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| Technical Report | |
| 3rd Generation Partnership Project;  Technical Specification Group Services and System Aspects  Study on 5G Security Enhancement against  False Base Stations  (Release 16 ) | |
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| ***3GPP***  Postal address  3GPP support office address  650 Route des Lucioles - Sophia Antipolis  Valbonne - FRANCE  Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16  Internet  http://www.3gpp.org |
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# Foreword

This Technical Report 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.

# Introduction

Editor’s Note: This clause contains some background information for the study.

The present document uses the term "false base station" in general to denote wireless devices that impersonate genuine base stations.

False base stations are also popularly known as IMSI catchers. While one of their initial attacks was to catch subscribers' IMSIs, more advancements have happened since - not only to the false base stations technologies, but also to the mobile network security.

Today, the capabilities of false base stations vary depending upon whether the mobile network is GPRS, UMTS, LTE, or 5G. The 5G system in particular has already made significant improvements to combat false base stations, the improvements like SUPI concealment, guaranteed GUTI refreshment, protected redirections, and a general informative detection framework. There are also other security features that the 5G security inherited from earlier generations like mutual authentication between UE and network, integrity protected signalling, and secure algorithm negotiations.

Some of the security solutions, constraints, and requirements studied in 3GPP TR 33.969 "Study on Security aspects of Public Warning System (PWS)"[3] may also be useful when considering security enhancement against false base stations specifically, the protection of the System Information (SI) broadcasts used for the PWS warning messages.

# 1 Scope

Study the potential threats and privacy issues associated with false base station scenarios.

Identify the potential solutions for mitigating the risks caused by false base station.

# 2 References

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 38.331: "NR; Radio Resource Control (RRC); Protocol specification".

[3] 3GPP TR 33.969: "Study on security aspects of Public Warning System (PWS)".

[4] Void

[5] Altaf Shaik, Ravishankar Borgaonkar, Shinjo Park, and Jean-Pierre Seifert. 2018. On the Impact of Rogue Base Stations in 4G/LTE Self Organizing Networks. In Proceedings of the 11th ACM Conference on Security & Privacy in Wireless and Mobile Networks (WiSec '18). ACM, New York, NY, USA, 75-86. DOI: <https://doi.org/10.1145/3212480.3212497>

[6] 3GPP TR 28.861: "Telecommunication management; Study on the Self-Organizing Networks (SON) for 5G networks"

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

[8] IEEE1363.3-2013 - IEEE Standard for Identity-Based Cryptographic Techniques using Pairings

[9] RFC6507 Elliptic Curve-Based Certificateless Signatures for Identity-Based Encryption (ECCSI)

[10] SM9, Identity-based cryptographic algorithms SM9

[11] ISO 29192-4, SC27 Lightweight crypto useing I2R-IBS

[12] [Dan Boneh](https://en.wikipedia.org/wiki/Dan_Boneh); [Ben Lynn](https://en.wikipedia.org/w/index.php?title=Ben_Lynn&action=edit&redlink=1) & [Hovav Shacham](https://en.wikipedia.org/w/index.php?title=Hovav_Shacham&action=edit&redlink=1) (2004). "Short Signatures from the Weil Pairing". Journal of Cryptology. 17 (4): 297–319.

[13] 3GPP TS 23.502: “Procedures for the 5G System (Release 15)”.

[14] 3GPP TR 33.861 v1.0.0: “Study on evolution of Cellular IoT security for the 5G System (Release 16)”

[15] 3GPP TS 36.331: " E-UTRA; Radio Resource Control (RRC); Protocol specification".

[16] 3GPP TS 38.300: “NR; NR and NG-RAN Overall Description”

# 3 Definitions of terms, symbols and abbreviations

## 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].

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

## 3.2 Symbols

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

<symbol> <Explanation>

## 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> <Expansion>

# 4 Security overview of 5G system against false base stations

Editor’s Note: This clause contains a high-level overview of the 5GFBS features, the security aspects and the potential impacts on the current Rel-15 security mechanisms.

The present document investigates key-issues and solutions that will potentially enhance 5G system's resistance to false base stations even further. The 5GC and NR/gNB are in the scope of the present document, and E-UTRA/ng-eNB is out of the scope.

The key-issues and solutions in the present document should state which of the following security and privacy areas they address:

#1 DoS attack on UE: attempts to hinder the UEs' access to the network.

#2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

#3 Rogue services: attempts to deliver unathorized or unsolicited services (e.g., SMS and calls) to the UEs.

#4 Subscriber privacy attack: attempts to identify subscriptions or trace the UEs.

Editor's Note: The above security and privacy areas list is preliminary, therefore non-exhaustive and subject to change.

# 5 Key Issues

Editor’s Note: This clause contains all the key issues identified during the study.

## 5.1 Key Issue #1: Security of unprotected unicast messages

### 5.1.1 Key issue details

This key issue covers both the uplink and downlink unicast message which could be sent unprotected. An example of unprotected uplink message is RRC UECapabilityInformation, and examples of unprotected downlink messages are RRC UECapabilityEnquiry, and REJECTs in RRC/NAS layers.

In current 3GPP standards, it has been a design choice to allow RRC UECapabilityEnquiry and RRC UECapabilityInformations messages to be sent unprotected "before" AS security activation. The reason for allowing that is to enable the network to do early optimization for better service/connectivity. It means that during the RRC connection, the gNB in theory could send UECapabilityEnquiry to ask for UE’s AS capability, and UE would then send UECapabilityInformation to gNB before AS SMC procedure. The false base station could behave as a man-in-the-middle and catch the UECapabilityInformation over-the-air. After that, the false base station could modify the value in this message to lower capability level and forward it to the real gNB, causing the UE to only operate with limited radio capability. It should be appreciated that security capabilities are protected from bidding down attack. And it is not certain if the bidding down of radio capabilities cause serious threat. However, it is only prudent to investigate if and how any protection mechanisms are to be introduced.

Another message to be considered are REJECT messages (in RRC and NAS layer) that the network can send to UEs without security protection. Even when the UE is in the RRC\_INACTIVE state, while the gNB and the UE continue to maintain the UE 5G AS security context, the RRC REJECT message is sent to the UEs without security protection.Depending upon the type and content of REJECT messages, UEs could potentially be out of service for some time. The REJECT messages serve a very important function in cellular network, i.e., to maintain the availability of the system to the already connected UEs. It has been a design choice, based on risk analysis, to achieve availability that the REJECT messages are not protected. Nevertheless, the design has included some security features that combat rogue REJECTs from unauthorized entries like false base stations. An example of such a security feature is - carefully selected wait timers which gives an opportunity to UEs to recover and avoid lock-outs. It is also important to notice that it is extremely impractical for an attacker to have massive-scale effect using rogue REJECTs. Normally, the effect is to a target UE or few UEs in a cell.In addition, as stated in key issue #10 of TR 33.861 [14], an attacker may forge a NAS REJECT message to the CIoT UE to force the UE redirect from 5GC to EPC network, which may lead unavailable of 5G security enhancement feature, e.g. SUPI protection, initial NAS protection, etc. The UE privacy may be exposed.

Another message to be considered RRCResumeRequest message. Currently, resumecause field in the RRCResumeRequest message is not protected by the ResumeMAC-I token. This means that the integrity of the resumecause field in the RRCResumeRequest message is not provided nor integrity protected. Therefore, A MiTM attack by a false base station is possible by modify the resumecause from one value to another. This attack could reduce the type of service offered by the network to the UE. In addition, since in 5G, “ran update” was added as another value of the resumecause field, if an attacker modify the resumecause field value from “emergency” to “ran update”, the network will not be able to detect the tampering and not only that but the network will immediately send the UE back to INACTIVE while the UE is waiting to establish an emergency call, for example.

In addition, in the case when the UE initiates RRC Resume procedure, the UE sends RRCResumeRequest which include ResumeMAC-I that is based on the old Krrcint and it include the I-RNTI amongst other parametrs. If the new gNB is busy, it usually sends RRCReject with a waittimer. When the UE receives the RRCReject message, it goes back to INACTIVE and retry one more time after the waittimer expires. When the UE retries, it is supposed to use the same I-RNTI and the same old Krrcint key. This means that the second RRCResumeRequest message is exactly the same as the original one before the RRCReject.

Thus, a MiTM false base station that is able to capture the first RRCResumeRequest message can possibly send the message to the new gNB before the UE waittimer expires and the old gNB will successfully validate the ResumeMAC-I as a valid one and will transfer the UE context to the new gNB. If the UE tries the resume procedure once again, the new target gNB will fail to allocate the UE context and thus the resume procedure will fail.

Therefore, it is important that the 5G system support a mechnaims that avoid the replay of RRCResumeRequest message after the UE receives an RRCReject.

It still is prudent to investigate further potential enhancements to the security features.

Therefore, this key issue is about investigating if and how further security features could be augmented in the system so that the risk caused by the unicast messages could be even further minimized.

### 5.1.2 Security Threats

Lack of security for unprotected unicast messages could potentially have following impacts in some cases:

- DoS attack on UE

- Limited network service.

Lack of security for NAS REJECT message, the UE may suffer bidding down attack.

### 5.1.3 Potential Requirements

The 5G system shall have support for protection against tampering of RRC UECapabilityInformation messages.

The 5G system should provide a means to ensure that a UE is able to determine the authenticity of the RRC Reject message from the gNB, regardless of RRC states.

The 5G system should provide a means to ensure that a UE is able to determine the authenticity of the NAS Reject message from the AMF.

Editor’s Note: which NAS reject message is FFS.

The 5G system shall have support for protection against replay of RRCResumeRequest message to avoid creating an out of synch state between the UE and the network.

The 5G system shall have support for protection against tampering of RRCResumeRequest message.

Editor’s Note: Requirements on other messages are FFS.

NOTE: Since "unicast message" is a broad term, requirements in this clause have to specify which layer (RRC or NAS) and which particular messages are meant. It is so because threat and complexity of solution are more than likely to be very different for different messages.

## 5.2 Key Issue #2: Security protection of system information

### 5.2.1 Key issue details

Broadcasting system information (SI) is one of the functions of the RRC protocol, defined in 3GPP TS 38.331 [2]. A cell periodically broadcasts synchronization signals and SI. These broadcasted messages are intended for all UEs which are camping on a cell. In the idle mode or inactive mode, the UE monitors the SI of cells and choose a suitable cell to camp on. The UE typically acquires the SI from the cell and performs initial access to transition to connected state to obtain services. The system information includes information, among others, like cell (re-)selection parameters, neighboring cell information, frequency priority, blacklisted cell, common channel configuration information, NAS common information, and public warning system (PWS) messages. In general, the system information is applicable for UEs in RRC\_IDLE, RRC\_INACTIVE, and RRC\_CONNECTED.

A Rel-15 NR UE in IDLE mode performs PLMN selection, monitor paging, performs cell selection, cell re-selection, and applies access control before making an access attempt. In future releases, other services such as MBMS, proximity services, etc. are also likely to be supported by UEs in IDLE mode.

This key issue is about investigating if and how a new protection mechanism could be introduced against over-the-air attackers who broadcast rogue SI messages or replay previously captured SI messages as-is (without modification). Since SI messages are broadcast messages meant for all UEs, it is not apparent that an integrity and replay protection is strictly necessary. Nevertheless, in general, an integrity and replay protected SIs could add security value by at least making it difficult for over-the-air attackers to succeed in using a rogue SI or a previously captures SI at a later time, e.g., to lure UEs using SI messages with incorrect neighboring cells, and to send self-crafted or old PWS messages.

It is very important that earlier studies done by the 3GPP TSG SA WG3 are taken into account in this key issue, the studies being the 3GPP TR 33.969 [3], and the study done during the start of 5G security standardization. For example, there are some distinct challenges that are known from earlier studies as below:

a) Key management. It is because of heterogenous trust-boundaries, and diverse regulations (or requirements) per countries (or regions);

b) Time synchronization. It is because of difficulty to achieve fairly acceptable time synchronization between one gNB and other gNBs, and between UEs and gNBs;

c) Signaling complexity. It is because of restrictive signaling expected from UEs in RRC\_IDLE.

Nevertheless, it is only prudent if the 5G system could be enabled (i.e., support) to achieve protection of SI messages in general.

NOTE 1: This key issue is concerned with the "over-the-air" interface. Therefore, integrity protection of SI "within-the-network" is not in the scope of this key issue.

### 5.2.2 Security Threats

Lack of protection of SI could potentially have following impacts in some cases:

- DoS attack on UE

- Rogue services

### 5.2.3 Potential Requirements

5G system should provide a means to ensure a UE in any RRC state is able to determine the authenticity of system information obtained from a cell.

## 5.3 Key Issue #3: Network detection of false base stations

### 5.3.1 Key issue details

The 3GPP measurements procedures (see 2) are primarily designed to enable handovers and SON (Self-Organizing Networks) features. However, the same procedures also serve security purpose in being useful to detect false base stations. Such a framework for false base station detection is currently described in the informative Annex E of the 3GPP TS 33.501.

The measurement reports sent by UEs to the network already contain various information of the surrounding radio conditions. And, those measurement reports could be further enriched so that the detection of false base stations becomes more effective. Further, different types of measurement reports could be taken into use, e.g., logged measurement reports.

The present key issue is for investigating potential enhancements to the detection framework and enrichments to the measurement reports to further strengthen the false base station detection.

Method of detecting false base stations is critical to further processing of the information to ascertain that a particular base station is false and doesn’t belong to the genuine operator network. Once a determination is reached that a particular base station is false, the genuine network can take actions to isolate such false base stations. The genuine network can help UEs with information to avoid connecting to the false base stations.

If UEs are using information from genuine base stations belonging to an operator, such guidance information from genuine base stations belonging to the operator network can be trusted to avoid false base stations both in CONNECTED mode and IDLE mode.

### 5.3.2 Security Threats

Undetected false base station could result in unwanted consequences without being noticed, as follow, thus depriving the network of taking corrective measures:

* DoS attack on network,
* DoS attack on UE (i.e., UE may lose incoming calls, paging messages, etc., and may not get service it requests),
* Fraud,
* Subscriber privacy attack (i.e., UE may be lured to LTE or other technology and IMSI might be revealed).

### 5.3.3 Potential Requirements

5G system should be able to detect false base stations.

5G system should be able to employ methods to prevent UEs from connecting to false base stations.

## 5.4 Key Issue #4: Protection against SON poisoning attempts

### 5.4.1 Key issue details

3GPP TR 28.861 [6] is a study on SON (Self-Organizing Networks) for 5G networks. The SON features standardized by 3GPP fall under three general categories, namely:

- Self-configuration/reconfiguration,

- Self-optimization, and

- Self-healing.

On a very high-level, the SON features work by receiving and processing measurement reports from UEs. The part in the UE which handle measurement reporting (called as modem, or baseband, or mobile termination (MT)) is generally secure against software malwares and user space application. Therefore, measurement reports from UEs can be generally considered trusted, meaning that measurement reports are not compromised by an attacker.

However, the UE performs the signal power measurement of the neighbouring cells based on the Synchronization Signal (SS) Block which carries the synchronization signal and Master Information Block (MB) without security protection [5][2]. Therefore, the UE cannot validate the authenticity of the SS Block signal, i.e., the SS Block could have been created by a false base station. If a false base station C counterfeits a legitimate base station B and the serving base station A receives the UE measurement reports (MR) measured from C, then A would assume that the MR is from B.

Thus, an attacker could try to poison the measurement reports by either (a) using a self-built UE (e.g., using software defined radios (SDRs) to send maliciously crafted measurement reports, or (b) creating false radio environment around uncompromised UEs (e.g., using false base stations) so that those UEs send the measurement reports that the attacker wanted.

As another example attack scenario, a false base station can discover the cell ID(s) of the surrounding real gNB(s), and can use one of them to impersonate as a real gNB. As UEs are not able to validate the system information sent by gNBs, UEs cannot distinguish whether the gNB is genuine or not. As a result, UE may react to the information received from a false base station, such as sending Measurement Report message to the currently connected gNB containing the signal level information of the false base station.

It is important to realize that in both the above cases, the attacks (assuming that they are successful) are very localized and in small scale, and therefore not massive. It will be significantly expensive and impractical (if possible, at all) for an attacker to go massive using those techniques.

What is more important to realize is that such poisoning attempts would only succeed if the network blindly uses the measurement reports from UEs. Generally, it is not so because proper SON implementations take the possibility of falsified information in the measurement reports into account and therefore have good resilience features, meaning that the effects of such poisoning attempts may be completely futile or have very little impact.

However, poor SON implementations could result in unwanted consequences like potential signalling flood in the network and cell outages (see [5]).

Therefore, it is only prudent that security and privacy use cases in SON are investigated where standardized solutions could be specified, or security and privacy guidelines could be given to help the implementations become better.

### 5.4.2 Security Threats

Poor SON implementations that do not take the possibility of SON poisoning attempts (i.e., falsified information in the measurement reports) into account could result in unwanted consequences, as follow:

- DoS attack on network

- DoS attack on UE

### 5.4.3 Potential Requirements

The system shall support protection mechanism against potential SON poisoning attempts (i.e., falsified information in the measurement reports) so that the network (NG-RAN or 5GC) is protected against unintended updates of various configuration or criteria caused by false base station.

Editor's Note: Depending upon the result of investigation, it might be that the final choices and details are not in the sole merit of the 3GPP TSG SA WG3 group. Hence, the final output (solutions, conclusions) from this key issue could also be inputs (LSes) to other groups like 3GPP TSG SA WG5 and other standards like 3GPP TR 28.861 [6].

## 5.5 Key Issue #5: Mitigation against the authentication relay attack

### 5.5.1 Key issue details

A victim UE may be attracted to the false base station. Then the false base station collaborates with another malicious UE through a private channel. The false base station and the malicious UE are far apart, and the two may be linked by LAN or WAN to form a malicious network through two PLMNs. The false base station forwards the registration request message of the victim UE to the remote malicious UE, and the malicious UE forwards it to the remote core network through the remote legitimate base station. Similarly, the false base station and the malicious UE forwards the response message sent by the core network to the victim UE, and completes the authentication. In this way, the network-aware user's location and the user's actual location may be inconsistent, providing a way to set up a false alibi or undermine a criminal investigation with fake evidence. A legitimate UE may be directed by an attacker to access the roaming network, resulting in a charging fraud.

### 5.5.2 Security Threats

In case the authentication relay attack occurs, the threats of this attack include:

**(1) Deception:** The adversary deceives the victim into believing that the victim UE is connected to the core network.

**(2) Location History Poisoning:** The malicious UE can poison the location history of the victim UE by performing this attack successively from different tracking areas. As a result, a fugitive or criminal hiding in one location can deceive the core network into believing that the criminal has attached to the core network from a different location.

**(3) Complete or Selective DoS:** The malicious UE and the false base station can deny the victim UE’s phone-calls/SMS/data transfers completely/selectively. Consequently, the operational network is deprived of the charges for the incoming/outgoing calls and SMSs.

**(4) Attack on SON:** By relaying a geographically remote base station, an attacker may confuse the network’s self-organized network configuration, because UEs will report measurements of the false base station signal strength, or signal strength of the radio environment to the relayed base station.

### 5.5.3 Potential Requirements

There should be a means to mitigate the authentication relay attack caused by the false base station.

## 5.6 Key Issue #6: Resistance to radio jamming

### 5.6.1 Key issue details

Radio jamming could be an act of an illegitimate radio device attempting to disrupt radio communication between a legitimate sender and a legitimate receiver.

There are some technical features in the 5G system that could make the radio jamming attack difficult in the first place, e.g., beamforming, duplication of PDCP PDUs in case of multi-connectivity and carrier aggregation, MR-DC, and a completely dedicated network-slices or PLMNs. Further, the nature of the radio jamming is such that it is challenging (if possible, at all) for an attacker to go undetected. Furthermore, it is infeasible for an attacker to have a sustained attack because the system self-recovers when the attacker goes away.

