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| 3GPP TR 33.809 V0.16.0 (2021-8) | |
| Technical Report | |
| 3rd Generation Partnership Project;  Technical Specification Group Services and System Aspects  Study on 5G Security Enhancement against  False Base Stations (FBS)  (Release 17 ) | |
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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:

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

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

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

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

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

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

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

**should** indicates a recommendation to do something

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

**may** indicates permission to do something

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

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

**can** indicates that something is possible

**cannot** indicates that something is impossible

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

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

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

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

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

In addition:

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

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

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

# Introduction

Editor's Note: This clause contains 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

The present document studies the potential threats and privacy issues associated with false base station scenarios.

The present document identifies 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] IEEE 1363.3-2013: "IEEE Standard for Identity-Based Cryptographic Techniques using Pairings"

[9] IETF RFC 6507: "Elliptic Curve-Based Certificateless Signatures for Identity-Based Encryption (ECCSI)"

[10] SM9: "Identity-based cryptographic algorithms SM9"

[11] ISO 29192-4: "SC27 Lightweight crypto using 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"

[17] 3GPP TS 38.413, "NG-RAN; NG Application Protocol (NGAP)".

[18] 3GPP TR 36.355 :"Evolved Universal Terrestrial Radio Access (E-UTRA); LTE Positioning Protocol (LPP)".

[19] Rupprecht, David & Kohls, Katharina & Holz, Thorsten & Poepper, Christina. (2020). "IMP4GT: IMPersonation Attacks in 4G NeTworks". 10.14722/ndss.2020.24283. https://imp4gt-attacks.net/media/imp4gt\_camera\_ready.pdf.

[20] Rupprecht, David & Kohls, Katharina & Holz, Thorsten & Popper, Christina. (2019). "Breaking LTE on Layer Two". 1121-1136. 10.1109/SP.2019.00006. Available online at https://alter-attack.net/media/breaking\_lte\_on\_layer\_two.pdf.

[21] Chlosta, Merlin & Rupprecht, David & Holz, Thorsten & Pöpper, Christina. (2019). "LTE security disabled: misconfiguration in commercial networks". 261-266. 10.1145/3317549.3324927. Available online http://poepper.net/papers/WiSec19-LTEmisconfig.pdf.

[22] Hussain, Syed & Echeverria, Mitziu & Karim, Imtiaz & Chowdhury, Omar & Bertino, Elisa. (2019). "5GReasoner: A Property-Directed Security and Privacy Analysis Framework for 5G Cellular Network Protocol". 669-684. 10.1145/3319535.3354263.

[23] Hojoon Yang, Sangwook Bae, Mincheol Son, Hongil Kim, Song Min Kim, and Yongdae Kim. 2019. "Hiding in plain signal: physical signal overshadowing attack on LTE. In Proceedings of the 28th USENIX Conference on Security Symposium (SEC'19)". USENIX Association, USA, 55-72.

[24] IETF RFC 4082: "Timed Efficient Stream Loss-Tolerant Authentication (TESLA): Multicast Source Authentication Transform Introduction".

[25] IETF RFC 5280: "Internet X.509 Public Key Infrastructure Certificate and Certificate Revocation List (CRL) Profile".

[26] 3GPP TS 22.071: "Location Services (LCS); Service description; Stage 1"

[27] 3GPP TS 38.305: "NG Radio Access Network (NG-RAN); Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN"

[28] A. Sibila, 5G Network Deployment Seminar, March 2019

# 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].

## 3.2 Symbols

Void.

## 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].

# 4 Security overviews 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 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 unauthorized 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 UE Capability Enquiry, 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 #11 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, resume cause field in the RRCResumeRequest message is not protected by the ResumeMAC-I token. This means that the integrity of the resume cause 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 resume cause 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 resume cause field, if an attacker modify the resume cause 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 parameters. If the new gNB is busy, it usually sends RRCReject with a wait timer. When the UE receives the RRCReject message, it goes back to INACTIVE and retry one more time after the wait timer 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 wait timer 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 mechanism 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 should 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 should 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 should 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 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, neighbouring 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.

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 neighbouring cells, and to send self-crafted or old PWS messages.

SA3 has studied the PWS security in TR 33.969 [3], in which the security mechanisms used to protect the Warning notifications message from Public Warning System against false base station can be reference for the study in the present document. There are some distinct challenges when studying the broadcast messages protection 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 does not 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.

### 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 the present 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. A MitM false gNB transports messages between the UE and the network. For example, it may transport security protected messages without any modification while dropping, altering and/or injecting unprotected messages, such as:

- the pre-authentication traffic

- MAC/RLC layer message headers

- lower layer control messages such as buffer status reports

In some situations, a MitM attack mainly works by replaying messages i.e., the MitM sits between the actual base station and a UE and the MitM forwards the messages of the base station towards the UE and the messages of the UE towards the base station. In this position, the MitM might do nothing for a very long time making it very difficult to detect. However, in certain occasions the MitM might inject/alter/drop messages. The basic requirement to defeat MitM attacks is often related to replay protection.

The exact behaviour of a FBS (False Base Station) operating as a MitM false gNB may vary depending on the goals of the attacker. In particular, the degree to which the FBS mimics the impersonated gNB with respect to its radio configuration is unknown. In known attacks that have been done in real networks as a proof of concept rather than with malicious intentions (e.g. [19], [20]), the FBS did not comprise the feature to mimic closely the behaviour of the impersonated gNB. However, this may be different in a true attack, when the attacker takes into account that UE and/or network may implement measures to detect the FBS.

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

Note that the authentication relay attack (Key Issue #5) is a special case of a Man-in-the-Middle false gNB attack, using what can be called a "distributed Man-in-the-Middle false gNB", consisting of a FBS at one location connected to a malicious UE at another location.

A repeater simply forwarding all traffic unchanged is not considered a MitM false base station for the purposes of this key issue. There may be legitimate use for such devices, such as range extension.

### 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.

A MitM false base station may perform a linkage attack by SUCI replay, i.e. replace a SUCI in a registration request or in an identity response by a previously captured SUCI and observe whether the UE will be authenticated and receive service.

When UP integrity protection is not used, a MitM false base station may further perform attacks like aLTEr [20] or IMP4GT [19], i.e. trick the UE into accessing malicious websites or even impersonating the UE on the IP layer, which includes decryption of downlink traffic and performing encryption of faked uplink traffic.

### 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: According to TS 38.331 [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 should 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 should be set to current KRRCint;

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

- DIRECTION : its bit should be set to 1;

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

- MESSAGE : it should 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 should 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.



Figure 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 does not 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 false gNB, therefore the false 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 does not have the security context, the UE gets an RRCReject without MAC-I, it cannot differentiate whether this is a genuine RRCReject message or a false 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 should 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 should 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 should 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 should support the following new information about camped and neighbouring 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 is computed without including the SFN in MIB. It should contain its corresponding recorded time.

NOTE 3: The sib\_info could contain its corresponding recorded time.

NOTE 4: The network can set the requesting frequency for CGI info, similar to the ANR frequency configuration. That is implementation specific.

It is 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 should send the above information to the network only after a successful AS security mode command procedure.

The network should 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: The definition of new information to be included in measurement reports is out of scope of the present document

## 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 should 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 forwards the registration request message of the victim UE to the legitimate base station gNB through the remote malicious UE.

4. The gNB sends 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 stores the Location Info-gNB.

6. The AMF initiates authentication procedure and NAS SMC procedure.

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

8. The victim UE sends the Location Info-UE to the FBS in the uplink NAS message which should be ciphered and integrity protected by the NAS keys in the current 5G security context. The uplink NAS message should 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 should be sent in the initial NAS message, and can be protected by the initial NAS message protection mechanism.

9-11. The FBS forwards 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 should 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 user's actual location information should 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] and [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 prepared RRC configuration information.

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 detaches from the source cell.

Step 7: The UE tries to synchronize and camp on the target cell based on the broadcasted SSB signal (including the synchronization signal and MIB signal) and SIB1. Because the SSB signal and SIB1 are not security protected, the UE cannot 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

##### 6.6.2.2.0 General

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 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 6.6.2.2.1-1: HO procedure with second measurement and HO decision

The source gNB (A) should support to turn 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 verifies the 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 the present document.

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 [9] 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 6.7.2.1, 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 the present document.

#### 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 [2]. 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 6.7.2.3-1) 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 6.7.2.3-2). 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.



Figure 6.7.2.3-1: Cell authenticity verification using other SI



Figure 6.7.2.3-2: 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 6.7.2.4-1.



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 should have signature, e.g., TAIs, PCIs, and Cell IDs. It is proposed that at least the TAIs are included.

3.2) SI numbers which should be covered by the signature. It is proposed that at least the minimal SI (i.e., MIB and SIB1) should 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 clause A.3

#### 6.7.4.1 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:

- On receiving the system information the UE verifies the 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 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.

Identity Based Cryptography for Digital Signature Verification:

- The UE act as the "verifier" (according to the definitions in RFC 6507 [9]).

- UE uses the public key of the CN and the cell ID specific PVT to verify the signature.

Reduce the overhead using other SI:

- Upon UE's request, the other SI may either be broadcast, or provided in a dedicated manner by the gNB.

- The UE checks that the timestamp is within an acceptable time-window before it verifies the signature to prevent replay attacks.

#### 6.7.4.2 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.

#### 6.7.4.3 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.

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

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

#### 6.7.4.5 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 [9] 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.

#### 6.7.4.6 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 the present document.

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 [9] 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 6.7.2.3-1) 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 6.7.2.3-2).

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 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 [9] 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 6.7.2.3-1) 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 6.7.2.3-2).

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.

#### 6.7.4.8 HPLMN aspects

No HPLMN aspects/impacts

#### 6.7.4.9 Network sharing aspects

No Network sharing aspects/impacts

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

#### 6.7.4.10 Roaming aspects

No roaming aspects identified

#### 6.7.4.11 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.

#### 6.7.4.12 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).

#### 6.7.4.13 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.

#### 6.7.4.14 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 does not 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

This solution does not require any changes to the UE so will not need new UEs to enable the service.

This solution uses the servicing base station to detect that a false base station is present within a cell which then can be used to alert the operational teams who manage the serving network. The way in which the operational team locate and mitigate the False Base Station is outside the scope of this solution.

This solution will not prevent the UE from camping on a false base station, however it does not suffer from sevice interruptions due to incorrectly marking genuine basestations as false base stations.

## 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:

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

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

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

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

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

- 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 false cell due to receiving a replayed SI message, the UE will detect that the cell is a false 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 should have the same security requirement as Long Term Key (LTK), which means the USIM should 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 should 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 should 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 should 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 should 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 should 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 should 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 should 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 should 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 should 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 should 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 should be short enough to make the key cracking impossible in time.

The serving network should 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 should 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 should 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 should 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.

NOTE 1: 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 should also send the HASHMS to the USIM, otherwise, the ME should 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.

NOTE 2: 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 should be ready to perform registration procedure. If the UE is ready to send an initial NAS message before timeout, the UE should stop the verification timer. When the UE is ready to send an initial NAS message (due to timeout or not), the UE should 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 should 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 false cell in cache, otherwise remove the cell from the cache. The UE may report the suspect, high-risk, and false 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 truncates 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.

a) 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.

b) 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 should support ECDH, and all the credentials should be preprovisioned.

#### 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.

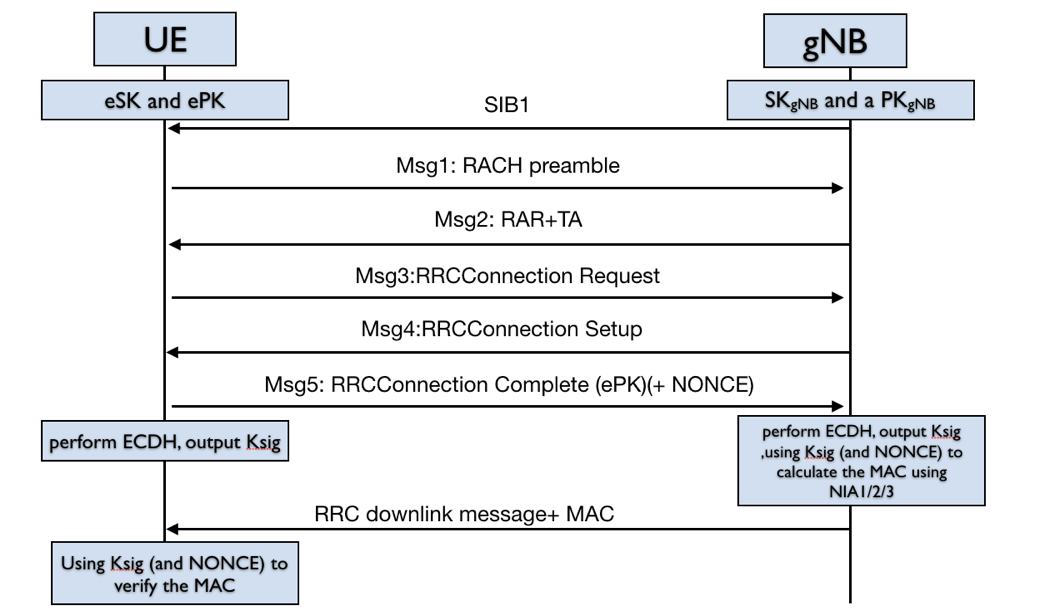


Figure 6.10.2.5-1: Protect unicast message using ECDH and MAC

### 6.10.3 Assessment using clause A.3

#### 6.10.3.1 UE aspects

UE and gNB should support ECDH, and all the credentials should be pre-provisioned, which can be performed in implementation-independed way.

#### 6.10.3.2 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 should drop the message.

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

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

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

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

MitM attack and Bidding down attack.

#### 6.10.3.5 Provisioning of keys

There are 2 methods to provision PKgNB into the UE:

a) The PKgNB can be provisioned into the UE at manufacture time, in USIM or in ME.

b) 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.

#### 6.10.3.6 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.

#### 6.10.3.7 VPLMN aspects

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

However, there will be another choice. If the UE is only pre-provisioned 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. Even though this is not a perfect solution, it is better than nothing, given the fact that people spend much more time in the home network than in the visited network.

#### 6.10.3.8 HPLMN aspects

This solution can detect the FBS in the HPLMN.

#### 6.10.3.9 Network sharing aspects

Not applicable to protection of unicast messages.

#### 6.10.3.10 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

#### 6.10.3.11 Regulatory aspects

TBD

#### 6.10.3.12 Signature schemes

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

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

#### 6.10.3.13 Signature length

MAC length: 32bits.

#### 6.10.3.14 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 Infrastructure). 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' CA public key. UE should 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 should have the capability to support storing more than one CA Root certificate, which can be stored in USIM or other implementation-dependent way.

NOTE 1: 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 provisioned the first certificate.

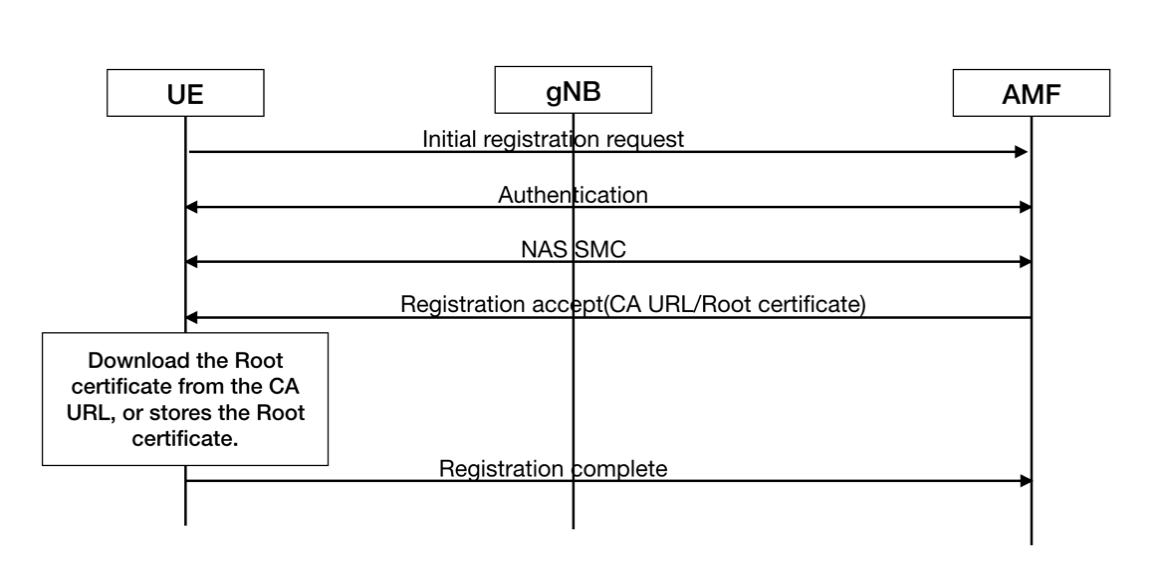


Figure 6.11.2.1-1: AS-based key provisioning procedure

NOTE 2: The vendor can provision a list of Root certificate into the UEs, the length of the list depends 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 should also be given in the message from gNB to the UE to link back to the Root CA. gNB should use its private key to generate signature of the broadcast message, and the gNB certificate should 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 should support the ECDSA (Elliptic Curve Digital Signature Algorithm) [x].

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

#### 6.11.2.3 Procedures

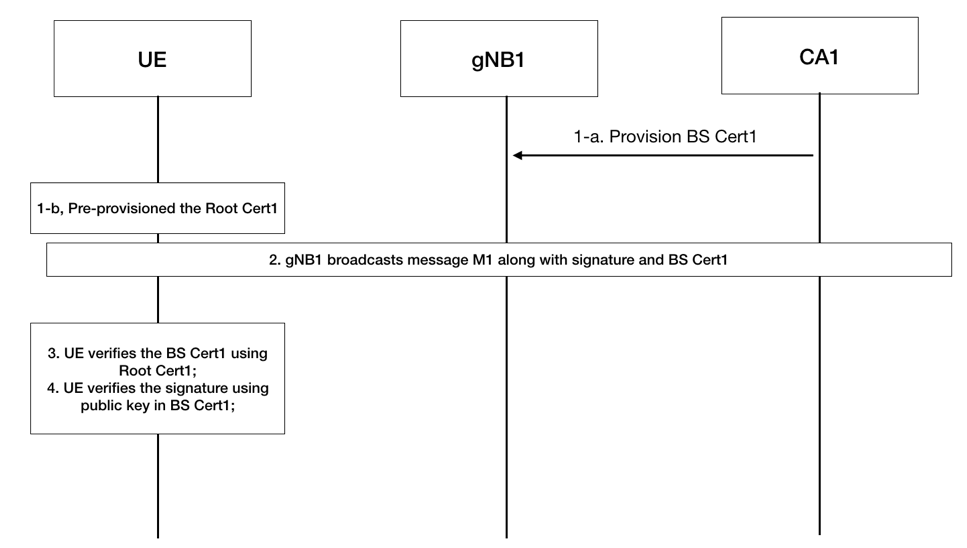


Figure 6.11.2.3-1: Certificate based signature broadcast message procedure

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 should 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 should first verify the validity of the BS Cert1 using the corresponding CA public key. If the UE is provisioned the corresponding Root Cert and the verification fails, it should drop this message.

