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| 3GPP TS 35.234 V0.2.0 (2024-08) |
| Technical Specification |
| 3rd Generation Partnership Project;Technical Specification Group Services and Security Aspects;Specification of the MILENAGE-256 algorithm set;An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f3, f4, f5, f5\* and f5\*\*;Document 1: General(Release 19) |
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# Foreword

This Technical Specification has been produced by the 3rd Generation Partnership Project (3GPP).

The contents of the present document are subject to continuing work within the TSG and may change following formal TSG approval. Should the TSG modify the contents of the present document, it will be re-released by the TSG with an identifying change of release date and an increase in version number as follows:

Version x.y.z

where:

x the first digit:

1 presented to TSG for information;

2 presented to TSG for approval;

3 or greater indicates TSG approved document under change control.

y the second digit is incremented for all changes of substance, i.e. technical enhancements, corrections, updates, etc.

z the third digit is incremented when editorial only changes have been incorporated in the document.

In the present document, modal verbs have the following meanings:

**shall** indicates a mandatory requirement to do something

**shall not** indicates an interdiction (prohibition) to do something

The constructions "shall" and "shall not" are confined to the context of normative provisions, and do not appear in Technical Reports.

The constructions "must" and "must not" are not used as substitutes for "shall" and "shall not". Their use is avoided insofar as possible, and they are not used in a normative context except in a direct citation from an external, referenced, non-3GPP document, or so as to maintain continuity of style when extending or modifying the provisions of such a referenced document.

**should** indicates a recommendation to do something

**should not** indicates a recommendation not to do something

**may** indicates permission to do something

**need not** indicates permission not to do something

The construction "may not" is ambiguous and is not used in normative elements. The unambiguous constructions "might not" or "shall not" are used instead, depending upon the meaning intended.

**can** indicates that something is possible

**cannot** indicates that something is impossible

The constructions "can" and "cannot" are not substitutes for "may" and "need not".

**will** indicates that something is certain or expected to happen as a result of action taken by an agency the behaviour of which is outside the scope of the present document

**will not** indicates that something is certain or expected not to happen as a result of action taken by an agency the behaviour of which is outside the scope of the present document

**might** indicates a likelihood that something will happen as a result of action taken by some agency the behaviour of which is outside the scope of the present document

**might not** indicates a likelihood that something will not happen as a result of action taken by some agency the behaviour of which is outside the scope of the present document

In addition:

**is** (or any other verb in the indicative mood) indicates a statement of fact

**is not** (or any other negative verb in the indicative mood) indicates a statement of fact

The constructions "is" and "is not" do not indicate requirements.

# Introduction

Editor's Note: This clause contains information provided by ETSI SAGE.

The present document contains a 256-bit example of set of algorithms, collectively called MILENAGE-256, which may be used as the authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*. It is not mandatory to use the particular algorithms specified in this document – all eight functions are operator-specifiable rather than being fully standardised. Operators electing to employ this example set can further personalise the algorithms (as described in the text). The present document is one of four documents, which collectively comprise the entire specification of the example authentication and key generation algorithms. Namely:

- **3GPP TS 35.234: "Specification of the MILENAGE-256 algorithm set: An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*; Document 1: MILENAGE-256 General".**

- 3GPP TS 35.235 [2]: "Specification of the MILENAGE-256 algorithm set: An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*; Document 2: MILENAGE-256 Algorithm Specification".

- 3GPP TS 35.236 [3]: "Specification of the MILENAGE-256 algorithm set: An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*; Document 3: Implementors’ Test and Design Conformance Test Data".

- 3GPP TS 35.237 [4]: "Specification of the MILENAGE-256 algorithm set: An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*; Document 4: Summary and Results of Design and Evaluation".

# 1 Scope

Editor's Note: This clause contains scope information from ETSI SAGE for selected option.

The present document contains a high level specification of the MILENAGE-256 algorithm set which constitutes an example set of 3GPP authentication and key generation functions with a 256-bit target security level.

The example set is based on the block cipher Rijndael-256-256 with 256-bit key and 256-bit block size [8, 14] (recall that the 128 bit Advanced Encryption Standard, AES-128, corresponds to Rijndael-128-128 [8]). MILENAGE-256 used with the Rijndael-256-256 kernel is referred to as MILENAGE-256-R.

ETSI SAGE defined an optional-to-use function, ***f5\*\****, which was designed according to candidate solutions discussed in 3GPP SA3 [12], with the aim of countering certain replay attacks that can lead to traceability of subscribers [13]. When used, the optional function ***f5\*\**** replaces ***f5\****.

The specification and associated test data for the example algorithm set is documented in two documents:

* A formal specification of the mode and the example kernel [2].
* A detailed test data document, covering mode and the example kernel [3].