Nevertheless, it is important that 3GPP investigates how resistance to radio jamming is further enhanced. For example, an attacker would be deterred when the probability of being detected is high and especially if the detection solution results in the attacker's asset information to be revealed, e.g. attacker's location.

NOTE: This key issue appears in the current document for completeness. It is not in the merit of the 3GPP TSG SA WG3 to work on solutions for this key issue. Other groups especially the 3GPP TSG SA RAN groups will be liaised.

### 5.6.2 Security Threats

Undetected or un-prevented radio jamming could potentially have following impacts in some cases:

- DoS attack on UE

- DoS attack on network

### 5.6.3 Potential Requirements

NOTE: This issue is not to be addressed in this document.

## 5.7 Key Issue #7: Protection against Man-in-the-Middle false gNB attacks

### 5.7.1 Key issue details

Typical false base station attacks result in denial of service to UE. Consequently, UE or user may infer such attacks based on the service unavailability and take an action accordingly. However, a more sophisticated attacker may launch various types of attacks in a stealth manner using false base stations. MitM false gNB transports security protected messages between the UE and the network without any modification while altering and/or injecting unprotected messages.

Without addressing the MitM threats, detection of false base stations and countermeasures against them have limited effectiveness.

### 5.7.2 Security Threats

A MitM false base station may force a UE to camp on to it by passing all the message on between the UE and real base station. It may then deny the UE service, e.g. reject or drop service request, not pass on paging messages etc.

### 5.7.3 Potential Requirements

TBD

## 5.x Key Issue #x: Title

### 5.x.1 Key issue details

TBA

### 5.x.2 Security Threats

TBA

### 5.x.3 Potential Requirements

TBA

# 6 Candidate Solutions

Editor’s Note: This clause contains the proposed solutions addressing the identified key issues.

## 6.1 Solution #1: Protection for the UE Capability Transfer

### 6.1.1 Introduction

This solution addresses the security requirement in Key Issue #1 for unicast RRC messages.

### 6.1.2 Solution details

The two messages exchanged in the UE Capability transfer procedure, namely UECapabilityEnquiry and UECapabilityInformation, needs to be sent after the AS security establishment and activation.

NOTE: In the current 5G RAN RRC specification TS38.331 [2], it is implementation specific whether the gNB initiates UE Capability Transfer procedure after the AS SMC and AS security context established or before it.

### 6.1.3 Evaluation

Advantage:

This solution needs only a few changes to the current 5GS, without introducing extra cost and complexity.

Editor Note: Other evaluations for this solution are FFS.

## 6.2 Solution #2: Protection of RRCReject message in RRC\_INACTIVE state

### 6.2.1 Introduction

This solution#2, addresses the key Issue#1 “Security of unprotected unicast messages” and the following security and privacy areas:

#1 DoS attack on UE: attempts to hinder the UEs' access to the network.

#2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

### 6.2.2 Solution details

The RRC\_INACTIVE state allows gNB to suspend the UE's RRC connection while the gNB and the UE continue to maintain the UE 5G AS security context. While the UE is in RRC\_INACTIVE state, the UE and last serving gNB store the UE 5G AS security context which can be reactivated when the UE transitions from RRC\_INACTIVE to RRC\_CONNECTED. The gNB and the UE keep the current AS key KRRCint. The gNB and the UE stores the sent I‑RNTI together with the current UE context including the remainder of the AS security context for the next state transition.

When the UE decides to resume the RRC connection to transit from RRC\_INACTIVE to RRC\_CONNECTED or to notify the network, if it moves out of the configured RNA, the UE sends RRC Resume Request message. On receiving the RRC Resume Request message, if the gNB is not able to handle the procedure, due to congestion, then the gNB decides to send the RRCReject message. When the gNB decides to reject the RRC Resume Request message from the UE, the RRC Reject message shall include the resume cause and a rejectMAC-I. The rejectMAC-I is the message authentication code, the gNB calculates it using the integrity algorithm (NIA) in the stored AS security context, which was negotiated between the UE and the source gNB and the current KRRCint with the following inputs:

- KEY : it shall be set to current KRRCint;

- BEARER : all its bits shall be set to 1.

- DIRECTION : its bit shall be set to 1;

- COUNT : all its bits shall be set to 1;

- MESSAGE : it shall be set to with the following inputs:

*source C-RNTI, source PCI, target Cell-ID, resume cause, waitTime.*

If the gNB is the not the last served gNB, then the target gNB shall request the last served gNB to provide the rejectMAC-I. Then the rejectMAC-I is calculated by the last serving gNB, which responds to the target gNB including an encapsulated RRCReject message. The security context is not relocated from the last served gNB to the target gNB. In this case, the target gNB forwards the protected RRCReject message to the UE.



**Fig 6.2.2-1. RejectMAC-I calculation during the Resume Request procedure**

On receiving the RRC Reject message from the gNB, the UE calculates the rejectMAC-I in the same way as the gNB did in step 2. If the rejectMAC-I check is successful, then the UE follows rest of the procedure as specified in TS 38.331. If the rejectMAC-I check fails, then the UE ignores the received RRC Reject message. UE moves to RRC Idle, deletes the 5G AS context and I-RNTI, and indicates to upper layer with appropriate cause value for NAS recovery.

Editor's Note: How the solution address the case when the RRCResumeRequest is sent to a new gNB is FFS.

### 6.2.3 Evaluation

When UE in the RRC-INACTIVE state, there are 2 kinds of situation, gNB has the security context, and gNB doesn't have the security context.

When the gNB has the security context, the rejectMAC-I, is the authentication token used for verification of the authenticity of the gNB by the UE, even though it is sent using SRB0. Since the gNB and the UE are in possession of the AS security context during RRC\_INACTIVE state, the stored context is used to calculate the rejectMAC-I. The AS security context, stored in the UE and in the genuine gNB is not available/revealed to the fake gNB, therefore the fake gNB cannot successfully send the RRC Reject message to the UE, by impersonating as the genuine gNB.

Note that in the proposed solution the RRC Reject message is sent on SRB0 with minimum impacts to the specification TS 33.501[7] and RRC procedure in TS 38.331[2].

When the gNB doesn’t have the security context, the UE gets an RRCReject without MAC-I, it cannot differentiate whether this is a genuine RRCReject message or a fake RRCReject message.

## 6.3 Solution #3: Protection of uplink UECapabilityInformation RRC message

### 6.3.1 Introduction

This solution addresses the following key issues:

- Key issue #1: security of unprotected unicast messages.

The solution provides a mechanism for protection of the uplink RRC UECapabilityInformation message.

### 6.3.2 Solution details

Current security mechanisms for RRC UECapabilityInformation are listed in Annex B.1 (Protection of RRC messages) of 3GPP TS 38.331, which can be summarized as follows:

(1) The RRC UECapabilityInformation shall not be sent unprotected after AS security activation.

(2) The RRC UECapabilityInformation may be sent unprotected before AS security activation.

Mechanism #(1) ensures that the RRC UECapabilityInformation cannot be tampered after AS security activation.

For mechanism #(2), which is the root cause of the problem, this solution introduces two recommendations for the system (the network and the UE):

- The network should not send RRC UECapabilityEnquiry to the UE before AS security has been activated.

- When the UE gets an RRC UECapabilityEnqiry message from a gNB, the UE should first verify that the AS security has been activated, i.e., an RRC security mode command procedure has been successfully performed. If the above verification succeeds, the UE shall send corresponding RRC UECapabilityInformation message to the gNB as a ciphered and integrity protected message. Else if the above verification fails, i.e., an RRC security mode command procedure has not been performed or has failed, the UE should not send RRC UECapabilityInformation message to the gNB. The UE may send the RRC UECapabilityInformation message to the gNB later, after AS security has been activated.

However, if the system (the network and the UE) has to perform the mechanism #(2), e.g., for early optimization, this solution mandates that the system supports a recovery mechanism from tampered uplink RRC UECapabilityInformation message. It means the followings:

- The network shall taint the UE capabilities so that the network (i.e., same gNB/AMF or different gNB/AMF at handovers) can determine whether those UE capabilities were received before or after the AS security activation.

- Once a successful security activation is performed, depending on the security policy, the network may re-enquire the UE capabilities if they were received earlier without security protection. To re-enquire the UE capabilities, the network may send to UE a Boolean flag in AS SMCommand message, or a HASH of locally stored UE capabilities, or a new RRC UECapabilityEnqiry message.

### 6.3.3 Evaluation

Editor's Note: The following evaluation is preliminary. It may be updated.

Editor’s Note: Evaluation of the security vulnerabilities for allowing the network to accept unprotected UECapabilitiesInformation is FFS.

## 6.4 Solution #4: Enriched measurement reports

### 6.4.1 Introduction

This solution addresses the first security requirement in the following key issue:

- Key issue #3: network detection of false base stations (first requirement).

The solution provides a mechanism for enhancing the detection of false base stations by enriching the measurement reports from the UE. The solution is applicable to UEs in RRC\_IDLE, RRC\_INACTIVE, and RRC\_CONNECTED states.

### 6.4.2 Solution details

#### 6.4.2.1 Enrichment of measurement report

The UE measurement reports specified in 3GPP TR 38.331 [2] already contain several information relevant for the detection of false base stations, e.g., identifier and received-signal strength information of the cell. Additionally, 3GPP TS 38.331 provides support for reporting of Cell Group Info (CGI\_info) which contains information broadcasted in MIB and SIB1.

In addition to the existing information, the system shall support the following new information about camped and neighboring cells to be included in the measurement report:

- mib\_info = hash of the MIB, which helps in detection of DoS attempts, e.g., cellBarred=barred;

- sib\_info = list of {SIB number, hash of the SIB}, which helps in detection of DoS, fraud, and subscription identification attempts, e.g., ims-EmergencySupport=false, tampered SI-SchedulingInfo, and useFullResumeID=true;

NOTE 1: The sib\_info could contain at least SIB1 which the UE currently obtains to generate CGI\_info.

NOTE 2: The mib\_info and sib\_info could contain their corresponding recorded time.

NOTE 3: The network can set the requesting frequency for CGI info, similar to the ANR frequency configuration. That is implementation specific.

It’s suggested to reuse the algorithm of SHA256 to calculate the hashes of MIB/SIBs.

In addition to the information above which can be transmitted by UEs in CONNECTED mode, it is also possible to extend the logged measurements, currently discussed in TS 38.331 for Rel-16, to include the following information that can help in detecting false base stations:

- reject\_info = information about REJECTs that the UE had received earlier, which helps in detection of DoS attempts, e.g., presence of rogue REJECTs;

- signal\_info = information about signal as below, which helps in detection of DoS attempts, e.g., presence of erratic radio signals:

- just power: signal is not associated with any normal pilots or reference signals.

- power with just pilots: signal is associated with normal pilots or reference signals, but those signals do not provide any readable system information.

- power with pilots and system info: signal is associated with normal pilots or reference signals and those signals provide system information, but the system information is wrong (e.g., inconsistent information, not possible to access the network according to the information).

The UE shall send the above information to the network only after a successfull AS security mode command procedure.

The network shall verify and compare the above information with what is expected, e.g., comparing hashes of MIB/SIBs for reported cells with those of genuine cells using the same hash algorithm used in the UE.

To verify the hashes of MIB/SIBs reported by the UE in the MR, the gNB should store the hashes of all broadcasted MIB/SIBs of all cells that belong to the gNB and records the changed time when the MIB/SIBs are modified.

#### 6.4.2.2 Verification of the MIB/SIBs Hashes

When the serving cell receives a MR/logged MR with hashes of neighbouring cell MIB/SIBs, the serving cell can report the MR/logged MR to OAM, then the OAM communicates with the corresponding neighbouring cells to do the MIB/SIBs hashes verification; the serving cells also can communicate with the OAM to get the corresponding neighbouring cell’s MIB/SIBs hashes, and verify the reported MIB/SIBs hashes in local. The communication between OAM and cells are implementation specific.

If verification fails, e.g., the hashes do not match, the network may consider it as a factor to detect the presence of the false base station.

During handovers, the serving cell may use the above information, i.e., the MIB/SIBs hashes verification result, to decide whether or not to attempt handover of the UE to the reported neighbouring cell.

### 6.4.3 Evaluation

Editor's Note: Impacts on UE power consumption is FFS.

Enriched measurement reports certainly help in enhancing the detection of false base stations.

NOTE: It is not in the merit of SA3 alone to define new information to be included in measurement reports. SA3 could give directions to RAN groups about information helpful for false base station detection. Then, RAN groups would design solutions. Hence, RAN groups must be liaised.

## 6.5 Solution #5: Mitigation against the authentication relay attack

### 6.5.1 Introduction

This solution addresses key issue #5: Mitigation against the authentication relay attack, assuming that the victim UE and malicious UE, as defined in key issue #5, are residing in the same PLMN.

### 6.5.2 Solution details

It is assumed that the victim UE may be camped to the false base station FBS. Then the FBS collaborates with another malicious UE through a private channel. The FBS forwards the NAS message of the victim UE to the remote malicious UE, and the malicious UE forwards the message to the remote core network through the remote legitimate base station gNB. In this case, the solution works as follows:

In the registration request procedure, the victim UE sends a registration request message to the AMF through the FBS, the malicious UE and the gNB. The gNB forwards the registration request message to the AMF through the N2 interface, which includes the user's location information reported by the gNB (indicated by "Location Info-gNB"). The AMF stores the Location Info-gNB. After the authentication and SMC procedure. The victim UE sends an UP-link NASmessage, which includes Location Info-UE, to the AMF through the FBS, the malicious UE and the gNB. The AMF then compares the Location Info-UE with the Location Info-gNB.

For the already registered UE, the Location Info-UE shall be sent using the initial NAS message, and can be protected by the initial NAS message protection mechanism.

In this solution, the Global Navigation Satellite System (GNSS) information is used as the Location Info-UE, which is obtained by the GNSS chip in the ME from the GNSS. For the privacy issue, the user can manually configure the privacy setting based on the eLCS procedure to indicate whether the UE is allowed to submit its GNSS information to the core network. It is assumed the GNSS information is accurate.

If the AMF determines that the Location Info-UE and the Location Info-gNB are consistent, the subsequent procedures are normally performed.

If the AMF determines that the Location Info-UE and the Location Info-gNB are inconsistent, the registration rejection message may be sent to the UE, where the reason value carried indicates the location positioning of the UE.



**Figure 6.5.2-1 Anti-authentication relay attack procedure**

1. In the registration request procedure, the victim UE sends a registration request message to the false base station FBS.

2-3. The FBS shall forward the registration request message of the victim UE to the legitimate base station gNB through the remote malicious UE.

4. The gNB shall send the registration request message to the AMF with the user's location information reported by the gNB (indicated by "Location Info-gNB").

5. The AMF shall store the Location Info-gNB.

6. The AMF shall initiate authentication procedure and NAS SMC procedure.

7. If the victim UE decides to enable the anti-authentication relay attack feature. The victim UE shall obtain the user's actual location information (indicated by "Location Info-UE"). The user's actual location information shall be the GNSS information obtained by the GNSS chip in the ME from the GNSS application..

8. The victim UE shall send the Location Info-UE to the FBS in the uplink NAS message which shall be ciphered and integrity protected by the NAS keys in the current 5G security context. The uplink NAS message shall be NAS Security Mode Complete message or other NAS message after the NAS SMC completed.

NOTE 1: In case of the UE is already registered, the Location Info-UE shall be sent in the initial NAS message, and can be protected by the initial NAS message protection mechanism.

9-11. The FBS shall forward the uplink NAS message to the AMF through the malicious UE and the gNB.

12. The AMF obtains the Location Info-UE, and compares the Location Info-UE with the Location Info-gNB.

13. If the AMF determines that the Location Info-UE and the Location Info-gNB are consistent, the subsequent procedures shall be performed. If the AMF determines that the Location Info-UE and the Location Info-gNB are inconsistent, the authentication relay attack report message may be sent to the UE with the cause value, which indicates the location positioning of the UE.

### 6.5.3 Evaluation

The solution mitigates the threats of the authentication relay attack by using the AMF to compare the location information reported by the UE and the gNB. The the user's actual location information shall be the identified with GNSS information. In addition, based on the eLCS procedure, the UE is allowed to submit its location to the core network. The privacy issue would be solved based on the privacy setting, which is agreed by the UE.

In addition, the UE reports the Location Info-UE through the NAS message after the authentication and the SMC procedure or the initial NAS message in case of the UE is already registered. At this time, the uplink NAS message has been encrypted and integrity protected, and the initial NAS message has been protected by the initial NAS message protection mechanism. Therefore, the location information of the UE cannot be tampered by the false base station.

This solution only works with UE that has GNSS, and GNSS may be spoofed and jammed.

Editor Note: Evaluation on privacy aspects is FFS.

## 6.6 Solution #6: Avoiding UE connecting to false base station during HO

### 6.6.1 Introduction

This solution addresses the security requirement in key issue #3 for preventing UE from connecting to false base station.

### 6.6.2 Solution details

#### 6.6.2.1 Background

Usually, the 5G RAN HO decision is based on the UE MR (Measurement Report).The UE executes the signal power measurement of the neighbour cell based on the SS Block which carries the broadcasted synchronization signal and MIB signal which is sent without security protection [1] [2]. Assuming there is a false base station C counterfeiting the system information of a legitimate base station B. The serving base station A receives the UE MR which include measurements from C. Base station A would assume the included information in the UE MR belongs to base station B and then may decide to handover the UE to B and consequently the UE instead connects to the false base station C. Eventually, the handover will fail, as shown in figure 6.6.2.1-1.



Figure 6.6.2.1-1: HO procedure caused by false base station C

Step 0: The UE reports the measurement report (MR) to the source gNB (A).

Step 1: The source gNB (A) decides the measurement from false gNB C meets the HO trigger threshold, then the source gNB (A) lookup the NCRT (neighbour cell relation Table) [16] with the reported PCI (physical cell identity), and finds the target cell of gNB (B).

Step 2: The source gNB (A) sends HO request to target gNB (B).

Step 3: The target gNB (B) makes the HO admission decision and prepares radio resource for the UE (e.g. SRB and DRB resource for the UE).

Step 4: The target gNB (B) responds with the HO request ACK message containing all the preparaed RRC configuration informations.

Step 5: The source gNB (A) sends HO command to indicate the UE to execute the HO to the target cell.

Step 6: The UE detachs from the source cell.

Step 7: The UE tries to synchrocnize and camp on the target cell based on the broadcasted SSB signal (including the synchronizaiton signal and MIB signal) and SIB1. Because the SSB signal and SIB1 are not security protected, the UE can not verify the authenticity of these message. The false gNB can copy the SSB signal and SIB1of the target cell, and sends that with stronger power. Finally, the UE camps on the false cell.

Step 8: The UE sends MSG1 to the camped cell in clear.

Step 9: The false cell responds with MSG2 in plaintext, instructing the UE to send the next uplink message using the dedicated UL allocation resource.

Step 10: The UE sends the HO confirm message using the dedicated UL allocation resource. Although, HO Confirm message is protected using the AS security keys with the real target gNB, the false base station does not need to send any confirmation or acknowledgement to the UE in order for the UE to validate that the receiving base station is the real base station which holds the same AS security context.

The real target cell does not receive the HO confirm message from the UE, then thinks the HO fails. And the source cell does not receive the UE context release message from target cell, then decides the HO failure.

For the UE, the false cell does not have the UE security context, the UE would find RLF at later time. But the UE has camped on the false cell, the false cell can launch some attacks to the UE, e.g. sending spoofing SIBs with false cell reselection blacklisted to the UE.