NOTE: If the UE does not own a corresponding Root Cert for verification, then the UE should 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 cannot 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 cannot 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 should drop this message.

When there is more than one level of CA, for example, the MNO has a Sub CA, and it should 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 [25] could be used for its flexibility, otherwise more compact certificate format such as Card Verifiable Certificate (CVC) can be considered.

The specification should define the certificate profile.

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

### 6.11.3 Assessment using clause A.3

#### 6.11.3.1 UE aspects

UE needs to be pre-provisioned of a list of root certificate.

The provision of the certificate is in clause 6.11.3.5.

The UE should support the storage of the Root certificate.

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

#### 6.11.3.2 UE actions upon detection of invalid signature

If the UE does not own a corresponding Root Cert for verification, then the UE should 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 cannot 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 cannot find a corresponding Root certificate to verify.

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

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

#### 6.11.3.4 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 private keys/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 clause 6.11.2.1. when UE is registered into the network, the AMF in serving network should provision a list of certificates for a bunch of gNBs. If the UE is provisioned the certificate of the gNB, then it should 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.

#### 6.11.3.5 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.

#### 6.11.3.6 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).

#### 6.11.3.7 VPLMN aspects

As stated in clause 6.11.3.4, there are 2 different methods to provision the Root certificates. If the first one is chosen, 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 chosen, 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. Even though this is not a perfect solution, it is better that nothing, given the fact that people spend much more time in the home network.

#### 6.11.3.8 HPLMN aspects

This solution can detect the FBS in the HPLMN.

#### 6.11.3.9 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 may be 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.

#### 6.11.3.10 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 does not support this scheme, then UE will not be protected against false base station.

If the UE's HPLMN cannot 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 clause 6.11.2.1 can be used. Comparing the 1st one, the 2nd root certificate provision method (NAS based method in clause 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 does not carry a signature.

#### 6.11.3.11 Regulatory aspects

The CA construction should follow the local regulatory.

#### 6.11.3.12 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.

#### 6.11.3.13 Signature length

RSA: 256 bytes

ECDSA: 64 bytes

#### 6.11.3.14 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 cryptographic 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 does not require the huge size certificate to be send in the broadcast message. One of these above 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 should 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

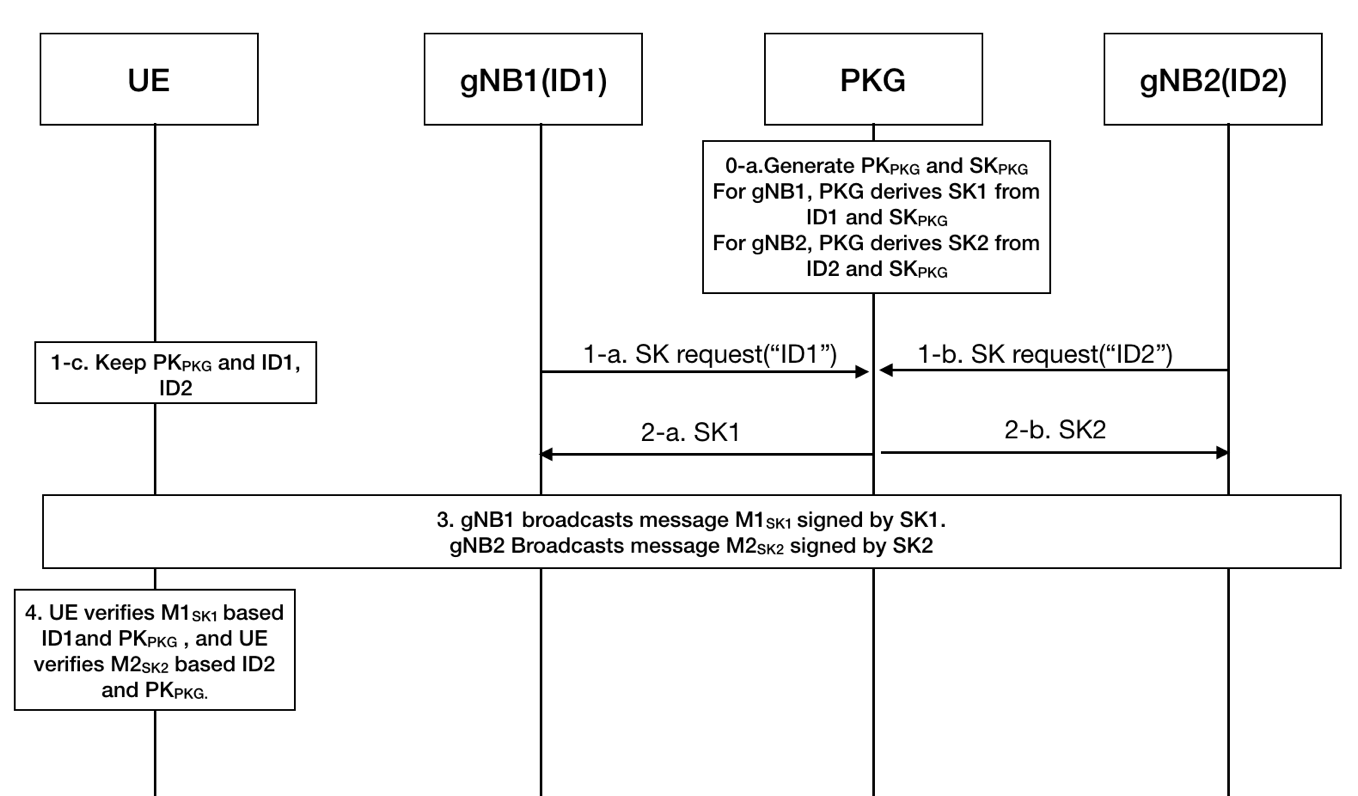


Figure 6.12.2-1: Procedure of ID based solution

0) 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 global 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 1: The format of the ID is FFS. For example, ID = "PLMN ID" | "gNB global unique ID" | "TAC(optional)" |"other information".

1) gNB1 sends request for SK1 with ID1, and gNB2 sends requests for SK2 with ID2. Meanwhile, UE stores the PKPKG and ID1, ID2 when it receives PKPKG and ID1, ID2.

NOTE 2: UE constructs ID1 and ID2 from information received in broadcast messages.

2) PKG sends SK1 to gNB1, and sends SK2 to gNB2.

3) When gNB1 needs to broadcast messages, it uses SK1 to sign this message; When gNB2 needs to broadcast messages, it uses SK2 to sign this message.

4) UE uses PKPKG and ID1 to verify the message from gNB1, and uses 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 drops this message. If the UE is not provisioned the valid PKPKG, the UE should be provisioned 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 should send the new ID to request for a new SK, as step 1 in clause 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 clause A.3

#### 6.12.3.1 UE aspects

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

The provision of the PKPKG is in clause 6.12.3.4.

The PKPKG should be stored in USIM.

UE should support the update of the PKPKG.

#### 6.12.3.2 UE actions upon detection of invalid signature

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

If the UE is not provisioned the valid PKPKG, the UE should be provisioned 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.

#### 6.12.3.3 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.

#### 6.12.3.4 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.

#### 6.12.3.5 Provisioning of keys

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

a) The PKPKG can be provisioned into the UE at manufacture time.

b) 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.

#### 6.12.3.6 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].

#### 6.12.3.7 VPLMN aspects

As stated in clause 6.12.3.4, there are 2 different methods to provision the PKPKG. If the first one is chosen, the UE needs to be provisioned into PKPKG, then his solution works for VPLMN/roaming cases. If the second method is chosen, 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 pre-provisioned 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. Even though this is not a perfect solution, it is better that nothing, given the fact that people spend much more time in the home network.

#### 6.12.3.8 HPLMN aspects

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

#### 6.12.3.9 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 may be 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 2,976 bit[1], so if the message allows, the SIB can carry as much as it can to verify the authenticity of the SIB.

#### 6.12.3.10 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.

#### 6.12.3.11 Regulatory aspects

TBA

#### 6.12.3.12 Signature schemes

There could one or more signature specification like:

- BLS [12]

- IEEE 1363.3 [8]

- RFC 6507 [9]

- SM9 [10]

- others

Editor's Note: Further explanations are TBD.

#### 6.12.3.13 Signature length

BLS [12]: 160 bit

SM9 [10]: 520 bit

#### 6.12.3.14 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 should 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 should 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 should 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. The PCI of the cell is additionally included when generating the hash values of MIB/SIB, but the SFN in MIB should not be included.

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 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.

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 base station 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 station or UE could block it.
* The victim UE should 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 should 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, since this message would lead to a key mismatch in UE and AMF for the integrity protection of the NAS message.

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, i.e. as all messages in step 10 may be dropped.

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.

The serving network has the best information about the NAS protocol and the potentially dropped messages as well as the integrity failure of the NAS SMC due to key mismatch.

The UDM can take the information of the AMF into account as well as the sudden PLMN changes within a short timeframe since the last UDM update. The UDM may use the information from the AMF for the detection of an authentication relay attack in order to enhance the precision of the detection, since it is very likely that a UE is a victim of an authentication relay attack if all factors are taken into account. The UDM may check whether other UEs were concerned previously with the same issues and trying to register to the same serving network, i.e. camping at the same false base station and being relayed to the same malicious UE.

### 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 that the UE sends an invalid 5G-GUTI from another network in the initial NAS message.
* Detect that the authentication procedure is performed correctly with the UE.
* Detect NAS SMC failure due to key mismatch and notify UDM with error cause NAS key mismatch, or that NAS SMC procedure is never performed due to dropped messages.
* Provide information about the probability of an attack to the UDM

Editor's Note: How the AMF estimates the probability of an attack is FFS.

Impacts on the UDM:

- Detect location change in unreasonable time and reject authentication request with error cause location mismatch. The location change is on PLMN granularity and the definition of reasonability is left to implementation, e.g. changes between neighbour countries may not lead to an alarm.

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 minutes [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 should integrity protect the Wait Time, and the UE will only accept the value after verifying the integrity protection. Otherwise, the UE should 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 should 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 should directly use the value to deny the access. But when the Wait Time is greater than the specific threshold value, the UE should check whether there is a RejectMAC-I. If not, the UE should deny the access for the Wait Time of the specific threshold value. However, if the RejectMAC-I is included, the UE should verify the RejectMAC-I as described in clause 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 should 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 should 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 should 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 should process as described in clause 6.16.2.1. If the wait tine is greater than the specific threshold value, the UE should verify the RejectMAC-I. . If it is successful, then the UE should deny the access until the Wait Time is expired. If the RejectMAC-I check fails, then the UE should 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 decides to resume the RRC connection to transit from RRC\_INACTIVE to RRC\_CONNECTED, the UE should use the whole RRCResumeRequest message, except the ResumeMAC-I/shortResumeMAC-I, as an additional input parameter to the VarResumeMac-Input part in order to calculate ResumeMAC-I/shortResumeMAC-I. The UE should 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 should validate the ResumeMAC-I/shortResumeMAC-I received from the UE.

The terms of legacy UE, legacy gNB/ng-eNB, and legacy network respectively refer to the UE, gNB/ng-eNB, and network that supports only the Rel-15 (legacy) version of ResumeMAC-I/shortResumeMAC-I.

The terms of newer UE, newer gNB/ng-eNB, and newer network respectively refer to the UE, gNB/ng-eNB, and network that support the newly proposed way of ResumeMAC-I/shortResumeMAC-I calculation and handling.

A newer network uses the newer version of ResumeMAC-I/shortResumeMAC-I only if supported by the UE. Otherwise the network uses 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 should indicate its capability of supporting the new version of ResumeMAC-I in SI message (i.e., SIB1, refer to a closely related feature called useFullResumeID in SIB1).

- gNB/ng-eNB should also indicate its capability of supporting the new version of ResumeMAC-I in RRCRelease message with SuspendConfig, which is sent after AS SMC thus protected.

In this way, UE receives source gNB/ng-eNB’s capability in both SIB message and RRCRelease message, among which RRCRelease message is protected and can be trusted. UE receives target gNB/ng-eNB’s capability of supporting new ResumeMAC-I (e.g. forwarding the new ResumeMAC-I and the whole ResumeRequest message to the source gNB/ng-eNB for verification) in SIB message, but not in RRCRelease message.

If UE receives both source and target gNB/ng-eNB’s capability of supporting new ResumeMAC-I, UE will include the new new ResumeMAC-I in the ResumeRequest.

If either source or target gNB/ng-eNB doesn’t indicate its capability of supporting new ResumeMAC-I, then UE will use legacy ResumeMAC-I in the ResumeRequest.

In any case that the target gNB/ng-eNB rejects the ResumeRequest, it shall indicate the reject cause (e.g. wrong version of ResumeMAC-I) and the original “resumecause” in the Resume Reject message to make UE to verify.

NOTE 1: Since Resume Reject message is not protected, it is still possible for attackers to modify this message. However, adding the reject cause and the original “resumecause” can be taken as the enhancement. Besides, when the reject message is protected in the future, this enhancement will be reliable from then on.

NOTE 2: The protection of the Resume Reject message will be discussed separately.

Editor's Note: RAN2/RAN3 will be liaised 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

This solution fulfils the security requirement in key issue#1, which is “The 5G system should have support for protection against tampering of RRCResumeRequest message.” If both the UE and the source/target gNB/ng-eNB support this solution, this solution helps to detect the tempering of the RRCResumeRequest message.

This solution has an impact on UE, source/target gNB/ng-eNB. To support the new calculation for ResumeMac-I, both network and UE have to support the feature and it should be known in both the network and UE when it is to be used.

The ResumeMac-I verification is done by the source gNB and not the target gNB. Further, the ResumeRequest message itself is not sent over the Xn interface by the target gNB to the source gNB. The current Xn specification does not provide the full ResumeRequest message to the source gNB to calculate the ResumeMac-I using the new method. Hence the target gNB needs to be updated to provide the full ResumeRequest message over Xn. Hence to support the new calculation of ResumeMac-I, the:

• Target gNB needs to provide the full ResumeRequest message to the source gNB

• Source gNB needs to support the new calculation and handling of the full ResumeRequest message from target gNB.

Hence both the source gNB and target gNB should support the new mechanism.

## 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. RAN2 TS 38.331[2] supports high handover robustness to avoid ping-pong effect, and it is recognized that avoiding UE connecting to false 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 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 6.18.2.2-1: 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 false 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 false 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 false 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 false 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 false 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, it is not an issue since broadcasting information can be pre-signed and signed in batch (see clause 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.

More specifically, the (single) signature is calculated over the following information attributes:

* PCI (PSS, SSS)
* MIB
* SIB1
* Time counter
* Downlink frequency

Other SIBs can be signed along with SIB1 or individually depending on their periodicity.

Signing of dynamic fields such as SFN are described in clause 6.20.2.2.1.

#### 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.



Figure 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, a few days of the MIB and SIB1are collected 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. To accommodate such fields, at least three options can be considered:

First, if such field is of short length (e.g.,1-bit for cellBarred), signatures can be precomputed for all possible values of such field during the window it is expected to change. For example, if cellBarred flag is to change for a certain period of time, signatures can be generated for both cellBarred=0 and cellBarred=1 for such period. A signature needs to be paired with its corresponding input value so that it can be selected properly for a given input. This results in double the number of signatures for this period. Note this option is not scalable in case multiple fields are changed.

Second, when some fields in a SIB are to change, new signatures can be requested from DSnF. Usually SIBs do not change often (e.g., unchanged for about 3 hours). In the special case (e.g., in high load), SIBs may change more frequently than usual, but the interval between changes is usually reasonable to allow UE to be paged to reacquire a new SIB. Thus, it should also allow a gNB to request new digital signatures from DSnF.

Third, a temporarily public and private key pair and a short-live certificate (e.g., valid for an hour) can be issued by DSnF to a gNB during such circumstance to allow gNB to generate the signatures itself. This short-live certificate can be signed by the DSnF digital signing certificate, thus chained to the trust anchor. Although it is usually a CA certificate that issues another certificate, IETF is working on to allow an entity certificate (such as the DSnF certificate) to sign a short live certificate. Security risk from compromising a private key associated with a short-live certificate is minimal since it expires quickly.

Editor's Note: how to broadcast short-lived certificate 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.

##### 6.20.2.2.4 Short-term Certificate: request and usage

A concrete instantiation of the short-term certificates taking into account how to achieve efficient replay protection and low overhead towards the DSnF is as follows.

Each base station has to send a request to sign static information to the DSnF where the static information is considered to remain static during 10.24 s, i.e., the time it takes for the SFN to repeat. Upon reception of the signing request, the DSnF signs the static fields of the SI as well as (i) DSnF starting time for which this set of data is valid, the gNB's SFN value for this DSnF starting time (T\_DSnF(gNB's SFN=0)), as well as a short-term public-key that can be used by the UE to verify dynamic data signed by the base station in this period of time of 10.24 s. The DSnF sends this signed data, whose validity is limited to 10.24 s, together with the private key associated with the signed short-term public key to the gNB.

When a period of 10.24 s starts, the gNB starts broadcasting the short-term certificate for this period of time. It is left for normative phase in which SIB this information is broadcasted. Furthermore, the base station broadcast the SI dynamic fields, in particular the SFN, that are signed with the corresponding short-term private key associated to this period of time.

Upon reception of both static and dynamic data, the UE can obtain the time in which the SI has been broadcast (T\_Broadcast\_SI) as

T\_Broadcast\_SI = T\_DSnF(gNB's SFN=0) + 10\*SFN

The UE checks the freshness of T\_Received\_SI comparing it with its current UE time.

There are two main alternatives for the signing technology used in the short-term certificates:

An option is to use the same type of algorithm as in the DSnF.

