injective agreement on data t of a role A towards a role B is modeled via the following formula:

\[
\forall a b t \neq i. \text{Claim\_commit\_agr}(a, b, (A, B, t_s))@i \Rightarrow (\exists j. \text{Claim\_running\_agr}(b, a, (A, B, t_s))@j).
\]

D SECURITY ASSUMPTIONS AND GOALS
This section extends Section 3.

This section is dedicated to our interpretation of security assumptions and goals that are relevant to authentication methods in 5G as precise formal statements. We shall support our interpretation by relevant excerpts from Technical Specification (TS) documents and Technical Requirement (TR) documents issued by 3GPP. Note that we may cite documents specifying aspects of earlier generations (3G and 4G) when relevant.

D.1 Security Assumptions and Threat Model
D.1.1 Assumptions on Channels.

Channel SN-HN. As part of the E2E core network, the channel between the SN and HN is supposed to provide confidentiality, integrity, authenticity, and, replay protection. Those assumptions are explicitly specified:

[TS 33.501, Sec. 5.9.3] Requirements for E2E core network interconnection security:
- The solution shall provide confidentiality and/or integrity end-to-end between source and destination network for specific message elements identified in the present document. For this requirement to be fulfilled, the SEPP - cf [2], clause 6.2.17 shall be present at the edge of the source and destination networks dedicated to handling e2e Core Network Interconnection Security. The confidentiality and/or integrity for the message elements is provided between two SEPPs of the source and destination PLMN-.
Table 6: Notations and Messages

<table>
<thead>
<tr>
<th>Message Name</th>
<th>Content</th>
<th>Internal Ref.</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUPI</td>
<td>(IMSI, MMC, MNC)</td>
<td>Section 2.1</td>
<td>[TS 23.501, Sec. 5.9.2]</td>
</tr>
<tr>
<td>SUCI</td>
<td>(aenc((SUPLi, Rk), MMC, MNC))</td>
<td>Section 2.2</td>
<td>[TS 33.501, Sec. C.3]</td>
</tr>
<tr>
<td>SName</td>
<td>('5G', 'm', 'Srid')</td>
<td>Section 2.1</td>
<td>[TS 33.501, Sec. 6.1.4]</td>
</tr>
<tr>
<td>MAC</td>
<td>f1(K, (SQN₁, R))</td>
<td>Section 2.2</td>
<td>[TS 133.102, Sec. 6.3.2]</td>
</tr>
<tr>
<td>AK</td>
<td>f5(K, R)</td>
<td>Section 2.2</td>
<td>[TS 133.102, Sec. 6.3.2]</td>
</tr>
<tr>
<td>AUTN</td>
<td>(SQN₁ @ AK, MAC)</td>
<td>Section 2.2</td>
<td>[TS 33.501, Sec. 6.1.3]</td>
</tr>
<tr>
<td>RES</td>
<td>f2(K, R)</td>
<td>Section 2.2</td>
<td>[TS 133.102, Sec. 6.3.2]</td>
</tr>
<tr>
<td>CK</td>
<td>f3(K, R)</td>
<td>Appendix A</td>
<td>[TS 133.102, Sec. 6.3.2]</td>
</tr>
<tr>
<td>IK</td>
<td>f4(K, R)</td>
<td>Appendix A</td>
<td>[TS 133.102, Sec. 6.3.2]</td>
</tr>
<tr>
<td>RES</td>
<td>KDF((CK, IK), (Sname, R, RES))</td>
<td>Section 2.2</td>
<td>[TS 33.501, Sec. A.4]</td>
</tr>
<tr>
<td>Challenge(K, R, SName)</td>
<td>RES</td>
<td>Section 2.2</td>
<td>None</td>
</tr>
<tr>
<td>HXRES</td>
<td>SHA256((R, RES))</td>
<td>Section 2.2</td>
<td>[TS 33.501, Sec. A.5]</td>
</tr>
<tr>
<td>MACS</td>
<td>f1*(K, (SQN₁, R))</td>
<td>Section 2.2</td>
<td>[TS 133.102, Sec. 6.3.3]</td>
</tr>
<tr>
<td>AKS</td>
<td>f5*(K, R)</td>
<td>Section 2.2</td>
<td>[TS 133.102, Sec. 6.3.3]</td>
</tr>
<tr>
<td>AUSF</td>
<td>(SQN₁ @ AKS, MACS)</td>
<td>Section 2.2</td>
<td>[TS 133.102, Sec. 6.3.3]</td>
</tr>
<tr>
<td>Kₐₚₜ</td>
<td>KDF((CK, IK), (SName, SQN @ AK))</td>
<td>Section 2.2</td>
<td>[TS 33.501, Sec. A.2]</td>
</tr>
<tr>
<td>Kₖₑₜ</td>
<td>KDF(Kₐₚₜ, SName)</td>
<td>Section 2.2</td>
<td>[TS 33.501, Sec. A.6]</td>
</tr>
<tr>
<td>KeySeed(K, R, SQN₁, SName)</td>
<td>Kₖₑₜ</td>
<td>Section 2.2</td>
<td>None</td>
</tr>
</tbody>
</table>