To avoid this HO procedure and the possibility for UE connecting to false base station during HO, this solution introduces a second measurement based on a specific CSI-RS (Channel State Information Reference Signal) [5] assigned by the target gNB to the UE.

#### 6.6.2.2 Procedure

There are two options for this solution as follows:

Option A: Always On feature: In this option the proposed solution is always on and activated at the source gNB; thus it is on on all gNBs.

Option B: On demand feature: The source gNB turns this feature on to a specific target gNB when the number of handover failures to this target gNB exceed a specific threshold, i.e., when the source gNB suspect the presence of a false base station in the area, it automatically turns this feature on.

##### 6.6.2.2.1 Always on Feature

The target gNB B assigns a specific CSI-RS to the UE during the preparation phase, and carries the CSI-RS information in the HO request ACK message. The source gNB A indicates the UE to do second measurement based on the dedicated CSI-RS information. Only when the second UE MR meets the HO trigger condition, then the source gNB A would indicate the UE to do the HO execution.

Because the false gNB C does not know the dedicated CSI-RS information in advance, therefore the second MR reported by the UE is measured with the real reference signal of the target gNB B.



Figure 6.6.2.2-1: HO procedure with second measurement and HO decision

The source gNB (A) should support to trun on/off this feature according to the network circumstances.

Step 2: When the local configuration in the source gNB indicates that the feature of second measurement is enabled, the source gNB (A) sends HO request with a new indicator to request the target gNB to prepare a specific CSI-RS for the UE.

Step 3: The target gNB (B) performs admission control and prepares basic RRC configuration information for the UE, including a dedicated CSI-RS information.

Step 4: The target gNB (B) respond with the HO request ACK message containing all the prepared RRC configuration information (including the dedicated CSI-RS information).

Step5: When the source gNB (A) receives the CSI-RS information in the Handover request ACK, and the feature is turned on, the source gNB decides to request the UE for a second time measurement based on the specified CSI-RS information.

Step 6: The source gNB (A) sends a measurement task including the CSI-RS information to the UE while being protected with RRC security context.

Step 7: The UE executes a second measurement of the dedicated CSI-RS signal indicated in the measurement task.

Step 8: The UE reports the second MR to the source gNB (A).

Step 9: Based on the second MR, the source gNB (A) decides whether or not to continue the HO. If the second MR meets the HO trigger threshold, that means the real reference signal power of the target cell is strong enough, the source gNB A sends the HO command to indicate the UE to execute the HO to the target cell. Otherwise, the source gNB A sends HO cancel to the target gNB B to stop the HO procedure.

##### 6.6.2.2.2 On demand Feature

The details of the solution in this option is the same as in option A with the difference that this solution is turned on when needed, i.e., on demand. The solution is turned on dynamically by a source gNB.

Note: It is implementation specific for the source gNB to trigger and turn on this solution. For example, the source gNB may turn on according to the FBS detection report.

Editor’s Note: RAN2 Feedback is needed.

### 6.6.3 Evaluation

The solution addresses Key Issue #3 to avoid the UE connecting to FBS during Handover procedure.

CSI-RS is used for the UE to do measurement, it is a UE specific parameter which is assigned by the target RAN, and is different for each UE. In the solution, CSI-RS is provided to the UE in a ciphered and integrity protected RRC Measurement Task message, so, the FBS cannot know this parameter, and cannot forge the right CSI-RS. Thus, the UE will measure true signalling of the target RAN, and will not initiate wrong HO caused by forged cell of FBS.

The solution requires new signalling overhead before Handover, but it can be configured on-demand. If the RAN suspects that there is FBS, then, the feature is on. If not, the feature can be off.

Editor’s Note: The solution does not mitigate dumb radio repeater attacks.

Editor’s Note: Further evaluation is ffs based on RAN2 Feedback is needed.

## 6.7 Solution #7: Verification of authenticity of the cell

### 6.7.1 Introduction

This solution#7, address the key Issue#2 “Security Protection of system information” and the following security and privacy areas:

#1 DoS attack on UE: attempts to hinder the UEs' access to the network.

#2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

A cell periodically broadcasts synchronization signals and system information (SI). UE detects a cell based on the synchronization signals. If the signal quality of detected cell is above a defined threshold then UE determines whether the cell is authentic or not, to camp on it. A cell is authentic, if the authenticity verification of the system information received from the cell is successful. This solution does not verify the authenticity of the cell during initial registration procedure.

### 6.7.2 Solution details

#### 6.7.2.1 System Information verification using Digital Signatures

This solution is applicable only for verification of authenticity of the cell during RRC\_IDLE mode and RRC\_INACTIVE mode cell reselection. This solution is not applicable for cell authenticity verification during initial Registration procedure.

In order to enable the UE to validate the authenticity of received system information, the NR digitally signs the broadcasted system information as shown in Figure 6.7.2.1-1. System information to be broadcasted, Private security key (K-SIGPrivate) and Time Counter are input to security algorithm to generate the digital signature. The input also contains downlink frequency and physical cell ID of the cell that is broadcasting the SI message, which ensures that any replay of the SI message in a different frequency/PCI is detected by the UE. The generated DS together with some least significant bits of Time Counter is added to the system information before transmitting over the air. K-SIGPrivate is specific to the Tracking area. The private key (K-SIGPrivate) is provisioned in the gNB by the MNO. The public K-SIGPublic key and its lifetime is provisioned by the core network to the UE, when performing location update procedure, as shown in Figure 6.7.2.1-2. Time Counter is maintained based on UTC time (number of UTC seconds in 10 ms units since 00:00:00 on Gregorian calendar date 1 January, 1900 (midnight between Sunday, December 31, 1899 and Monday, January 1, 1900), similar to the mechanism used in ProSe Discovery protection TS 33.303) and can be units of milliseconds or seconds or minutes. The gNB obtains a value for a UTC-based counter associated with a transmission slot based on UTC time. The UE may obtain UTC time from any sources available, e.g. the RAN (via SIB, as in LTE via SIB16), NITZ, NTP, GPS (depending on which is available). The Time Counter input to the security algorithm is the value of counter corresponding to time slot in which system information is transmitted. The usage of Time Counter ensures that received system information cannot be replayed. There can be differences in the Time Counter maintained in the UE and the AN because of different UTC source or implementation errors. To take care of these errors least significant bits of Time Counter are also transmitted along with system information.

Editor's Note: The impact of new signature inputs is FFS.

In addition, the along with the public key, the AMF provides the UE with a MAX\_OFFSET parameter. The UE stores the MAX\_OFFSET parameter. The UE sets a clock which is used for authenticity verification to the value of CURRENT\_TIME, obtained from the SIB (as LTE SIB16 provides the *timeReferenceInfo* which is time reference with 0.25 us granularity). Current Time (maintained at the UE) provides the UE with the time at the base station, and along with the Max Offset parameter, is used to ensure that the time the UE associates with the MIB/SIB transmission slot is reasonably close to the real time. Max Offset indicates how close the time associated with the discovery slot needs to be to the time provided by the base station. The MAX\_OFFSET parameter is used to limit the ability of an attacker to successfully replay digitally signed MIBs and SIBs for later use. This is achieved by using MAX\_OFFSET as a maximum difference between the UTC-based counter associated with the discovery slot and the CURRENT TIME held by the UE (at 0.25 us granularity).

On receiving the system information the UE generates digital signature. The system information with digital signature received, public security key (K-SIGPublic) and Time Counter of the time slot in which system information is received are used to check the authenticity of the SI. If authenticity verification is successful, then the system information is authentic and the UE considers the cell as authentic.

The size of the digital signature leads to increase in the signalling overhead. In order to reduce the overhead, digital signature can be generated for multiple system information together instead of generating the digital signature for each system information. System information is periodically broadcasted, in order to reduce the overhead; protection can be applied once every ‘N’ period instead of every period. Mechanisms to reduce the overhead are detailed in the clause 6.7.2.3 of this TR.

Editor’s Note: It is FFS whether the K-SIG-Priv of all gNBs within a TA are same or different. The possible key leakage if the same K-SIG-Priv is shared by all eNBs needs to be considered.



Figure 6.7.2.1-1: System Information verification using Digital Signatures



Figure 6.7.2.1-2: Provisioning of Public Keys to the UE

Editor’s Note: It is FFS, how the UE handles location update reject message from a false base station.

#### 6.7.2.2 System Information verification using Identity Based Cryptography

The network provisions UEs and NR with a set of credentials for Elliptic Curve-Based Certificateless Signatures for Identity-Based Encryption (ECCSI), as defined in IETF RFC 6507 [33] along with the public key of the CN. Furthermore, UEs are provisioned with the Public Validation Token (PVT) specific to each cell and the NR are configured with the Secret Signing Key (SSK) associated with its cell identity. In order to verify the authenticity of the cell, the NR act as "signer" and the UE act as the "verifier" (according to the definitions in RFC 6507). The NR uses SSK associated to the cell to sign the system information, and the UE uses the public key of the CN and the cell ID specific PVT to verify the signature.

As mentioned in the clause X.Y.2.1, the time counter is used as the input for signature generation and also to reduce the overhead; digital signature can be generated for multiple system information together and protection can be applied once every ‘N’ period instead of every period. Mechanisms to reduce the overhead are detailed in the clause 6.7.2.3 of this TR.

#### 6.7.2.3 Optimization of SI verification using the other SI

5G SI is divided into minimum SI and other SI. The other SI may either be broadcast, or provided in a dedicated manner by the gNB, triggered either by the network or upon request from the UE [62]. The authenticity verification information can be classified into the other SI. The gNB generate the digital signature with the minimum SI broadcasted, Private security key (K-SIGPrivate) and Time Counter as input (as shown in Figure 6.7.2.1-3) and provides the digital signature in the other SI (as a separate SI) either periodically or upon request from the UE (as shown in Figure 6.7.2.1-4). As the UE needs to verify the authenticity of the gNB, only signing of the minimum SI is performed in order to reduce the overhead in the UE and in the gNB.



Figure 6.7.2.1-3: Cell authenticity verification using other SI



Figure 6.7.2.1-4: Transmission of cell authenticity verification using other SI

6.7.2.4 Capability negotiation

The UE and the VPLMN require a secure negotiation mechanism so that both have a common understanding of where and which SI messages are protected. This solution proposes the NAS layer based negotiation as shown in the Figure 6.Y.2.7-1.



**Figure 6.7.2.4-1: SI protection capability negotiation**

This proposed negotiation works as below:

1) The UE indicates its capability to verify SI signatures to the AMF in a Registration Request message.

2) The AMF uses the UE's capability to decide whether or not to give SI protection information to the UE.

3) For capable UEs, the AMF sends the following SI protection information in a Registration Accept message:

Editor's Note: The feasibility of including these parameters in this step is FFS.

3.1) Cells for which the broadcast SI shall have signature, e.g., TAIs, PCIs, and Cell IDs. It is proposed that at least the TAIs are included.

3.2) SI numbers which shall be covered by the signature. It is proposed that at least the minimal SI (i.e., MIB and SIB1) shall always be covered.

The sending of SI protection information from the AMF to the UE in the Registration Accept message covers both types of Registration Request, i.e., the initial registration and the mobility registration update. It also covers handovers with AMF change because the mobility registration update follows a handover.

### 6.7.3 Evaluation

This solution can protect the broadcast message in any RRC mode, UE can verify the authenticity of SIB messages after the public keys are being provisioned to the UE.

UE cannot verify the SIB message during the initial registration procedure.

The key provision procedure is leveraging the legacy NAS signalling and no extra signalling is needed.

Given the fact that replay attack cannot being 100% eliminated, the method given by this solution helps to mitigate the reply attack.

Editor’s Note: Further evaluation details are FFS.

### 6.7.4 Assessment using Annex A.3

#### 6.7.4.1a UE aspects

Based on threshold of detected cell’s signal, UE determines whether the cell is authentic or not, to camp on it. A cell is authentic, if the authenticity verification of the system information received from the cell is successful.

Verification using Digital signatures:

1. On receiving the system information the UE generates digital signature. The system information with digital signature received, public security key (K-SIGPublic) and Time Counter of the time slot in which system information is received are used to check the authenticity of the SI. If authenticity verification is successful, then the system information is authentic and the UE considers the cell as authentic.
2. The UE may obtain UTC time from any sources available, e.g. the RAN (via SIB, as in LTE via SIB16), NITZ, NTP, GPS (depending on which is available).
3. The Time Counter input to the security algorithm is the value of counter corresponding to time slot in which system information is transmitted.

Identity Based Cryptography for Digital Signature Verification:

1. The UE act as the "verifier" (according to the definitions in RFC 6507).
2. UE uses the public key of the CN and the cell ID specific PVT to verify the signature.

Reduce the overhead using other SI:

1. Upon UE’s request, the other SI may either be broadcast, or provided in a dedicated manner by the gNB.
2. The UE checks that the timestamp is within an acceptable time-window before it verifies the signature to prevent replay attacks.

#### 6.7.4.1b UE actions upon detection of invalid signature

If the signal quality of detected cell is above a defined threshold then UE determines whether the cell is authentic or not, to camp on it. If the verification of the signature fails at UE, then the UE considers system information is not authentic and therefore the cell is not authentic. The UE initiates cell re-selection procedure.

#### 6.7.4.2 Threats that are mitigated by signed SI messages

This solution address the key Issue#2 “Security Protection of system information” and the following security and privacy areas:

#1 DoS attack on UE: attempts to hinder the UEs' access to the network.

#2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

This solution is applicable only for verification of authenticity of the cell during RRC\_IDLE mode and RRC\_INACTIVE mode cell reselection.

Replay attempts that re-transmit a captured SI message from one frequency/PCI to another will be detected. The attacker's cell is forced to operate in same frequency/PCI and compete with the genuine cell. This is unsuitable for the attacker because the UE will not stick to the attacker's cell.

#### 6.7.4.3 Threats that are not mitigated by signed SI messages

This solution is not applicable for cell authenticity verification during initial Registration procedure

#### 6.7.4.4 Provisioning of keys

For Digital Signatures,

1. K-SIGPrivate is specific to the Tracking area. The private key (K-SIGPrivate) is provisioned in the gNB by the MNO.
2. The public K-SIGPublic key and its lifetime is provisioned by the core network to the UE, when performing location update procedure, as shown in Figure 6.7.2.1-2.

For Identity based cryptography,

1. The network provisions UEs and NR with a set of credentials for Elliptic Curve-Based Certificateless Signatures for Identity-Based Encryption (ECCSI), as defined in IETF RFC 6507 [33] along with the public key of the CN.
2. UEs are provisioned with the Public Validation Token (PVT) specific to each cell and the NR are configured with the Secret Signing Key (SSK) associated with its cell identity.

#### 6.7.4.5 RAN aspects

A cell periodically broadcasts synchronization signals and system information (SI).

Verification using Digital signatures,

1. NR digitally signs the broadcasted system information as shown in Figure 6.7.2.1-1.
2. System information to be broadcasted, Private security key (K-SIGPrivate) and Time Counter are input to security algorithm to generate the digital signature.
3. The generated DS together with some least significant bits of Time Counter is added to the system information before transmitting over the air.
4. The gNB obtains a value for a UTC-based counter associated with a transmission slot based on UTC time.
5. System information is periodically broadcasted, in order to reduce the overhead; protection can be applied once every ‘N’ period instead of every period. Mechanisms to reduce the overhead are detailed in the clause 6.7.2.3 of this TR.

Verification using Identity Based Cryptography,

1. The network provisions UEs and NR with a set of credentials for Elliptic Curve-Based Certificateless Signatures for Identity-Based Encryption (ECCSI), as defined in IETF RFC 6507 [33] along with the public key of the CN.
2. NR are configured with the Secret Signing Key (SSK) associated with its cell identity.
3. In order to verify the authenticity of the cell, the NR act as "signer" (according to the definitions in RFC 6507).
4. The NR uses SSK associated to the cell to sign the system information

Other SI Optimization,

1. The gNB generate the digital signature with the minimum SI broadcasted, Private security key (K-SIGPrivate) and Time Counter as input (as shown in Figure 6.7.2.1-3) and provides the digital signature in the other SI (as a separate SI) either periodically or upon request from the UE (as shown in Figure 6.7.2.1-4).
2. As the UE needs to verify the authenticity of the gNB, only signing of the minimum SI is performed in order to reduce the overhead in the UE and in the gNB

#### 6.7.4.6 VPLMN aspects

Verification using Digital signatures,

1. The public K-SIGPublic key and its lifetime is provisioned by the Serving network to the UE, when performing location update procedure, as shown in Figure 6.7.2.1-2.

Verification using Identity Based Cryptography,

1. The serving network provisions UEs and NR with a set of credentials for Elliptic Curve-Based Certificateless Signatures for Identity-Based Encryption (ECCSI), as defined in IETF RFC 6507 [33] along with the public key of the CN.
2. Furthermore, UEs are provisioned with the Public Validation Token (PVT) specific to each cell and the NR are configured with the Secret Signing Key (SSK) associated with its cell identity.

Other SI Optimization,

1. The gNB generate the digital signature with the minimum SI broadcasted, Private security key (K-SIGPrivate) and Time Counter as input (as shown in Figure 6.7.2.1-3) and provides the digital signature in the other SI (as a separate SI) either periodically or upon request from the UE (as shown in Figure 6.7.2.1-4).
2. As the UE needs to verify the authenticity of the gNB, only signing of the minimum SI is performed in order to reduce the overhead in the UE and in the gNB.

#### 6.7.4.7 HPLMN aspects

No HPLMN aspects/impacts

#### 6.7.4.8 Network sharing aspects

No Network sharing aspects/impacts

Editor’s Note: Network sharing aspects to be further assessed.

#### 6.7.4.9 Roaming aspects

No roaming aspects identified

#### 6.7.4.10 Regulatory aspects

The solution is about digital signature and can be optional for UE to verify during Idle or Inactive state, therefore no Regulatory aspects identified.

#### 6.7.4.11 Signature schemes

There could be one or more signature schemes like:

* Profile 0 (null-scheme) which means that there is no signature.
* Profile A (ECCSI) which means Elliptic Curve-Based Certificateless Signatures for Identity-Based Encryption (ECCSI), as defined in IETF RFC 6507 [9].
* Profile B (ECDSA) which means using a widely standardized signature scheme called the ECDSA (Elliptic Curve Digital Signature Algorithm).

#### 6.7.4.12 Signature length

The signature length depends upon the signature scheme and its domain parameters. For example, when using a null-scheme which has no signature, the length would be 0. And, when using an ECDSA signature that provides 128 bit security level, the length would be a minimum of 512 bits. In any case, the length is deterministic.

#### 6.7.4.13 Resistance against Quantum Computing

None identified as of now.

## 6.8 Solution #8: Network detection of nearby false base stations from call statistics and measurements

### 6.8.1 Introduction

This solution addresses Key Issue #3: Network detection of nearby false base stations

When false base stations are present in a PLMN network, most often they will be broadcasting MIB and SIB messages copied from one of the real PLMN base stations. Thus, a UE, unsuspectingly might consider this as a real base station and based on the active or idle state of the UE.

1. If the UE is active, UE will consider the false base station as a potential target for handover, and if mobility conditions are correct, will attempt to do handover to it.
2. If the UE is Idle, it will do cell reselection and start listening to broadcast messages and Paging.

The solution here particularly focusses on the UEs in active state. The active UEs which does handover from real base station to false base station will fail, and the UE will select a new target cell. Because the UE subsequently gets connected to a new target, even if the handover once failed, so far, the information gathered from this procedure is usually ignored.