NOTE: Since the digital signature only needs to remain valid for a short period of time, 10.24 s, the key sizes can likely be shorter, e.g., an ECDSA curve with a length of 224 (equivalent security of 112 bits) might be used instead of a curve of length 256 (equivalent security of 128 bits). This improves performance, e.g., it decreases the communication overhead. Specific parameters are out of scope of the present document and would be defined in the normative phase.

Another option is the use a type of hash chain solution as TESLA. In a concrete instantiation, the DSnF signs the anchor of a hash chain with 64 links assuming that a hash chain link is needed every 160 ms, i.e., each step of 16 SFNs is linked to a new hash chain link (see note 2). This hash chain is then h64 🡨 h63 🡨 …🡨h1 🡨h 0 🡨 seed where h64 is the public anchor of the hash chain and seed is the secret seed of the hash chain. h0=HASH(seed) and hi = HASH(h{i-1}) with i = 1, …, 64 and HASH() is a cryptographic hash function. The public anchor is signed by the DSnF as part of the static data and is the seed of the hash chain is provided to the gNB in a secure way. When the base station broadcasts a message, it discloses the message authentication code (MAC) that is computed with hash chain link that is only disclosed in the following message. For instance, the first message M0 will contain the current values of dynamic fields denoted here as m0, a MAC of the dynamic fields computed with h63. Next to it, M0 also includes the current hash chain link, in this case, this corresponds to the anchor h64, i.e.,

NOTE 2: This fits the periodicity of 160 ms of SIB1 as described in TS 38.213, clause 13. A higher frequency can be used if it decided to sign MIB/SIB1 more frequently in order to allow UEs to take a decision faster regarding the trustworthiness of a base station.

M0 = m0, h64, MAC(m0, h63)

The UE needs to buffer m0 and the MAC that can be verified in the following timeslot (after 160 ms) when the following message M1 = (m1, h63, MAC(m1, h62) is received. In particular, the verification consists in checking: (i) whether h64 = HASH(h63) and the message authentication code is correct.

The following diagram illustrates how MIB and SIB1 are digitally signed by DSnF and how a hash chain is generated and used to verify dynamic fields (e.g., SFN). It shows that MIB can be extended to include some bits of a MAC if not a complete MAC due to its constraint in size, and SIB1 can be extended to include a MAC. When the MAC is included in MIB or SIB1, the corresponding hash key used to generate the MAC may be disclosed in a new SIB that is broadcasted after SIB1. In this way, a UE can verify both static and dynamic fields after acquiring the new SIB.



Figure 6.20.2.2.4-1: Authentication of MIB and SIB1 with a combination of digital signature and TESLA

#### 6.20.2.3 gNB Behaviours

##### 6.20.2.3.0 General

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.

Two new NG RAN procedures can be defined between gNB and AMF/SEAF to support the signing of SIBs by DSnF.

* SIB Digital Signing Request: gNB to AMF/SEAF
* SIB Digital Signing Response: AMF/SEAF to gNB

These procedures use non-UE associated signalling, as with some other NG-RAN procedures (e.g., Uplink/Downlink RIM Information Transfer [17]).

##### 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 gNBs to request digital signatures is given below.



Figure 6.20.2.4-1: Procedure for DS request

SIB Digital Signing Requests and responses have impact on the N2 interface by consuming network bandwidth and adding processing overhead.

The actual bandwidth consumption depends on the frequencies of signing requests and responses being exchanged between gNB and AMF. Static fields are signed by DSnF and dynamic fields (e.g., SFN) are signed by gNB (e.g., using secondary signing keys such as a short-lived key pair of shorter key length or symmetric keys as used in TESLA [24]). Periodicity of DSnF signing of static fields and secondary signing keys is the maximum duration of SFN cycle, which is 10.24 seconds (10 ms x1024). This means that a DSnF signed messages can be rebroadcasted for every 10.24 seconds.

Editor Note: Evaluation of the usage of the TESLA protocol is FFS.

Further assume that a SIB is of maximal size of 2976 bits (372 bytes) [2] and the digital signature algorithm is 256-bit ECDSA with the digital signature of 64 bytes. It is assumed that the response also contains secondary signing keys. If TESLA is used, the secondary signing keys are a chain of 1023 keys of 256bit each. However only the first key on the chain needs to be sent by DSnF to gNB, since the rest keys can be computed from the first key. Note the last key is signed by DSnF as the anchor key, and the rest keys on the chain are used in reversed order to sign dynamic fields (e.g., SFN). In this case, a signing response is of 192 bytes (64 bytes + 32 bytes) considering only the signature and the secondary signing keys. If a short-lived key public key is used to sign dynamic field, the response would be larger.

Without considering the overhead from other data (e.g., packet headers), the bandwidth consumption for each request and response is of 372 bytes and 64 bytes respectively.

Without considering response aggregation, there would be 8438 (24x3600/10.24) signing requests and responses exchanged between a gNB and an AMF. Without considering the bandwidth overhead from other accompanying data in each request and response, the total bandwidth consumption from signing requests and responses are about 3.2 MB and 0.8 MB respectively. When the number of SIBs to be protected increases, the bandwidth consumption from a signing request increases. When signing requests are aggregated, bandwidth consumption from a signing request is reduced. For example, if each signing request asks for 60 digital signatures (to be used for next 10 minutes), the bandwidth consumption from sending signing requests would be reduced by 60 folds to 50K bytes per day.

From AMF perspective, one AMF may interact with a number of gNBs. Thus, the bandwidth consumption at the AMF is proportional to the number of served gNBs and the number of cells configured at each gNB and inversely proportional to the number of requested signatures in each signing request. The table below provides bullbalk estimates of bandwidth and processing overhead at AMF, based on the estimation at gNB (with one configured cell) as described above.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Frequency of broadcasting a new signature | Total # of signatures required per day | # of signatures asked per signing request | Total # of signing requests per day | Total bandwidth overhead (bytes) at gNB per day | # of served gNBs per AMF | Total # of messages processed at AMF | Total bandwidth overhead at AMF (bytes) |
| Every 10.24 seconds | 3600 x 24/10.24=8438 | 1 | 8438 | Signing Requests: 3.2M  Signing responses: 0.8M | 100 | Signing requests from all gNB:  =  Signing responses to all gNB:  =  843,800 | Signed requests from all gNB: 314M  Signing responses to all gNB: 81M |
| 1000 | Signing requests from all gNB:  =  Signing responses to all gNB:  =  86,400,000 | Signed requests from all gNB: 32G  Signing responses to all gNB: 800M |
| 60  (each request asks 60 signatures to be used for 10 minutes) | 6x24=144 | Signing Requests: 50K  Signing responses: 0.8M | 100 | Signing requests from all gNB:  =  Signing responses to all gNB:  =  144,00 | Signed requests from all gNB: 5.4M  Signing responses to all gNB: 81M |
| 1000 | Signing requests from all gNB:  =  Signing responses to all gNB:  =  1,440,00 | Signed requests from all gNB: 53.6M  Signing responses to all gNB: 800M |

Although gNB needs to send signing requests and receive signing response periodically, a constant connection between gNB and AMF may or may not need to be maintained. In the example used above, a gNB sends a signing request to AMF every 10 minutes. A constant connection could be maintained between gNB and AMF, but such connection could also be closed and reopen for each request. Optimization can be left to implementation.

#### 6.20.2.5 UE Behaviours

##### 6.20.2.5 General

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.

There are four models of establishing Certification Authorities to support the signing of SIB messages, which have been adopted by other industries.

First, a common root CA is established among global mobile industry to issue intermediate CA certificates or signing certificates to each mobile operator, and GSMA appears suitable for hosting such root CA. This model is adopted by the cable industry.

Second, regional root CAs are established to serve mobile operators within that specific region. This model is adopted by Internet Registries (RIR) to support Resource Public Key Infrastructure (RPKI) for validating IP prefix origin in the Border Gateway Protocol (BGP), with each of the five Regional Internet Registries (RIR) hosting its own root CA.

Third, one or several security companies can be selected by the mobile industry as the trusted third party to issue intermediate CA or signing certificates to mobile operators. Since mobile operators have been partnering with SIM card vendors for long time, SIM card vendors appear suitable for hosting such root CAs. This model is adopted by WiFi Alliance.

Fourth, each mobile operator establishes or leverages its current CAs to issue signing certificates. Many mobile operators already have internal CAs for other purposes, which can be leveraged to sign system information. For scalability analysis of a CA model, the total number of trust anchors resulted from a CA model needs to be considered.

In the first model, there is a common root CA for all operators. Thus, only one trust anchor is required.

In the second model, regional root CAs are used by the operators in each region. The number of trust anchors depend on the number of regions involved. For RPKI, there are five regions resulting in five trust anchors. If each country is considered a region and share a common CA, there would be about 180 trust anchors.

In the third model, public CAs are leveraged to issue public certificates for operators. Thus, the number of trust anchors depend on the number of public CAs that are chosen by mobile industry for this service, which could be in the range of a few to tens.

In the fourth model, each operator establishes its root CA without depending on any third party. The number of trust anchors depends on the number of roaming partners chosen by an operator, which is usually around 300. In an unlikely case that a mobile operator chooses every mobile operator in the world as its roaming partner, the number of trust anchors would be about 1250 according to GSMA.

To summarize, In the most efficient scenario (i.e., model 1), only ONE single trusted anchor is needed. in the least efficient scenario (i.e., model 4), there will be about 300 to 1250 trust anchors.

These four models are not mutually exclusive and can also be adopted in a hybrid manner, based on the preference of each operator. Thus, a realistic number of trust anchors will be fewer than three hundreds. The end result is a list of CA certificates, which can be exchanged among roaming partners or via a trusted third party (e.g., GSMA). For example, GSMA provides a Network Settings Exchange program, which can be leveraged to maintain the list of trusted CA certificates.

This list of CA certificates needs to be provisioned into UEs as trusted anchors to allow UEs to verify signatures carried in the SIB messages. The following table provides the storage requirement of an ECC CA certificate of different key size and security level:

Table 6.20.2.5.1-1: Brainpool-r curves and ecdsa-with-SHA256

|  |  |  |
| --- | --- | --- |
| Key size (Bit) | CA Certificate | |
| DER Format (bytes) | PEM Format (bytes) |
| 160 | 462 | 680 |
| 192 | 513 | 749 |
| 224 | 530 | 774 |
| 256 | 545 | 794 |
| 320 | 577 | 839 |
| 384 | 609 | 879 |
| 512 | 677 | 973 |

Assuming a key size of 256-bit, the total storage requirement of trust anchors in the best case, normal case, and worst case of roaming scenarios is 545x1 bytes, 545x300=160K bytes, and 545x1250=665.3K bytes respectively.

Since USIM has limited memory space, it may not be possible to store all needed trust anchors inside the USIM if the number of the needed trust anchors is high. Thus, shared CAs appear desirable or alternative secure storage may be used to store trust anchors.

Since such a list is public information and available to both operators and vendors, it can be provisioned into UEs during manufacturing (e.g., by USIM vendor, chip vendor, or UE vendor). Trust anchors can also be provisioned during UE onboarding and updated after registration (e.g., based on the NAS procedure as proposed in solution #7) or over-the-air updates by an operator. This allows for deployment flexibility and trust anchor update when the home operator or any of its roaming partners changes its trust anchor.

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.

Editor's Note: It is FFS which CA model(s) described above will be adopted by 3GPP and how and where they would be standardized.

Trust anchors and DSnF certificates should include a scope (e.g., PLMNs, physical areas, etc) and the scope of a DSnF certificate is supposed to be within the scope of the issuing trust anchor. When a UE receives a signed broadcasted SI, it verifies not only the signature of the signed SI, but also the certificate chain from the signing certificate (e.g., DSnF certificate) toward a trust anchor, including verification of the scope within each certificate on the chain. The specific parameters of certificate scope can be specified during normative phase.

For instance, a UE might contain a trust anchor associated to an NPN located in a very specific area. It is extremely important to check that the private key associated with the DSnF certificate issued by this NPN trust anchor is not misused to sign SI outside the scope of the NPN designated area.

##### 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 UE should obtain a direct time indication from the DSnF (as described in Section 6.20.2.5.3), and use this to verify the consistency of received time counters (as described in Section 6.20.2.5.5).

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

##### 6.20.2.5.3 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.

##### 6.20.2.5.4 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 the consistency of time counters received from multiple cells is checked, the time counter may not be checked against UE local time. This may allow to eliminate the need of time synchronization among all UEs and the network.

In the following situations it would be beneficial for a UE to obtain a direct time indication from the DSnF:

1) A UE has access to too few base stations, e.g. a single base station.

2) A UE detects multiple cells with the same PCI.

3) A UE observes time values broadcasted by multiple base stations, but those time values are not close to each other, indicating a possible attack.

4) A UE observes time values broadcasted by multiple base stations, the values are close to each other, but the freshness checks fail.

5) A UE requires high security level and it requires a 100 % trusted time source,

6) It is the first time a UE is started, or

7) The UE requires learning the DSnF time very quickly, i.e., without scanning all frequencies.

In the above situations, the UE should follow the subsequent (high-level) process: the UE scans looking for cells. As soon as it detects a base station with a high enough received signal strength, the UE acquires MIBs and SIBs and checks the signature. If the signature is valid, then, the following (high-level) protocol is triggered:

- UE computes a nonce, e.g., a randomly generated 128-bit long number and sends it to the DSnF as part of a request message to the DSnF for a reference time. At the time of sending, the UE starts a timer, denoted UE\_timer. The DSnF signs the received nonce and its current DSnF time (Signed\_DSnF\_time), and possibly other information such as any known processing time at the DSnF (e.g., time required to compute the digital signature). The DSnF sends the signed information back to the UE.

NOTE: For requesting and receiving a signed reference time from the DSnF, existing protocols such as NTP could be re-used. Further details can be left to stage-3.

- The UE stops its timer upon reception of the message. The UE checks the validity of the signature and the presence of the nonce it included in the first message. If both checks are correct and the UE\_timer does not reach a maximum time threshold, e.g., 40 ms., the UE uses the received reference time for further processing (as described in clause 6.20.2.5.5). If the protocol does not return a reference time, e.g., because no reply is received, the UE can then perform certain actions. As a first step, the UE can retry a number of times. If no message is received, the communication with the base station is aborted.

This protocol should be triggered as soon as feasible before any UE related information is disclosed, for instance, the nonce could be sent together with the RRCSetupRequest or with the NAS identity response. DoS countermeasures can be incorporated to prevent an attacker from misusing this protocol to perform DoS attacks, e.g., against the DSnF.

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. . In case a UE detects cells with conflicting PCIs, the UE should temporarily exclude these cells from the selection process and obtain a reference time indication directly from the DSnF and use this to verify the consistency of received time counters. 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 following scenarios:

a) some digital signatures are good but their associated time counters are bad. In this case, assuming no duplicate PCIs were detected, select the cell with the good digital signature and the highest time counter.

b) all digital signatures are bad. In this case, the time counters become irrelevant, since they can be forged.

c) cells had conflicting PCIs and were temporarily excluded from the selection process. In this case, the UE may further analyse these cells and check if the signatures are valid. If so, the UE may keep the cell with the most recent system information/time and exclude the cell with older system information/time. If all remaining cells have the same PCI and the same time counter, the UE should ignore these cells.

By this stage, if no cell has been selected, it means all cells supporting digital signing have failed the signature verification or have conflicting PCIs and same time counter. The UE is left with three types of cells:

a) cells supporting digital signing but with bad signatures

b) cells not support digital signing at all (no signatures)

Cells that cannot be trusted because they have conflicting PCIs and same time counter. 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 should 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

##### 6.20.2.6.0 General

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. Potential downgrade attacks are described .

##### 6.20.2.6.1 Mitigating Replay Attacks

There are 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 obtain a direct time indication from the DSnF and use this to verify the consistency of received time counters.

Depending on how the attack is performed, a local replay attack may 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, 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 the consistency of time counters among multiple cells is checked, 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[23]) 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 should 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 Assessment using clause A.3

#### 6.20.3.1 UE aspects

UE needs to be provisioned of a list of trust anchors (see clause 6.20.2.5.1).

UE should support secure storage of trusted anchors.

UE needs to take into consideration results from signature and freshness verification of SI for cell selection and reselection (see clause 6.20.2.5).

Editor Note: further assessment is required, e.g., SIB acquisition, (gNB) certificate/key acquisition depending on the solution variants.

#### 6.20.3.2 UE actions upon detection of invalid signature

Upon detection of invalid signature, UE should not select the cell as described in clause 6.20.2.5.5.

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

Man-on-the-side attacks (e.g., SigOver), man-in-the-middle attacks (e.g., replay and relay), and some denial of services (e.g., from tampering with SI) are mitigated.

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

Some denial of services (such as from bitflipping or radio jamming of all available cells) cannot be mitigated.

#### 6.20.3.5 Provisioning of keys

Trusted anchors need to be provisioned into UE during manufacture, onboarding, or after registration.

#### 6.20.3.6 RAN aspects

gNB needs to request digital signatures and obtain short-lived keys from DSnF.

gNB needs to sign dynamic fields (e.g., SFN) using short-lived keys.

gNB needs to broadcast digital signatures along with SIs

Editor Note: further assessment is required, e.g., certificate/key broadcast depending on the solution variants.

#### 6.20.3.7 VPLMN aspects

If the trust anchor of VPLMN is provisioned into a UE, the UE is protected when accessing the VPLMN.

#### 6.20.3.8 HPLMN aspects

If the trust anchor of HPLMN is provisioned into a UE, the UE is protected when accessing the HPLMN.

#### 6.20.3.9 Network sharing aspects

When a gNB is shared by multiple PLMNs, the operator owning the gNB can sign SIs as long as the trust anchor of the gNB operator is provisioned into a UE.

#### 6.20.3.10 Roaming aspects

See clause 6.20.3.6 VPLMN aspects.

#### 6.20.3.11 Regulatory aspects

Regulatory requirements, if there are any, can be supported.

#### 6.20.3.12 Signature schemes

Potential signature schemes include:

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

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

- **RSA**

- others

NOTE: The hash based approach in 6.20.2.2.4 only requires a hash function.

#### 6.20.3.13 Signature length

RSA: 256 bytes

ECDSA: 64 bytes

#### 6.20.3.14 Resistance against Quantum Computing

Next to the general remarks in Appendix A.3.14 and Table A.3.14-1, hash functions are only mildly affected by quantum computers [x]. Thus, the hash based approach in 6.20.2.2.4 is a potential quantum resistant solution for suitable parameters. See [y] for a related application. Note that this requires the trust anchor of the hash chain to be securely deployed by means of a quantum resistant algorithm.