A detailed summary of the evaluation is provided in a public evaluation report [4].

The present document provides an overview of the overall work conducted by the task force.

# 2 References

The present document …

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non‑specific.

- For a specific reference, subsequent revisions do not apply.

- For a non-specific reference, the latest version applies. In the case of a reference to a 3GPP document (including a GSM document), a non-specific reference implicitly refers to the latest version of that document *in the same Release as the present document*.

[1] 3GPP TR 21.905: "Vocabulary for 3GPP Specifications".

[2] 3GPP TS 35.235: "Specification of the MILENAGE-256 algorithm set: An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*; Document 2: MILENAGE-256 Algorithm Specification".

[3] 3GPP TS 35.236: "Specification of the MILENAGE-256 algorithm set: An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*; Document 3: Implementors’ Test and Design Conformance Test Data".

[4] 3GPP TS 35.237: "Specification of the MILENAGE-256 algorithm set: An example set of 256-bit 3GPP authentication and key generation functions f1, f1\*, f2, f2, f3, f5, f5, f5\* and f5\*\*; Document 4: Summary and Results of Design and Evaluation".

[5] 3GPP TS 33.102: "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; 3G Security; Security Architecture".

[6] 3GPP TS 33.105: "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; 3G Security; Cryptographic Algorithm Requirements".

[7] 3GPP TS 33.501: "Security architecture and procedures for 5G system".

[8] Rijndael information page, NIST archived AES submissions, https://csrc.nist.gov/projects/cryptographic-standards-and-guidelines/archived- crypto-projects/aes-development#rijndael

[9] The Advanced Encryption Standard (AES), NIST FIPS 197, 2001.

[10] 3GPP TS 35.205: "3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; 3G Security; Specification of the MILENAGE Algorithm Set: An example algorithm set for the 3GPP authentication and key generation functions f1, f1\*, f2, f3, f4, f5 and f5\*; Document 1: General".

[11] 3GPP TS 35.231: "Specification of the TUAK algorithm set: A second example algorithm set for the 3GPP authentication and key generation functions f1, f1\*, f2, f3, f4, f5 and f5\*; Document 1: Algorithm specification".

[12] 3GPP TR 33.846, "Study on authentication enhancements in the 5G System (5GS)".

[13] R. Borgaonkar, "New Privacy Threat on 3G, 4G, and Upcoming 5G AKA Protocols", in Proceedings on Privacy Enhancing Technologies 2019(3):108-127. Also available at https://eprint.iacr.org/2018/1175.pdf (published online: July 2019).

[14] J. Daemen and V. Rijmen, "The design of Rijndael", Springer Verlag, 2002.

[15] H. Gilbert: "The Security of One-Block-to-Many Modes of Operation", in T. Johansson (Ed): Proceedings of FSE 2003, LNCS 2887, Springer Verlag, pp. 376- 395.

[16] A. Maximov and M. Näslund, "Security analysis of the Milenage-construction based on a PRF", Cryptology ePrint Archive, available at https://eprint.iacr.org/2023/607.

…

[x] <doctype> <#>[ ([up to and including]{yyyy[-mm]|V<a[.b[.c]]>}[onwards])]: "<Title>".

# 3 Definitions of terms, symbols, and abbreviations

Editor's Note: This clause contains notation that applies to the present document.

## 3.1 Terms

For the purposes of the present document, the terms given in 3GPP TR 21.905 [1] and the following apply. A term defined in the present document takes precedence over the definition of the same term, if any, in 3GPP TR 21.905 [1].

Definition format (Normal)

**<defined term>:** <definition>.

**example:** text used to clarify abstract rules by applying them literally.

**AKA-specific terminology**

**AMF:** Authentication Management Field

**AK:** Anonymity key

**AK\*:** Anonymity key used during resynchronisation

**CK:**  Cipher Key

**f1, f1\*, f2, f3, f4, f5, f5\*, f5\*\*:** Cryptographic functions used to derive AKA parameters

**IK:** Integrity Key

**K:** Subscriber key

**MAC-A:** Network Authentication Code

**MAC-S:** Resynchronisation Authentication Code

**RAND :** Random Challenge

**RES:** Response to Challenge

**SQN:** Sequence Number

**SQNHE:** Local value of SQN as available in the HE

**SQNMS:** Local value of SQN as available at the MS XMAC-A Expected value of **MAC-A**

**XMAC-S:** Expected value of **MAC-S**

**XRES:** Expected Response to Challenge

**Additional terminology**

**5G HE AV:** 5G Home Environment AV, an AV consisting of **RAND**, **AUTN**, XRES\*

**ALGONAME:** An ASCII character string encoding of a name assigned for a particular instance/application of the MILENAGE-256 algorithm set instance