Figure 4: The EAP-AKA’ protocol (continuing Figure 2). AT_MAC denotes a MAC over the other messages with key K.
• The destination network shall be able to determine the authenticity of the source network that sent the specific message elements protected according to the preceding bullet. For this requirement to be fulfilled, it shall suffice that a SEPP in the destination network that is dedicated to handling e2e Core Network Interconnection Security can determine the authenticity of the source network.
• The solution shall cover prevention of replay attacks.

Channel Subscribers—SNs. The channel between the subscribers and SNs, on the radio physical layer, is subject to eavesdropping (by passive attackers) or manipulations, interception, and injection of messages (by an active attacker). A passive attacker listens to signaling messages (i.e., messages sent on the radio physical layer) on specific bandwidths and can therefore easily eavesdrop on all messages exchanged in its vicinity. An active attacker sets up a fake base station to receive and send signaling messages; e.g., to impersonate SNs. While no 5G-specific hardware is publicly available yet, we recall how easily an attacker can set-up fake base stations in 4G using open-source and freely available software and hardware [23, 35]. From now on, we shall consider active attackers, except when explicitly stated otherwise.

D.1.2 Assumptions on Cryptographic Primitives. According to [TS 33.102, Sec. 3.2.6.3.2], the functions \( f_1, f_1^*, f_2 \) are message authentication functions while \( f_3, f_4, f_5, f_5^* \) are key derivation functions. To the best of our knowledge, there is no standardized, explicit security requirements for these functions. One could infer from the informal presentation [TS 33.102, Sec. 3.2] that the former are integrity protected and the latter are integrity and confidentiality protected. However, since \( f_1 \) and \( f_1^* \) are used to MAC sensitive data such as SQN (see the Section dedicated to privacy in Appendix D.2.3), it is our understanding that they should additionally preserve the confidentiality of their inputs.

Therefore, we assume \( f_1, f_1^*, f_3, f_4, f_5, f_5^* \) are integrity and confidentiality protected while \( f_2 \) is integrity protected. We also stress that \( f_1 \) and \( f_1^* \) are underspecified.

D.1.3 Assumptions on Parties. We consider compromised scenarios in order to provide stronger and more fine-grained guarantees. Our analyses will be parametrized by those compromised scenarios; in the worst case, a property will hold only when the attacker cannot compromise any agent. First, we consider an attacker who can compromise certain SNs. This means that the attacker gets access to an authenticated channel between the compromised SN and HNs, which he can use to eavesdrop on and inject messages. This is a reasonable assumption in 5G, where authentication methods should provide security guarantees even in presence of genuine but malicious SNs. In such situations, the HNs may cooperate with such SNs to authenticate some subscriber. In practice, this may happen in roaming situations. The following excerpt shows that in 5G, this is a threat model that should be considered (home refers to HN and visited network refers to SN):

**NOTE:** The security assessment scheme used for the security evaluation of the tamper resistant secure hardware component is outside the scope of 3GPP specifications.

[TS 33.501, Sec. 6.1.4.1] **Increased home control:** The authentication and key agreement protocols mandated to provide increased home control [compared to previous generations]. The feature of increased home control is useful in preventing certain types of fraud, e.g., fraudulent Nudm_UeCM_Registration Request for registering the subscriber’s serving AMF in UDM that are not actually present in the visited network.

Furthermore, we consider that the attacker may have genuine USIMs and compromised USIMs under its control. For those compromised subscribers, the attacker can access all secret values stored in the USIMs; i.e., SUPI, K, and SQN. Finally, the attacker can access all long-term secrets \( K, sk_{HN} \), and SUPI from compromised HNs.