The expected performance and properties of quantum resistance algorithms and solutions should be considered to facilitate interoperability in the future. For instance, Table 6.20.3.14-2 describes the features (pros/cons) of different potential configurations based on Section 6.20.2.2.4 assuming some specific digital signing algorithms.

**Table 6.20.3.14-1**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Configuration | DNsF signing algorithm | gNB signing algorithm | Features | |  |
| Quantum resistant | Message size to distribute the short-term certificate | Do short-term certificate and/or signature fit in a single SIB? |
| #1 | ECDSA | ECDSA | No | Short: ECDSA signature using DSnF’s ECDSA private key on a short-term gNB ECDSA public-key | Yes |
| #2 | ECDSA | Hash Chain-based | No | Short: ECDSA signature using DSnF’s ECDSA private key on the new gNB’s hash chain anchor. | Yes |
| #3 | Rainbow | Rainbow | Yes | Long: Rainbow signature using DSnF’s rainbow private key on a short-term gNB’s rainbow public-key (long) | No: 1) the signature fits; 2) the short-term certificate does not fit in a single SIB. |
| #4 | Rainbow | Hash Chain-based | Yes | Short: Rainbow signature using DSnF’s Rainbow private key on the new gNB’s hash chain anchor. | Yes |
| #5 | Falcon | Falcon | Yes | Medium: Falcon signature using DSnF’s Falcon private key on a short-term gNB Falcon public-key | No: 1) a signature generated by the gNB does not fit in a SIB; 2) the short-term certificate does not fit in a single SIB. |
| #6 | Falcon | Hash Chain-based | Yes | Medium-short: Falcon signature using DSnF’s Falcon private key on the new gNB’s hash chain anchor. | No: 1) only the signature fits; 2) the short-term certificate does not fit in a single SIB. |

Based on the numbers in Table A.3.14-1, the expected sizes for the public key + signature of configuration #4 (short), configuration #3 (medium), and configuration #5 (long) are 114 bytes, 1563 bytes, and 58.9 kB, respectively. The first value assumes that the hash chain anchor is 48 bytes long.

### 6.20.4 Evaluation

This solution addresses KI#2 and fulfils its potential security requirement by providing message authenticity to prevent unauthorized modification and mitigate replay of system information independently of UE state.

This solution uses a digital signing network function (DSnF) located at core network to sign system information, allowing for proper authorization of information signing (e.g., only entity legitimately originating a message is allowed to request the signing of that particular message). For example, gNB is allowed to request the signing of SIB1, but may not sign SIB6 since the latter is a public warning message and should not be originated by a gNB. This helps to mitigate security risk in the event that an entity gets compromised.

This solution requires UEs to be provisioned with a trust anchor (e.g., the root public key certificate of a network) to verify the authenticity of messages signed by a particular network. An operator deploying this solution can prevent its own subscribers from accepting unauthorized system information within its own network. If a roaming partner also deploys this solution and the home network operator also provisions the root public key certificate of the roaming partner network into a UE, the UE is also prevented from accepting unauthorized system information over the roaming partner's network.

This solution requires new system information block(s) to carry a digital signature and the certificate chain used to verify the digital signature.

This solution requires gNBs to communicate with DSnF in the core network to get static system information signed and obtain temporary keys to sign dynamic information elements (e.g., SFN).

This solution supports incremental deployment with incremental security benefit (i.e., protecting UE against unauthorized system information) in that it can be deployed over time by an operator independently.

Editor's Note: Further evaluation is FFS.

Editor's Note: Different solution variants may require separate evaluation.

## 6.21 Solution #21: Certificate based solution against false base station for Non-Public Networks

### 6.21.1 Introduction

This solution leverages the certificate framework outlined in solution #11 (Certificate based solution against false base station) and provides asymmetric-key-system encryption to unicast signalling messages before the primary authentication is completed as well as provides digital signatures to broadcast system information messages for a standalone NPN. By NPN, it is meant a private 5G network that is independent from a PLMN.

With this solution in an NPN deployment, the gNB and UEs can encrypt unicast signalling messages, before the primary authentications is completed and security is enabled. The gNB and UEs will accept the messages only after the message is successfully decrypted. The locations of the certificates are located in the core network and the UEs. The core network provides the network certificates to all the gNB in an NPN.

In addition, the gNB can digitally sign system information messages (e.g., master information block [MIB] and system information block type 1 [SIB1]). The UEs will accept the messages only after the signature of the message is successfully verified and can detect a suspicious false gNB upon verification failure.

A false base station is not able to digitally sign the system information messages as a legitimate base station is. This solution addresses the security and privacy areas for #2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs.

For UEs without the valid certificate(s), those UEs are not able to process system information messages from a legitimate gNB. This solution addresses the security and privacy areas for #1 DoS attack on UE: attempts to hinder the UEs' access to the network.

In addition, the UE will not accept any unicast signalling messages from the attacks of the false base station before the primary authentication is completed. As a result, the primary authentication for the UE will not get completed. Another benefit of this solution is the false base station is not able to sniff the unicast signalling messages since these messages are encrypted which further enhance the privacy for the UE. This solution addresses the security and privacy areas for # 3 Rogue services: attempts to deliver unauthorized or unsolicited services (e.g., SMS and calls) to the UEs.

Furthermore, since the UE cannot attach to a false base station, the false base station is unable to conduct attacks to track the UE. This addresses the security and privacy areas for # 4 Subscriber privacy attack: attempts to identify subscriptions or trace the UEs.

In summary, this solution addresses key issues 1 and 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

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

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

### 6.21.2 Solution details

#### 6.21.2.1 Certificate Provisioning

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

For an NPN, the core network is provisioned to store certificates for all authorized UEs, and each UE to have the core network certificate.

NOTE: A core network already has the capability to store subscriber's information for many UEs so scalability of the proposed solution should not be an issue on the core network side.

The following is the method to provision certificates into the UE:

**Initial UE certificate provisioning:**

The initial UE certificate can be provisioned into the UE at manufacture time or at deployment by the NPN operator, in USIM or another secure storage method.

**Certificate update / revocation:**

UEs should support the certificate update / revocation, which can be performed in implementation independent way or over the air. UE's certificate will need to be updated before the expiration date.

UEs are pre-loaded with X.509 certificates with a signed public key for the network in which they are allowed to connect. The core network would likewise be pre-loaded with certificates of eligible UEs. With this type of public and private key pair relationship between UEs and the core network, an implicit mutual authentication between UEs and the core network has been accomplished during the certification provisioning process.

Editor's Note: Scalability of the solution is FFS.

* Each core network has a public and private key pair (core\_PUB\_Key, core\_PRI\_Key).
* UEs have a corresponding public and private key pair (UE\_PUB\_Key, UE\_PRI\_Key).
* Each core network shares its public key (core\_PUB\_Key) with a certificate with all UEs.
* UEs share their public keys (UE\_PUB\_Key) with a certificate with the core network
* Each gNB is provisioned with a different public and private key pair (gNB\_PUB\_Key, gNB\_PRI\_Key)
* The serving gNB shares its public key (gNB\_PUB\_Key) with a certificate signed by the core network private key (Core\_PRI\_Key) and which is inside the system information message.

NOTE: In this scheme, the core network is acting as a CA.

Editor's Note: it is FFS what is the impact on the UEs when more gNBs are introduced to the NPN.

Editor's Note: It is FFS the mechanism for the core network to transfer its certificate to all gNBs of the NPN and how the gNBs store the certificate.

Editor's Note: Private key distribution in the network are FFS.

Editor's Note: It is FFS if RAN or CN is the right entity to have UE's public keys.

#### 6.21.2.2 Procedure for NPN Deployments

##### 6.21.2.2.1 Procedure

The gNB performs the following procedure for adding signature to the system information message:

- Create a message digest by applying a hashing algorithm to the system information message plus a timestamp

- Sign the digest and message with gNB\_PRI\_Key which become the signature

- The signature is appended to the system information message.

Editor's Note: We can also add some form of geo-location to the hash such that you prevent system information message from being replayed later in time or somewhere else about the same time. There is a trade between security and complexity and is left for FFS.

The UE performs the following procedure for verifying the system information message:

* The UEs extract the certificate from the system information messages, and verify its signature using the core\_PUB\_key. If the signature of certificate is valid, the UE extracts the gNB\_PUB\_Key.
* The UEs use the corresponding gNB\_PUB\_Key to verify the signature of system information messages. If the signature is successfully verified and the timestamp is within a pre-defined range (derived from the over-the-air propagation time, assuming that gNB generates sign of system information messages every time this message is sent), UEs will accept the messages; otherwise, the messages are discarded.

All UEs encrypt RRC messages that are send before primary authentication is completed using gNB\_PUB\_Key. The gNB uses the gNB\_PRI\_Key to decrypt the UE messages.

The gNB encrypt those RRC messages that are the clear before primary authentication is completed using UE\_PUB\_Key. The UEs use the UE\_PRI\_Key to decrypt gNB messages.

Editor's Note: It is for FFS for the types of messages to be encrypted before primary authentication is completed including Message 1 during RACH, RRC messages and/or initial NAS messages.

Editor's Note: It is FFS how a message encrypted by gNB is replay protected

#### 6.21.2.3 Certificate format:

ITU-T Recommendation X.509 [25] certificate can be used for its flexibility, otherwise more compact certificate format such as Card Verifiable Certificate (CVC) can be considered.

The specification should define the certificate profile.

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

### 6.21.3 Assessment using clause A.3

#### 6.21.3.1 UE aspects

The provision of the certificate into the UE is in clause 6.21.3.4.

The UE should support the secure storage of certificates.

UE should support the certificate update/revocation, which can be performed in implementation independent way or over the air.

#### 6.21.3.2 UE actions without the network's certificate

If the UE does not have a corresponding core public key, the UE will be unable to process any system information messages. As a result, the UE will be unable to be connected to the network.

If the UE does not have the UE certificate the UE will not be able to process unicast signalling messages, and the unicast signalling messages will be discarded.

#### 6.21.3.3 Threats that are mitigated by protectingsystem information messages using Digital Signature as well as encryptingunicast signalling messages

As discussed in the Introduction, this solution addresses key issues 1 and 2 and the following security and privacy areas:

1. #1 DoS attack on UE: attempts to hinder the UEs' access to the network
2. #2 DoS attack on network: attempts to hinder the network's ability to provide services to the UEs
3. #3 Rogue services: attempts to deliver unauthorized or unsolicited services (e.g., SMS and calls) to the UEs.
4. #4 Subscriber privacy attack: attempts to identify subscriptions or trace the UEs.

#### 6.21.3.4 Threats that are not mitigated by protecting system information messages using Digital Signature or encrypting unicast signalling messages.

Void.

#### 6.21.3.5 Provisioning of certificates into the UE

The following is the method to provision initial certificates into the UE:

The initial UE certificate can be provisioned into the UE at manufacture time or at deployment by NPN operator, in USIM or another secure storage method.

#### 6.21.3.6 RAN aspects

There is added overhead for the system information messages from the RAN aspects due to addition of digital signature.

There is no added overhead for the unicast signaling messages encryption from the RAN aspects; however, there is processing cost.

#### 6.21.3.7 VPLMN aspects

VPLMN is not applicable for NPNs.

#### 6.21.3.8 HPLMN aspects

HPLMN is not applicable for NPNs.

#### 6.21.3.9 NSPN aspects

This solution can mitigate the false base station attacks in rogue services and subscriber privacy as discussed in the introduction.

#### 6.21.3.10 Network sharing aspects

Network sharing aspects are not applicable for NPN use case.

#### 6.21.3.11 Roaming aspects

This solution is for NPN. Roaming aspects are not applicable.

#### 6.21.3.12 Regulatory aspects

The CA construction should follow the local regulatory requirements.

#### 6.21.3.13 Encryption schemes

There could one or more signature schemes like:

- **ECDSA (recommended with named curves),** where the ECDSA profile for SUCI can be reused.

- **RSA**

- others

#### 6.21.3.14 Signature / Encryption length

RSA: 256 byte

ECDSA: 64 byte

#### 6.21.3.15 Resistance against Quantum Computing

TBD.

## 6.22 Solution #22: Detecting false base stations based on UE positioning measurements

### 6.22.1 Introduction

This solution addresses the security requirements in key issue #3 "network detection of false base stations".

According to the informative Annex E of TS 33.501 [7] for UE-assisted network-based detection of false base station, measurement reports sent by the UE can be used to detect a false base station. Besides the measurement reports (based on MIB/SIB) sent to the serving gNB for signalling purpose described as an example in TS 33.501 [7] clause E.2, the measurement reports sent by the UE to the core network for service purpose can also be used for false BS detection.

Enhanced location-based service is one of the 5G key features supporting location critical applications, for which the integrity/accuracy of UE's location is one of the feature's requirements. While the core network is able to estimate UE's location based on the positioning measurement reports from the UE, false base stations which may attack UEs for location distortion, could be a major threat against the location accuracy.

The UE location could be estimated as follows: the base stations nearby the UE broadcast a set of positioning reference signals (PRS) - a type of beacon signals detected and measured by the UE for the purpose of positioning. Then the UE reports the PRS related measurements to the core network, which processes the measured data and, given its knowledge on the network topology (i.e. registered location of BSs and potential time drifts on the respective departure times of PRS), estimate the location of the UE.



Figure 6.22.1-1: The attacking scenario of UE positioning with a false base station

The problem is that not all measured PRS are necessarily originating from legitimate base stations. In case there is a false BS (as shown in Figure 6.22.1-1) nearby the UE, the PRS received by the UE may not be authentic, because the PRS are non-encrypted beacons, which can be forged/tampered/replayed by a false BS. For example, a false BS can forge the PRS from an unknown location or tamper the PRS intercepted from a legitimate BS nearby the UE (BS-N). A false BS can also replay the PRS intercepted from a legitimate BS (BS-F) which is however not within the broadcasting reach to UE and far deviated from UE's actual position.

As the UE is not able to distinguish between legitimate and non-legitimate measurements, all received measurements are sent to the core network, of which one or more measured PRS may not originate from the BSs registered in the core network. Hence, by reporting such unauthentic measurements, the UE location estimated by the core network could be distorted, i.e., not corresponding to the ground truth.

This solution provides a mechanism for the core network to detect false base stations by utilizing the positioning measurement reports in conjunction with other information sent from the UE. The solution is applicable to UEs in RRC\_CONNECTED state.

### 6.22.2 Solution details

In this solution, besides the estimation of UE location, the locations of gNBs are also estimated based on the UE location estimate. A PHY-layer method in RAN and a checking mechanism in core network are introduced to facilitate the network to identify whether the measurements reported by the UE contain unauthentic PRS from potentially one or more false BSs. In case there is at least one false BS, the measurement associated with the false BS is discarded and the UE location is estimated again with the measurements from legitimate gNBs only. The assistance information is then updated by the core network for the UE to exclude the measurements associated with the false BS in future reports. The procedure details are described as follows.



Figure 6.22.2-2: The attacking scenario of UE positioning with false base stations

1. The LMF sends configuration information for the UE to report angle and timing information for each gNB measured at the UE.

2. The UE reports the following to the LMF:

a. UE positioning measurements, e.g. the reference signal time difference (RSTD) for the case of Downlink time difference of arrival (DL-TDoA).

b. Reference signal time difference (RSTD) reports (with respect to serving cell and each neighbour gNB) together with TA of serving gNB.

c. The measurements used for estimation of the angle of departure (AoD) at the gNB side. These are typically the beam-specific radio signal received power (RSRP) measurements for each of the beams detected at the UE side.

3. The LMF estimates the UE location via an existing positioning method (e.g. DL-TDoA) first, following which it also infers the potential location of the neighbouring gNBs, by using the information received from the UE in step 2 as follows:

a. The LMF uses the estimated UE location and the TA information (2b) to obtain the approximate distance to each of the gNBs.

b. The LMF identifies the angle at which each gNB is reached from the UE using the AoD information at the gNB side (2c).

Subsequently the estimation of gNB location is obtained by combining the approximate distance to the gNB (3a) and the angle at which the gNB is reached from the UE (3b). The estimation requires either synchronization amongst the gNBs or the LMF's awareness of clock differences amongst the gNBs.

NOTE 1: The required accuracy of gNB location estimate for detecting FBS can refer to the accuracy requirements for location services defined in Table 4.1 of TS 22.071 [26]. If the detection of FBS can be regarded as an example of network maintenance or network demand monitoring or asset tracking, the required accuracy of gNB location estimate for identifying FBS is 75m~125m.

4. The LMF compares the estimated locations of the gNBs with the list of registered locations of gNBs (obtained e.g. from the AMF based on serving gNB location and UE's tacking area). If there is a mismatch of at least one gNB, the LMF discards the measurements associated with this gNB and reiterates the UE location estimation with the remaining gNBs as follows:

- Suppose there are measurements from N gNBs, the LMF repeats the UE location estimation N times using N-1 gNBs each time, where in the i-th iteration the i, i=1,…,N gNB is excluded from the procedure.

- If at the i-th iteration all the involved gNBs turn out to be legitimate, the procedure stops and the UE location is taken as legitimate. The gNB excluded from that iteration is then considered as a likely false BS.

NOTE 2: In this repeated computation of UE location, if the above iteration by excluding one BS could not reach the match of legitimate gNB locations, the same iteration by excluding two BSs can be performed until the remaining gNBs match the registered legitimate gNBs. In such a way, multiple FBSs can be detected. Although detecting multiple FBSs may take some computation resource and time, it is regarded as a rare case where there are multiple FBSs within a PRS measurement area of a given UE, as the intention of such attack deployment and cost is unclear.

5. The LMF updates the assistance data to the UE, indicating each of the PRS sources (i.e., the gNBs) as legitimate or not based on the outcome of step 4. For example, the assistance data specified in TS36.355 [x] may include updated information on *OTDOANeighbourCellInfoList IE*, where the false BS is flagged. For a specified time interval in the future, the PRS transmitted by the false BS is not considered by the UE and excluded from being reported to the core network.

NOTE 3: As the solution is based on the PRS measured by the UE, which does not contain PLMN information, the PRS broadcast by the base stations shared by different PLMNs is not bound to a specific PLMN. The positioning measurements reported by the UE work for each of the PLMNs sharing the base stations. The LMF of each of the PLMNs can detect FBS using the UE reported measurements defined in this solution, depending on which PLMN the UE is attached to.