### 6.8.2 Solution details

#### 6.8.2.1 Detection of false base Stations from Active UE Measurement report

If the UE is in active mode, during the handover preparation phase it is possible that the UE measured and selected a false base station as a handover target. When UE measurement reports are received by the source base station, when handover thresholds are crossed, the source base station tries to establish X2/Xn links to the reported target Cell IDs. Looking at the configuration data of neighbour Cell IDs in the source base station, the source base station finds IP address of the target cells and tries to establish X2/Xn links for handover. But this X2/Xn link set up will fail, if the target Cell ID reported by the UE happens to be a false base station.

Here a serving base station can conclude that, if the Cell ID reported by the UE in its measurement report as one of the strong neighbour cells, but if such a neighbour cell is absent in its configuration data base, or if the serving base station fails to establish X2/Xn links with the reported neighbour, the target cell is not part of the PLMN network. The serving base station can make the determination that the reported Cell ID doesn’t belong to its PLMN network.

#### 6.8.2.2 Detection of false base stations from duplicate Cell IDs in Active UE Measurement report

It is also possible that a false base station copies the Cell ID belonging to a real Cell and then operate in very close proximity to it, broadcasting the real Cell ID. In this case the UE will report two measurements for the same Cell ID with different values, since the UE is detecting and measuring two transmitters, which will differ in power at least very slightly.

The serving base station can detect the operation of a duplicate false base station from the duplicate Cell IDs from the measurement report of multiple UEs. But it is difficult for a serving base station to detect which Cell ID, as measured by the UE in the measurement report belongs to a genuine base station of the PLMN and which one is false.

Editor’s Note: It is FFS how a serving base station resolves duplicate Cell IDs as genuine vs false.

### 6.8.3 Evaluation

TBD

## 6.9 Solution #9: Using symmetric algorithm with assistance of USIM and home network

### 6.9.1 Introduction

#### 6.9.1.1 General

This solution address key issue #1 “Security of unprotected unicast messages” and key issue #2 “Security Protection of system information”.

The idea of this solution is that serving network dynamically provisions keys of gNBs to the ME encrypted with assistance of home network, which cannot be decrypted by the ME, and gNB uses symmetric algorithm to generate a 32-bit MAC-I for the radio signaling, then the ME verify the MAC-I with assistance of USIM. The concept of the solution is highlighted as following:

1. Information for radio signaling authenticity is provisioned between the serving network and the ME;

2. The provisioned information is encrypted and cannot be decrypted by the ME;

3. The decryption of the provisioned information can only be done by USIM;

4. The storage of encryption key in the USIM shall have same security requirement as Long Term Key (LTK);

5. The encryption key and the provisioned information are periodically changed.

6. The ME sends provisioned information and radio signaling to the USIM for verification.

#### 6.9.1.2 Mitigate replayed broadcast attack

The network integrity protects broadcast messages, e.g. MIB, SIBs, warning messages, etc., together with the DL ARFCN. When the UE camps on a cell of a gNB, the serving network only provisions a limited number of keys to the USIM, which makes the UE be able to only handle messages sent by a limited number of gNBs. The area covered by those gNBs called protection area (PA), c.f. sub-clause 6.9.2.2.2.

When the attacker has captured a message broadcasted by a cell in a PA, the attacker can only impersonate the cell to broadcast the unchanged message using the same DL ARFCN to a UE in the same PA. This makes the attack difficult and localized, or easy to be detected by network. When the UE tries to camp on the fake cell due to receiving a replayed SI message, the UE will detect that the cell is a fake cell using the security procedure of the unicast messages as described in sub-clause 6.9.2.3.2, and then re-select other cell to camp on.

Broadcasting the captured warning message in the same PA may also be a threat. It is recommended that the warning message includes information of time and area to avoid the threat (i.e. application layer replay protection solution).

### 6.9.2 Solution details

#### 6.9.2.1 Framework

##### 6.9.2.1.1 General

Following figure shows the 4 stages of the solution – Protection Key Agreement (PKA) procedure, Protection Key Transfer (PKT) procedure, Protection Area Information Provisioning (PAIP) procedure, and Cell Authenticity procedure, wherein the stage 1 and stage 2 are executed together, i.e. stage 2 always follows stage1:



Figure 6.9.2.1.1-1: Four stages of cell authenticity with symmetric algorithm

The protection key (CKp) agreed between the home network and the USIM shall have the same security requirement as Long Term Key (LTK), which means the USIM shall prevent reading out the CKp that used to encrypt the provisioned information (e.g. keys of gNBs).

The serving network provisions protection area (PA) information to the ME, which includes keys that the gNBs uses to integrity protect the radio signaling. The keys in the PA information are encrypted by the CKp and can only be decrypted by the USIM. The ME sends the protection area information and the radio signaling to the USIM for cell authenticity. The CKp and the keys used by the gNBs shall be updated periodically, so that they will be useless when they have been cracked.

This solutions can also provide capability to encrypt sensitive information in the radio signaling before 5G security context is active.

##### 6.9.2.1.2 Principle of dynamic provisioning

The following figure shows the principle of dynamic information provisioning:



Figure 6.9.2.1.2-1: Principle of dynamic information provisioning to ME

#### 6.9.2.2 Provisioning

##### 6.9.2.2.1 Protection Key Agreement (PKA) and Protection Key Transfer (PKT) procedure

Pre-condition:

- For roaming case, the N32 interface between the HPLMN and VPLMN are integrity, confidentiality, and replay protected.

The Protection Key Agreement (PKA) procedure is done during registration procedure, which combined with Protection Key Transfer (PKT) procedure.

Following figure illustrates the PKA combined with PKT procedure:



Figure 6.9.2.2.2-1: PKA procedure combined with PKT procedure

1. The UE sends a Registration Request message to the serving network. If the UE decides to change protection key (CKp), the UE may include a flag for key agreement in the Registration Request.

2. In case of initial registration procedure, or, if the flag is received, the AMF/SEAF shall initiate Protection Key Transfer (PKT) procedure by sending UE Protection Key Transfer Request message to the UDM. In case of authentication or re-authentication is needed, the UE Protection Key Transfer Request message is UE Authentication Request message, and if the flag is received, the AMF/SEAF shall include the flag in the UE Authentication Request message.

3. In case of authentication with SUCI, or if the flag is received, or if the UDM decides to refresh the CKp during authentication procedure based on local policy, the UDM shall generate a CKp based on the user’s long term key and a random NONCE.

4. The UDM returns the random NONCE and the CKp to the AMF/SEAF to finish the PKT procedure. The AMF/SEAF shall report the CKp to the Anti-False-Base-station Function (AFBF) (e.g. in OAM platform or is a dedicate network function), so the AFBF can computes EKRBS by encrypting the KRBS with the CKp on demand.

5. If the NONCE and the CKp are received, the AMF/SEAF sends a Registration Accept (NONCE) message to the UE.

6. If the NONCE is received and the UE supports Anti-False-Base-Station (AFBS), the ME shall initiate Key Initiation Procedure with the USIM by sending the NONCE to the USIM.

7. The USIM computes CKp based on the long term key as well as the received NONCE as same as UDM does, and stores the CKp. The USIM shall make sure the CKp cannot be read out.

8. The USIM returns an indication to the ME after CKp has been generated.

NOTE: If the protection key is updated, the Protection Area Information Provisioning (PAIP) procedure as described in sub-clause 6.9.2.2.3 must be performed combined with the PKA and PKT procedure.

##### 6.9.2.2.2 Protection area

In order to reduce the encrypted keys provisioned to the ME, a group of gNBs can share a root key (i.e. 256-bit KRBS) that used for deriving key per gNB (i.e. 256-bit KBS) for base station protection, hence the serving network can just provision the encrypted root keys of groups in the PA to the ME. The group is called Share Root Key Group (SRKG). Each gNB is included in one and only one SRKG. Each SRKG is identified by a Group Key Identifier (i.e. 24-bit bsGKI), each gNB in a SRKG is identified by a Group Node Identifier (i.e. 8-bit bsGNI).

Each SRKG is included in one or more PAs, and each of those PAs includes the full SRKG. The following figure illustrates the relationship between SRKG and protection area (PA).



Figure 6.9.2.2.2-1: Relationship between shared root key group (SRKG) and protection area (PA)

Any registration area (RA) is fully covered by one and only one PA, so that when UE performs registration procedure, the serving network can provision encrypted keys of the PA to the ME. The following figure illustrates the relationship between registration area (RA) and protection area (PA).



Figure 6.9.2.2.2-2: Relationship between registration area (RA) and protection area (PA)

During registration procedure (initial, mobility, or periodic) or other initial NAS message handling, the AMF shall provide the information of the protection area, which includes a list of bsGKI, corresponding encrypted root keys, and corresponding expiry time, to the ME. The ME shall store the protection area information. Only the USIM can de-conceal the encrypted root keys. The expiry time is used to avoid a false base station, who cracks a KBS of a gNB, to cheat the UE after key expiration. The expiry time shall be short enough to make the key cracking impossible in time.

The serving network shall change the root key of a SRKG before expiration. In order to improve performance, a PA should include those gNBs that adjacent to the tracking area that fully covered by the PA, so that the UE can have protection information of every neighbour gNBs when it is at the edge of a tracking area.

The PA shall not be too large. It will be difficult to mitigate the false base station attack based on replayed broadcast radio signalling if the PA is too large.

##### 6.9.2.2.3 Protection Area Information Provisioning (PAIP) procedure

Pre-conditions:

1. The serving network provides the bsGKI and bsGNI to the corresponding gNB, e.g., via OAM platform or a dedicated network function.

2. The serving network manages root keys and related information for the SRKGs, e.g., on OAM platform or a dedicated network function. The serving network derives KBS based on the KRBS, bsGKI, and bsGNI for each gNB as follow:

KBS = HMAC-SHA-256 (KRBS, <bsGKI, bsGNI>)

The combination of <bsGKI, bsGNI> is a 32-bit value. The serving network also has provided the KBS to the corresponding gNB. In order to make sure that different gNB has different KBS, the combination of <bsGKI, bsGNI> should be unique on each gNB.

Following figure illustrates the initial shared key provisioning procedure between UE and the serving network.



Figure 6.9.2.2.3-1: Protection Area Information Provisioning (PAIP) procedure

0. The protection key (CKp) has been transferred from hone network to the serving network during Protection Key Transfer (PKT) procedure.

1. The UE sends a Registration Request message to the AMF/SEAF. This message may also trigger the PKA and PKT procedure as described in sub-clause 6.9.2.2.1.

2. If the AMF/SEAF supports Anti-False-Base-Station (AFBS), the AMF/SEAF shall obtain the PA information, i.e. a list of {bsGKI, EKRBS, expiry time} associated with the PA that covers the tracking area that the UE resides in. The EKRBS is encrypted KRBS based on the CKp, the expiry time indicates that the EKRBS will have been changed after that.

3. The AMF/SEAF sends Registration Accept (PA information) to the UE.

4. If the ME supports AFBS, the ME stores the received PA information.

NOTE: The procedure also can be triggered by other initial NAS message, if the step 1 is not registration request, the step 4 can be other DL NAS message, e.g. UE Configuration Update.

#### 6.9.2.3 Authenticity

##### 6.9.2.3.1 Security procedure for broadcast messages

The following figure illustrates the security procedure for broadcast message:



Figure 6.9.2.3.1-1: Broadcast message protection procedure

1. The gNB decides to broadcast a message (e.g. MIB or SI) via a cell, the message shall include <bsGKI, bsGNI>. If the length of message plus the length of DL\_ARFCN is larger than 32 BYTES, the gNB generates a HASHNW as following:

HASHNW = SHA-256 (DL ARFCN || message)

The gNB then computes a 32-bit MAC-I based on the KBS, as well as the concatenation of DL\_ARFCN and message (length <= 32 BYTES) or the HASHNW (length > 32 BYTES).

2. The gNB broadcasts out the message along with the MAC-I.

3. The ME received the message including a <bsGKI, bsGNI> and a MAC-I via a cell. The ME checks whether the bsGKI exists in the protection area information. If the check fails, then the ME marks the cell as suspect cell in cache. If the check success, then continues with step 4.

NOTE1: The UE may lost contact with network for a while and move to another PA, in this case, all the cells around the UE are genuine cells but UE has no corresponding PA information.

4. If the length of the DL\_ARFCN plus the length of the received message is larger than 32 BYTES, the ME computes HASHMS as the same that gNB computes HASHNW, then the ME sends the EKRBS, <bsGKI, bsGNI> to the USIM. If HASHME has been calculated, the ME shall also send the HASHMS to the USIM, otherwise, the ME shall send the concatenation of DL\_ARFCN and the received message to the USIM. The EKRBS is corresponding to the bsGKI.

5. The USIM decrypts the EKRBS based on the stored CKp to get KRBS, derives KBS from the KRBS and <bsGKI, bsGNI> as described in sub-clause 6.9.2.2.3, and then calculates the XMAC-I based on KBS as the same that gNB computes MAC-I based on KBS,

6. The USIM returns the XMAC-I to the ME. The ME compares XMAC-I with MAC-I. If they are equal, the ME handles the broadcast message. Otherwise, the ME marks the cell as high-risk cell in cache.

NOTE2: The serving network may update the KRBS without notifying the UE, in this case, the MAC-I verification fails but gNB is genuine.

If all the cells around the UE are marked as suspect cell or high-risk cell, the UE may start a verification timer. When the verification timer is timeout, the UE shall be ready to perform registration procedure. If the UE is ready to send an initial NAS message before timeout, the UE shall stop the verification timer. When the UE is ready to send an initial NAS message (due to timeout or not), the UE shall try to send the initial NAS message via the suspect cells one by one then high-risk cells one by one until succeeds.

After the UE successfully authenticates the network, the UE shall check whether the suspect or high-risk cell in cache is in the protection area (updated or not), if not, then mark the cell as suspect cell in cache, if yes, then verify the cell. If verification fails, the UE marks the cell as fake cell in cache, otherwise remove the cell from the cache. The UE may report the suspect, high-risk, and fake cells in cache to the serving network.

##### 6.9.2.3.2 Security procedure for unicast messages

This solution for unicast message protection is only applied when AS security context cannot be obtained in UE and gNB. The following figure illustrates an example that demonstrates the security procedure for unicast radio messages:



Figure 6.9.2.3.2-1: Unicast message protection procedure

1. The ME tries to camp on a cell and decides to send message1 to the cell. If message1 is not Preamble, it generates a 32-bit random string NONCE. The NONCE is used as replay protection parameter for the successive downlink message.

2. The ME may decide to protect a sensitive information, e.g. NSSAI, in the message1 (there’s no sensitive information in Preamble). In that case, the ME sends the EKRBS, <bsGKI, bsGNI>, the sensitive information, and NONCE to the USIM. The <bsGKI, bsGNI> is obtained from a broadcast message (e.g. SI or MIB) sent by the cell. The EKRBS corresponds to the bsGKI. The USIM decrypts the EKRBS to get KRBS, derives KBS from the KRBS and <bsGKI, bsGNI>. The USIM then derives the Ke from the KBS and returns the Ke to the ME. The ME generates keystream based on the Ke and NONCE and computes the exclusive or of the sensitive information and the keystream to encrypt the information.

3. The ME sends the message1 to the cell, which includes the NONCE if the message1 is not Preamble, the message1 may be partially encrypted.

4. The gNB receives the message1. If it is partially encrypted, then the gNB decrypts the encryption part to get plaintext information.

5. The gNB decides to send message2 to the UE. The gNB gets temp-message = (NONCE || message2) and computes MAC-I for the temp-message as described in sub-clause 6.9.2.3.1.

6. The gNB sends the message2 along with the MAC-I to the UE via the cell.

7. The ME receives the message2, performs message verification procedure as described in step 4~6 of sub-clause 6.9.2.3.1 with the exception that the ME uses temp-message = (NONCE || message2) instead of message2 for verification.

NOTE 1: Preamble (MSG1) and RAR (MSG2) are special radio messages. If the message1 is Preamble, then the 32-bit NONCE = (2-bit padding || 6-bit RA-RNTI || 2-bit padding || 6-bit RAPID || 16-bit Temporary C-RNTI). The NONCE is not included in the Preamble. The RAR may contain a combined reply for multiple UEs, in this case, RAR includes multiple 16-bit short MAC-Is, which means ME must truncate the XMAC-I returned from USIM for verification. In order to provide backward compatibility, short MAC-I can be appended sequentially after the payload.

NOTE 2: The message1 is a message before message2, which means message2 can be a request, response, or an indication. The message2 does not include <bsGKI, bsGNI>.

### 6.9.3 Evaluation

Editor’s Note: Each solution should motivate how the potential security requirements of the key issues being addressed are fulfilled.

## 6.10 Solution #10: Protection on the unicast message based on ECDH

### 6.10.1 Introduction

This solution addresses key issue #1 and the following security and privacy areas:

#1 DoS attack on UE: attempts to hinder the UEs' access to the network.

#2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

This solution is based on the ECDH. The UE has a eSK and ePK, and the gNB has a SKgNB and a PKgNB.

After both gNB and UE get the ePK and the PKgNB, they can perform ECDH to get a shared key Ksig, which can be used to protect all the unicast messages before the AS security activation.

Editor Note: It is FFS how the gNBs are provisioned and the associated security requirement(s) on storage and processing the keys/certificates.

Editor Note: It is FFS how the legacy USIM/ME are handled.

### 6.10.2 Solution details

#### 6.10.2.1 General description

This solution is based on the ECDH. The UE has an eSK and an ePK, and the gNB has a SKgNB and a PKgNB.

1. The gNB can provision the PKgNB in the early stage, so the UE can get the PKgNB of gNB. There are 2 methods to provision PKgNB into the UE: The PKgNB can be provisioned into the UE at manufacture time, in USIM or in ME. Which means, it can be performed in implementation-independed way;

Editor Note: It is FFS in the manufacturing time how the PKgNB for the target network/markets are known by the ME/USIM manufactures.

1. After UE registered and performed authentication with the network, UE applies for the PKgNB from the trusted Serving network.

The UE can send the ePKin the uplink message, for example, in Msg5, so the gNB can get the ePK of UE.

After both gNB and the UE get the ePK and the PKgNB , they can perform ECDH to get a fresh shared key Ksig, which can be used to protect all the unicast messages before the AS security activation.

The gNB and UE could use NIA1/2/3 to do integrity protection of the subsequent unicast messages, the MAC size is only 32bits.

The gNB is supposed to use the generated shared key to generate MAC for the integrity protection of the unicast message, so UE would know if this gNB is false or not as early as in the first message after Msg5, for example, RRCReConfiguration.

#### 6.10.2.2 Pre-provision

UE and gNB shall support ECDH, and all the credentials shall be preprovioned.

#### 6.10.2.3 Message used to send ePK uplink

The UE can use Msg3 or Msg5 to send ePKto the gNB, since the size of Msg3 is limited by size, and the ECDH public key could be 256bit, so the Msg5 is more practical.

#### 6.10.2.4 Replay resistant

The way to resist replay attack is adding one NONCE in the Msg5, as the input of the MAC. This can be used to mitigate some replay attacks. However, the MitM attack could not be mitigated.

#### 6.10.2.5 Procedures

Detailed call flow is as following.