**D.1.4 Assumptions on Data Protection.**

**Subscriber credentials.** The subscriber credentials, notably the key K and the identifier SUPI, shared between subscribers and HNs, should be initially secret (provided they belong to uncompromised agents):

[TS 33.501, Sec. 3.1] **Subscription credential(s):** set of values in the USIM and the ARP, consisting of at least the long-term key(s) and the subscription identifier SUPI, used to uniquely identify a subscription and to mutually authenticate the UE and 5G core network.

[TS 33.501, Sec. 5.2.4] The following requirements apply for the storage and processing of the subscription credentials used to access the 5G network:

• The subscription credential(s) shall be integrity protected within the UE using a tamper resistant secure hardware component.
• The long-term key(s) of the subscription credential(s) (i.e. K) shall be confidentiality protected within the UE using a tamper resistant secure hardware component.
• The long-term key(s) of the subscription credential(s) shall never be available in the clear outside of the tamper resistant secure hardware component.
• The authentication algorithm(s) that make use of the subscription credentials shall always be executed within the tamper resistant secure hardware component.
• It shall be possible to perform a security evaluation / assessment according to the respective security requirements of the tamper resistant secure hardware component.

NOTE: The security assessment scheme used for the security evaluation of the tamper resistant secure hardware component is outside the scope of 3GPP specifications.

**Sequence Number.** The sequence number SQN is a 48-bit counter (a 43-bits counter in some situations, see [TS 33.102, Sec. C.3.2]), therefore guessable with a very low probability. We consider a reasonable threat model where the value of SQN is unknown to the attacker when the attack starts, but the attacker knows how it is incremented during the attack. This corresponds to an attacker who
We now extract and interpret from the 5G documents the security (i) can monitor the activity of targeted subscribers in its vicinity during the attack but, (ii) cannot guess the initial value of SQN, (iii) nor he can monitor targeted subscribers all the time (i.e., from the very first use of the USIM up to the attack time).

**Other data.** While not explicitly stated in the specification, we shall assume that the private asymmetric key $sk_{HN}$ is initially private.

### D.2 Security Requirements

We now extract and interpret from the 5G documents the security goals the authentication method 5G-AKA should achieve according to the 5G standard.

#### D.2.1 Authentication Properties

5G specifications make semi-formal claims about authentication properties at different places in the documents. We have identified relevant claims and translate them into formal security goals, indicated in purple and cursive text. When doing this, we rely on Lowe’s taxonomy of authentication properties [28]. The first benefit is that the Lowe’s taxonomy provides precise properties that are now well established and understood, which can very often clarify an ambiguity [8]. The second benefit is that there exists a formal relation between the Lowe’s taxonomy and mathematical formulations of security properties that can be directly modeled in Tamarin [1].

We give an overview of this taxonomy and its relation with mathematical formulations in Appendix C. Intuitively, it specifies, from an agent A’s point of view, four levels of authentication between two agents A and B: (i) aliveness, which only ensures that B has been running the protocol previously, but not necessarily with A; (ii) weak agreement, which ensures that B has previously been running the protocol with A, but not necessarily with the same data; (iii) non-injective agreement, which ensures that B has been running the protocol with A and both agree on the data; and (iv) injective agreement, which additionally ensures that for each run of the protocol of an agent there is a unique matching run of the other agent, which prevents replay attacks.

We start by recalling the (informal) goals of authentication methods in 5G:

**[TS 33.501, Sec. 6.1.1.1]** The purpose of the primary authentication and key agreement procedures is to enable mutual authentication between the UE and the network and provide keying material that can be used between the UE and network in subsequent security procedures. The keying material generated by the primary authentication and key agreement procedure results in an anchor key called the KSEAF provided by the AUSF of the home network to the SEAF of the serving network.

As we shall see, 5G aims at providing stronger guarantees than in older generations, e.g., than in 3G:

**[TS 133.102, Sec. 5.1.2]** (3G) The following security features related to entity authentication are provided:

- user authentication: the property that the serving network corroborates the user identity of the user;
- network authentication: the property that the user corroborates that he is connected to a serving network that is authorized by the user’s HE to provide him services; this includes the guarantee that this authorisation is recent.