**𝑐0, 𝑐1, 𝑐2, 𝑐3, 𝑐4, 𝑐5, 𝑐6, 𝑐7:** 128-bit operator-customisable constants, used during the computation of **f1, f1\*, f2, f3, f4, f5, f5\***, and **f5\*\***

**𝐼𝑁0, 𝐼𝑁1, 𝐼𝑁2, 𝐼𝑁3, 𝐼𝑁4, 𝐼𝑁5, 𝐼𝑁6, 𝐼𝑁7:** 256-bit instance-specific input values constructed within the computation of the functions **f1, f1\*, f2, f3, f4, f5, f5\***, and **f5\*\***

**KSZ:** The length of the subscriber key **K**, in octets

**KAUSF:** 5G-specific key, resulting from post-processing of **CK** and **IK**

**OP :** A 256-bit Operator Variant Algorithm Configuration Field that is a component of the functions **f1, f1\*, f2, f3, f4, f5, f5\*** and **f5\*\***

**𝑂𝑃C:** A 256-bit value derived from OP, ALGONAME, KSZ and **K**, and used within the computations of the functions **f1, f1\*, f2, f3, f4, f5, f5\*** and **f5\*\***

**RES\*:** 5G-specific, post-processed **RES** value

**V:** A 256-bit intermediate value constructed from ALGONAME and KSZ, and used in the computation of 𝑂𝑃)

**XRES\*:** 5G-specific, post-processed **XRES** value

NOTE: Bold variables in definition above are part of the general AKA specification [5]. Additional explanation of the usage of boldface, italics, etc within MILENAGE-256 appears in the MILENAGE-256 Algorithm Specification [2].

## 3.2 Symbols

For the purposes of the present document, the following symbols apply:

Symbol format (EW)

<symbol> <Explanation>

= The assignment operator

:= The definition operator

⊕ The bitwise exclusive-OR operation

∥ The concatenation of the two operands

NOTE: In the detailed specification of MILENAGE-256 provided in [2], concatenation operates differently, depending on the type of values concatenated. For the purpose of the high-level description of the present document, this difference is of no concern.

E K(*X*) Encryption of *X* under key K

PRFK Pseudo-random function defined by key K

Rijndael-b-n Rijndael block cipher with b-bit block and n-bit key

## 3.3 Abbreviations

For the purposes of the present document, the abbreviations given in 3GPP TR 21.905 [1] and the following apply. An abbreviation defined in the present document takes precedence over the definition of the same abbreviation, if any, in 3GPP TR 21.905 [1].

Abbreviation format (EW)

<ABBREVIATION> <Expansion>

3GPP 3rd Generation Partnership Project

AES Advanced Encryption Standard

AKA Authentication and Key Agreement ARPF Authentication Repository Function

ASCII American Standard Code for Information Interchange

AUTS Re-synchronisation Token

AV Authentication Vector

DPA Differential Power Analysis

EM Electromagnetic Emanations

eSIM Embedded SIM

ETSI SAGE ETSI Security Algorithms Group of Experts

HE Home Environment

MAC Message Authentication Code

MDPH Merkle-Damgård with Permutation and Hirose compression function

ME Mobile Equipment

MS Mobile Station

PRF Pseudo-Random Function

PRP Pseudo-Random Permutation

SPA Simple Power Analysis

TA Timing Attack

UDM Unified Data Management

UE User Equipment

UICC Universal Integrated Circuit Card

USIM Universal Subscriber Identity Module

NOTE: MS is a legacy term from 2G specifications which in later specifications is usually replaced by the term UE (or ME, if omitting the USIM-part). Nevertheless, the base specification of the AKA framework [5] still uses the term MS for certain AKA-specific purposes.

# 4 Structure of this specification

Editor's Note: this clause details the structure of the present document.

This specification is organised as follows:

* Clause 5 provides background information on the Authentication and Key Generation algorithms;
* Clause 6 provides background information on security and functional requirements on the algorithms and their use;
* Clause 7 describes how the SAGE Task Force designed the algorithms and produced the specification and associated test data;
* Clause 8 gives an overview of the evaluation work carried out by the SAGE Task Force and the conclusions of the evaluations.

# 5 Background to the 3GPP Authentication and Key Agreement Algorithm

Editor's Note: this clause provides background information from ETSI SAGE.

Within the mobile communication systems specified by 3GPP, there is a need to provide security features. These security features have gradually increased in sophistication and security level from the 3rd generation (3G) networks up to the current 5th (5G) generation [6], and are realised with the use of cryptographic functions and algorithms. One such set of algorithms is the authentication and key generation algorithms. These algorithms, called ***f1***, ***f1\****, ***f2***, ***f3***, ***f4***, ***f5***, ***f5\****, are not standardised, allowing each operator to freely construct proprietary algorithms. The context for these algorithms is described for 3G usage in 3GPP TS 33.102 [5] and remains valid in 5G. The generic requirements for these algorithms are specified in 3GPP TS 33.105 [6], which, apart from a desire to increase security level and flexibility (see below) also largely remain valid.