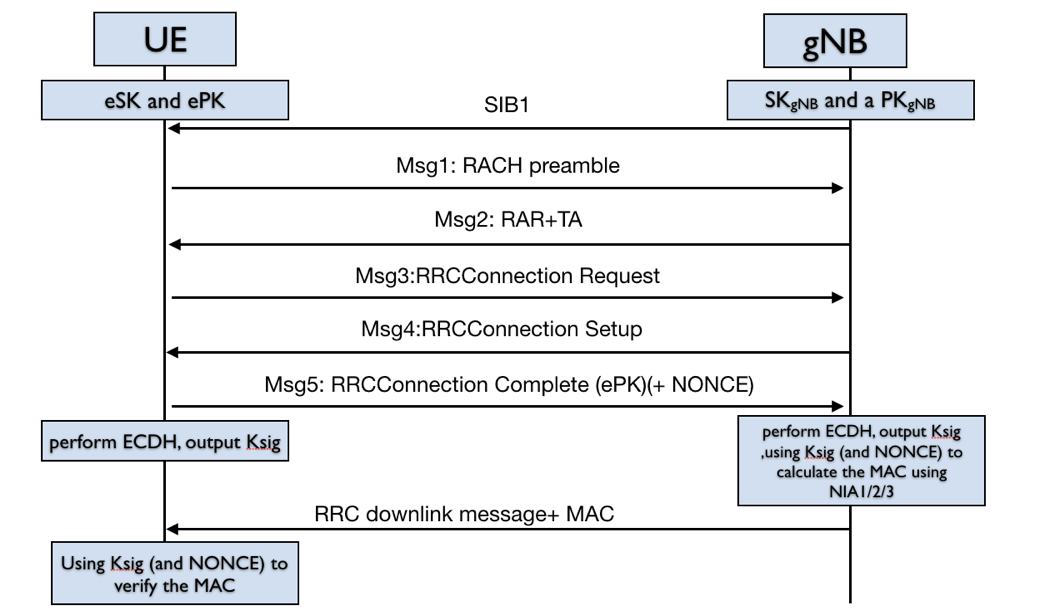


Fig 6.10.2.3 Protect unicast message using ECDH and MAC

### 6.10.3 Assessment using Annex A.3

#### 6.10.3.1a UE aspects

UE and gNB shall support ECDH, and all the credentials shall be preprovioned, which can be performed in implementation-independed way.

#### 6.10.3.1b UE actions upon detection of invalid signature

For the unicast message which is not with a MAC, UE have 2 choices: 1) drop every message which is send without a MAC. 2) UE takes every message as genuine without a MAC.

For the unicast message which is with a false MAC, UE shall drop the message.

Editor Note: it is FFS how to know which gNB is supposed to add the MAC in the unicast message.

#### 6.10.3.2 Threats that are mitigated by signed SI messages

Key issue #1 are mitigated. All unicst message before security activation can be integrity protected using the this solution.

#### 6.10.3.3 Threats that are not mitigated by signed SI messages

MitM attack and Bidding down attack.

#### 6.10.3.4 Provisioning of keys

There are 2 methods to provision PKgNB into the UE:

1. The PKgNB can be provisioned into the UE at manufacture time, in USIM or in ME.
2. After UE registered and perform authentication with the network, UE apply for the PKgNB from the trusted Serving network.

The UE can send the ePKin the uplink message, for example, in Msg5, so the gNB can get the ePK of UE.

#### 6.10.3.5 RAN aspects

Msg5 is used to carry the ePK from UE to send uplink to the gNB.

MAC is carried in the downlink message, and the length of the MAC is only 32bit, which is much shorter than signature.

#### 6.10.3.6 VPLMN aspects

If the VPLMN supports the ECDH solution and the UE is provioned with the PKgNB of the visited network, then this solution works in VPLMN..

However, there will be another choice. If the UE is only preprovisioned PKgNB of home network, then the UE can achieve anti-FBS in home PLMN. This is a restricted case that only achieve anti-FBS security in home network. Eventhough this is not a perfect solution, it is better that nothing, given the fact that people spend much more time in the home network than in the visited network.

#### 6.10.3.7 HPLMN aspects

This solution can detect the FBS in the HPLMN.

#### 6.10.3.8 Network sharing aspects

Not applicable to protection of unicast messages.

#### 6.10.3.9 Roaming aspects

Same as 6.10.3.7 VPLMN aspects.

Editor Note: It is FFS how roaming cases are addressed/handled

Editor Note: How the UE is prevented to camp on the false base station is FFS

#### 6.10.3.10 Regulatory aspects

TBD

#### 6.10.3.11 Signature schemes

It is using NIA/1/2/3 to do the integrity protection.

Editor Note: It is FFS whether other MAC algorithms is needed.

#### 6.10.3.12 Signature length

MAC length: 32bits.

#### 6.10.3.13 Resistance against Quantum Computing

TBD.

## 6.11 Solution #11: Certificate based solution against false base station

### 6.11.1 Introduction

This solution addresses key issue 1&2 and the following security and privacy areas:

#1 DoS attack on UE: attempts to hinder the UEs' access to the network.

#2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

This solution is based on the PKI(Public Key Infrustructure). The gNB can sign the broadcast message with its own private key and send the message, the signature, together with gNB’s certificate to the UE, and UE will be able to verify the authenticity of the message with the provisioned root of trust, e.g. the certificate issuers’s CA public key. UE shall accept the message after a successful message authentication.

### 6.11.2 Solution details

#### 6.11.2.1 Pre-provision and certificate distribution

This solution requires the network to support PKI (Public Key Infrastructure), Which needs the MNO have one or more CAs as the root of the trust chain.

UE shall has the capability to support storing more than one CA Root certificate, which can be stored in USIM or other implementation-dependent way.

NOTE: There are 2 methods to provision Root certificates into the UE:

1. The Root certificate can be provisioned into the UE at manufacture time, in USIM or in ME.

Editor Note: It is FFS in the manufacturing time the Root certificates for the target network/markets are known by the ME/USIM manufactures.

The legacy USIM/ME cannot support this solution.

1. After UE registered and perform authentication with the network, UE apply for the Root certificate from the trusted Serving network. UE gets the certificate from the serving network directly or it gets the URL for downloading the certificate. This would lead to UE unprotected before registration and provioned the first certificate.

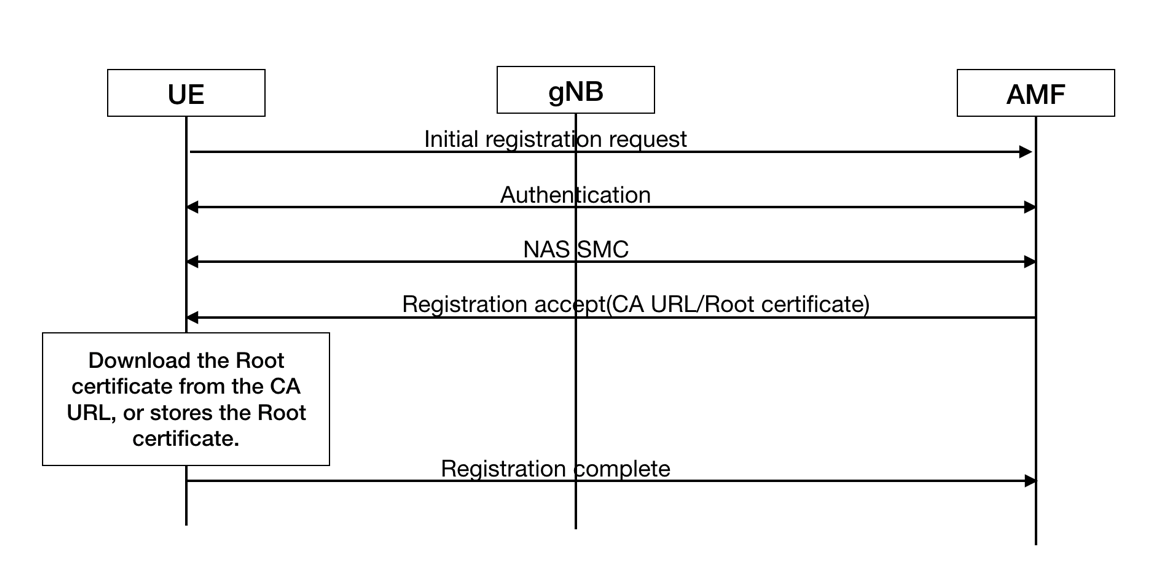


Fig 6.11.2.1-1. NAS-based key provisioing procedure

NOTE: The vendor can provision a list of Root certificate into the UEs, the length of the list depend on the capability of the UE. Since the Root certificate usually has a long lifecycle, the update of the Root certificate may not happen before the user change the UE. In case the CA is compromised, then the Root certificate needs to be changed, then the vendor uses their private channel to update the Root certificate, like the software update. It is FFS how the MNOs control the CA provisioning and revocation.

Each gNB should be provisioned with its own private key and a certificate. If the certificate is from a sub CA, then the cert chain shall also be given in the message from gNB to the UE to link back to the Root CA. gNB shall use its private key to generate signature of the broadcast message, and the gNB certificate shall be sent to the UE, either together with the signature or in a separate message.

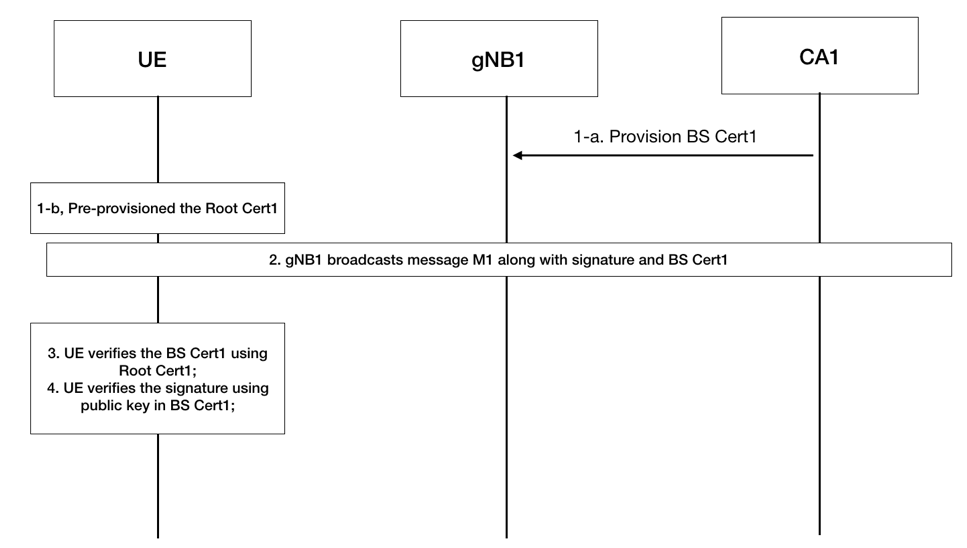
Editor‘s Note: It is FFS how the gNBs are provisioned and the associated security requirement(s) on storage and processing the keys/certificates.

#### 6.11.2.2 Signature algorithm

UEs supporting this solution shall support the ECDSA (Elliptic Curve Digital Signature Algorithm) [x].

Editor’s Note: Other feasible signature algorithms are FFS.

#### 6.11.2.3 Procedures



**Fig 6.11.2.3-1. Certificate based signature broadcast message procedure**

1-a. The MNO1 implements CA1 and the root certificate is Root Cert1, then CA1 distributes to gNB1 a BS Cert1 containing gNB’s public key associated with its corresponding private key.

1-b. UE is provisioned with the public key of CA1, which may be provisioned in ME or USIM.

2. When gNB1 broadcasts messages, it shall send message M1, the signature and BS Cert1 to the UE. The signature is generated from the message and the gNB private key, the BS Cert1 contains the public key required to verify the signature.

3.When UE receives the message, it shall first verify the validity of the BS Cert1 using the corresponding CA public key. If the UE is provioned the corresponding Root Cert and the verification fails, it shall drop this message.

Note: If the UE does not own a correspongding Root Cert for verification, then the UE shall be provisioned a local policy to decide how to deal with these messages. UE may have 2 choices: 1) drop every message which is send with the BS Cert for which UE can not find a corresponding Root certificate to verify; 2) UE takes every message as genuine, which is send along with the BS Cert for which the UE can not find a corresponding Root certificate to verify.

4. Then UE uses the gNB public key in the BS Cert to verify the signature. If the verification of the signature succeeds, the UE takes this message genuine, otherwise, it shall drop this message.

When there is more than one level of CA, for example, the MNO has a Sub CA, and it shall use Sub CA to sign for the gNB. Then the gNB has to send not only its own Cert to the UE, but also the Sub CA Cert(s).

#### 6.11.2.4 Certificate format:

ITU-T X.509 certificate could be used for its flexibility, otherwise more compact certificate format such as Card Verifiable Certficate (CVC) can be considered.

The specification shall define the certificate profile.

Editor’s Note: The profile of the certificate is FFS.

### 6.11.3 Assessment using Annex A.3

#### 6.11.3.1a UE aspects

UE needs to be preprovisioned of a list of root certificate.

The provision of the certificate is in 6.11.3.5.

The UE shall support the storage of the Root certificate.

UE shall support the certificate update, which can be performed in implementation-independed way.

#### 6.11.3.1b UE actions upon detection of invalid signature

If the UE does not own a correspongding Root Cert for verification, then the UE shall be provisioned a local policy to decide how to deal with these messages. UE may have 2 choices: 1) drop every message which is send with the BS Cert for which UE can not find a corresponding Root certificate to verify; 2) UE takes every message as genuine, which is send along with the BS Cert for which the UE can not find a corresponding Root certificate to verify.

#### 6.11.3.2 Threats that are mitigated by signed SI messages

Key issue 1&2 are mitigated. All broadcast message before security activation can be signed using the this solution.

#### 6.11.3.3 Threats that are not mitigated by signed SI messages

The bidding down attack are not prevented. However, the bidding down attack is caused by the partial deployment, and it is not specific to this solution but applied to every solution. To mitigate the bidding down attack, there will be 2 possible ways:

1. the MNOs make sure to provision all the gNB with privatekeys/certificates, then when UE received a SIB without a signature, it can be taken as a false one.
2. the second certificate provision method should be chosen in 6.11.2.1. when UE is registered into the network, the AMF in serving network shall privision a list of certificate for a bunch of gNBs. If the UE is provisioned the certificate of the gNB, then it shall verify the SIs from this gNB.

Editor’s Note: How the MitM attack is addressed is FFS.

Editor’s Note: How the UE is prevented to camp on the false base station is FFS.

#### 6.11.3.4 Provisioning of keys

There are 2 methods to provision Root certificates into the UE:

1. The Root certificate can be provisioned into the UE at manufacture time, in USIM or in ME.
2. After UE registered and perform authentication with the network, UE applies for the Root certificate from the trusted Serving network. UE gets the certificate from the serving network directly or it gets the URL for downloading the certificate.

#### 6.11.3.5 RAN aspects

Signature and the certificate need to be carried in the broadcast message, and the length of the signature and the certificate is approximately >600 byte (RSA based).

#### 6.11.3.6 VPLMN aspects

As stated in 6.11.3.5, there are 2 different methods to provision the Root certificates. If the first one is choosen, the UE needs to be provisioned into Root certificates of VPLMN or there are mutual trust between 2 different CAs, this solution works for VPLMN/roaming cases.

If the second method is choosen, UE can get the Root certificate or the URL for downloading the Root certificate after authentication with the VPLMN, this solution works for the VPLMN. In this case, VPLMN needs to support the corresponding signaling for sending the Root certificate or the URL.

However, there will be another choice. If the UE is only preprovisioned of certain Root certificates, then the UE can achieve anti-FBS in certain PLMN. This is a restricted case that only achieve anti-FBS security in home network. Eventhough this is not a perfect solution, it is better that nothing, given the fact that people spend much more time in the home network.

#### 6.11.3.7 HPLMN aspects

This solution can detect the FBS in the HPLMN.

#### 6.11.3.8 Network sharing aspects

gNB can broadcast a list a PLMN in the SIB message, if the gNB is shared gNB, it may carry more than one PLMN ID. In this case, supposing all the PLMN support the signature based solution, there maybe different method to add signature on this kind of SIB:

1. only one signature is carried, which is for verification of the first PLMN.
2. The SIB message max size is 2976bit[1], so if the message allows, the SIB can carry as much as it can to verify the authenticity of the SIB.

#### 6.11.3.9 Roaming aspects

Same as 6.11.3.7 VPLMN aspects.

When both HPLMN and VPLMN support this scheme, UE can be protected against false base station with this solution.

If UE’s HPLMN supports this scheme, but UE roams to the VPLMN that doesn’t support this scheme, then UE will not be protected against false base station.

If the UE’s HPLMN can not support this scheme, but UE has already implemented the Root certificates of several VPLMN or UE can support to apply the Root certificate from VPLMN that support this scheme, then when UE roams to one of these VPLMN, it can enable this feature to detect false base station.

Both key provision method in 6.11.2.1 can be used. Comparing the 1st one, the 2nd root certificate provision method (NAS based method in 6.11.2.1) is more flexible to address the roaming issue. When the VPLMN supports this scheme with the NAS based certificate provision method, it is not needed for UE to get preprovisioned a root certificate, instead, it can apply the certificate when it roams to the VPLMN.

Interworking will not be impacted. The UE will verify the signature when it receives a SIB with signature, otherwise it will follow the legacy RRC procedure when the SIB doesn’t carry a signature.

#### 6.11.3.10 Regulatory aspects

The CA construction shall follow the local regulatory.

#### 6.11.3.11 Signature schemes

There could one or more signature schemes like:

- **ECDSA (recommended with named curves)**

Editor’s Note: the ECDSA profile for SUCI can be reused.

- **RSA**

- others

Editor's Note: Further explanations are TBD.

#### 6.11.3.12 Signature length

RSA: 256 byte

ECDSA: 64 byte

#### 6.11.3.13 Resistance against Quantum Computing

TBD.

## 6.12 Solution #12: ID based solution against false base station

### 6.12.1 Introduction

This solution addresses key issue 1&2 and the following security and privacy areas:

#1 DoS attack on UE: attempts to hinder the UEs' access to the network.

#2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

This solution is based on ID based asymmetric cryptogriohic methods, for example: IEEE1363.3[8], RFC6507[9], SM9[10], and ISO SC27 Lightweight crypto useing I2R-IBS in 29192-4 (for IoT NFC tag use cases)[11].

In this solution, the ID based signature scheme is introduced, which is more lightweight than certificate based solution, since it doesn’t require the huge size certificate to be send in the broadcast message. One of these aboved ID based algorithm could be adopted, or other feasible ID based cryptography is also acceptable.

Editor’s Note: It is FFS where the PKG is located in the network.

### 6.12.2 Solution details

#### 6.12.2.1 Pre-provision

In this solution, a key management center is needed, called PKG (Private Key Generator), which can generate the PKPKG and SKPKG, SKPKG are kept secret in PKG, and never be send out, while PKPKG are preprovisioned to the UEs.

There are 2 methods to provision the PKPKG into the UEs.