We now list the security goals in terms of authentication by pairs of entities. Note that the specification considers some authentication properties to be implicit. This means that the guarantees is provided only after an additional key confirmation roundtrip (w.r.t. $K_{SEAF}$) between the subscribers and the SN. We discuss and criticize this design choice in Section 5.

**Authentication between subscribers and HNs.** First, the subscribers must have the assurance that authentication can only be successful with SNs authorized by their HNs.

**[TS 33.501, Sec. 5.1.2]** Serving network authorization by the home network: Assurance shall be provided to the UE that it is connected to a serving network that is authorized by the home network to provide services to the UE. This authorization is ‘implicit’ in the sense that it is implied by a successful authentication and key agreement run.

**[TS 33.501, Sec. 6.1.1.3]** The binding to the serving network prevents one serving network from claiming to be a different serving network, and thus provides implicit serving network authentication to the UE.

Formally, a subscriber must obtain non-injective agreement on Snname with its HN after key confirmation.

In 5G, the trust assumptions are balanced differently than in previous standards (e.g., 3G or 4G). Most notably, the level of trust the system needs to put into SNs has been reduced. One important property provided by 5G is that a SN can no longer fake authentication requests with the HNs for subscribers that are not attached to one of its base station:

**[TS 33.501, Sec. 6.1.4.1]** Increased home control: The authentication and key agreement protocols mandated to provide increased home control [compared to previous generations]. The feature of increased home control is useful in preventing certain types of fraud, e.g. fraudulent Nudm_UECM_Registration Request for registering the subscriber’s serving AMF in UDM that are not actually present in the visited network.

Formally, the HNs obtain aliveness of its subscribers at that SN, which is non-injective agreement on Snname from the HNs’ point of view with the subscribers.

**Authentication between subscribers and SNs.** As expected, the SNs shall be able to authenticate the subscribers:
**D.2.2 Confidentiality Properties.** While it is not clearly specified, it is obviously the case that 5G authentication methods should achieve secrecy of $K_{\text{SEAF}}$, $K$, and $sk_{\text{SN}}$. We recall similar goals for 3G:

**[TS 33.501, Sec. 5.1.2]** Subscription authentication: The serving network shall authenticate the Subscription Permanent Identifier (SUPI) in the process of authentication and key agreement between UE and network.

Formally, the SNs must obtain non-injective agreement on SUPI with the subscribers, which is weak agreement from the SNs towards subscribers (since the SUPI is the subscriber’s identifier).

Conversely, the subscribers shall be able to authenticate the SNs:

**[TS 33.501, Sec. 5.1.2]** Serving network authentication: The UE shall authenticate the serving network identifier through implicit key authentication.

NOTE 1: The meaning of ‘implicit key authentication’ here is that authentication is provided through the successful use of keys resulting from authentication and key agreement in subsequent procedures.

NOTE 2: The preceding requirement does not imply that the UE authenticates a particular entity, e.g. an AMF, within a serving network.

Formally, and because $SN_{\text{name}}$ is the SN’s identifier, the subscribers must obtain weak agreement with the SNs after key confirmation.

Authentication between SNs and HNs. The SNs shall be able to authenticate the subscribers that are authorized by their corresponding HN:

**[TS 33.501, Sec. 5.1.2]** UE authorization: The serving network shall authorize the UE through the subscription profile obtained from the home network. UE authorization is based on the authenticated SUPI.

Formally, the SNs must obtain non-injective agreement on SUPI with the HNs.

5G should ensure that knowing the $K_{\text{SEAF}}$ established in a certain session is insufficient to deduce a $K_{\text{SEAF}}$ key that has been established in a previous session or that will be established in a later session:

**[TS 33.501, Sec. 3]** backward security: The property that for an entity with knowledge of $K_n$, it is computationally infeasible to compute any previous $K_{n-m}$ ($m > 0$) from which $K_n$ is derived.

NOTE 5: In the context of $K_{\text{gNB}}$ key derivation, backward security refers to the property that, for a gNB with knowledge of a $K_{\text{gNB}}$, shared with a UE, it is computationally infeasible to compute any previous $K_{\text{gNB}}$ that has been used between the same UE and a previous gNB.

**[TS 33.501, Sec. 3]** forward security: The property that for an entity with knowledge of $K_m$ that is used between that entity and a second entity, it is computationally infeasible to predict any future $K_{m+n}$ ($n > 0$) used between a third entity and the second entity.