For 5G, an optional-to-use alternative to ***f5\****, denoted ***f5\*\**** is also defined in order to thwart some recently discovered attacks on privacy. Further, in order for the algorithm to be both future proof and backward compatible, ETSI SAGE decided to design the new algorithm set to accept inputs of varying size, as well as being able to produce outputs of variable size.

These algorithms can in principle be chosen by each operator without causing interoperability problems as long as the input/output parameters agree with the formats defined in the 3GPP specifications. However, to enable secure instantiation of the algorithm set, one or more concrete example algorithm sets is highly beneficial and to simultaneously meet operator customisation requirements, such algorithm sets should be configurable by parameters that create operator-specific instances, without risk of affecting security negatively.

Two such algorithm sets have been defined in the past: MILENAGE and TUAK [10, 11]. For future-proof usage (e.g. resistance to quantum computing), it becomes necessary to support keys larger than 128 bits. This support already exists for TUAK but not for MILENAGE. These two algorithm sets also differ in terms of using different kernels (a hash function and a block cipher, respectively) and retaining this diversity at the 256-bit security level was judged to be desirable. For this reason, ETSI SAGE decided to define an upgraded version of MILENAGE with a 256-bit target security level, denoted MILENAGE-256.

With MILENAGE being based on AES [9], a natural choice for kernel of MILENAGE-256 is just to "scale up" by instead using the Rijndael block cipher with 256-bit key and block size [8, 14]. This is because Rijndael-256-256 is structurally very similar to AES-256 and Rijndael-128-256 is exactly identical to AES-256. Kernel is however provably secure under certain assumptions on the underlying block-cipher, with quantitatively similar security bounds.

# 6 Outline of algorithm requirements specifications

Editor's Note: this clause provides requirement from ETSI SAGE.

The basic requirements for the authentication and key generation functions were specified in 3GPP TS 33.105 [6].

Additionally, a recently discovered subscriber-tracing attack [13] led SA3 to study countermeasures to this attack in 3GPP TR 33.846 [12]. Concretely, this has been done by defining an optional-to-use function ***f5\*\****.

## 6.1 The Authentication and Key Generation Functions

The mechanism for authentication and key agreement [5] requires the following cryptographic functions:

***f0*** the random challenge generating function;

***f1*** the network authentication function;

***f1\**** the re-synchronisation message authentication function;

***f2*** the user authentication function;

***f3*** the cipher key derivation function;

***f4*** the integrity key derivation function;

***f5*** the anonymity key derivation function;

***f5\**** the anonymity key derivation function for the re-synchronisation message.

Additionally, the present document defines:

***f5\*\**** an alternative to f5\* which provides additional protection against subscriber tracing.

An example for the random challenge generation function, ***f0***, is not proposed by the Task Force, consistent with the expectations of 3GPP SA3.

For each of the algorithms ***f1*** to ***f5\**** (and ***f5\*\****), it is required that it should be computationally infeasible to derive the subscriber key **K** using knowledge of the input(s) and output (other than **K** itself). Further requirements assumed to hold for the current 128-bit MILENAGE algorithm set, e.g. that outputs are computationally unpredictable and indistinguishable from random bits, also need to be met by MILENAGE-256.

For the specific case when the ***f***-functions are provided by MILENAGE-256, the structure follows the framework of figure 7.2-1.

The following clauses describe the usage of the algorithms on the network side and the terminal side. Under normal operation, the process is initiated on the network side as described in clause 6.2, followed by corresponding processing in the terminal in clause 6.3. If a re-synchronisation procedure is required (as determined by clause 6.3), the processing of clause 6.4 next takes place, followed by the processing of clause 6.5.

## 6.2 Use of the algorithm on the UDM/ARPF side

When generating a 5G HE AV comprising (**RAND**, **AUTN**, *XRES\****,** *KAUSF*), the function ***f0*** is first used to generate **RAND**, the details of which are outside the scope of the present document. Dependency on OPc and **K** is for simplicity omitted in the following.

1. The function ***f1*** is used to generate **MAC-A** from **RAND**, and the current **SQNHE** and **AMF**, as available at the UDM/ARPF.
2. The function ***f5*** is used to generate **AK** from **RAND**.
3. The **AUTN** is formed from **AMF**, **SQN**, **AK** and **MAC-A** [5, 7], namely as **AUTN** = (**SQNHE**  **AK)|| AMF || MAC-A**.
4. The function ***f2*** is used to generate **XRES** from **RAND**.
5. The functions ***f3*** and ***f4*** are used to generate **CK** and **IK**, respectively, from **RAND**.
6. *XRES\** is generated from **XRES**, **CK** and **IK**, as described in Annex A of 3GPP TS 33.501 [7].
7. *K****AUSF*** is generated from (**SQNHE**  **AK)**, **CK** and **IK**, as described in Annex A of 3GPP TS 33.501 [7].