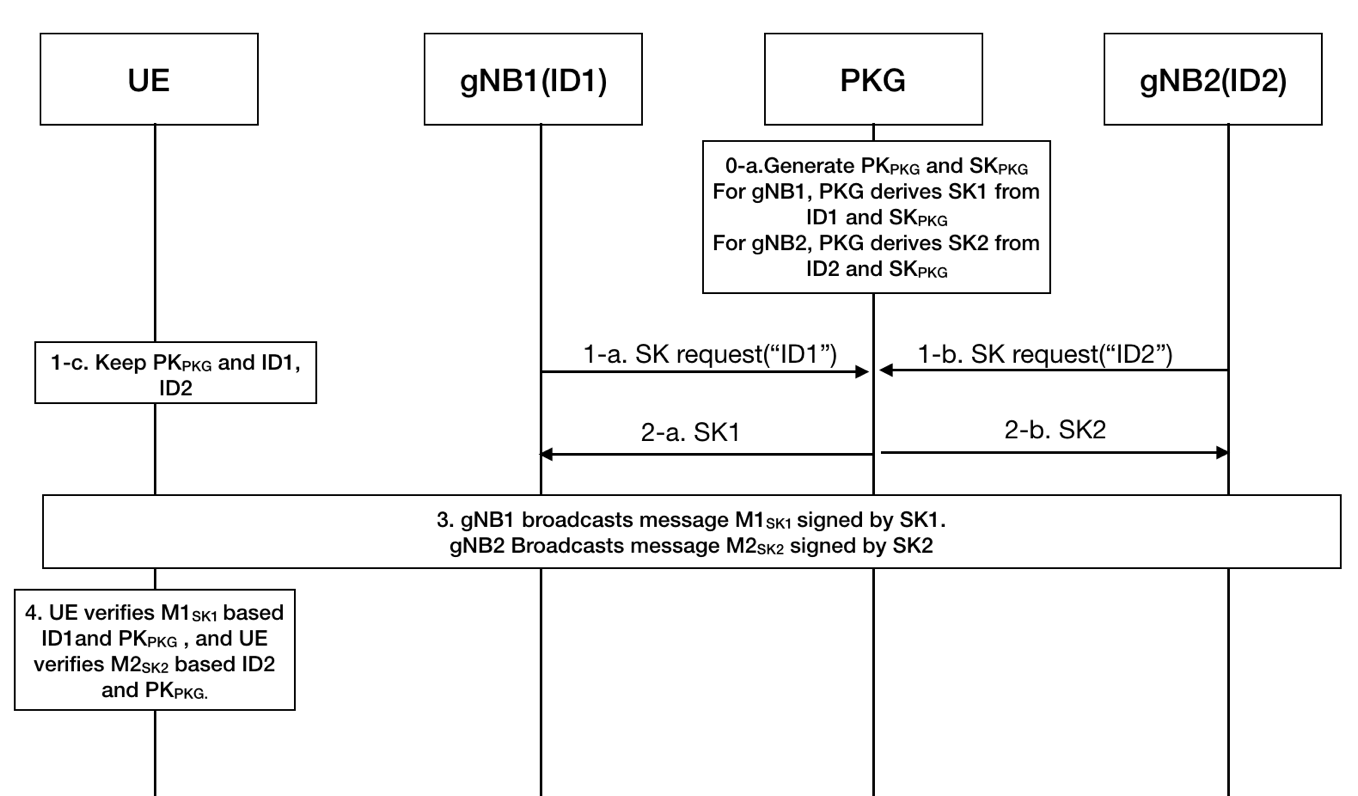
1. The PKPKG can be provisioned into the UE at manufacture time.
2. After UE registered and perform authentication with the network, UE applies for the PKPKG from the trusted Serving network in the NAS SMC complete message. This would lead to UE unprotected before registration and getting the first PKPKG.

The interface between gNB and PKG is a private interface in network domain.

UE shall support one ID based algorithm same with the PKG.

Editor’s Note: It is FFS that which ID based algorithm should be adopted.

#### 6.11.2.2 Procedure



**Fig 6.12.2-1 Procedure of ID based solution**

1. The PKG generates a pair of keys, PKPKG and SKPKG, SKPKG are kept secret in PKG, and is never send out, while PKPKG is pre-provisioned to UEs via feasible ways. PKG derives SKs for every gNB using ID and SKPKG,

Every gNB has a gloable ID, which is unique and public. SK is bound to any concatenated info contained in the ID string. Any change of the ID requires verification at PKG and issuing of a new ID string and corresponding SK.

NOTE: the format of the ID is FFS. For example, ID = “PLMN ID” | “gNB global unique ID” | “TAC(optional)” |“other information”.

1. gNB1 shall send request for SK1 with ID1, and gNB2 shall send requests for SK2 with ID2. Meanwhile, UE shall store the PKPKG and ID1, ID2 when it receives PKPKG and ID1, ID2.

NOTE: UE constructs ID1 and ID2 from information received in broadcast messages.

1. PKG shall send SK1 to gNB1, and shall send SK2 to gNB2.
2. When gNB1 needs to broadcast messages, it shall use SK1 to sign this message; When gNB2 needs to broadcast messages, it shall use SK2 to sign this message.
3. UE shall use PKPKG and ID1 to verify the message from gNB1, and shall use PKPKG and ID2 to verify the message from gNB2. If the UE is provisioned the valid PKPKG and the verification succeeds, the UE treats the information as genuine. If the UE is provisioned the valid PKPKG and the verification fails, the UE shall drop this message. If the UE is not provioned the valid PKPKG, the UE shall be provioned a local policy to decide how to proceed such a message.

#### 6.12.2.3 Revocation

The revocation can be achieved by adding time stamp in the ID string to show the validity period, e.g. “YYYY|MM|WW”. For example, the BS ID is set to “PLMN ID” | “gNB global unique ID” | “TAC(optional)” |“ 2020|06|01”, which means, this ID and the corresponding credentials will be revocated in June 1st, 2020. After this time, the BS needs to update the ID and request for new Keys.

After the ID update, the gNB shall send the new ID to request for a new SK, as step 1 in 6.12.2.2.

Editor’s Note: Other revocation method are FFS.

Editor’s Note: The ID format is FFS.

### 6.12.3 Assessment using Annex A.3

#### 6.12.3.1a UE aspects

UE needs to be preprovisioned of a public key PKPKG of the PKG.

The provision of the PKPKG is in 6.12.3.5.

The PKPKG shall be stored in USIM.

UE shall support the update of the PKPKG.

#### 6.12.3.1b UE actions upon detection of invalid signature

If the UE is provisioned the valid PKPKG and the verification fails, the UE shall drop this message.

If the UE is not provioned the valid PKPKG, the UE shall be provioned a local policy to decide how to proceed such a message.

Editor’s Note: How the UE is prevented to camp on the false base station is FFS.

#### 6.12.3.2 Threats that are mitigated by signed SI messages

Key issue 1&2 are mitigated. All broadcast message and unicast messages before security activation can be signed using this solution.

#### 6.12.3.3 Threats that are not mitigated by signed SI messages

The bidding down attack are not prevented.

Editor’s Note: How the MitM attack is addressed is FFS.

Editor’s Note: How the UE is prevented to camp on the false base station is FFS.

#### 6.12.3.4 Provisioning of keys

There are 2 methods to provision the PKPKG into the UEs.

1. The PKPKG can be provisioned into the UE at manufacture time.
2. After UE registered and perform authentication with the network, UE applies for the PKPKG from the trusted Serving network in the NAS SMC complete message. This would lead to UE unprotected before registration and getting the first PKPKG.

#### 6.12.3.5 RAN aspects

Signature needs to be carried in the broadcast message, and the length of the signature can be as short as 160 bit using BLS[12].

#### 6.12.3.6 VPLMN aspects

As stated in 6.12.3.5, there are 2 different methods to provision the PKPKG. If the first one is choosen, the UE needs to be provisioned into PKPKG, tthen his solution works for VPLMN/roaming cases. If the second method is choosen, UE can get the PKPKG of the VPLMN in the NAS SMC complete message, this solution works for the VPLMN.

However, there will be another choice. If the UE is only preprovisioned of PKPKG of the HPLMN, then the UE can achieve anti-FBS in HPLMN. This is a restricted case that only achieve anti-FBS security in home network. Eventhough this is not a perfect solution, it is better that nothing, given the fact that people spend much more time in the home network.

#### 6.12.3.7 HPLMN aspects

HPLMN shall support the PKG, and also the This solution can detect the FBS in the HPLMN.

#### 6.12.3.8 Network sharing aspects

gNB can broadcast a list a PLMN in the SIB message, if the gNB is shared gNB, it may carry more than one PLMN ID. In this case, supposing all the PLMN support the signature based solution, there maybe different method to add signature on this kind of SIB:

1. only one signature is carried, which is for verification of the first PLMN.
2. The SIB message max size is 2976 bit[1], so if the message allows, the SIB can carry as much as it can to verify the authenticity of the SIB.

#### 6.12.3.9 Roaming aspects

Same as 6.12.3.7 VPLMN aspects.

Editor’s Note: How the roaming scenario is addressed is FFS.

Editor’s Note: How the interworking with legacy network is FFS.

#### 6.12.3.10 Regulatory aspects

TBA

#### 6.12.3.11 Signature schemes

There could one or more signature specification like:

- BLS[12]

- IEEE1363.3[8]

- RFC6507[9]

- SM9[10]

- others

Editor's Note: Further explanations are TBD.

#### 6.12.3.12 Signature length

BLS[12]: 160 bit

SM9[10]: 520 bit

#### 6.12.3.13 Resistance against Quantum Computing

TBD.

### 6.12.4 Evaluation

TBA

## 6.13 Solution #13: Protecting RRCResumeRequest against MiTM

### 6.13.1 Introduction

This solution addresses the following key issues:

- Key issue #1: The 5G system shall have support for protection against tampering of RRCResumeRequest message.

The solution provides a mechanism to protect the RRCResumeRequest message from tampering with the I-RNTI, resumecause field and the spare bit for future use (1 bit) and against MiTM attack.

### 6.13.2 Solution details

When the UE initiates the RRC Resume procedure, the UE shall use the I-RNTI, resumecause field value and spare bit as inputs parameter when calculating the ResumeMAC-I as indicated below.

RRC-Resume-Request = ResumeMAC-Input “Source (C-RNTI+PCI) + Target Cell ID + I-RNTI + resumecause+ spare bit”

When the new gNB receives RRCResumeRequest message, the new gNB shall include the resumecause field value and spare bit in addition to the I-RNTI and PCI in the RETRIEVE UE CONTEXT REQUEST message sent to the old gNB.

When the old gNB validates the ResumeMAC-I, the old gNB shall calculate the ResumeMAC-I as the way the UE calculated it by also including the I-RNTI, resumecause field value and spare bit as inputs to the ResumeMAC-Input.For addressing backward compatibility, the following is proposed:

* release 16 UE which support this feature will exchange its capability to the gNB over NAS when the UE attach to the network. The serving gNB (old gNB) will keep an indication of the UE support of this feature in the UE context even after sending the UE to INACTIVE.
* When the UE come from RRC-INACTIVE state by sending the RRCResumeRequest message, the UE protect the resumecause when calculating the ResumeMAC-I. When the new gNB receives the RRCResumeRequest, the new gNB sends the resumecause value in addition to the UE I-RNTI, ResumeMAC-I in the RETRIEVE UE CONTEXT REQUEST message to the old gNB.
* After the old gNB identify the UE context using the UE I-RNTI, the old gNB validate the UE capability of whether it supports “resumecause” protection or not. If the UE support this feature, the old gNB validate the ResumeMAC-I using the resumecause as one of the ResumeMAC-Input parameters. If the UE does not support, the old gNB ignores the received resumecause when calculating the ResumeMAC-I.
* In the rare case when the new gNB is Rel-15 gNB while the old gNB is a Rel-16 gNB, when the new gNB receives the UE RRCResumeRequest message, the new gNB will include the UE I-RNTI, ResumeMAC-I and other parameters but without the resumecause filed value in the RETRIEVE UE CONTEXT REQUEST. When the old gNB allocate the UE context and verify that the UE supports resumecause protection while no resumecause value has been received, the old gNB either reject the new gNB request in RETRIEVE UE CONTEXT REJECT with proper cause value that causes the new gNB to send the UE to RRC-IDLE or optionally, the old gNB can iterate the validation of the UE ResumeMAC-I by including one of already standardized resumecause value at a time and check the ResumeMAC-I. If the ResumeMAC-I passes validation with any of the resumecause values, the old gNB respond with RETRIEVE UE CONTEXT RESPONSE as in the successful case. If ResumeMAC-I failed with all resumecause values, the old gNB reject the new gNB request.

### 6.13.3 Evaluation

Since I-RNTI, spare IE and resume cause IE are included in computation of shortResumeMAC-I, the whole RRCResumeRequest message is integrity protected, and the security issues raised in key issue #1 is eliminated.

## 6.14 Solution #14: Shared key based MIB/SIBs protection

### 6.14.1 Introduction

This solution addresses the security requirement of Key Issue #2: Security protection of system information.

The basic idea is to have UE reports the hash of the MIB/SIBs it has read to access the network, to the gNB after it has established an AS security context. For the initial access, the AS security mode complete is the first message that is both ciphered and integrity protected by the UE, hence is used to carry the hash of the MIB/SIBs.

When gNB receives the hash value and it verifies the correctness of the hash. If the verification fails, the gNB indicates the mismatch and in addition provides the MIB/SIBs, to the UE.

### 6.14.2 Solution details



**Figure 6.14.2-1. System information protection**

The procedure is as follows.

1. UE sends an initial NAS message to the network.

2. (optional) UE performs a primary authentication with the network.

3. (optional) AMF sends a NAS Security Mode Command to the UE optionally with indication of support for system information protection. If the UE receives the indication of support for system information protection, the UE stores it as part of the security context.

NOTE 1: If the indication of support for system information protection is indicated in the NAS SMC, system information protection is applied to the entire system (i.e., all gNBs in the PLMN).

4. (optional) UE sends a NAS Security Mode Complete to the AMF.

5. gNB sends an AS Security Mode Command to the UE optionally with indication of support for system information protection.

NOTE 2: Support for system information protection is indicated in the AS SMC if it is not supported system wide.

6. UE sends a Security Mode Complete with the hash of the MIB/SIBs. The hash value is both ciphered and integrity protected. Also, the UE indicates the list of SIBs that were used to calculate the hash value.

7. gNB decrypts and integrity checks the AS Security Mode Complete. If the verification is successful, the gNB further verifies the hash of the MIB/SIBs.

8. gNB sends RRC message to UE. The RRC message includes the MIB/SIBs (with the list of SIB #s) if the hash verification has failed in the previous step 7.

NOTE 2: UE may determine to change the cell if a MitM false base station is highly suspected based on the received MIB/SIBs from the gNB.

Editor’s Note: It is FFS how the MitM attack is addressed.

The rest of the procedure is same as in TS 23.502 [13].

### 6.14.3 Evaluation

This solution fulfils the potential security requirement of the KI #2 when the UE is in the RRC-Connected state.

This solution does not fulfil the potential security requirement of the KI #2 when the UE is in the RRC-Idle or the RRC-Inactive state.

Editor’s Note: How to protect the MIB/SIBs when AS security is not supported is FFS.

## 6.15 Solution #15: Mitigation against the authentication relay attack with different PLMNs

### 6.15.1 Introduction

This solution addresses key issue #5: Mitigation against the authentication relay attack, assuming that the victim UE and malicious UE, as defined in key issue #5, are residing in different PLMNs.

### 6.15.2 Solution details

If the victim UE and the malicious UE are located in different PLMNs, then it is not possible to setup a successful registration since the serving network name is part of the key derivation, thus the NAS keys would differ in the victim UE and in the AMF serving the malicious UE. The NAS SMC would fail, but neither UE nor the AMF know why. It is assumed here that the malicious base station does not use the PLMN ID of the malicious UE, since the victim UE would not perform any PLMN reselection to the malicious base station, but rather would camp on it if it is the same PLMN as the surrounding PLMN. This solution tries to capture indications within the three potentially involved networks of the victim UE, the malicious UE and the HPLMN of the victim UE.

Indications in the AMF:

* The AMF receives a Service Request from a completely unknown UE with a wrong GUTI pointing to a different PLMN. The AMF also does not have the security context used by the UE and will reject the NAS message.
* The authentication with the victim UE is successful, but NAS SMC with the victim UE fails since the NAS keys in the AMF and in the victim UE are different. The victim UE may send a Security Mode Reject message with an indication that the integrity check failed of the NAS SMC from the AMF. The malicious basestation or UE may block the reject message since it can be send only in clear.

Indications in the UDM/AUSF:

* The UDM detects that the victim UE suddenly “moves” to a different PLMN. The UDM may compare the time of last successful registration with the new authentication request from the PLMN the malicious UE is located and also may compare the distance. It may be easy for PLMNs in different continents but more difficult with a high density of PLMNs and countries, e.g. in Europe. If the AMF would provide more fine granular location information than the serving network name, then the UDM may be able to perform a better estimation since the last serving cell ID is stored in the UDM with time stamp.
* UDM may get suspicious if the authentication was successful but AMF reports failed NAS SMC.

Indications in the (victim) UE:

* The UE assumes to be successfully registered to the network but receives a reject message to the Service Request.
* The UE performs successful authentication but then is not able to verify the integrity of the NAS SMC.
* The UE may try to inform the AMF with a Security Mode Reject message, but since it is send in clear text, the malicious base stantion or UE could block it.
* The victim UE shall perform cell reselection and start initial registration. The victim UE may internally mark the cell of the malicious base station as an invalid cell so that it does not go back to it at a later time after performing cell-reselection.

The indications could be combined together in the following procedure:



Figure 6.15.2-1: Procedure to detect Authentication Relay Attack in different PLMNs

1. It is assumed that during the RRC establishment procedure (step 1), the victim UE and the malicious UE act independently in the different locations. The malicious UE may be triggered with the first RRC message, RRC Setup Request or RRC Setup Complete. It is further assumed that the Malicious UE replaces the victim UE's S-TMSI (e.g. NG-5G-S-TMSI) from the RRC Setup Request with a malicious UE's S-TMSI in form of a random string. Usually the RRC layer uses a random string when there is no S-TMSI provided from the upper layers (e.g. NAS layer). The Genuine Base station in PLMN#2 and the HPLMN of the Victim UE (UDM/AUSF) do not necessarily need to be the same one. Once the AMF in the PLMN#2 receives the Initial NAS message forwarded from the Malicious UE in step 1, the AMF determines that there is no NAS context (e.g. security, access and mobility context) corresponding to the 5G-GUTI and AMF determines that the 5G-GUTI contains PLMN ID different from the PLMN ID of PLMN#2. The AMF is not able to check the integrity protection of the NAS message and is not able to de-cipher the NAS container. It is assumed that the UE still assumes it is in the same network (PLMN#1), i.e. when the UE has a security context, the UE shall send a message that has the complete initial NAS message ciphered in a NAS Container along with the cleartext IEs with whole message integrity protected. This Initial NAS message may be a Service Request or a periodic/mobility Re-Registration request message because if a UE would perform PLMN selection e.g. due to roaming, then it would send the SUCI in the unprotected initial NAS message since it does not have a security context and a valid 5G-GUTI assigned from the PLMN where the UE camps. Depending on the NAS message, the AMF rejects the request since the UE is unknown in the network and may include an error cause that the 5G-GUTI is invalid. Based on reject message, the Victim UE starts an Initial Registration Request with its SUCI and UE capabilities

2. According to normal procedure the AMF sends a Nausf\_UEAuthentication\_Authenticate Request message in step 5 to the AUSF of the HPLMN of the Victim UE. This message contains also the serving network (i.e. PLMN#2) identifier.

3. The UDM makes a plausibility check whether it is possible to travel from the last known location to the new location within the time when this new registration request occurred. If implemented in the HPLMN, then the HPLMN could already deny the authentication request to the AMF with a location mismatch cause value.

4. The AUSF provides the challenge to the AMF (SEAF), e.g. the AKA’ challenge or the 5G Serving Environment Authentication Vector (RAND, AUTN, HXRES\*).

5. The AUSF will perform normal primary Authentication procedure (e.g. 5G AKA or EAP-AKA’) of the UE

6. Once the authentication is successful, the UE and the AUSF derive in the KSEAF but with different PLMN IDs as input to the KDF, resulting in two different keys in the UE and in the AUSF i.e. KSEAF1 and KSEAF2.

7. The AUSF provides the KSEAF2 to the AMF, which further derives the KAMF and the NAS keys.

A successful authentication procedure always results in a new KSEAF, which means all derived other keys KAMF and for NAS and AS are renewed in AMF and the UE, thus the Security Mode Command procedure needs to be carried out after every authentication procedure.

8. The AMF sends the Security Mode Command to the UE, integrity protected with KNASint2.

9.- Upon reception of the Security Mode Command message, the UE knows that the Authentication procedure was successful. The UE tries to verify the integrity of the Security Mode Command but the UE fails due to the key mismatch of KSEAFs and the resulting KNASint keys, i.e. KNASint1 is different to KNASint2.