NOTE 6: In the context of $K_{\text{gNB}}$ key derivation, forward security refers to the property that, for a gNB with knowledge of a $K_{\text{gNB}}$, shared with a UE, it is computationally infeasible to predict any future $K_{\text{gNB}}$ that will be used between the same UE and another gNB. More specifically, $n$ hop forward security refers to the property that a gNB is unable to compute keys that will be used between a UE and another gNB to which the UE is connected after $n$ or more handovers ($n = 1$ or more).

Since we do not consider the full key hierarchy and how $K_{\text{gNB}}$ can be derived from $K_{\text{SEAF}}$, we shall consider those properties for $K_{\text{SEAF}}$ directly. Formally, it should be the case that $K_{\text{SEAF}}$ established in a given session remains confidential even when the attacker learns the $K_{\text{SEAF}}$ keys established in all other sessions. Note that this is different from forward secrecy and post-compromise secrecy [15] which fail to hold as we shall see in Section 5.1.

Note that some other confidentiality properties are considered to be privacy properties (see Appendix D.2.3).

**D.2.3 Privacy Properties.** We first emphasize the importance given to privacy in 5G:

**[TR 33.899, Sec. 4.1.4.2]** Subscription privacy deals with various aspects related to the protection of subscribers’ personal information, e.g. identifiers, location, data, etc. [...] The security mechanisms defined in NextGen shall be able to be configured to protect subscriber’s privacy.

**[TR 33.899, Sec. 5.7.1]** The subscription privacy is very important area for Next Generation system as can be seen by the growing attention towards it, both inside and outside the 3GPP world.

Outside the 3GPP, an alliance of mobile network operators, vendors, and universities called NGMN [9] has identified security and privacy as an enabler and essential value proposition of NextGen system and has presented that built-in privacy should be included as a design principle [10]. Similarly, a 5G PPP project called 5G-Ensure [11] has also identified privacy
as one of the topmost priorities for the NextGen system stating that the privacy has an important social impact [12]. [...] 

**[TS 33.501, Sec. F.2]** EAP-AKA' includes optional support for identity privacy mechanism that protects the privacy against passive eavesdropping.

This important role given to privacy can be explained by numerous and critical attacks that have breached privacy (e.g., with IMSI-catcher [35, 36]) in previous generations; see the survey [32]. We also recall that privacy was already a concern in 3G:

**[TS 133.102, Sec. 5.1.1]** (3G) The following security features related to user identity confidentiality are provided:

- **user identity confidentiality**: the property that the permanent user identity (IMSI) of a user to whom a service is delivered cannot be eavesdropped on the radio access link;
- **user location confidentiality**: the property that the presence or the arrival of a user in a certain area cannot be determined by eavesdropping on the radio access link;
- **user untraceability**: the property that an intruder cannot deduce whether different services are delivered to the same user by eavesdropping on the radio access link.

Thus, already for 3G, user identity confidentiality, anonymity, and untraceability were security requirements. However, those properties were required against a passive attacker only (we discuss and criticize this restriction to a passive attacker in Section 5). Note that anonymity and untraceability (often called unlinkability) are not clearly defined. We propose formalization in Section 4.3.

We now list more precise statements specifying how privacy should be protected in 5G.

**Confidentiality of SUPI.** In 5G, the SUPI is considered sensitive and must remain secret since it uniquely identifies users. Indeed, an attacker who would be able to obtain this value from a subscriber would be able to identify him, leading to classical user location attacks (i.e., see [TS 133.102, Sec. 5.1.1] above), much like IMSI-catcher attacks.

**[TS 33.501, Sec. 5.2.5]** The SUPI should not be transferred in clear text over 5G RAN except routing information, e.g. Mobile Country Code (MCC) and Mobile Network Code (MNC).

**[TS 33.501, Sec. 6.12]** Subscription identifier privacy: In the 5G system, the globally unique 5G subscription permanent identifier is called SUPI as defined in 3GPP TS 23.501 [2]. The SUCI is a privacy preserving identifier containing the concealed SUPI. [...] 

Formally, **the SUPI shall remain secret in the presence of a passive attacker.**

**Confidentiality of SQN.** For similar reasons, SQN must remain secret. An additional reason that is not explicitly stated is that SQN leaks the number of successful authentications the corresponding USIM has performed since it was manufactured, which is strongly correlated to its age and activity. This is even more critical when the attacker learns SQN at different times.