NOTE 1: The ordering of some of the above steps can be changed without affecting the results.

NOTE 2: For the sake of clarity, it is pointed out that the normative document 3GPP TS 33.102 [5] uses the term Conc(**SQNHE**) when referring to performing the operation (**SQNHE** ⊕ **AK\***) where Conc() denotes "concealment".

NOTE 3: The AKA parameters computed in steps 6 and 7 also undergo further 5G-specific post-processing [7].

## 6.3 Use of the algorithm on the USIM and ME

Dependency on OPc and **K** is for simplicity omitted in the following. Upon receipt of **RAND** and **AUTN** = (**SQNHE** ⊕ **AK**) || **AMF** || **MAC-A**, the USIM (or eSIM) performs the following:

1. The function ***f5*** is used to generate **AK** from **RAND**.

2. **AK** is used to extract the **SQNHE**-value from **AUTN**.

3. The **SQNHE** is compared with the local **SQNMS**, and if a mismatch is detected, the resynchronisation procedure of clause 5.4 takes place [5, 7].

4. **AMF** is extracted from **AUTN** and the function ***f1*** is used to generate a local **XMAC-A** value from **RAND**, **SQNHE** and **AMF**.

5. The locally generated **XMAC-A** is compared with the **MAC-A** value available as part of **AUTN**, and if a mismatch occurs, an authentication failure procedure takes place [5, 7].

6. The USIM applies ***f2***, ***f3***, and ***f4*** to **RAND** in order to generate **RES**, **CK** and **IK**, respectively, in analogy to steps 4 and 5 of Clause 5.2. The USIM makes these values available to the ME.

7. The ME applies processing analogous to steps 6 and 7 of Clause 5.2 in order to generate *RES\** and *KAUSF* from **CK**, **IK**, and the (**SQNHE** ⊕ **AK**) part of **AUTN**.

NOTE 1: The present document does not make assumptions on the form factor of the physical device implementing the USIM functionality, e.g. whether it is a UICC or eSIM.

NOTE 2: The AKA parameters computed in steps 6 and 7 also undergo further 5G- specific post-processing [7].

## 6.4 Use of the algorithm for resynchronization in the USIM

The resynchronisation token **AUTS**, carrying the protected value of **SQNMS,** is generated as follows (dependency on OPc and **K** is omitted for simplicity).

1. The function ***f1\**** is used to generate **MAC-S** from **RAND**, the current **SQNMS** and an all-zero **AMF**.

2. The function ***f5\**** is used to generate **AK\*** from **RAND**.

3. The re-synch token **AUTS** is formed from **SQNMS**, **AK\*** and **MAC-S** [5, 7], namely as **AUTS** = (**SQNMS** ⊕ **AK\*) || MAC-S.**

NOTE: In MILENAGE-256 the output of ***f5\**** is denoted as **AK\*** and the label **AK** is reserved for the output of ***f5***. Any reference to the output of ***f5\**** in the relevant 3GPP technical specifications [5, 7] is therefore to be interpreted as **AK\*** within the context of MILENAGE-256 [2].

If the optional resynchronisation protection mechanism provided by ***f5\*\**** is used, then step 2 above shall be replaced by computing an **AK\*** value by applying ***f5\*\**** to **RAND** and **MAC-S**.

## 6.5 Use of the algorithm for resynchronization in the UDM/ARPF

The resynchronisation token **AUTS** is used in the UDM/ARPF as follows (dependency on OPc and **K** is again omitted for simplicity).

1. The function ***f5\**** is used to generate **AK\*** from **RAND**.

2. The quantity (**SQNMS** ⊕ **AK\*)** is extracted from **AUTS** and XORed with **AK\***, giving (**SQNMS** ⊕ **AK\*)** ⊕ **AK\*** = **SQNMS**.

3. The function ***f1\**** is used to generate **XMAC-S** from **RAND**, the extracted **SQNMS** and an all-zero **AMF**.

4. **MAC-S** is extracted form **AUTS** and compared with the expected value **XMAC-S**.

NOTE: In MILENAGE-256 the output of ***f5\**** is denoted as **AK\*** and the label **AK** is reserved for the output of ***f5***. Any reference to the output of ***f5\**** in the relevant 3GPP technical specifications [5, 7] is therefore to be interpreted as **AK\*** within the context of MILENAGE-256 [2].