NOTE 4: For a mobile UE, it is straightforward that potentially multiple FBSs along the moving path of the UE can be detected depending on the changing positions of the moving UE.

NOTE 5: According to TS 38.305 [27], PRS configuration on the UE is PLMN specific, as it is sent by the LMF of the serving PLMN the UE is connected to. That means, the PRS transmitted by legitimate base stations of a different PLMN will not be measured by the UE, as the legitimate base stations of a different PLMN will not be included in the PRS configuration from the LMF of the serving PLMN, hence will not be mistakenly detected as FBSs.

Editor's Note: Details in radio related methods/techniques and whether the required accuracy can be met are to be confirmed by RAN2.

### 6.22.3 Evaluation

This solution fulfils the potential security requirement of Key Issue #3 when the UE is in the RRC-Connected state.

This solution does not fulfil the potential security requirement of Key Issue #3 when the UE is in the RRC-Idle or the RRC-Inactive state.

This solution fits in the framework for false BS detection in TS 33.501 [7] Annex E.

This solution enables the network to not only detect the existence of potential false BSs but also estimate the location of the detected false BSs.

This solution can serve the purposes of both false BS detection and enhancement of UE location estimate.

This solution cannot detect FBS if the FBS does not transmit PRS.

This solution has minimum impact on the existing signalling procedure. Impacts on the specific elements are as follows:

- Impacts on the UE

- Support enriched positioning measurement reporting.

- Impacts on the gNB

- None.

- Impacts on the LMF

- Support additional computation for deriving the locations of measured gNBs and finding out the potential false BS among the measured gNBs.

- Support assistance data updating to the UE

Editor's Note: Further evaluation is FFS based on RAN2 and SA2 feedback, e.g. the evaluation for the performance vs the number of UE reports, and computation complexity on the LMF.

## 6.23 Solution #23: Cryptographic CRC to avoid MitM relay nodes

### 6.23.1 Introduction

This solution addresses KI#3, KI#5 and #7.

This solution firstly addresses KI#7. As indicated in KI#7, MitM attacks and FBSs are related but different attacks [23]. A standalone FBS is only capable of attracting UEs and getting the first phases of the communication through it, however, the communication will stop as soon as the mutual authentication handshake between UE and core network fails. A MitM attack is more powerful since the attacker can forward all messages and the authentication between UE and core network. This allows the attacker to observe, intercept and manipulate, and/or attack later phases of the communication. Integrity protection may not always be in place nor protect every message, so an efficient way to detect and protect against MitM attacks is still useful to have.

A MitM relay node typically includes a false base station (FBS) and a false UE (FUE). A layer-two attacker can place a MitM relay node between a real UE (RUE) and a real BS (RBS). As shown in Figure 6.23.1-1, the MitM attacker can intercept, drop, and forward messages with unaltered or altered content [19]. These capabilities can lead to multiple attacks including amongst others aLTEr [20], imp4gt [19], network misconfiguration [21], or 5Greasoner [22].

Real gNB (RBS)

R

e

a

l

U

E (RUE)

F

a

k

e

g

N

B(FBS)

F

a

k

e

U

E (FUE)

M

i

t

M

I

n

t

e

r

c

e

p

t

s

,

f

o

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Figure 6.23.1-1: MitM relay node

This solution introduces the concept of cryptographic CRC, which provides an effective solution to MitM attacks, without requiring digital signatures, time synchronization at system level, or verification of location information. This solution may be used in conjunction with already existing integrity protection mechanisms (e.g. to avoid attacks on messages that may not be integrity protected (such as PDCP Control PDUs)), or in cases where integrity protection is not enabled (e.g. based on security policy for certain PDU sessions).

This solution also addresses KI#5 since this solution provides the RUE and RBS with the means to reject the messages that have been forwarded by a MitM and allows the RUE and RBS to detect the MitM, and if present, stop the communication.

This solution also supports KI#3 (first requirement) since it allows the gNB to detect MitM and this information can be shared with the network, for network-based detection of MitM attackers.

### 6.23.2 Solution details

#### 6.23.2.1 Requirements

a) RUE and RBS share a symmetric key. This key is denoted as K\_PHYint.

b) Each transport block (TB) resulting from MAC layer is allocated to Physical resource blocks (RBs), i.e., the time and frequency physical resources used to transmit the data. The allocated RBs are identified by a unique identifier called blockID. This identifier is assumed long enough and unique within the scope of K\_PHYint.

c) The 24-bit CRC included per transport block in the Physical layer is replaced by CRC' computed as:

CRC' = MessageAuthenticationCodeComputation(K\_PHYint, CRC|blockID) (\*)

where MessageAuthenticationCodeComputation() is a function that returns a 24 bit message authentication code.

#### 6.23.2.2 Operation

Upon setup of K\_PHYint, once AS is established, then from the first subsequent SFN 0 until it wraps around (10.24 seconds), RBS schedules for the RUE at least a data transmission in each SFN:

RUE sends a transport block by doing the following:

* RUE compute the 24-bit CRC value.
* RUE obtains information about the allocated RBs to send the transport block and derives the blockID.
* RUE computes CRC'.
* RUE places CRC' in the CRC field.

RBS receives a transport block by doing the following:

* RBS receives a message in certain RBs and derives the blockID.
* RBS compute the 24-bit CRC\_r value given the received transport block.
* RBS computes CRC'\_r given CRC\_r and blockID.
* RBS checks whether the computed CRC'\_r value equals the received CRC' value. If the values do not match, then the transport block is rejected; if the values match, then the transport block is accepted proving that it does not contain transmission errors and that it has been transmitted in the same physical resources, i.e., it has not been replayed.
* At the end of this time period, the RBS determines the presence of a MitM attacker by checking whether the number of times the CRC’ check failed exceeds a threshold. Assuming that 2^10 TB can be exchanged in 10.24 seconds and the CRC has a length of 24 bits, this threshold can be derived from a binomial test and a given confidence level. If a MitM attacker is detected, the RBS informs the UE and the network about the presence of the MitM relay node.

The above description is further detailed as follows:

a) The MAC computation in equation (\*) may be implemented by truncating the output of HMAC-SHA256 [NIST SP 800-107] so that only the 24 least significant bits are returned.

b) The blockID may be constructed by combining the identifiers of the used resources when communicating with a given base station gNB. These identifiers include gNB identifiers such as PCI; in the time domain, this can include the Hyper Frame Number, the System Frame Number, the slot number, the OFDM symbol identifier, the time duration of the resource blocks; in the frequency domain, this can include the lowest frequency and the used frequency band. A specific construction is as follows:

blockID = Frame | Subframe | Slot | Allocated\_Resources\_TIME | Allocated\_Resources\_Frequency

where | means concatenation and Allocated\_Resources\_Time and Allocated\_Resources\_Frequency determine the resources that are used for transmission in the given Frame/Subframe/Slot.

c) K\_PHYint may be derived from K\_gNB in a similar way as K\_RRCenc, K\_RRCint, K\_UPenc, andK\_UPint where value 0x07 is used for the algorithm type distinguisher in clause A.8 of [7]. In the case of DU CU split, all DU units use the same K\_PHYint.

d) In CU-DU split architectures, K\_PHYint is to be delivered in a secure way from the CU to the DUs through the F1-C interface as described in Section 9.8.2 in TS 33.501[7].

e) To allow for interoperability with legacy nodes, the base stations should announce this security capability to the UEs. Since this solution uses AS, this can be done as extensions in the SecurityModeCommand message. The UE can confirm its activation of this algorithm in the SecurityModeComplete.

Signaling in cell change can be performed as specified in Section 6.9.2 in TS 33.501. Furthermore, some extensions are required to make sure that UE and target gNB run the solution once the handover is completed. To this end, the current gNB needs to inform the target gNB of the UE’s C-CRC capabilities over the Xn Application Protocol defined in TS 38.423. This can be done in the Handover Request message as part of the UE Security capabilities. Next, the target gNB needs to confirm whether it supports the C-CRC capability. Upon reception of this confirmation, the gNB will send a RRCReconfiguration (TS 38.331) message informing the UE about the capabilities of the target gNB. By doing this, both UE and target gNB will execute this solution as soon as the HO is completed.

The specific description of these extensions is left for normative phase.

f) There is no need for key refresh since the cryptographic CRC is only computed and checked till the SFN component of the blockID wraps around. This is enough to detect the presence of a MitM and take actions.

#### 6.23.2.3 Prevention of MitM attacks:

**a) prevention of message forwarding (replay):** an attacker placing a MitM relay node between RUE and RBS would like to forward traffic by receiving, processing, and resending packets. Since the FUE, part of the MitM relay node, impersonates the RUE, it is supposed to transmit and receive in the same RBs assigned to the RUE.

A detailed description of the protection against message forwarding requires detailing the differences between the uplink and the downlink. The UE is allocated resource blocks by the base station. This allocation is done for both uplink and downlink by means of the PDCCH except in uplink semipersistent schedule (SS) (type 1 and 2) that is sent encrypted in an RRC message. Since the MitM is in between RUE and RBS, the resource allocation will arrive with some delay to the RUE. This affects in particular the uplink since it induces a delay that prevents the RUE from using the right timeslots and leads to a change in the blockID that is expected by the RBS. An attacker might try to delay the downlink, including the schedule delivery and reference time. However, this only works as long as the uplink is not active. Once the uplink is active, the MitM cannot be involved anymore in the downlink since otherwise it would trigger a mismatch.

Thus, the replay protection provided by this solution can be understood by considering the blockID as a freshness parameter that is linked to the physical resources used in the communication link.

Forwarding at a later point of time is not feasible since the RBs change, and thus, the verification of the CRC' will fail. Instantaneous reception and transmission in the same RBs are also not feasible because of two reasons: a) the resources are already used and b) because of the processing time.

**b) prevention of message modification:** a MitM relay node placed between RUE and RBS can only modify additional traffic if it first receives a message from either RUE or RBS, processes it, modifies it, and sends it again. The attacker cannot perform this action since the CRC' value is computed including the blockID, and this value will change when the attacker tries to send out the message at a later point of time using different RBs having a different blockID.

**c) prevention of message injection:** injecting a message means that the receiving party, either RUE or RBS, will accept a message from the MitM relay node. The MitM relay node does not have, however, K\_PHYint, and thus, the MitM relay node cannot compute CRC'.

### 6.23.3 Evaluation

This solution detects and blocks replay attacks of resource blocks at MAC/PHY layer without requiring time checks that need tight time synchronization, and in this way, solves, e.g., KI#5 and KI#7. This solution also solves the first requirement in KI#3, but it does not prevent a UE from camping on a FBS (second requirement in KI#3). This solution could be used in combination with Solutions for KI#2 when those solutions are still prone to replay attacks.

This solution has several features:

This solution derives K\_PHYint from K\_gNB. This implies that the solution only starts operating once AS security has been established. For devices that do not support AS security, then other key derivation may be implemented without requiring them to use AS security.

This solution requires modifications in gNB and UE to:

* implement the Cryptographic CRC,
* derive K\_PHYint,
* signal (gNB) and process (UE) the CRC-C security capability.

Editor’s note: Further evaluation about the impact on PHY processing changes is FFS.

## 6.24 Solution #24: UE&Network-assisted UE avoidance and Network detection of FBS

### 6.24.1 Introduction

This solution addresses the security requirements in KI #3. According to the informative Annex E of TS 33.501 [7] for UE-assisted network-based detection of false base station, measurement reports sent by the UE can be used to detect a false base station. KI#3 also states that 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/prevent UEs from connecting to false base stations both in CONNECTED mode and IDLE mode. In particular, the 5G system should be able to:

**- Detect false base stations**

**- Employ methods to prevent UEs from connecting to false base stations**

This solution describes how to extend Annex E of TS 33.501 to achieve this functionality in KI #3 (in bold) so that UEs avoid FBS both in IDLE and CONNECTED mode.

The basic idea behind this solution is based on the cell search procedure where a UE has to acquire the synchronization signal block (SSB). SSBs are transmitted in a burst, where different SSB in the burst have a different identifier (SB#) and each SSB is transmitted in a beam in a different direction. The maximum number of SSBs in a SS burst beams depends on the frequency. There are up to 4 SSBs if the frequency is under 3 GHz, up to 8 SSBs if the frequency is between 3 and 6 GHz, and up to 64 SSBs for frequencies higher than 6 GHz. Depending on the relative position of the UE with regard to a base station, the UE will measure a different power level for different beams. The UE will use the beam with the highest received power.



Figure 6.24.1-1: Example

For instance, in Figure 6.24.1-1, UE2 scans the trustworthy base station (TBS) and receives the highest power from the green beam, the lowest power from the blue beam, and a power level in between the previous two from yellow and red beams.

Thus, if a UE knows (1) the position and expected radiation pattern (direction of the SB# sent by different beams) of a base station and (2) its own UE location, then the UE can estimate the expected SB# power distribution. Next, the UE can receive the SS burst of the base station and the measured SB# power distribution for the different beams. The UE can correlate both signals, e.g., regarding number of beams or relative powers, to obtain an indication whether the base station is a good one or not.

For instance, if UE2 in Figure 1 scans the fake base station (FBS), it would receive the highest power levels from the blue and yellow beams and a lower power level from the green and red beams. Then UE2 would have a strong indication that the BS is a fake one since this is not the expected radiation pattern from the trustworthy base station.

A way to see this proposal is to compare it with the operation of an email spam filter: (a) If an attacker writes a targeted phishing email towards a user, the spam filter usually cannot detect it; (b) a spam filter sometimes does not manage to filter out 100 % of the spam. However, spam filters are still very useful since they manage to get rid of most of the spam reducing the impact of attacks. This proposal proposes a solution with similar features.

- An attacker might try to focus on a single victim, e.g., UE1 in Figure 1. In this case, UE1 receives the same power pattern from the FBS as it would receive from the trustworthy BS since the attacker is focusing on UE1 in his attack and the attacker has redirected the beams of the FBS so that they have the same radiation pattern as TBS from UE1's location. Even if this targeted attack is feasible, all other UEs in the area will receive the wrong power patter. Thus, this approach reduces the impact of FBS attacks and it can do this already during the cell search procedure, even before the UEs connect to a BS and they are still in RRC\_Idle mode. Even if an attacker can launch such a targeted attack towards UE1, UE1 will also realize inconsistencies since there are two base stations with exactly the same radiation pattern. The UE will share this information with the CN following Annex E of TS 33.501.

- Real-world experiments, e.g., [27], indicate that the measured SB# power distribution correlates with the expected beam distribution. Thus, this solution will allow the majority of the UEs to "filter out" most FBS very early in the cell search process, i.e., still in IDLE mode, saving resources and improving performance. It is true that due to the wireless propagation features, a UE might measure a slightly different power distribution at some locations, e.g., due to reflections. UEs in those locations might classify a base station as less trustworthy.

This approach complements the methods in Annex E of TS 33.501.

### 6.24.2 Solution details

#### 6.24.2.1 UE Initialization

This solution requires that each UE has some information (INFO\_gnb) about surrounding base stations. INFO\_gnb includes:

- amount of SSB beams used by each base station, identified by its Physical Cell Identifier (PCI).

- (optional) the position of trustworthy base stations as well as the beam orientation (radiation pattern) when transmitting SSBs.

- (optional) the position of known fake base stations as well as their known radiation pattern, assuming that the network has detected any FBS before.

INFO\_gnb can be pre-configured in advance. Alternatively, the first time a UE enters a tracking area, the UE receives base station information (INFO\_gnb) for that tracking area from the network.

The usage of the optional INFO\_gnb requires that a UE can obtain its own location.

The distribution of INFO\_gnb needs to be done in a secure way. This can be done by using AS security.

During this UE initialization phase, a UE does not have INFO\_gnb, thus, the UE cannot discern trustworthy BS from FBS in IDLE mode. As soon as UE goes into connected mode, INFO\_gnb is received in a secure way.

#### 6.24.2.2 UE Operation (IDLE mode)

BASIC CHECK: When a UE in IDLE mode needs to connect to the network, the UE performs cell search, the UE obtains the SSBs of a base station and checks whether the number of SSB beams observed from a base station with a given PCI matches the expected number of beams in INFO\_gnb.

- If this check does not succeed, the UE returns a low similarity score and goes to Step 4.

- If the check succeeds, it returns a high similarity score and goes to Step 3.

EXTENDED CHECK: If the UE has been provisioned with the optional INFO\_gnb data and has access to its own location (e.g., through GPS data), the UE monitors the power level for different beams (PL\_measured). Given its own position, and the known position of the base station it is scanning, the UE estimates the expected power level (PL\_estimated) that it should measure. The UE can compute the similarity between both signals, PL\_measured and PL\_estimated, updating the similarity score (SS). For instance, the UE can compute the cross-correlation of the signals to obtain the SS.

For each scanned base station, the UE computes such a similarity score, giving preference to base stations with a high SS when taking the final decision on joining a specific base station. An example of the expected operation is as follows:

- Example 1: a UE observes two base stations and both of them are supposed to be trustworthy base stations. However, the SS obtained from the base stations are quite different. For BS#1, the SS is positive meaning that the radiation pattern is as expected, but for BS#2 the radiation pattern does not match. Thus, the UE takes the decision to join BS#1. The UE sends measurements to the core network.

#### 6.24.2.3 UE Operation (CONNECTED mode)

When the UE is in RRC-Connected state, the UE keeps scanning and reading SSBs and measuring the SS. If a UE is connected to a base station, and its SS is low, e.g., when it changes its position, while the SS of other cells are higher, then the UE can take the decision to switch cells.

Once the UE has joined a base station, the UE provides the network with measurements regarding the measured radiation patterns at certain positions when obtaining the SSB and the computed SS. This information can be used by the network to (i) verify the UE decisions, (ii) centrally identify FBS updating INFO\_gnb, or (iii) improve the algorithm to compute SS score. In particular:

- the UE can provide the network with information about the beams that have been used for communication over time, i.e., including beam index and timing. The network can compare this information with the beam indexes that were used by the UE. If these two sets of information differ, then the network can detect the FBS presence.

- the Network configures the UE to do specific CSI measurements and reporting using a protected RRC message. Being protected, the specific CSI instruction to the UE, and measurements report from the UE are only known between the real base station and the UE, not to any MitM. This method is used to detect the presence of a potential FBS.

#### 6.24.2.4 Network operation

**Network initialization:** The network is in charge of tracking of the positions of base stations and their radiation patterns.