10. The UE sends a Security Mode Reject message including an appropriate error cause value, i.e. integrity check failure. The UE may integrity protect the message (e.g. Security Mode Reject) with UE's own derived key KNASint1. This message may be dropped by the False BS or Malicious UE.

11. The AMF can then verify whether it was a transmission failure or a key mismatch in based on the one of the following criteria:

- the AMF receives a Security Mode Reject with the error cause that the UE could not verify the integrity of the previously sent Security Mode Command; and/or

- in addition the AMF is also unable to verify the integrity of the Security Mode Reject from the UE, considering also that the AMF knows that UE performed successful authentication (as received from AUSF in step 6).

- the AMF never receives any answer to the NAS SMC for all retransmissions.

12. The AMF rejects the registration and may indicate to the UE to re-register after a cell or PLMN reselection in order to allow the UE to try from another (perhaps genuine) cell. This message may be dropped by the False BS or Malicious UE.

13. The AMF informs the UDM about the NAS key mismatch. One reason for the key mismatch may be a man in the middle attack. Especially in case the UDM takes into account the result of step 3 and in case the Victim UE changes now to a genuine cell and starts now Initial Registration from PLMN#1 again.  
In parallel the UE performs cell reselection and starts initial registration. The Victim UE may internally mark the cell of the False BS as an invalid cell so that it does not go back to it at a later time after performing cell-reselection.

### 6.15.3 Evaluation

Impacts on the UE:

* NAS SMC reject to the AMF with error cause integrity protection failure.

Impacts on the AMF:

* Detect NAS SMC failure due to key mismatch and notify UDM with error cause NAS key mismatch.

Impacts on the UDM:

* Detect location change in unreasonable time and reject authentication nrequest with error cause location mismatch.

Editor’s Note: Further evaluation is FFS

## 6.16 Solution #16: Protection of RRC Reject Message

### 6.16.1 Introduction

This solution addresses the key issues #1 “Security of unprotected unicast messages” for RRC Reject message protection. The solution provides a means to ensure that a UE is able to determine the authenticity of the RRC Reject message from the gNB regardless of RRC states.

The RRC Reject message is sent on SRB0 without integrity protection, if the RAN is not able to handle the procedure, e.g. due to congestion. The RRC Reject message includes the IE Wait Time, the UE will deny the access until the Wait Time is expired. For IoT UEs, the Wait Time is extendedWaitTime, which can be 30 minute [15]. Thus, a forged RRC Reject message which includes a long value of Wait Time will be a DoS attack to the UE, because once the attacker sends the forged message to the UE, the UE will be in a non-service state for a long time. The attacker does not need to trigger an active MiTM attack.

However, if the Wait time does not exceed a specific threshold value, e.g. 16s, it is not a big issue, since the attacker needs to trigger an active MiTM attack to make the same threat as mentioned above which may be detected by the operator.

Editor’s Note: how to determine and configure the threshold value is FFS.

Thus, the solution proposes to integrity protect the Wait Time according to the value of the Wait Time. If the network wants to reject the UE with a Wait time greater than the specific threshold value (eg.16s), the network shall integrity protect the Wait Time, and the UE will only accept the value after verifying the integrity protection. Otherwise, the UE shall only wait with the specific threshold value no matter what Wait Time indicates. The solution has no backward compatibility issue, and adapts with both RRC\_IDLE and RRC\_INACTIVE case.

### 6.16.2 Solution details

#### 6.16.2.1 Protection of RRC Reject Message in RRC\_IDLE state

UE in RRC\_IDLE state may send RRC Setup Request message to the RAN to establish RRC connection. When the RAN wants to reject the UE when receiving RRC Setup Request, the RAN shall not set the Wait Time greater than a specific threshold value because the RAN has no AS context for this UE.

When the UE receives RRC Reject with a Wait Time, and the Wait Time is less than the specific threshold value (eg.16s), the UE shall directly use the value to deny the access. But when the Wait Time is greater than the specific threshold value, the UE shall check whether there is a RejectMAC-I. If not, the UE shall deny the access for the Wait Time of the specific threshold value. However, if the RejectMAC-I is included, the UE shall verify the RejectMAC-I as described in 6.16.2.2.

#### 6.16.2.2 Protection of RRC Reject Message in RRC\_INACTIVE state

UE in RRC\_INACTIVE state may send RRC Resume Request message to the RAN to establish RRC connection. When the RAN wants to reject the UE when receiving RRC Resume Request, but the RAN has no AS security context locally, which means the RAN will not fetch AS security context from the initial RAN, the RAN shall not set the Wait Time greater than a specific threshold value. However, when the RAN has the AS security context locally, the RAN could set the Wait Time greater than the specific threshold value, and the target RAN shall include the Wait Time and RejectMAC-I in the RRC Reject message.

NOTE 1: If the RAN is busy, the RAN may not fetch UE context from the initial RAN, because it may involve additional Xn signalling overhead. So, for mobility case, the RAN treat it as the RAN has no AS security context.

The RAN shall calculate the RejectMAC-I as similar as calculation in clause 6.2.2 with a new input: target C-RNTI. The target C-RNTI is a freshness parameter and it changes even UE access the same target cell. So the RRC Reject message cannot be replayed.

On receiving the RRC Reject message from the target RAN, the UE shall process as described in 6.16.2.1. If the wait tine is greater than the specific threshold value, the UE shall verify the RejectMAC-I. . If it is successful, then the UE shall deny the access until the Wait Time is expired. If the RejectMAC-I check fails, then the UE shall deny the access for the Wait Time of the specific threshold value.

### 6.16.3 Evaluation

The solution address key issue #1“Security of unprotected unicast messages” for RRC Reject message protection. The solution is applicable for IoT UE or future release UE with long wait time setting.

In this solution, RRC Reject message is only integrity protected when the RAN has UE AS security context locally and the RAN wants to reject the UE exceed a specific threshold value, which means RRC Reject message will not be integrity protected when the UE is in IDLE, or when the UE moves to a new RAN in INACTIVE.

That is because RRC Reject message is usually used to handle UE congestion case, the solution tries to involve minimal computation overhead to protect the UE from being DoS rather than involving big Xn communication overload to fetch UE AS security context. Thus, the solution is a balance between overload and security.

## 6.17 Solution 17: Integrity protection of the whole RRCResumeRequest message

### 6.17.1 Introduction

This solution addresses key issue #1 for the protection against tampering of RRCResumeRequest messages.

### 6.17.2 Solution Details

When the UE initiates the RRC Resume procedure, the UE shall use the whole RRCResumeRequest message, except the ResumeMAC-I/shortResumeMAC-I, as input parameter in order to calculate ResumeMAC-I/shortResumeMAC-I. The UE shall send the calculated ResumeMAC-I/shortResumeMAC-I in the RRCResumeRequest message.

When the gNB/ng-eNB receives the RRCResumeRequest message from the UE, the gNB/ng-eNB shall validate the ResumeMAC-I/shortResumeMAC-I received from the UE.

Editor’s Note: The alignment of terminology for new/ older version is FFS.

Newer network use the newer version of ResumeMAC-I/shortResumeMAC-I only if supported by the UE. Otherwise the network use the legacy version of ResumeMAC-I/shortResumeMAC-I.

Newer UE use the newer version of ResumeMAC-I/shortResumeMAC-I only if supported by both the source and target gNB/ng-eNB. Otherwise, the UE use the legacy version of ResumeMAC-I/shortResumeMAC-I.

The UE and the network negotiate/learn each other's capability/support of using the newer version of ResumeMAC-I/shortResumeMAC-I as below:

- UE's capability is part of an RRC message (i.e., AS SMComplete).

- gNB/ng-eNB's capability is part of a SI message (i.e., SIB1, refer to a closely related feature called useFullResumeID in SIB1).

Editor’s Note: SIB indication needs to be justified.

Editor’s Note: RAN2/RAN3 will be liased for stage 3 details. They could advice if there are other preferable alternatives like UE's capability could be part of a NAS message (e.g., Registration Request) and gNB/ng-eNB's capability could be part of an RRC message (e.g., RRC release with suspendConfig).

The processing overhead of using the whole RRCResumeRequest message as input to one of NIA/EIA algorithms is expected to be minimal.

### 6.17.3 Evaluation

## 6.18 Solution #18: Avoiding UE connecting to False Base Station during Conditional Handover

### 6.18.1 Introduction

This solution addresses the security requirement in key issue #3 for preventing UE from connecting to false base station. Conditional handover is already agreed in RAN2 to support high handover robustness to avoid ping-pong effect, and it is recognized that avoiding UE connecting to fake base station can be supported losslessly. Thus, the solution is proposed to support conditional handover in addition to solution 6.

The solution proposes the similar mechanism with solution 6 to support for conditional handover, i.e. target gNB B assigns a specific CSI-RS to the UE to indicate the UE to measure the real reference signal of the target gNB B, which could avoid the UE to measure false base station. The difference is that the source gNB A sends threshold to the UE to make the HO decision. So, handover decision can be performed on the UE. Thus, additional signalling to report measured signalling is not needed so that handover robustness can be guaranteed, meanwhile, this can avoid UE connecting to false base station during conditional handover.

### 6.18.2 Solution details

#### 6.18.2.1 General

Similar with solution 6, there are two options for this solution:

Option A: Always On feature: In this option the proposed solution is always on and activated at the source gNB; thus it is on on all gNBs.

Option B: On demand feature: The source gNB turns this feature on to a specific target gNB, when the source gNB suspects the presence of a false base station in the area, it automatically turns this feature on.

#### 6.18.2.2 Always on Feature



Figure 6.18.2-1: CHO procedure with indicated second measurement

1. The UEs performs measurement, and sends measurement report including measured signal 1 of this specific cell to the source gNB (A). The measured signal may be fake gNB C’s who forged the same cell to the target gNB B.
2. -2. When the source gNB receives Measurement Report, the measured signal is going to trigger Conditional Handover, the source gNB (A) sends CHO request with a CSI-RS to request the target gNB to prepare a specific CSI-RS for the UE.
3. The target gNB (B) performs admission control and prepares basic RRC configuration information for the UE, including a dedicated CSI-RS information.
4. The target gNB (B) responds with the CHO request ACK message containing all the prepared RRC configuration information (including the dedicated CSI-RS information).
5. Once the source gNB (A) receives the CSI-RS information in the Conditional Handover request ACK, the source gNB attaches threshold of HO.
6. The source gNB (A) sends CHO Command including the dedicated CSI-RS information and threshold to the UE while being protected with RRC security context.
7. The UE executes a second measurement of the dedicated CSI-RS signal indicated in the CHO Command, and get measured signal 2.
8. Based on the signal 2 and measurement condition, the UE decides whether or not to continue the HO. If the signal 2 meets the threshold, that means the real reference signal power of the target cell is strong enough, the UE sends the HO confirm to the target cell, no latency is added. Otherwise, the signal 1 may be fake gNB C’s signal, and the UE will not trigger handover. Thus, the UE will not connect to the false base station.

#### 6.18.2.3 On Demand Feature

The details of the solution in this option is the same as in option A with the difference that this solution is turned on when needed, i.e., on demand. The solution is turned on dynamically according to detection report of network or UE. If source gNB A detects suspicion of false base station nearby or receives suspicion of false base station from the UE, the source gNB A may send CSI-RS request to the target gNB B to turn on this feature. Other fake base station detection method of Key Issue #3 could be used too.

### 6.18.3 Evaluation

The solution addresses Key Issue #3 to avoid the UE connecting to FBS during Conditional Handover procedure.

CSI-RS is used for the UE to do measurement, it is a UE specific parameter which is assigned by the target RAN, and is different for each UE. In the solution, CSI-RS is provided to the UE in a ciphered and integrity protected RRC Reconfiguration message, so, the FBS cannot know this parameter, and cannot forge the right CSI-RS. Thus, the UE will measure true signalling of the target RAN, and will not initiate wrong HO caused by forged cell of FBS.

The solution reuses agreed conditional handover procedure, and requires new signalling overhead. Only new IEs are added, so, the impact is small, and the feature can be always turned on.

Editor’s Note: The solution does not mitigate dumb radio repeater attacks.

Editor’s Note: Further evaluation is ffs based on RAN2 Feedback is needed.

## 6.19 Solution #19: AS security based MIB/SIBs integrity information provided by gNB

### 6.19.1 Introduction

This solution addresses the security requirement of Key Issue #2: Security protection of system information.

The basic idea is to have gNB provide the hash of the MIB/SIBs to the UE after it has established an AS security context. For the initial access, the AS security mode command is the first message that is integrity protected by the gNB, hence is used to carry the hash values of the MIB/SIBs. PCI (Physical Cell Identity) is additionally included in the calculation of the MIB/SIB hash.

UE determines whether it has read the correct MIB/SIBs by comparing the gNB provided hash values with the locally computed ones. If hash mismatch is detected, the UE requests the concerned MIB/SIBs.

### 6.19.2 Solution details



Figure 6.19.2-1. System information protection

The procedure is as follows.

1. UE sends an initial NAS message to the network.

2. (optional) UE performs a primary authentication with the network.

3. (optional) AMF sends a NAS Security Mode Command to the UE optionally with indication of support for system information protection. If the UE receives the indication of support for system information protection, the UE stores it as part of the security context.

NOTE 1: If the indication of support for system information protection is indicated in the NAS SMC, system information protection is applied to the entire system (i.e., all gNBs in the PLMN).

4. (optional) UE sends a NAS Security Mode Complete to the AMF.

5. gNB sends an AS Security Mode Command to the UE with a list of hash values of MIB/SIBs. The hash values of MIB/SIB are generated by additionally including the PCI of the cell.

NOTE 2: Hash of MIB and hash of each SIB are provided separately so that UE can only validate the MIB and SIBs that it has read.

6. UE compares the received hash values of the MIB/SIBs with the locally computed ones and determines whether the MIB/SIBs that it has read are correct.

NOTE 3: UE may determine to change the cell if a MitM false base station is highly suspected based on the received MIB/SIBs from the gNB.

7. UE sends an AS Security Mode Complete optionally including a list of MIB/SIB(s) whose hash mismatch is identified in step 6.

8. (optional) gNB sends RRC message to UE that includes the MIB/SIBs if UE provided a list of MIB/SIB(s) in step 7.

The rest of the procedure is same as in TS 23.502 [13].

### 6.19.3 Evaluation

This solution fulfils the potential security requirement of the KI #2 when the UE is in the RRC-Connected state.

This solution does not fulfil the potential security requirement of the KI #2 when the UE is in the RRC-Idle or the RRC-Inactive state.

This solution does not require any additional key provisioning and setup procedure. This solution only requires transporting the hashes of MIB/SIBs or MIB/SIBs using secure RRC signalling.

This solution allows UE to verify not only the MIB/SIBs that it has already read but also those it would read later time.

This solution requires RAN node to provide the hashes of all MIB/SIBs to UE including those that UE is not interested in.

Since the MIB/SIBs mostly contain the radio configuration information that is used for the UE to make a connection to the network and stay in the connected state, enabling to detect the modification of MIB/SIBs during the connection establishment would significantly reduce the impact of SI modification by false base station.

Further addition of PCI in generation of hashes of MIB/SIBs will make it difficult for the fake gNB to replicate as a real one and also if any modification is done in this operational parameter, leads to failure of the hash verification at the UE. Addition of this parameter will increase the toughness in the fake relay base station to mount the MitM attack and restrict wider range of operation (restricted to a cell).

Editor’s Note: How the solution can work with SI that is modified while the UEs are in connected state is FFS

## 6.20 Solution #20: Digital Signing Network Function (DSnF)

### 6.20.1 Introduction

This solution#20 address the key Issue#2 “Security Protection of system information”.

This solution is similar to solutions #7 and #11 in that they all protect system information blocks with digital signatures. Each cell periodically broadcasts digitally signed system information (SI). A UE makes cell selection based on a number of criteria including the authenticity of broadcasted system information. It differs from solutions #7 and #11 in that it delegates digital signing from gNB to a network function, namely Digital Signing Network Function (DSnF). In other words, it is the DSnF, instead of each cell itself, that compute digital signatures of system information.

While delegated digital signing may appear counter-intuitive, the concept of delegation in security has been applied to other problems on the Internet. For example, many websites use Content Distribution Networks (CDNs) to improve performance and security (e.g., defending against DDoS and web attacks). To use CDN, a website would have to share its TLS certificate and the associated private key with CDN. This is a common practice for many websites but considered unacceptable to some websites (e.g., banks) with high security requirements. CDNs servers are distributed on the Internet and may be located in untrusted locations. Sharing private keys with those untrustworthy servers bear high security risks. To solve this problem, some banks adopted the concept of delegation and implemented so called Keyless SSL [1]. In Keyless SSL, the private key of a website (e.g., a bank) is stored in the website’s secure environment (e.g., HSM) and never shared with a CDN server. When a CDN server needs to use the private key to process data (to decrypt keying material) during TLS handshaking with a client (e.g., a browser), the CDN server sends the data (the encrypted keying material from the client) to the bank website to be processed, receives the results (decrypted keying material) from the bank website, and continue the TLS handshaking with the client.

Similarly, each cell in this proposal does not have the private key for digital signing. It sends the information blocks to the DSnF to be digitally signed. While delay is incurred from delegated signing, we believe it is not an issue since broadcasting information can be pre-signed and signed in batch (see 6.20.2.2.1 for more discussions).

In addition to the difference in who signs the information blocks, this solution differs from solutions #7 and #11 in that timing information that is digitally signed for anti-replay attacks is based on the time of the signing server, not the time of gNB. This removes the need for UE to synchronize time with all gNBs.

This contribution also provides additional consideration on how UE verifies message freshness and performs cell selection and additional security analysis of digital signature-based protection.

### 6.20.2 Solution details

#### 6.20.2.1 Digital Signatures of System Information

System information is digitally signed along with a number of other attributes, including time information (such as a Time Counter as proposed in solution #7), physical cell ID, downlink frequency, etc.

Editor's Note: The exact list of information attributes to be digitally is FFS.

#### 6.20.2.2 Digital Signing Network Function (DSnF)

DSnF exposes service-based interfaces to provide digital signing services to other network functions. The service interfaces can be named such as Ndsnf\_Digital\_Signing\_Request and Ndsnf\_Digital\_Signing\_Response.

Editor's Note: The exact service interfaces need to be further defined.



Fig 6.20.2.2-1 Network architecture of DSnF

##### 6.20.2.2.1 Digital Signing Request

The signing request allows to request for one digital signature or a set of digital signatures.

To request a single digital signature, the request includes a single group of information elements that need to be digitally signed, such as [MIB, SIB1, SIB2, Cell\_ID, Downlink\_Frequency, Time\_Counter].

To request a set of digital signatures, the request can contain a set of information element groups, each of which will be digitally signed. A set of information element group can be aggregated to reduce the size of the request. For example, if all element groups contain the same information elements except Time\_Counter, they can be aggregated to, for example, [MIB, SIB1, SIB2, Cell\_ID, Downlink\_Frequency] | [Starting\_Time\_Counter, Increment\_of\_Counter, Number\_of\_Increments]. This allows a cell to use one request to obtain digital signatures for a certain period of time, e.g., an hour.

A Time\_Counter is generated based on the time of DSnF. When the first time a gNB sends to the DSnF an aggregated digital signing request, the Starting\_Time\_Counter is set to a known value (e.g., 0) so that the DSnF will generate the initial Time\_Counter based on its local time. When the gNB sends an aggregated digital signing request for a next period of time, the Starting\_Time\_Counter can be set to a Time\_Counter received in the response for the current period of time (e.g., set to the last Time\_Counter in the current period of time).

Editor's Note: The exact format and content of the digital signing requests are FFS.