If the optional resynchronisation protection mechanism provided by ***f5\*\**** is used, then step 1 above shall be replaced by computing an **AK\*** value by applying ***f5\*\**** to **RAND** and the **MAC-S** available as part of **AUTS**.

## 6.6 Implementation aspects

All the ***f***-functions have been designed so that they can be implemented on typical current IC cards and produce all output parameters in less than 500msec execution time.

## 6.7 Generic requirements on the authentication and key generation functions

Clause 4 in 3GPP TS 33.105 [6] provides generic requirements for all 3GPP cryptographic functions and algorithms. No corresponding document exists for the 5G setting, but parts assumed relevant for 5G are summarised below (in italics). Additional requirements and clarifications which were deemed necessary for the MILENAGE-256 context are also stated (in normal typeface).

***Resilience***

*The functions should be designed with a view to their continued use for a period of at least 20 years. This includes resistance against possible advances in quantum computing. Successful attacks with a workload significantly less than exhaustive key search through the effective key space should be impossible. Attacks distinguishing outputs from random bit-strings of the same length should require effort meeting expectations for the target 256-bit security level.*

*The designers of above functions should design algorithms to a strength that reflects the above qualitative requirements.*

***World-wide availability and use***

*Legal restrictions on the use or export of equipment containing cryptographic functions may prevent the use of such equipment in certain countries.*

*It is the intention of the MILENAGE-256 design that UE and USIMs which embody these algorithms are unencumbered by restrictions on export or use, in order to allow the free circulation of 5G terminals. Network equipment, including UDM/ARPF, could be expected to come under more stringent restrictions.*

NOTE: Under current international agreements, UE and USIMs are considered as mass market products and are therefore, in most cases, exempt from export control, provided the cryptography is based on published standards and is not easily modifiable by the user. While the mass market exception might not apply to network equipment, export is still usually uncomplicated as long as the cryptographic design abides by the same principles.

## 6.8 Subsequent requirements on the authentication and key generation functions

SAGE design for MILENAGE-256, denoted MILENAGE-256-R, employs Rijndael-256-256 [8, 14] as the kernel.

Part of the motivation for increasing the key length in MILENAGE-256 is to resist potential attacks involving quantum computers. Accordingly, the SAGE AF TF assumed that, in addition to brute force key searches by a quantum computer, other attacks, judged feasible in the quantum computing model, were also to be considered. This matter is discussed in more detail in Document 4 [4].

# 7 Algorithm design

Editor's Note: this clause provides essential design criteria defined by ETSI SAGE

Based on the requirements and fixed starting points ETSI SAGE established the following essential design criteria.

## 7.1 Design and evalution criteria

1. Without knowledge of secret keys, the functions ***f1, f1\*, f2, f3, f4, f5, f5\**** and ***f5\*\**** should be practically indistinguishable from independent random functions of their inputs **RAND**, **SQN**, and **AMF**.

2. It should be practically impossible to determine any part of the secret key **K**, or the operator variant algorithm configuration field, *OP*, by manipulation of the inputs and examination of the outputs to the algorithm.

3. Events tending to violate criteria 1 and 2 should be regarded as insignificant if they occur with probability approximately 2-256 (or require approximately 2256 operations) or less.

4. Events tending to violate criteria 1 and 2 should be examined if they occur with probability approximately 2-128 (or require approximately 2128 operations) to ensure they do not have serious consequences. Serious consequences would include recovery of a secret key or ability to emulate the algorithm on a large number of future inputs.

5. The design should build upon well-known structures and avoid unnecessary complexity. This will simplify analysis and avoid the need for a formal external evaluation.

6. The security analysis should, if possible, be further supported by a formal security proof covering the entire design or critical properties thereof.

7. Simple (hard-to-get-wrong) guidelines for how to securely perform operator customisation of the algorithms should be possible to state.

8. The algorithm set should be able to accept input parameters of different sizes and also produce output parameters of different sizes, and this flexibility should not introduce weaknesses, beyond those inherent to the selected parameter sizes.

Regarding (8), ETSI SAGE has assumed (and also recommends) that, as a general principle, a specific implementation of MILENAGE-256 only supports a given set of parameter sizes among the possible choices. Exceptions from this principle could be motivated for certain parameters, e.g. the size of the subscriber key **K** and/or the size of **RAND** as part of a migration strategy towards increased security levels.

EXAMPLE: An implementation could initially be deployed with 128-bit **K** and then later upgraded to 256-bit **K**.

NOTE: **RAND** is currently limited to 128 bits. To reach an overall 256-bit level of security in all regards, this maximum value needs to be increased to 256 bits.

## 7.2 Chosen design for the framework

The following diagram shows the MILENAGE-256 framework for the functions ***f1, f1\*, f2, f3, f4, f5, f5\**** and ***f5\*\**** using the kernel function denoted PRFK.