**(UE in IDLE mode)** When a UE enters in a given area, the network is in charge of distributing INFO\_gnb to the UE.

**(UE in CONNECTED mode)** The network collects from the UE information in a secure way about the radiation pattern that a UE observes from different base stations at different locations. This information can be used together with other parameters, by the network to:

- Verify the computations by the UE,

- Detect the presence of FBSs and MitM devices,

- Estimate the position of FBS,

- Improve the SS computation algorithm on UE.

### 6.24.3 Evaluation

This solution supports KI#3 partially, as follows:

- This solution allows UEs to detect FBS both in IDLE and CONNECTED modes

- During IDLE mode, an attacker might be able to carry out a tailored attack against UEs at a specific area. Thus, this solution acts as an additional line of defense that allows the majority of the UEs to detect and avoid FBS even before SIB1 is acquired

- Beamforming is not a compulsory feature. This means that base stations that do not support beam forming cannot support this solution

- Based on RAN 2 evaluation (S3-211427): ‘the reporting RSRP/RSRQ/RSSI/beam level information of SSB or CSI-RS is supported since Rel-15’. Therefore, the approach proposed for connected mode (first bullet in 6.24.2.3) in which the UE reports the used beam and the network compares them with the used ones is feasible to implement without big changes.

Editor's Note: Feasibility and effectiveness in a real environment are for FFS.

Editor's Note: RAN needs to evaluate the potential impact in IDLE mode.

Editor's Note: The complexity of the storage and management of gNB information on the UE, while the UE is mobile, is FFS.

## 6.25 Solution #25: Detection of Man-in-the-Middle false base stations

### 6.25.1 Introduction

This solution addresses the first requirement of key issue #3 “Network detection of false base stations”.

A false base station (FBS) capable of performing man-in-the-middle (MitM) attacks consists of two parts, i.e. a fake gNB unit and a fake UE unit. The logic between the fake gNB and the fake UE allows an attacker to process incoming message and just forward them, but also drop, manipulate or inject specific messages. These operations require receiving, processsing, and retransmissing the messages and cannot be performed without introducing some processing delay.

This solution is based on the link allocated resource parameters between a UE and the gNB, i.e. UE’s *SFN*(system frame number). The gNB can compare the SFN it has allocated to the UE (it would be the SFN of the “fake UE” if one sits in between) and the “real” SFN that the UE has reported to determine the existence of a FBS.

This solution does not address the scenario where a malicious node RF repeater relays messages of a victim UE to the real gNB. Note that even if such malicious RF repeaters relays are present, those devices cannot perform a MitM attack as such since they cannot drop/inject/manipulate specific messages as such.

### 6.25.2 Solution Details

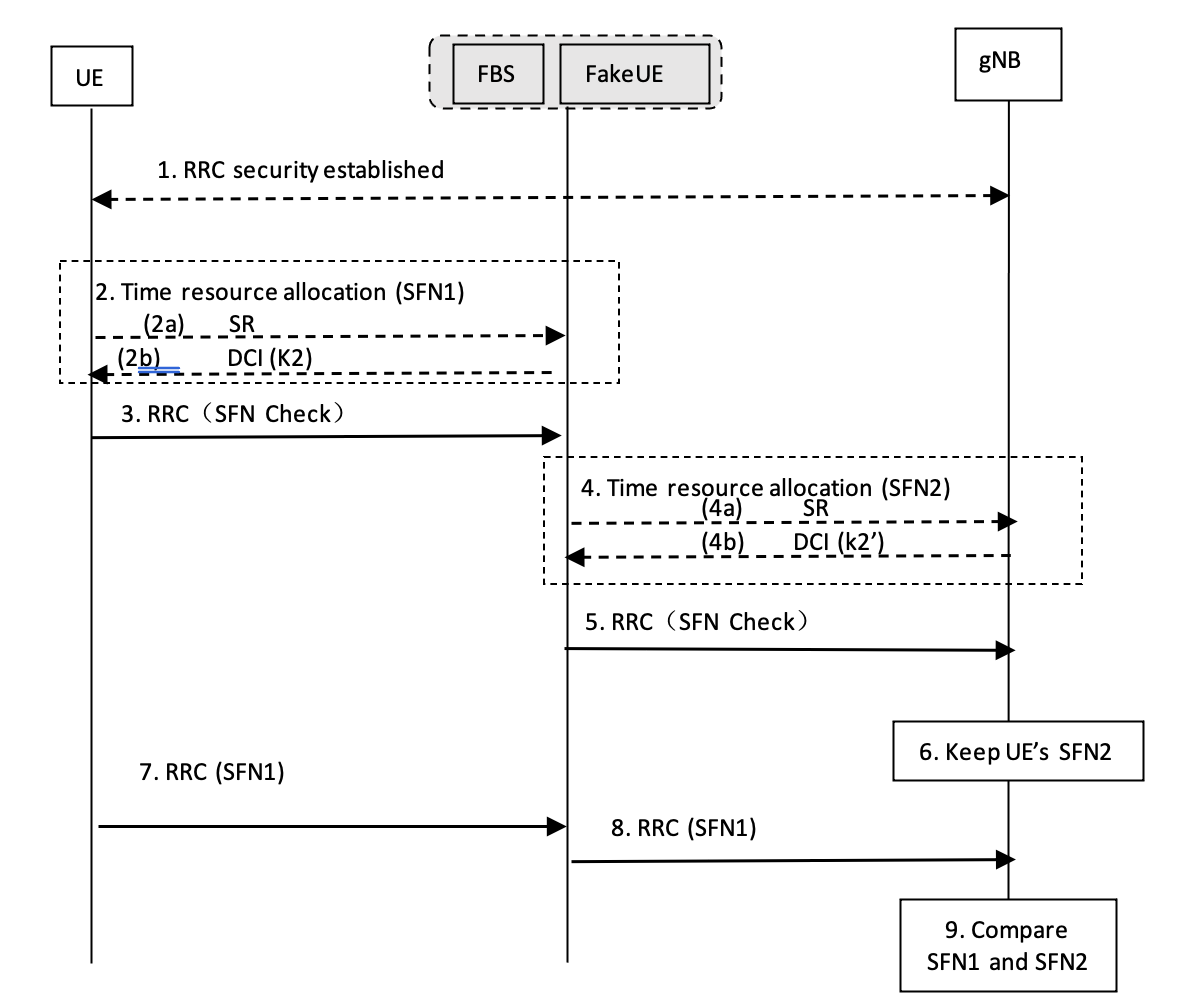


Figure 6.25.2-1 – Flow diagram showing detection of man-in-the-middle attack

The steps can be summarized as follows.

1. Assuming a UE has established a connection with a real gNB through a MitM gNB. The RRC security is established, i.e. all RRC messages are protected from the FBS.
2. In order for a UE to send a RRC message (to trigger the FBS detection), the UE requests resource from the FBS according to the current RAN procedure. Assuming the set of SFN parameters allocated by the FBS is indicated by SFN1 (in this solution SFN refers to system frame number, subframe number, timeslot, start symbol as well as parameters in the resource allocation message, in particular, the “k2” value).
3. The UE sends a RRC message to trigger FBS detection. To avoid defining a new RRC message, the existing RRC message “UEAssistanceInformation” can be used with a new optional element “SFN Check” to trigger FBS detection.
4. As usual, the FBS intends to forward the RRC message to gNB. First, the FBS (or the fake UE) needs to request resource from the gNB. Assuming the gNB will allocate a set of SFN parameters, i.e. SFN2 to the Fake UE.
5. The FBS (Fake UE) forwards the RRC message to the gNB according to the scheduled SFN2.
6. Once received the “SFN Check” indicator, the gNB stores SFN2 it allocated.
7. The UE sends the SFN1 value (allocated at step 2) in a RRC message (security protected from FBS). To avoid defining a new RRC message, the existing RRC message “UEAssistanceInformtion” can be used with a new optional element “SFN result” (its value set to SFN1).
8. The FBS (Fake UE) unknowingly forwards to the gNB.
9. The gNB compares the SFN1 value received with the SFN2 value stored and determine whether there is a FBS

This solution can be adapted to support “on demand” FBS detection by having the base station send a protected RRC message to the UE indicating that the FBS detection procedure needs to be started. This message is included between message 1 and message 2 in the Figure. Since this message is security protected, the attacker is not able to know the content or tell from a normal RRC messeage.

NOTE1: SFNs are not protected by crypto. So, this solution should study whether a resourceful attacker can acquire all SFNs from legitimate gNB and use the one that fits the case.

NOTE2: This solution may not work against a resourceful attacker that can surreptitiously drop messages.

### 6.25.3 Evaluation

TBA.

## 6.26 Solution #26: KI#2 with PKC-based and without tight time synchronization

### 6.26.1 Introduction

This solution addresses key Issue#2 "Security Protection of system information" by using public-key cryptography (PKC) to sign and verify system information. In this way, a UE has guarantees on the origin of the signed data. Key issue#2 also requires replay protection. This solution uses the cryptographic CRC solution (Solution #23) to verify that the messages that are being exchanged with the base station are not being replayed. This construction is proposed since this does not require tight time synchronization that might be difficult to achieve in some settings.

##### 6.26.2 Solution details

##### 6.26.2.1 Requirements

The solution assumes the same PKC settings as in, e.g., Solution #7, including:

1. each base station gNB broadcasts signed system information (SI),
2. K-SIGPrivate, the private key used to sign the SI, is specific to the Tracking area. Each gNB in the tracking area has it.
3. each UE has the required trust anchors to verify the received signed SI, including PK, the public-key required to verify a signature created with K-SIGPrivate.

This solution also requires replacing the CRC at MAC layer with the Cryptographic CRC (C-CRC) as described in Solution #23:

C-CRC = MessageAuthenticationCodeComputation(K, CRC|blockID)

where MessageAuthenticationCodeComputation() is a function that returns a 24 bit message authentication code, | indicates concatenation and blockID refers to a unique identifier identifying the Physical resource blocks (RBs), i.e., the time and frequency physical resources, used to transmit the data at MAC layer.

##### 6.26.2.2 Protocol Operation

The protocol operation of this solution is depicted in Figure 6.26.2.2-1:



**Figure 6.26.2.2-1 – Protocol flow**

The protocol flow is as follows:

1. gNB broadcasts system information signed with K-SIGPrivate.
2. UE verifies the validity of the digital signature with PK, verifying the SI. Note that this includes verifying whether the certificate has not expired. The UE will select a gNB based on the received and verified SI. See Remark 1 in Section 6.26.2.3.

If the UE selects a given gNB to connect to the network, then the UE goes on with the standard communication flow as follows. See Remark 2 in Section 6.26.2.3.

1. The UE generates symmetric-key K in a secure way.
2. UE sends K to gNB in a secure way by encrypting it with the public key of gNB. See Remark 3 in Section 6.26.2.3.
3. gNB confirms reception of K by sending Hash(K). UE checks that the message contains the correct hash. If it does not receive this message or this message does not contain the proper value, the UE determines the presence of a MitM. If the value is correct, the UE verifies that the right gNB has received K.

Editor’s note: Alternatives and required properties of the protocol in steps 4 and 5 are for ffs.

1. a. UE starts timer Ta after receiving message 5.

b. gNB starts timer Tb after sending message 5.

1. a. UE activates C-CRC method using key K after receiving message 5.

b. gNB activates C-CRC method using key K after sending message 5.

1. Standard protocol flow but protected with C-CRC. See Remark 4 in Section 6.26.2.3.
2. a. If Ta > Tmax and message 10 has not been sent by the UE, it decides that a MitM is present and proceeds to search another base station. See Remark 4 in Section 6.26.2.3.

b. If Tb > Tmax and message 10 has not been received by the gNB, it decides that a MitM is present and drops the communication. See Remark 4 in Section 6.26.2.3.

1. Final message sent by the UE that serves as implicit confirmation that no-MitM has been detected.
2. a. UE deactivates the C-CRC method after sending message 10.

b. gNB deactivates the C-CRC method after receiving message 10.

1. Standard communication.

##### 6.26.2.3 Clarifications regarding the protocol operation

The protocol operation described in Section 6.26.2.2 is clarified below by means of the following remarks:

* Remark 1: This relates to Step 2. Here, it is assumed that the certificate verification does not require tight time synchronization. For instance, if a certificate is valid for several weeks, then it is not required to have a time synchronization with an error of 1 milisecond.
* Remark 2: a UE adquires MIB and SIB1 and signature and performs the signature verification in Step 2. We note that Steps 3, 4, and so on are only executed if a UE selects a base station. UE is in IDLE mode only till Step 2.
* Remark 3: This relates to Step 4. The MitM does not have access to K since the MitM does not have K-SIGPrivate. Since the MitM does not have K, it cannot interfere with the authentication handshake (messages 4-5) and the MitM cannot compute the C-CRC correctly. This assumes that public-key, PK, can be used for both signature verification of the SI, as required in Step 2, and for public-key encryption (PKE), as required in Step 4. If the public-key for signature verification of Step 2 cannot be used for PKE, the certificate sent in the SIB should contain an additional gNB’s public-key for PKE in Step 4.

Editor’s note: It is FFS if same keys or different keys are used

If a UE is in IDLE mode, then the UE does not share a common key with the base station and thus steps 3, 4, 5 are executed. If a UE is in INACTIVE mode, the UE already shares a key with the base station and Steps 3, 4, 5 can be skipped. The encryption algorithm in Step 4 might be based, e.g., on ECIES(PK, K).

Editor’s note: It is FFS to explain why this solution is required for INACTIVE state UEs.

* Remark 4: A specific instantation of Messages 4, 5, 8, and 10 is as follows: contents of Message 4 could be included in RRCSetupRequest; Message 5 could be included in RRCSetup; Messages 8 might include the NAS handshake (without modification); Message 10 could be NAS Security Mode Complete (without modifications). It is important to observe that the the normal communication flow goes on as usual, with the only difference that C-CRC is active. This message choice is only an example, and details can be defined during the normative phase with the only requirement that both uplink and downlink traffic needs to be involved (see Section 6.23.2.3).

The C-CRC solution replaces the standard CRC at MAC layer in messages 8 and 10. This means that if there is a MitM forwarding, modifying, or injecting messages (in messages 8), those messages will be dropped by UE and/or gNB. Not receiving messages in Step 8 means that message 10 will not be sent/received either, since the previous messages are missing, and thus, the timers Ta and Tb will timeout, and the UE joining procedure will be dropped. Thus, this solution achives replay protection without requiring tight time synchronization.

The blockID used in the computation of the C-CRC should be unique to provide freshness. To this end, it can be constructed as follows

blockID = Frame | Subframe | Slot | Allocated\_Resources\_TIME | Allocated\_Resources\_Frequency

where | means concatenation and Allocated\_Resources\_Time and Allocated\_Resources\_Frequency determine the resources that are used for transmission in the given Frame/Subframe/Slot.

Since SFN has a period of 10.24 seconds, then this blockID construction sets a maximum value for Tmax. If Tmax is required to be longer, then a different blockID construction can be defined during normative phase.

* Remark 5 on backwards compatibility and downgrade attacks: In this solution, new UEs run the C-CRC for a limited amount of time. After step 10, UEs run the standard CRC. The activation of C-CRC is negotiated in Steps 4 and 5 and the backwards compatibility table is as follows:

|  |  |  |
| --- | --- | --- |
|  | Legacy UE | New UE |
| Legacy gNB | As currently done. | **Case nUE, lBS:** UE learns from SIB and lack of signature that legacy BS does not support C-CRC. Thus, UE skips addition of E(PK, K) in message 4 and does not activate C-CRC. |
| New gNB | **Case lUE, nBS:** Legacy UE does not look into signature since legacy UE does not know that field or new SIB is present. Legacy UE does not send E(PK, K) in message 4, and thus, gNB does not activate C-CRC and does not send Hash(K) in message 5. | As in the description in the proposal |

Note that such a negotiation protocol can be misused by an attacker to make a new UE think that it is talking to a legacy gNB. This can also happen in current solutions.

Note that in some current solutions, a UE might think that it is communicating with a proper gNB in a secure way (source origin verification and replay attack of the received SIB messages) and be under a replay attack, i.e., a MitM might forward the traffic between the real UE and the real gNB. This solution instead checks the validity of the signed SI and then checks through the usage of the C-CRC whether a MitM is in place, i.e., forwarding traffic between the UE and the real gNB.

##### 6.26.3 Evaluation

Editor’s note: Applicability of the solution due to message sizes and performance in terms of bandwidth needs is ffs.

Editor’s note: evaluation to be added.

Editor’s note: evaluation under the presence of repeaters is ffs.

KI#2 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 neighbouring cells, and to send self-crafted or old PWS messages*”

KI#2 includes as potential requirement: “*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.”*

This solution addresses both the authenticity and replay protection of system information.

The authenticity is provided by signing system information with a private key only known to the signing party. Authenticity of the received system information is ensured in any RRC state.

KI#2 acknowledges the difficulty of accurate time synchronization by stating that: “*Time synchronization. It is because of difficulty to achieve fairly acceptable time synchronization between one gNB and other gNBs, and between UEs and gNBs”.* When time synchronization is used, the UE has to check whether the received message is fresh compared with its current time. The UE should use a time window to deal with time differences due to, e.g., time synchronization or propagation delay. If the UE and gNB are not perfectly synchronized and time window is:

1) too big, then a MitM can perform replay attacks.

2) too small, then the likelihood of a UE rejecting a trustworthy gNB increases.

**

**Figure 6.26.3-1: Impact of a big or small time window when verifying the freshness of messages. In case 1), the UE might accept a replayed message by a FBS, in case 2) the UE might reject a message coming from a trustworthy gNB if the time window is small and time is not fully synchronized.**

Since detecting whether the SI is replayed or not is important but time checks might have some limitations, this solution proposes to apply the Cryptographic CRC solution as soon as feasible by negotiating a symmetric key so that the presence of a MitM replaying messsages is detected as soon as feasible.

## 6.27 Solution #27: Short-lived asymmetric key-based solution for protecting system information

### 6.27.1 Introduction

#### 6.27.1.1 General

For key issue #2 (security protection of system information) in TR 33.809 [2], there are multiple proposals including solutions 7, 9, 11, 12, 14, 19, and 20. These solutions can be classified into three categories (see Table 1 for a summary),

* public key based digital signature (solutions 7, 11, 12, 20),
* symmetric key based message authentication codes (MAC) (solution 9), and
* message hash consistency check without digital signature or MAC (solutions 14, 19).

Text

Description automatically generated

Table 6.27.1.1-1: Summary of the proposed solutions for KI#2

We next briefly discuss each category of the proposed solutions for KI#2.