**[TS 33.102, Sec. 6.2.3]** (3G) Here, AK is an anonymity key used to conceal the sequence number as the latter may expose the identity and location of the user. The concealment of the sequence number is to protect against passive attacks only. If no concealment is needed then IS ≡ 0 (AK = 0).

**[TS 133.102, Sec. C.3.2]** (3G) **User anonymity:** the value of SQN may allow to trace the user over longer periods. If this is a concern then SQN has to be concealed by an anonymity key as specified in section 6.3.

Formally, **the SQN shall remain secret in the presence of a passive attacker.**

**Anonymity and Untraceability.** Preventing the attacker from learning pieces of data that are identifying (e.g., SUPI, SQN) is insufficient to protect against traceability attacks, user location attacks, or even anonymity attacks (we explain why and discuss definitions in Section 4.3). While no formal statement is made on the necessity of ensuring untraceability or anonymity for 5G, the following excerpts and the fact that it was required for 3G ([TS 133.102, Sec. 5.1.1], see above), seem to imply that those properties are relevant for 5G as well.

On untraceability (also called unlinkability): [TS 133.102, Sec. 5.1.1], item 2 and:

**[TS 33.501, Sec. C.2]** The reason for mentioning the non-freshness is that, normally, in order to attain **unlinkability** (i.e., to make it infeasible for over-the-air attacker to link SUCIs together), it is necessary for newly generated SUCIs to be fresh. But, in case of the null-scheme, the SUCI does not conceal the SUPI. So unlinkability is irrelevant.

**[TR 33.899, Sec. 5.2.3.8.2]** **Security threats:** Over-use of a single UE key-pair may harm user privacy (allowing a user’s actions to be linked and tracked across multiple domains and services).

On anonymity: [TS 133.102, Sec. 5.1.1], item 3 and:

**[33.849, Sec. 6.4.2]** (TR on Privacy in 3GPP, 2016) The UMTS authentication procedure (TS 33.102 [10]) design is an example of how to fulfill anonymity:

1. Analysis of the authentication process: identity and location of the user may be exposed.
2. Identify an identifying attribute: sequence number may bring a risk of personal identification.
(3) Risk: The sequence number may expose the identity and thus the location of the user.
(4) Anonymizing technique used: use Anonymity Key in the Authentication Token to conceal (blind) the sequence number.

[TR 33.899, Sec. 5.1.4.14.3] If there was no single NAS security termination then the unencrypted part of a signalling message would have to contain parameters that would allow routing to the correct NAS entity, e.g. SM entity in a network slice. This information about the slice may give away information on the services used. However, user identity privacy should prevent that an eavesdropper can associate a particular signalling message with a particular subscriber. Editor’s Note: The above paragraph has been included for completeness. It is ofs whether leaving parameters unencrypted that are required for NAS-internal routing would endanger privacy.

Formally, it seems that 5G authentication methods are required to provide anonymity and untraceability of the subscribers in the presence of a passive attacker.

D.2.4 Other Properties. As specified below, the established keys should never be the same twice:

[TS 133.102, Sec. 6.2.3] (3G) Key reuse: A wrap around of the counter SQN could lead to a repeated use of a key pair (CK, IK). This repeated key use could potentially be exploited by an attacker to compromise encryption or forge message authentication codes applied to data sent over the 3GPP-defined air interfaces.

This will be analyzed as part of Injective agreement properties on the established key KSEAF for different pairs of parties.

Finally, 5G specify some security goals in the context of backward compatibility with older generations. We do not analyze those properties as they would require us to analyze the combination of the 5G authentication protocols with the older generations authentication protocols. This is left as future work.

[TS 33.501, Sec. 6.1.1.3] Key separation: Furthermore, the anchor key provided to the serving network shall also be specific to the authentication having taken place between the UE and a 5G core network, i.e. the KSEAF shall be cryptographically separate from the key KASME delivered from the home network to the serving network in earlier mobile network generations.

[TS 33.501, Sec. 5.11] An attacker could attempt a bidding down attack by making the UE and the network entities respectively believe that the other side does not support a security feature, even when both sides in fact support that security feature. It shall be ensured that a bidding down attack, in the above sense, can be prevented.