Figure 7.2-1: MILENAGE-256 framework. Use of the functions f5\* and f5\*\* are mutually exclusive, i.e. precisely one of them is configured for use within an AKA protocol.

The value OPc is derived from the subscriber key **K** and the operator dependent value *OP* by

OPc ∶= 𝑂𝑃 ⊕ 𝑃𝑅𝐹(𝑃𝑅𝐹(OP ⊕ 𝑉(𝐾SZ,, 𝐴𝐿𝐺𝑂𝑁𝐴𝑀𝐸))

Here, the function *V* formats the size of the subscriber key *KSZ* and an encoding of the algorithm name into a 256-bit input to the PRF [2].

It is recommended [10] that OPc is calculated outside the USIM cards and then stored in each card as an individual value. This provides better protection for *OP*, relative to the alternative choice of storing *OP* in every card.

Each of the values IN0, IN1, … , IN7 appearing in Figure 7.2-1 comprises

a) an encoding of the function instance (i.e. which of the eight functions ***f1*** to ***f5\*\**** is being computed),

b) encodings of the parameter sizes for any variable-size parameter that appears as input or output for the respective ***f***-function,

c) for certain ***f***-functions, additional input parameter(s), and

d) operator selectable customisation constants c0 , . . , c7 whose purpose is similar to those employed in MILENAGE [10].

EXAMPLE: Regarding (c) above, the function ***f1***, as an example, takes **SQN** and **AMF** as additional inputs.

The encodings of IN0, IN1, … , IN7, as well as the inclusion of *V*() in the *OP*-derivation, serve to satisfy a cryptographic instance separation requirement: it would be highly unlikely that algorithm instances used in different contexts, or instances using/producing parameters of different sizes, result in the same (or otherwise correlated) outputs.

NOTE: Though not explicitly shown, the input to ***f5\*\**** depends, via the value IN7, on the output value of ***f1\****. This serves to protect against resynchronisation attacks [13].

## 7.3 Analysis of the role of OP and OPC

The 256-bit value *OP* is the Operator Variant Algorithm Configuration Field, which the Task Force was asked to include, to enable different operators to personalise the functionality of the algorithms. Each operator may freely select a value for *OP*.

The algorithm set is designed to be secure whether or not *OP* is publicly known; however, operators could benefit from keeping their value of *OP* secret, as an unknown *OP* value provides an additional hurdle for attackers.

It should be difficult for anyone who has discovered even a large number of (*OPc*, **K**) pairs to deduce *OP*. Consequently the *OPc* associated with any other value of **K** will be unknown, potentially making it (slightly) harder to mount some kinds of cryptanalytic and forgery attacks.

An operator is more likely to successfully keep *OP* secret if the value is not stored on the USIM; otherwise it would only require a single USIM to be reverse engineered for *OP* to be discovered and published. Hence the task force recommends that OPc is calculated off the USIM.

## 7.4 Choice of kernel / PRF

The MILENAGE-256 algorithms employ a kernel, denoted as PRFK. The algorithm set was designed to permit plug-in replacements for this kernel. This replaceability allows operators to freely employ variant kernels, without adversely impacting the security of the algorithm set, provided the replacement kernel is a suitable keyed function employing a 256-bit key. Candidate replacement kernels should satisfy certain general requirements [2].

The *qualitative security requirements* on PRFK require that it is infeasible (or strongly believed to be infeasible) to distinguish the outputs of PRFK from the outputs of a randomly chosen function. The *quantitative security requirements* on PRFK require that the probability of distinguishing the output remains "small", even after observing on the order of  2128 (input, output) pairs for chosen input-values. This latter constraint is the strongest requirement that can be satisfied if the kernel function is a 1-1 (permutation) mapping, such as a block cipher, in which case the PRF is actually a *pseudo-random permutation* (PRP). If the kernel function is not a permutation, stronger quantitative bounds are sometimes possible, allowing observation of a (much) larger number of (input, output) pairs.

MILENAGE-256-R employs kernel provided by ETSI SAGE, namely the block cipher Rijndael-256-256, which has 256-bit inputs/outputs and uses a 256-bit key [8, 14]. Rijndael-256-256 was chosen owing to the extensive body of cryptanalysis and research already undertaken on the Rijndael family of block ciphers. Moreover, Rijndael block ciphers can be efficiently implemented in software or hardware and are generally held as being available IPR-free. The Rijndael-128-{128,192,256} algorithms were also selected as the AES [7] and have been well studied in this context. MILENAGE-256-R implements each PRFK instance as shown in Figure 7.2-1 by a straight-forward, single call of Rijndael-256-256.

## 7.5 Design methodology

The design process is summarised below.