#### 6.27.1.2 Hash-based consistency checks

Hash based consistency checks leverage existing NAS security context to detect spoofed or falsified broadcasting messages when UEs are in CONNECTED state. It provides certain security benefits without requiring any additional overhead in key management. However, it does not protect UEs in all states.

#### 6.27.1.3 Symmetric key based MAC

It is a common understanding that traditional symmetric key based MAC works well for two-party communication, or n-party communication when n is small, but not well for n-party communication when n is large and dynamic. This is because a symmetric key must be pre-shared among all group members [7], requiring a complex key distribution mechanism when the group is large, especially when the group membership is dynamic.

Mobile networks have a large number of base stations and UEs, and the relationship between UEs and base stations is dynamic, thus it is an n-party communication with n being large and dynamic. Therefore, traditional symmetric key based MAC does not appear suitable for authenticating broadcast messages in mobile networks.

Further, any member within a shared key group may be able to use the shared key to forge or tamper with messages unless the key usage is strictly limited to MAC verification only. Although USIM can be leveraged to protect the shared key so that it cannot be read out, it is not clear if it is possible for an attacker to use a USIM to generate a MAC using the shared key.

A non-traditional symmetric key based MAC, namely, TESLA [5], does not require a symmetric key to be pre-shared among group members. Rather, it discloses a key to all members. The key is not disclosed in the same message where its MAC is included. Rather, it is disclosed in a future message with a delay in time. Although TESLA nicely solves the problem of key distribution in a large and dynamic group, it requires other mechanisms such as digital signature to protect anchor keys that are used to authenticate regular keys used to generate MACs. Therefore, TESLA alone cannot solve the problem.

Editor’s Note: the use of TESLA to reduce computational overhead in digital signing and its potential quantum-resistance features is FFS.

#### 6.27.1.4 Asymmetric key based digital signatures

Asymmetric key or public key based digital signatures are naturally suited for authenticating broadcasting messages because they allow messages to be broadcast from one party and verified by many parties without the need to share the signing key. This is demonstrated by the proposed solutions (e.g., #7, #11, and #20) based on digital signature.

Editor’s Note: analysis of ID based solution is FFS.

However, there are still some gaps in the existing solutions that require further improvement. Particularly, outstanding issues in key management, replay mitigation, and cell selection need to be resolved for an asymmetric key based solution to be both secure and practical.

This solution fills these gaps and can satisfy the security requirements of KI#2 while also addressing various challenges in the solution deployment.

We next perform comprehensive analysis of various design options and outline the rationale of our design choices in three main areas including authenticity of system information, replay mitigation, and UE cell selection strategy.

### 6.27.2 Solution details

#### 6.27.2.1 Authenticity of system information

##### 6.27.2.1.1 Signing entities

In principle, a message should be signed by an entity that originates the message. Since system information blocks (e.g., MIB and SIB1-5) are originated by gNBs, gNBs should be able to sign those messages thus need to store the private keys used to sign the messages.

To minimize security risk, some deployments may want to reduce the exposure of signing keys and keep them in secure locations (e.g., at core networks to reduce the number of entities that can access the signing keys). This requirement could arise when the security protection of an entity (e.g., gNB) is not considered sufficient, e.g., due to the lack of physical security or the use of a shared environment, or outsourced management of the environment, or other security reasons.

Note that the significance of a signing key is different from other symmetric keys (e.g., for AS security) stored in gNB, the latter is of local impact while the former may be of global impact. More specifically, the stolen symmetric keys in a particular gNB only allows an attacker to access traffic for the users served by that gNB. However, a stolen signing key may allow an attacker to sign arbitrary system information, resulting in attacks on many more potential users. Thus, a signing key needs to be protected with more caution.

In the undesirable case when a signing key is stored in a gNB location, a central signing entity, e.g., the Digital Signing Network Function (DSnF) in solution 20, at the core networks can be used to sign messages for a gNB so that it does not need to store the signing keys. Note this delegated signing has some drawbacks such as transmission delayd and bandwidth overhead.

Editor’s note: the choice of signing entities is FFS.

**(D1): Both gNB and a core network function can perform digital signing of system information based on operator’s deployment and security requirements.**

##### 6.27.2.1.2 Raw public keys or certificates

Digital signatures are generated by a private key and verified by the corresponding public key. Public keys and trust anchors need to be distributed to UEs to enable them to verify digitally signed system information. A public key can be distributed in the form of a raw key or a public key certificate. A raw key consists of a public key, and maybe some other data such as a key identifier. A public key certificate such as X.509v3 has a well-defined data structure supporting key life cycle management, key hierarchy, and key usage, among other functionalities.

A raw public key is simple and of smaller size (comparing to a public key certificate), and is usually flat (i.e., it does not belong to a key hierarchy). This creates a challenge in trust anchor management. If each gNB uses a unique public and private key pair, each gNB’s public key would need to be configured as a trust anchor in UEs, resulting in many trust anchors and the difficulty to provision them out of band. If multiple gNBs share a public and private key pair, the number of trust anchors can be reduced but such practice will violate the basic security principle of key separation.

A public key certificate has rich semantics and supports key hierarchy, allowing multiple public key certificates to be verified using one trust anchor. But a public key certificate (e.g., X.509v3) is usually larger in size and may not fit into a single SIB due to the size limitation of SIB in the physical layer. Further, a public key certificate use leads to further management complexities and needs to be verified for its revocation status, e.g., using Certificate Revocation List (CRL) or Online Certificate Status Protocol (OCSP). Both CRL and OCSP require network connectivity, which had not yet been established at the stage of SIB acquisition.

One way to address the certificate revocation issue is to use short-lived public key certificates [8]. Since a public key certificate has a short expiration time (e.g., a few hours), a revocation check can be skipped assuming a compromised key will expire quickly. One challenge with short-lived certificates is that new certificates need to be issued frequently, thus requiring the issuing CA to be online. There are security risks in operating a CA online, which should be avoided if possible.

To this end, we propose a hybrid approach that combines the use of public key certificates and short-lived public keys. More specifically, a public key certificate is issued to an entity at the core network. This core network entity (e.g., DSnF in Solution 20) uses its private key to sign a gNB public key and other minimal data such as expiration time, key usage, etc. This signed object is valid for a short period of time (e.g., a few hours) and is referred to as short-lived public key (similar to the idea of delegated credentials for TLS [6]).

The advantages of using short-lived raw public keys include a) short-lived raw public keys belong to a key hierarchy, allowing them to be verified using one trust anchor; 2) certificate revocation check is not needed; b) there is no need to operate a CA online, since the short-lived raw public keys can be issued by an end entity (e.g., DSnF); and d) a short-lived raw public key is about 150 bytes (using 256-bit ECDSA) and can fit into a single SIB.

Editor’s note: further comparison of certificate revocation and short-lived public key is FFS.

**(D2): A public key certificate is issued to an entity in the core network, which then issues short-lived public keys to gNBs.**

##### 6.27.2.1.3 Trust anchors

Based on D2, a certificate chain consists of a root CA certificate, zero or more intermediate CA certificates, an end entity certificate, and a short-lived public key (see Figure 1). In theory, any certificate (from the root CA certificate, any intermediate CA certificate, or an entity certificate) on this certificate chain could be provisioned as a trust anchor. However, if a CA certificate is configured as a trust anchor, all subsequent certificates under the trust anchor including the short-lived public key must be sent to UEs for them to verify signed system information, resulting in higher transmission overhead.



Figure 6.27.2.1.3-1: Certificate chain and trust anchor

Based on Table 6.20.2.5.1-1 in solution 20, an X.509v3 certificate for ECDSA-256 with SHA-256 is of about 545 bytes. However, a SIB has a size limit of 2976 bits (372 bytes). It would take two system information blocks to carry one X.509v3 certificate, which does not appear desirable. Thus, we want to try to avoid transmitting public key certificates to UEs to minimize message overhead. In this solution, the end entity certificate issued to the core network is configured as a trust anchor. In this way, only a short-lived public key needs to be transmitted to UEs and it can fit into a single SIB.

**D3: The trust anchor on the UE is an end entity certificate issued to a core network entity that issues short-lived public keys to gNBs.**

##### 6.27.2.1.4 PKI trust models

A PKI is often used to manage the lifecycle of public key certificates. Various PKI trust models are discussed in solution 20. While a fully centralized PKI (e.g., GSMA managed PKI for all mobile operators) significantly reduces the number of trust anchors required, it also creates deployment dependence and other issues (e.g., operational costs).

Since an end entity certificate, not a CA certificate, is configured in UEs as a trust anchor, there is no obvious benefit in adopting a centralized PKI. Therefore, decentralized PKIs, each of which can be managed by an individual operator, are supported to remove deployment dependence on other parties.

**D4: A decentralized PKI trust model is supported, i.e., each operator issues its own certificates and manages its own trust anchor.**



Figure 6.27.2.1.4-1: PKI trust models - centralized vs decentralized

Note that a trust anchor (an end entity certificate) can be issued by an existing Certification Authority (CA) that an operator already has, or by a new PKI that is created (e.g., using tools such as OpenSSL) for the sole purpose of digitally signing system information.

The challenge in trust anchor provisioning in roaming scenarios (e.g., each roaming partner has its own trust anchor) can be managed with in-band provisioning (see 6.27.2.1.5).

##### 6.27.2.1.5 Trust anchor provisioning

Trust anchors can be provisioned into UEs (e.g., in USIM) using either out-of-band or in-band mechanisms. Out-of-band provisioning of trust anchors leaves no risk window since it allows a UE to verify signed SIs starting from the first registration with the network, thus it offers the best possible security. However, it may create dependence on other parties, particularly in roaming scenarios. In-band provisioning of trust anchors allows an operator to provision its own trust anchor independently while offering deployment flexibility. However, in-band provisioning may have a risk window during which a digitally signed message cannot be verified if the trust anchor has not been provisioned.

To avoid risk window, trust anchors should be provisioned out-of-band if possible, e.g., by a home network (the procedure for provisioning the public key for SUPI encryption can be reused), or by a Standalone Non-Public Networks (SNPN). In-band provisioning (e.g., based on the procedure proposed in solution 7) should also be supported to update existing trust anchors (e.g., due to certificate expiration).

**D5: Trust anchors are provisioned into UEs (e.g., stored in USIM) out-of-band, e.g., by a home PLMN or an SNPN but can be updated in-band when necessary.**

In roaming scenarios, the trust anchor of the roaming partners should be provisioned by a user prior to leaving the home network. If the trust anchor of a roaming partner is not provisioned, the UE is still able to select the partner’s network by following the cell selection strategy outlined in 6.27.2.3, provided that UE security policy allows for such selection.

Note that not all trust anchors of all roaming partners need to be preconfigured into the UE at the same time, reducing storage requirement of the trust anchors. For example, if a UE only visits a few roaming partners, the UE will only be provisioned with a few trust anchors. In a possible but unlikely event that a UE visits all the roaming partners and there is not enough storage space for all trust anchors, a stored trust anchor can be overwritten by a new one, e.g., based on the last time the trust anchor was accessed.

Editor’s note: Process and requirements for trust anchor/signature validation upon SIB reception are ffs.

Editor’s note: Who is root CA and how many root CAs are FFS.

Editor’s note: The impact of USIM storage for trust anchor provisioning is FFS.

Editor’s note: How to update CA certificate is FFS.

##### 6.27.2.1.6 Delivering signatures and short-lived public keys

With an entity certificate configured as the trust anchor, the digital signature (along with some other data, e.g., a timestamp) of System Information (SI) and a short-lived public key needed to be delivered to UEs for them to verify the SI. We consider three options for delivering a digital signature and a short-lived raw public key.

First, both the digital signature (e.g., of 64 bytes) and the short-lived raw public key (e.g., about 150 bytes) are included in a SIB. Although the combined size is about 214 bytes, which can fit into SIB (up to 372 bytes), it would reduce its capacity by more than half (e.g., to about 160 bytes). This does not appear ideal. Further, while a signature is based the content of a particular SIB, the short-lived raw public key cam be valid for many instances of different SIBs. Thus, neither is it necessary nor desirable to transmit the short-lived raw public key within each SIB.

Second, a new SIB (namely SIB\_x) is defined to carry both the digital signature and the short-lived raw public key. This option has the advantage of leaving other SIBs untouched. However, it may create a new problem in the scheduling of the new SIB\_x. Since the digital signature is computed based on the content of a particular SIB, the new SIB\_x carrying the digital signature may need to be scheduled precisely according to the schedule of existing SIBs to ensure that the SIBs and the digital signature acquired in two separate messages match each other. This is of particular challenge for SIB1, since it is repeated several times within a periodicity of 160ms. Although the repeated SIB1 may not change in content, timing related attribute associated with a repeated SIB1 may change. Thus, separating the digital signature from SIB1 would require precise scheduling of the new SIB\_x, which does not appear desirable.

Third, the short-lived raw public key is carried in a new SIB, but the digital signature of SIB is carried within the SIB. This option adds reasonable amount of message overheads to a SIB, but avoids the complexity of scheduling the new SIB\_x. Thus, we select this option.

Editor’s Note: it is FFS to analyse the impact of including a signature of 64 bytes in each SIB1.

Editor’s Note: The periodicity of the SIB broadcast carrying the short-lived certificate needs to be further clarified to analyse the impact of this solution.

**D6: the digital signature protecting a SIB is carried within the SIB, and the short-lived public key used to verify the SIB signature is carried by a new SIB to be defined.**

##### 6.27.2.1.7 System information to be protected

System information (SI) includes MIB and 9 SIBs (SIB1-9). We next discuss how each SI should be digitally signed.

Since MIB does not have enough space to carry a digital signature, one option is to digitally sign MIB and SIB1 together. Note that MIB and SIB1 are broadcasted at subframes 0 and 5 respectively at their scheduled frames. One challenge is that MIB and SIB1 have different periodicities of 80ms and 160ms respectively, and MIB and SIB1 are also repeated (e.g., 8 times) within their respective periodicity. Luckily, the SFN field within the MIB contains only the 6 most significant bits of the 10-bit SFN, thus it changes every 160ms. In other words, although MIB has a smaller periodicity than SIB1, it remains unchanged within the periodicity of SIB1, i.e., every 160ms. Therefore, MIB and SIB1 can be digitally signed together. For example, in Figure 3, there are 9 MIBs shown, each of which is broadcasted at SFN=0 (0x0000000000) to 8 (0x0000001000) respectively. While the 10-bit SFN changes in every MIB repetition, the 6 most significant bits (MSBs) of the SFN contained in the MIB remain 0x000000----) and do not change within 160ms.



Figure 6.27.2.1.7-1: Examples of MIB and SIB1 scheduling

**D7: MIB (including the SFN field) and SIB1 are digitally signed together with one digital signature.**

Editor’s Note: How often the UE needs to read a SIB is FFS.

Since SIB2-5 may be broadcasted at very different periodicity from SIB1 or may be acquired on-demand, it does not appear practical to sign some of them together or with SIB1. Thus, each of SIB2-5 can be signed individually. Assume that SIB1 and the new SIB\_x will be acquired prior to SIB2-5, only the digital signature of SIB2-5 needs to be delivered, which can be carried within each SIB.

SIB6-8 are originated from an external entity to the core network (CBCF and AMF) and then to gNBs. We currently do not consider the digital signing of SIB6-8 in this solution.

#### 6.27.2.2 Replay mitigation

Digitally signed messages cannot be tampered with but can be replayed. In order to mitigate replay attacks, message timeliness needs to be provided. This is often accomplished by including a time variant parameter along with the message when computing its digital signature. In addition, some properties of a message originator, if they cannot be easily spoofed, can also be included in the computation of the digital signature to further enhance mitigation against replay attacks.

##### 6.27.2.2.1 Message timeliness

Three types of time variant parameters are often used to provide message timeliness or uniqueness, including *random numbers*, *sequence numbers*, and *timestamps*.

A random number is often used in real-time interactive communication, such as a challenge-response authentication protocol, to ensure a response is uniquely computed based on a specific challenge. Since system information is not acquired by UE interactively with gNB, a random number is not suitable for providing message timeliness in system information.

A sequence number, either a serial number or incremental counter value, can uniquely identify a message. To use a sequence number to detect replay attack, a recipient needs to receive each and every message from an originator (e.g., gNB) and also maintains a state (e.g., the latest sequence number) for the originator. These requirements do not hold in system information broadcasting, since a UE does not acquire every system information block from every gNB. Thus, sequence number is not suitable for detecting replayed system information.

Timestamp can be included with a message to provide message timeliness to mitigate replay attacks. It does not require any state to be stored by a recipient but requires the local clocks of a message originator and a recipient to loosely synchronize. Given that a UE synchronizes its clock with a gNB prior to acquiring system information, we suggest that it is reasonable to assume the clocks between UE and gNB can be loosely synchronized. Therefore, a timestamp is recommended for mitigating replay attacks.

**D8: A timestamp is included with each SIB, and is digitally signed along with the SIB to mitigate replay attacks.**

A UE can check a timestamp in a SIB against its local time to see if the time difference is within an allowed window (t\_w). The smaller the t\_w is, the more likely a replay can be detected.

Editor’s Note: Further clarification on which one is accurate between local clock and timestamp in a SIB is FFS.

In a typical scenario where a message is sent out after a local time is obtained and the digital signature is then computed, the total network delay for the message to reach a receiver includes:

1. the computational delay - the time taken to compute the digital signature (in the order of us, based on Figure 4);

Table

Description automatically generated

Figure 6.27.2.2.1-1 - OpenSSL speed test for ECDSA on a VM

Editor’s note: The timing performance is based on a different software and hardware platform than the one typical for UEs. The timing performance on UE is FFS.

1. transmission delay at the sender – the time taken to transmit the message out from the sender’s memory to the network (in the order of us);
2. the propagation delay – the time taken to transmit the message from the sender to the receiver over the network (e.g., over the air) (in the order of us), and
3. transmission delay at the receiver – the time taken to transmit the message from the network to the receiver’s memory (in the order of us).

In this scenario, the total network delay (t\_d) is likely less than 1ms, but let’s say t\_d=1ms . Thus, the allowed delay window (t\_w) can be set to a value slightly higher than the network delay (t\_d+τ) to accommodate time deviation between the sender and the receiver. Let’s say τ=2ms, which would be the required accuracy of time synchronization. Then t\_w= t\_d+τ = 1ms+2ms = 3ms. Note these numbers are used here just as examples.