While MIB and SIB1 are broadcasted in high frequencies (e.g., every 40ms and 80ms respectively), their content is likely relatively static. To test this hypothesis, we collected a few days of the MIB and SIB1 from a large mobile operator. The data sets show almost all information elements in MIB and SIB1 stay static except a very few (e.g., SFN) that change. This measurement, albeit preliminary, is encouraging that MIB and SIB1 can be pre-signed.

Some fields (e.g., cellBarred) may change frequently, e.g., during high load scenario.

Editor's Note: How to accommodate fields that can change frequently is FFS.

##### 6.20.2.2.2 Digital Signature Computation

Upon receive a digital signing request, DSnF selects a signing key (if multiple signing keys are supported) and compute the digital signature over the information elements to be protected.

Editor's Note: The digital signature algorithms to be used and how to compute digital signatures are FFS.

##### 6.20.2.2.3 Digital Signing Response

A digital signing response includes one or a set of the digital signatures, along with other information (e.g., public key identifier) to facilitate the verification of the digital signatures.

Editor's Note: The exact format of the response is FFS.

#### 6.20.2.3 gNB Behaviours

A gNB supporting the integrity protection of system information makes periodically digital signing requests to DSnF to obtain the digital signatures of system information blocks and place the digital signatures in a repository where it can be retrieved to be broadcasted along with the corresponding protected system information blocks. For non-occurring SIBs, gNB can send the signing request to the DSnF on demand.

##### 6.20.2.3.1 Requesting Digital Signatures

A digital signing client is proposed on gNB. The client ensures that a digital signature is always available for a system information block under protection prior to the time slot the system information block is scheduled to be broadcasted.

gNB makes digital signing requests via N2 message to AMF/SEAF, which then generates a service request to DSnF. Alternatively, the client on gNB may make a direct request to the DSnF via HTTPS if this is allowed.

Editor's Note: The N2 messages for digital signing requests are FFS.

##### 6.20.2.3.2 Receiving Digital Signatures

gNB receives digital signing responses from DSnF via AMF/SEAF over N2 interface. DSnF may also push digitally signed data to gNB.

Editor's Note: The N2 messages for digital signing responses are FFS.

##### 6.20.2.3.3 Broadcasting Digital Signatures

As proposed in Solution #7, the digital signature of System Information can be carried in another System Information Block. This new SIB includes the digital signature along with supplement information to facilitate the verification of the digital signature. Examples of those supplement information include,

* Information elements indicating the SIBs that are being protected
* information elements for anti-reply attacks, such as PCI, downlink frequency, Time Counter, etc
* information elements for selecting a public key for signature verification, such as key identifier
* information elements for constructing certificate chains if needed
* information elements for signing algorithm selection if multiple digital signature algorithms are supported

Editor's Note: The exact format of the new SIB is FFS.

#### 6.20.2.4 Procedures for digital signature request and response

The overall procedure for gNB to request digital signatures is given below.

Editor's Note: The impact on the N2 interface from digital signing requests and responses is FFS.



Fig 6.20.2.4-1 Procedure for DS request

#### 6.20.2.5 UE Behaviours

There will be two types of UEs based on whether or not they support digital signature verification. If a UE does not support digital signature verification, its behaviour in cell scanning and cell selection remain unchanged. If a UE supports digital signature verification, its behaviour in cell scanning and cell selection needs to be modified to take into consideration the results from signature verification.

##### 6.20.2.5.1 Trust Anchors in UE

To verify the digital signatures from gNBs, UE needs to be preconfigured with a list of trust anchors. To support roaming, the trust anchor of each roaming partner network needs to be preconfigured in the UE. Trust anchors can be raw public keys or public key certificates. If the trust anchor is a raw public key, one trust anchor is required for each roaming partner (unless a key is shared among multiple roaming partners, e.g., those under the control of a common operator). If the trust anchor is a public key certificate, the number of trust anchors in the UE can be significantly reduced if common Certification Authority (CAs) are used among operators.

Trust anchors can be provisioned during manufacturing (e.g., by USIM vendor, chip vendor, or UE vendor). Trust anchors can also be provisioned and updated during registration (e.g., based on the NAS procedure as proposed in solution #7) or over-the-air updates by an operator.

An operator can create its own raw key pairs as the trust anchors, e.g., by reusing the process of generating and provisioning of the key pair for SUPI protection. Note that key pair is for digital signature in this use case, while the key pair for SUPI protection is for key encryption. Thus, their key usages are different, but they can follow the same key generation and provisioning process. An operator can also use public key certificate as the trust anchor instead of raw keys. Public certificates can be a root CA certificates, intermediate CA certificates, or an entity certificate (comparable to a raw public key). Public key certificates can be from operator’s internal PKI or external public PKI.

Editor's Note: the methods of provisioning of trust anchors in UEs are ffs.

##### 6.20.2.5.2 Cell Scanning

UE scans all supported bands and frequencies for available cells. UE stores the Physical Cell Identifier (PCI) computed based on the Primary Synchronization Signal (PSS) and Second Synchronization Signal (SSS) of each scanned cell. UE compares a new scanned PCI with the existing ones to detect conflict. If there is a conflict, the two cells with the same PCI are not used for cell selection or reselection.

Editor's Note: this procedure needs to be discussed with and defined by RAN.

##### 6.20.2.5.2 Verification of Digital Signatures

The UE, if configured with a setting to verify the authenticity of system information, acquires the system information block carrying the digital signatures. UE uses the acquired system information block to determine which other system information blocks are digitally signed. With this information, UE can compute a hash over the protected system information along with supplement information elements in the acquired system information block. UE then uses key identifier to retrieve the public key corresponding to the signing private key. With the computed hash, and the public key, a digital signature can be verified accordingly depending on the digital signing algorithm being used.

Editor's Note: The exact format of the new SIB and signature verification procedure are FFS.

##### 6.20.2.5.3 Verification of Time Counter

To mitigate replay attacks, the freshness of the message needs to be verified. This is usually done by comparing the timer counter in the message against UE local time. If the time difference is within a tolerant window, the message is considered fresh. Otherwise, the message is considered expired.

Such verification is simple. However, it may result in denial of service if the UE time is manipulated (e.g., clock is set to a future time). Note that time variants (e.g., time counters) in the signed messages are generated by DSnF (not by gNBs), which can be trusted to be accurate.

If a newly received time counter fails verification, either the message is replayed, or the UE time is inaccurate (e.g., manipulated). To mitigate the potential time attacks against UE, time counters received from multiple cells can be checked.

More specifically, when the digital signature from each cell is valid but the Time Counters recently received from multiple cells fail verification, the UE checks the consistency of the Time Counters from those cells. If they are close to each other, it indicates the UE time is out of sync with the network. If the Timer Counters are inconsistent, it indicates the presence of attacker (e.g., by replaying old information). In either case, UE can select the cell with the highest time counter, since a relayed time counter will highly likely not be the latest.

If we choose to check the consistency of time counters received from multiple cells, we may not need to check the time counter against UE local time. This may allow to eliminate the need of time synchronization among all UEs and the network.

Editor's Note: The exact format of the new SIB and signature verification procedure are FFS.

##### 6.20.2.5.5 Cell Selection and Reselection

Currently, cell selection and reselection are based on signal strength, i.e., the cell with the strongest signal gets selected. To prevent false base station from being selected, cell selection and reselection procedures need to be improved. More specifically, in addition to signal strength, cell selection and reselection needs to take into consideration of the authenticity and freshness of system information.

Changes to cell selection procedures need to be decided by RAN. But here is an example of how it may work:

UE scans the cells in all supported frequencies, record their PCIs, and measure their signal strengths. Cells with conflicting PCIs are temporarily excluded from the selection process. Assume there are N cells with good signals, which are ordered based on signal strength.

*For each of the N cells:*

*acquire MIB and SIBs;*

*If there is no digital signature, mark the cell as unprotected.*

*If there is digital signature, verify the digital signature and time counter;*

*if both digital signature and time counter are good, proceed with the cell and break; /\* this is the usual case, i.e., in the absence of an attacker \*/*

*if either digital signatures or time counter is bad, mark the signature as bad and store the time counter;*

*go to the next cell;*

*End of for loop;*

By the end of the above procedure, an authentic cell should have been selected in normal scenario. If no cell has been selected, it could be one of the two scenarios:

1. some digital signatures are good but their associated time counters are bad. In this case, select the cell with the good digital signature and the highest time counter.
2. all digital signatures are bad. In this case, the time counters become irrelevant, since they can be forged.

By this stage, if no cell has been selected, it means all cells supporting digital signing have failed the signature verification. The UE is left with two types of cells:

1. cells supporting digital signing but with bad signatures
2. cells not support digital signing at all (no signatures)

Such situation is highly likely due to the tampering of the message by an attacker. From the security perspective, the UE should go temporarily out of service instead of risking the selection a faked cell. Such approach follows the security principle of failing securely, i.e., the integrity of a system shall remain even availability is lost. Note this principle is widely adopted in system security design in which a system upon the detection of attacks often aborts or reboots.

Editor's Note: It is FFS to discuss with RAN about the cell selection and reselection taking into consideration of security related factors.

#### 6.20.2.6 Security Analysis

With the integrity protection of system information, an attacker cannot broadcast arbitrary system information and is forced to replay attacks or denial of service attacks. We also discuss potential downgrade attacks.

#### 6.20.2.6.1 Mitigating Replay Attacks

We consider two types of replay attacks, local replay attacks (LPA) and remote replay attacks (RPA).

Local Replay Attack (LPA) is an attack in which a false base station receives a broadcast information and rebroadcasts the same information. This can ensure that Time Counter in the replayed messages is current. However, it will have to use the same PCI as the original cell. Otherwise, the digital signature verification will fail. When two same PCIs are received by UE, it will detect the conflict and ignore both cells and choose another cell.

In other words, a local replay attack would result in the deselection of a legitimate cell. This would be equivalent to other types of attacks such as radio jamming or bit flipping of a legitimate cell.

Remote Replay Attack (RPA) is an attack in which a false base station records all broadcasting information including signatures from a remote location, tunnel the messages to another location, and re-broadcast. This is often referred to as wormhole attack [2]. In such attack, the PCI used by the false base station may not result in a conflict.

Wormhole attack requires the false base station to have Internet connectivity to receive the broadcasting information from a remote location. This requires the false base station to have a UE component to connect to the legitimate cell. However, the attacker’s UE may also connect to the false base station itself. To prevent the attacker’s UE from connecting to the false base station itself, the attacker usually needs to know in prior the PCI used by the false base station and statically configures the UE to not connect to the PCI used by the false base station. This is how the LTE relay used in aLTEr and IMP4AT attacks is implemented (confirmed by the author). Since in remote replay attacks, the false base station does not know which PCI will be successful, it becomes difficult, if not impossible, for the malicious UE to preconfigure itself. Thus, we consider RPA may not be practical to launch.

Even if remote replay attack is possible, there will be noticeable delay in rebroadcasted messages, due to the transmission and process delay over the tunnel. In other words, the time window during which remote replay attack can be successful is limited. If we choose to check the consistency of time counters among multiple cells, remote replay attacks can also be detected and prevented, since the messages from authentic cells will be more recent than replayed messages.

If needed, additional information such as the location information of each cell can be included and digitally signed in the broadcasting messages to counter the remote replay attack.

#### 6.20.2.6.2 Mitigating Denial of Services

DoS can be mounted by a number of methods, including but are not limited to,

* manipulation of chosen fields in MIB/SIBs,
* arbitrary bit flipping of signed MIB/SIBs,
* replay of signed MIB/SIBs,
* broadcast MIB/SIBs with invalid signatures
* manipulation of timing information in UE or gNBs.

Since MIB/SIBs are digitally signed, DoS based on manipulation of chosen fields in MIB/SIBs (e.g., barred cell) will be detected and prevented.

Arbitrarily overwriting a bit (e.g., using SigOver[3]) in a signed MIB/SIBs will result in the failure of digital signature verification. If broadcasted MIB/SIBs from all cells in a location are all tampered with and the stored MIB/SIBs in a UE have all expired, the UE may be out of service. In this case, it is equivalent to some other known attacks (e.g., tampering with synchronization signals or physical jamming). Such risk appears acceptable in radio networks.

Replaying of signed MIB/SIBs can cause conflict in PCIs which may result in the de-selection of a cell. If there is only one cell in a location, the UE may be out of service. The risk from this type of attack is similar to the bit-flipping attacks.

An attacker can broadcast MIB/SIBs with invalid signatures. UE will detect the invalid signature and try to select another cell. The attacker can then change its frequency and PCI and broadcast MIB/SIBs with invalid signatures again. The UE may think it is trying with a different cell but end up trying with the same attacking cell. This attack is possible if the UE tries to do a cell scanning after each failed cell. To mitigate such attack, the UE shall try with each of the cells from a list obtained from one scan.

If UE’s time is manipulated, e.g., to a time in the future, time counters in all broadcasting messages may fail validation. In this case, UE will select a cell with the most recent time counter to continue to be served.

If the time of a gNB is manipulated, it does not result in any security issues, since the time counters in the broadcasting messages are generated by DSnF, whose time can be trusted.

#### 6.20.2.6.3 Mitigating downgrading attacks

It is expected that gNBs with digital signature protection will be deployed overtime and there will be areas where cells supporting digital signature protection co-exist with cells not supporting this security feature.

An attacker may attempt to intercept digitally signed system information, tampered with the information, e.g., by removing all digital signature related information, and rebroadcast tampered information. This attack is possible but is equivalent to a false base station broadcasting its own faked system information. As long as the protected system information can be received by a UE, UE would prefer protected system information over unprotected information.

A protected gNB may be overloaded if there are too many UEs in the area prefer and select the cell. In this case, normal radio resource management procedure can be invoked by the gNB to limit the number of UEs to be served (e.g., using cellBarred=1). As a result, UEs may have to connect to legacy cells to stay in services if all protected gNB are overloaded. If there is a false base station in this area, it may be able to attract UEs to connect. However, a false base station cannot predict when such congestion would occur. A false base station can also try to proactively cause congestion in protected gNBs to force UEs away from the protected gNBs and then lure the UE to connect to the false base station. However, such proactive attacks could expose the false base station. Overall, security risk from downgrading attacks, albeit low, could exist prior to the full deployment of this solution.

An attacker may attempt to cause the digital signatures from all cells to fail verification. In this case, UE will go temporarily out of services, equivalent to DoS attacks.

### 6.20.3 Evaluation

TBD

## 6.x Solution #x: Title

### 6.x.1 Introduction

TBA

### 6.x.2 Solution details

TBA

### 6.x.3 Evaluation

TBA

# 7 Conclusions

Editor’s Note: This clause contains the agreed conclusions.

## 7.1 Conclusions on Key Issue #1

Following conclusions are made on Key Issue #1 “Security of unprotected unicast messages”:

- It is concluded that no additional normative work is required for the protection against tampering of RRC UE CapabilityInformation messages.

## 7.6 Conclusions on Key Issue #6

Following conclusions are made on Key Issue #6 “Resistance to radio jamming”:

- It is concluded that there will be no further action for Rel-16 as it is stated in the NOTE in the key issue details.

Annex A  
Assessment of system, architectural and security impacts of signing SI messages

## A.1 Introduction

This annex aims to study and assess the system, architectural, and security impacts of signed SI messages in 5G system.

It is important that any solution proposing signed SI messages take a holistic view into account and do not only consider one or few individual parts alone.

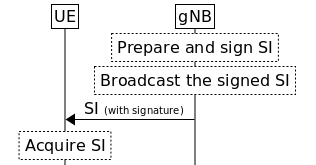
Complexity of solutions need to be assessed against the security and privacy benefits they bring.

Impacts and feasibility on various part of the 5G system (including UE, NG RAN, and 5GC) need to be assessed.

Impacts and feasibility on O&M and key provisioning aspects also need to be assessed.

## A.2 Example architecture

A high-level example architecture could look like Figure A.2-1.



**Figure A.2-1: A high-level example architecture for signed SI messages**

The steps in simplistic terms are described below:

- The gNB prepares and signs the SI message.

- The gNB sends the signed SI message.

- The UE acquires the signed SI message.

- The UE verifies the signature contained in the acquired SI message.

## A.3 Aspects that need to be addressed

### A.3.1a UE Aspects

### A.3.1b UE actions upon detection of invalid signature

Editor’s Note: TBD to explain – in absence of proper recovery action on UE side, benefits of having signed SI messages could be questionable.

### A.3.2 Threats that are mitigated by signed SI messages

Editor’s Note: Explanation is TBD.

### A.3.3 Threats that are not mitigated by signed Si messages

Editor’s Note: Explanation is TBD.

### A.3.4 Provisioning of keys

Editor’s Note: TBD to explain – distribution and storage of public/private keys.

### A.3.5 RAN aspects

Editor’s Note: Explanation is TBD.

### A.3.6 VPLMN aspects

Editor’s Note: TBD to explain – functionalities/responsibilities at VPLMN.

### A.3.7 HPLMN aspects

Editor’s Note: TBD to explain – functionalities/responsibilities at HPLMN.

### A.3.8 Network sharing aspects

Editor’s Note: TBD to explain – aspects related to network sharing.

### A.3.9 Roaming aspects

Editor’s Note: TBD to explain – aspects related to network sharing.

### A.3.10 Regulatory aspects

Editor’s Note: TBD to explain – any regulatory requirements.

### A.3.11 Signature schemes

There could one or more signature schemes like:

- **Scheme A (null-scheme)**

- It means that there is no signature.

Editor’s Note: Further explanations are TBD.

### A.3.12 Signature length

Editor’s Note: Explanation is TBD.

### A.3.13 Resistance against Quantum Computing

Editor’s Note: Explanation is TBD

Annex B (informative):  
Change history

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Change history** | | | | | | | |
| **Date** | **Meeting** | **Tdoc** | **CR** | **Rev** | **Cat** | **Subject/Comment** | **New version** |
| 2018-11 | SA3#93 | S3-183300 |  |  |  | TR skeleton | 0.0.0 |
| 2018-11 | SA3#93 | S3-183799 |  |  |  | Draft TR of TR33.809 | 0.1.0 |
| 2019-02 | SA3#94 | S3-190552 |  |  |  | S3-190274, S3-190554, S3-190068, S3-190555, S3-190 361 | 0.2.0 |
| 2019-03 | SA3#94bis | S3-190960 |  |  |  | S3-190553, S3-190997, S3-190938, S3-190939, S3-190940, S3-190941, S3-190942, S3-190943, S3-190944, S3-190825, S3-190945, S3-190946, S3-190947, S3-180985, S3-190986, S3-190987, S3-190989, S3-191021 | 0.3.0 |
| 2019-05 | SA3#95 | S3-191779 |  |  |  | S3-191195, S3-191620, S3-191781,S3-191782,S3-191780,S3-191790, S3-191240, S3-191241, S3-191789 | 0.4.0 |
| 2019-06 | SA3#95bis | S3-192448 |  |  |  | S3-192447, S3-192410, S3-192449 | 0.5.0 |
| 2019-08 | SA3#96 | S3-193176 |  |  |  | S3-193173 | 0.6.0 |
| 2019-10 | S3#96adhoc | S3-193752 |  |  |  | S3-193329, S3-193331, S3-193334, S3-193488, S3-193576, S3-193602, S3-193753, S3-193754, S3-193756, S3-193757, S3-193759, S3-193760, S3-193836, S3-193837, S3-193845, S3-193846 | 0.7.0 |
| 2019-11 | SA3#97 | S3-194684 |  |  |  | S3-194144, S3-194667, S3-194668, S3-194683, S3-194685, S3-194686, S3-194688, S3-194690 | 0.8.0 |
| 2020-05 | SA3#99-e | S3-201476 |  |  |  | S3-201475, S3-200995, S3-200996, S3-200997, S3-201459,S3-201463 | 0.9.0 |