The design of MILENAGE-256-R was conducted quite quickly and problem-free since it could be based on a drop-in replacement, using Rijndael-256-256 instead of AES. In this phase it was also decided to simplify the operator customisation options, removing the input rotations and streamline the handling of the input offsets (the customisation constants c0 , . . , c7).

A review on the security status of the Rijndael was made without any discouraging findings.

Test vectors were also produced as the design choices were made and the design could be finalised.

## 7.6 Specification of the Test Data

The algorithm specification and associated test data are documented in the MILENAGE-256 specification [3], where example program listings of the algorithm set in the C/C++ programming language also appear.

The Implementors’ Test Data and Design Conformance Data document [3] provides design conformance test data to help verify implementations of the algorithms. This document identifies intermediate points in the algorithms and provides input, internal and output parameters at these points, for use as test data. Different sets of test data listings are also provided.

# 8 Algorithm evaluation

Editor's Note: this clause provides several evaluations from ETSI SAGE.

## 8.1 Evaluation criteria

The algorithm requirements as summarised in Clause 6 and design criteria as listed in Clause 7.1 lead to evaluation criteria for the mathematical evaluation and statistical evaluations. Due to the fact that the Rijndael block cipher has undergone an extensive analysis, the Task Force performed no real cryptanalysis of Rijndael, but rather focused on the strength of the constructions for deriving the ***f1*** to ***f5\*\**** modes from a strong block cipher. However, as mentioned, a survey of known attacks against AES/Rijndael was performed, including a verification of the cryptologic status of the 256-bit block version of Rijndael [8, 14].

## 8.2 Mathematical evaluation of the modes

The mathematical evaluation focused on verifying the strength of the ***f1***-***f5, f1\*, f5\*,*** and ***f5\*\**** constructions provided by MILENAGE-256-A and MILENAGE-256-R, under the assumption that the underlying kernel is a strong block cipher. To be precise, more than one notion of "strong" is needed, see [4] for details.

The main criteria investigated were [4]:

* The strength of each algorithm, considered individually (resilience of key and subsequent outputs).
* The independence between algorithms (one algorithm's strength is not harmed by knowledge of input/outputs for other algorithms).

For MILENAGE-256-R, the "headroom" for possible insecurity depends *only* on how far from ideal Rijndael-256-256 is, when considered as a PRP. Roughly speaking, the security (in terms of indistinguishability from a random function) for MILENAGE-256-R is provable up to about  2128 queries by an attacker,

As noted, attacks involving possible future, cryptographically relevant quantum computers are briefly investigated in Document 4 of the specification [4].

## 8.3 Statistical evaluation

Statistical tests on MILENAGE-256 were considered to only yield results about the underlying kernel function. No statistical tests were performed on the kernel either, given that AES and Rijndael can be considered to be sufficiently tested and secure through the AES process and later analysis.

## 8.4 Side channel attacks evaluation

The design process concluded that it was not feasible to design a general algorithm framework that, by itself, would not be vulnerable to side channel attacks. AES/Rijndael, as with most other block ciphers, is potentially vulnerable to simple and differential power analysis (SPA and DPA) aiming to recover the secret key. It was also concluded that the use of operator constants, OPc, in the USIM cards can only play a limited role in protecting against these kinds of attacks. In general, any implementation without dedicated protection against power or electromagnetic emanations (EM)-based side-channel attacks could be vulnerable to such attacks. Deployment scenarios in which an attacker is assumed to have the power to mount such attacks require protected implementations, e.g. by masking. Also timing attacks (TA) could require implementation specific countermeasures. Rijndael, as the AES, has been shown to readily lend itself to protection measures against side channel attacks.

## 8.5 Complexity evaluation

Implementations of Rijndael with 256-bit block- and key size could be two times slower than AES with 128-bit block size and the same key size.

Optimised implementations could also save computational costs. For example, the need to compute ***f1\**** and ***f5\**** implies that computation of ***f2***, ***f3***, and ***f4*** is not needed, etc.

## 8.6 Evaluation report

The evaluation report [4] summarises all results of the complete design and evaluation process, and provides the main conclusions of the evaluation work carried out by the Task Force.

Annex A (informative):
Change history

|  |
| --- |
| **Change history** |
| **Date** | **Meeting** | **TDoc** | **CR** | **Rev** | **Cat** | **Subject/Comment** | **New version** |
| 2024-02 | SA3#115 | S3-240403 |  |  |  | TS skeleton | 0.0.0 |
| 2024-02 | SA3#115 | S3-240817 |  |  |  | TS skeleton using 3GPP template | 0.0.1 |
| 2024-02 | SA3#115 | S3-240407 |  |  |  | Addition of Introduction  | 0.1.0 |
| 2024-08 | SA3#117 | S3-243422 |  |  |  | Addition of the text based on the selection of Milenage-256-R to specify Milenage-256 algorithm. | 0.2.0 |