In reality, MIB and SIBs are broadcasted according to precise scheduling. More specifically, a MIB is broadcasted every 80ms and repeated every 10ms (at the starting of a frame), and SIB1 is broadcasted at a periodicity of 160ms and also repeated within a periodicity (e.g., every 20ms at the starting of a half frame). There are several options in assigning timestamp (thus a new digital signature) to SIB1.

First, each SIB1 repetition is assigned a new timestamp (see Figure 5). Thus, a new digital signature is also computed for each SIB1 repetition in every 20ms. In this case, there is no scheduled delay to be accommodated. Thus, t\_w= t\_d+τ = 1ms+2ms = 3ms.



Figure 6.27.2.2.1-2: Each SIB1 repetition has its own timestamp and a digital signature

Second, all SIB1 repetitions within a periodicity share a common timestamp, as well as a common digital signature (see figure below). Thus, a new timestamp is obtained, and a new digital signature is computed at the beginning of each SIB1 periodicity of 160ms. In this case, the allowed delay must include the maximum scheduled delay (t\_s), i.e., the delay of the last SIB1 repetition within the periodicity, which is 140ms. Therefore, t\_w=t\_s+t\_d+τ=140ms+1ms+1ms=143ms.



Figure 6.27.2.2.1-3: All SIB1 repetitions within a periodicity carry the same timestamp and digital signature

Third, it is also possible to have multiple SIB1 repetitions within a periodicity or across multiple periodicities that share a common timestamp. To generalize, let’s assume a timestamp is shared by N>=1 SIB1 repetitions. Then the maximum scheduled delay t\_s= (N-1)\*20ms. Thus, t\_w= t\_s+ t\_d+τ =(N-1)\*20ms +3ms. The value of N has two aspects.

On one hand, the smaller the N is, the more effective it is against replay attacks. For example, if N=1 and t\_w is set to 3ms, it would make it very difficult, if not impossible, for a false base station to successfully replay a SIB1. Since a replayed SIB1 has to be processed by the UE portion of the false base station and then broadcasted based on scheduling, it could add more than 3ms of delay, thus can be detected. However, if N is larger than 1, e.g.,N=8 and t\_w=143ms, it may leave enough time for an attacker to replay a SIB1 without being detected.

Editor’s note: it is FFS to analyze alternative approaches that might allow reusing the same signature in multiple SIBs while minimizing the risk window of SIB replaying attacks.

On the other hand, the smaller the N is, the higher the computational cost it incurs. For example, if N=1, a digital signature needs to be computed every 20ms. Based on the OpenSSL speed test of ECDSA-256, it takes about 24us to compute a digital signature. Although the computational overhead appears small, it is not negligible, particularly when one gNB-CU needs to compute digital signatures for multiple gNB-DUs in a distributed gNB architecture. Therefore, the value of N needs to be balanced between security and performance. To this end, we recommend leaving N configurable.

**D9: The number of SIB1 repetitions that share a timestamp and the digital signature should be configurable and can be adjusted dynamically by network operators.**

##### 6.27.2.2.2 gNB unique properties

Since timestamp alone may not fully mitigate replay attacks if the allowed delay window is large, additional parameters may be used to augment timestamp to improve replay mitigation. For example, if a sender has some properties that cannot be easily forged by an attacker or can be detected if forged, such properties can be included along with a timestamp to improve mitigation against replay attacks.

To this end, PCI and downlink frequency, as proposed in Solution 7, can be included in the computation of digital signature of system information. To replay a digitally signed MIB/SIB1, an attacker would have to use the same PCI and downlink frequency as a legitimate gNB. Although both PCI and downlink frequency can be forged, a forged PCI may allow a UE to detect the presence of an attacker when two cells use the same PCI. When an attacker is forced to use the same downlink frequency as a legitimate cell, it may introduce additional signal interference, also an indication of the potential presence of an attacker. Thus, both PCI and downlink frequency help improve mitigation against replay attacks, albeit not preventing them.

**D10: PCI and downlink frequency can be digitally signed along with timestamp and MIB/SIB1 to further mitigate replay attacks.**

Editor’s note: It is ffs the need and discussion of (dis)advanges of (not) signing additional fields in the PBCH such as the beam index.

##### 6.27.2.2.3 Time synchronization issues

By using a timestamp to mitigate replay attacks, we introduce an assumption that UE’s time and gNB’s time are loosely synchronized, e.g., to an accuracy of 2ms. This assumption is realistic since UE and gNB need to synchronize their clocks in the physical layer to the accuracy of 1ms or less..

However, we need to consider scenarios where UE’s time may not be synchronized with gNB’s time. Examples of such scenarios include, but are not limited to, a) The first time a UE is powered on and has never synchronized with a network before; b) UE has been powered off for too long so that its time is out of sync with the network; and c) UE’s time may be manipulated (e.g., by an attacker using other methods).

In those scenarios, the UE may reject the timestamp from a legitimate gNB, resulting in a denial of service of UE. This can be mitigated by checking the consistency of timestamps from multiple cells (assuming the gNB’s clocks are synchronized), as proposed in solution 20.

For example, let’s assume that a UE is located within the coverage area of two cells, each of which assigns a new timestamp for each SIB1 repetition. Let’s assume that the allowed delay window (t\_w) is set to 3ms, but the UE’s time deviates from a gNB’s time by one hour (3,600,000ms).

When the UE acquires a SIB1 repetition from the first cell, the SIB1 timestamp is t1 and the UE’s time is u1. If we ignore the network delay, the difference between u1 and t1 is about 3,600,000ms, let’s say |u1-t1|=3,600,000ms. Since this is significantly larger than t\_w=3ms, the UE will not accept the SIB1.

When the UE acquires another SIB1 repetition from the second cell, the SIB1 timestamp is t2 and the UE’s time is u2. With the network delay ignored, |u2-t2|=3,600,000ms, which is also significantly larger than t\_w=3ms. Thus, the UE will not accept the SIB1 from the second cell either.

This time deviation from the network could result in denial of service to the UE. However, by checking the consistency of |u1-t1| and |u2-t2|, the UE can detect that its time has gone out of sync with the network and can proceed to select one of the cells since their times are consistent. Note that if the two cells assign a new timestamp to SIB1 repetitions at different rates, the scheduling delay needs to be considered, e.g., by leveraging the redundancy version in each SIB repetition.

In the presence of FBSs, it can be considered as a byzantine fault problem and the consistency check of times continues to work as long as 2/3 of the received SIB1 by a UE belong to real base stations.

Editor’s note: the protocol for consistency checking and its underlying assumptions needs to be clarified and detailed.

Editor’s note: potential limitations of consistency checking (e.g.., when a single gNB in reach) and discussion on complementary methods (if required) is ffs.

**D11: Consistency check of gNB times can be performed when UE’s time goes out of sync with the network to avoid failure in timestamp verification.**

##### 6.27.2.2.4 Limitations

Digital signatures provide authenticity and message integrity of system information, preventing an attacker from originating any MIB/SIBs or tampering with an existing MIB/SIB. However, a timestamp may not prevent a replay attack if the allowed delay window is set to a value that is long enough for a replay to succeed.

Further, PCI may not always allow a UE to detect a replay if the UE is out of the range of a legitimate gNB whose system information is being replayed. This can be illustrated in Figure 6.27.2.2.4-1.

Editor’s note: Figure 6.27.2.2.4-1 assumes an omnidirectional antenna. Attacking area when a gNB uses beamforming is ffs.

Assume R1 be the broadcasting area of a real base station (RBS1), and F be the broadcasting area of the false base station (FBS). If the FBS replays the system information from RBS1 and uses the same PCI as the RBS1, A UE located within the intersection of R1 and F, denoted by F∩R1, will be able to detect the duplicated PCI from two base stations. However, a UE located within the area of F but outside the area of R1, i.e., F-F∩R1, will not be able to detect the duplicated PCI. Although the area where UEs may be attacked by an FBS is reduced by digitally signing PCI, an FBS may choose to replay the system information from another RBS to expand its attacking area. For example, the FBS can replay the system information from RBS2 to attack UEs located within the area of F∩R1.

|  |  |
| --- | --- |
|  |  |

Figure 6.27.2.2.4-1: Attacking areas of an FBS by relaying system information from RBSs

Although it is possible to replay system information in theory, there are practical challenges an attacker needs to overcome in order to succeed.

First, to replay system information in real-time (or relay system information), an FBS needs to include a UE and a gNB. By using the same PCI and downlink frequency, an attacker must find a strategy to prevent FBS-UE from connecting to FBS-gNB.

Editor’s note: FBS-UE and FBS-gNB are under the control of the attacker. It is ffs what prevents an attacker from modifying the software of the FBS-UE to not connect to the FBS-gNB.

Second, even if an FBS manages to successfully relay system information from a legitimate gNB, it is not clear if it can also successfully lure UEs away from their camped cells. According to [9], an FBS needs to use a tracking area code (TAC) that is different from a UE’s current TAC to trick the UE into believing that it has entered a new tracking area to reselect the FBS. Since TAC in SIB1 is integrity protected, the FBS is unable to modify the TAC. Thus, it is not clear how much impact replayed system information could have on UEs currently camped on the nearby cells.

Editor’s Note: Whether an FBS needs to use a different TAC is FFS.

Third, replayed system information can be detected by the UEs which can receive both the original system information and the replayed one. In other words, an FBS cannot go undetected. It is not clear what strategy an FBS can adopt to hide.

Editor’s Note: Whether the UE can receive both the original SI and the replayed one is FFS.

Fourth, when a replayed system information is detected based on duplicated PCI, a UE could report to the network. If necessary, the network can adjust its configuration on the SIB1 timestamp to reduce the allowed delay window so that other UEs can detect replayed SIB1 based on timestamp.

To summarize, while it is theoretically possible to relay integrity protected system information, the security impact from the relay attack remains to be seen. We suggest this could be an active research area in the near future. Additional mitigation can be further introduced if needed, e.g., based on future research results.

It is also worth noting there are legitimate devices that need to relay signals from legitimate cells, e.g., to expand network coverage. For example, RAN recently approved a new WID [10] on NR repeaters. Thus, it is also necessary to allow system information to be relayed.

Editor’s Note: how to handle NR repeater is FFS.

#### 6.27.2.3 Cell selection and reselection

With MIB/SIB1 digitally signed, cell selection and reselection need to take into consideration of not only signal strength, but also the authenticity and freshness of MIB/SIB1. Section 6.20.2.5 in solution 20 provides an example of how cell selection and reselection can be performed based on digitally signed MIB/SIB1.

Table 2 lists 10 possible scenarios based on the combinations of the states of digital signature, trust anchor, timestamp, and PCI uniqueness. The first case (Case #A) is the normal case, in which the digital signature of MIB/SIB1 is valid, the public key used to verify the digital signature is trusted (i.e., signed by a provisioned trusted anchor), the timestamp is fresh, and there is no PCI conflict. In this case, the cell can be immediately selected if the signal strength meets the criteria. In all other cases, there is some issue with at least one of the parameters. Therefore, in any of those cases, the cell cannot be immediately selected, nor fully rejected. If UE immediately selects a problematic cell, security could be compromised. If the UE fully rejects such cell, it may result in UE service degradation or outage.

We suggest that UE should prioritize cells for selection and reselection based on the results of MIB/SIB1 verification. Table 2 suggests a priority for each case. The first case (#A) is given the priority of 1.1, the highest priority. Case #B is of priority 1.2, the second highest, since it is likely that the UE clock is out of sync with the network, requiring consistency check with additional cells. Cases #C and #D likely indicate that the UE leaves its home network and enters a roaming partner’s network. The rest of cases are likely the results caused by an attacker. Note that the last case (#J) is likely from a legitimate base station that does not implement digital signing. However, we may not want to give it a higher priority. Otherwise, a MITM attacker could strip digital signature from SIB1 (and other related fields) to pretend that a cell has not implemented the feature.

If all available cells have a priority of 3.x, the UE could decide how to proceed based on local policy. The strictest security policy may force the UE to go out of service since an invalid digital signature or the absence of a digital signature does not provide guarantee that the cell is authentic. A moderate security policy may allow the UE to randomly select one of the cells to continue the service but may log and report the event. Although there is a security risk here, it forces an attacker to interfere and jam all other cells in order to force this scenario, significantly raising the bar for the attack.

Editor’s Note: It is FFS whether this cell selection and reselection strategy is feasible needs to be consulted by RAN2.

Editor’s Note: How to determine the UE local security policy is FFS.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Case # | Priority in cell selection | Is digital signature valid? | Is digital signature trusted | Is timestamp fresh? | Is PCI unique? | Notes |
| A | 1.1 | Yes | Yes | Yes | Yes | Normal case |
| B | 1.2 | Yes | Yes | No | Yes | UE clock is out of sync with the network, or replayed MIB/SIB1 |
| C | 2.1 | Yes | No | Yes | Yes | Trust anchor has not been provisioned (e.g., first time in a roaming network) |
| D | 2.2 | Yes | No | No | Yes | Trust anchor has not been provisioned, and UE clock is out of sync with the network or replayed MIB/SIB1. |
| E | 3.1 | Yes | Yes | Yes | No | Replayed MIB/SIB1 |
| F | 3.1 | Yes | Yes | No | No | Replayed MIB/SIB1 |
| G | 3.1 | Yes | No | Yes | No | Replayed MIB/SIB1, no trust anchor |
| H | 3.1 | Yes | No | No | No | Replayed MIB/SIB1, no trust anchor |
| I | 3.2 | No | Not relevant | Not relevant | Not relevant | MIB/SIB1 has been tampered with, e.g., using bit-flipping attack. Other parameters become irrelevant since they can be forged. |
| J | 3.2 | Without signature | Not relevant | Not relevant | Not relevant | Signature may have been stripped, or digital signing has not been implemented (e.g., eNodeB) |

Table 6.27.2.3-1 - Priority list for cell selection and reselection

**D12: UE should support prioritize cell selection and reselection based on the results of MIB/SIB1 verification and UE local security policy.**

### 6.27.3 Assessment using clause A.3

#### 6.27.3.1 UE aspects

UE needs to be provisioned of a list of trust anchors (see clause 6.27.2.1.3).

UE needs to support secure storage of trusted anchors.

UE needs to take into consideration results from signature and freshness verification of SI for cell selection and reselection (see clause 6.27.2.3).

UE needs to be configured with a local policy to prioritize security and availability for cell selection and reselection.

#### 6.27.3.2 UE actions upon detection of invalid signature

Upon detection of invalid signature, UE should perform cell selection and reselection as described in clause 6.27.2.3.

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

Man-on-the-side attacks (e.g., SI modification using SigOver), man-in-the-middle attacks (e.g., replay and relay), and some denial of services (e.g., from tampering with SI) are mitigated.

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

Some denial of services (such as from bit-flipping or radio jamming of all available cells) cannot be mitigated if all available cells are under the attack simultaneously.

#### 6.27.3.5 Provisioning of keys

Trusted anchors can be provisioned into UE during manufacture, onboarding, or after registration.

#### 6.27.3.6 RAN aspects

gNB needs to obtain short-lived keys from the core network.

gNB needs to perform digital signature computation of SIs.

gNB needs to broadcast digital signatures along with SIs, as well as the short-lived public key.

#### 6.27.3.7 VPLMN aspects

If the trust anchor of VPLMN is provisioned into a UE, unauthorized SI modification can be mitigated when all gNBs are upgraded to support the signature scheme when accessing the VPLMN.

#### 6.27.3.8 HPLMN aspects

If the trust anchor of HPLMN is provisioned into a UE, unauthorized SI modification can be mitigated when all gNBs are upgraded to support the signature scheme when accessing the HPLMN.

#### 6.27.3.9 Network sharing aspects

When a gNB is shared by multiple PLMNs, the operator owning the gNB can issue short-lived public key to the gNB, if the trust anchor of the gNB operator is provisioned into a UE.

#### 6.27.3.10 Roaming aspects

See clause 6.27.3.6 VPLMN aspects.

#### 6.27.3.11 Regulatory aspects

#### 6.27.3.12 Signature schemes

Potential signature schemes include:

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

Editor's Note: the ECDSA profiles for SUCI can be reused.

- **RSA**

- others

#### 6.27.3.13 Signature length

RSA: 256 bytes

ECDSA: 64 bytes

#### 6.20.3.14 Resistance against Quantum Computing

TBD.

### 6.27.4 Evaluation

This solution provides message authenticity to mitigate unauthorized modification and replay of system information independently of UE state.

This solution requires UEs to be provisioned with a trust anchor (e.g., the public key certificate of a network) to verify the authenticity of messages signed by a particular network. An operator deploying this solution can prevent its own subscribers from accepting unauthorized system information within its own network when all gNBs in an operator support the proposed scheme. If a roaming partner also deploys this solution and the public key certificate of the roaming partner network is provisioned into a UE, the UE is also prevented from accepting unauthorized system information over the roaming partner's network.

This solution requires SIB1 to be extended to carry a digital signature.

This solution requires new a system information block to carry a short-lived public key used to verify the digital signature.

This solution requires gNBs to communicate with the core network to obtain short-lived public keys.

Editor's Note: Further evaluation is FFS.

## 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.

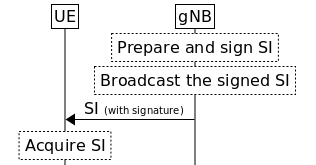


Figure A.2-1: A high-level example architecture for signed SI messages

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.3.1 UE Aspects

## A.3.2 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.3.3 Threats that are mitigated by signed SI messages

Editor's Note: Explanation is TBD.

## A.3.4 Threats that are not mitigated by signed Si messages

Editor's Note: Explanation is TBD.

## A.3.5 Provisioning of keys

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

## A.3.6 RAN aspects

Editor's Note: Explanation is TBD.

## A.3.7 VPLMN aspects

Editor's Note: TBD to explain - functionalities/responsibilities at VPLMN.

## A.3.8 HPLMN aspects

Editor's Note: TBD to explain - functionalities/responsibilities at HPLMN.

## A.3.9 Network sharing aspects

Editor's Note: TBD to explain - aspects related to network sharing.

## A.3.10 Roaming aspects

Editor's Note: TBD to explain - aspects related to network sharing.

## A.3.11 Regulatory aspects

Editor's Note: TBD to explain - any regulatory requirements.

## A.3.12 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.3.13 Signature length

Editor's Note: Explanation is TBD.

## A.3.14 Resistance against Quantum Computing

Editor's Note: Explanation is TBD

Annex B:  
Taxonomy of attacks against 5G UE over radio interfaces

# B.1 Introduction

Each key issue in clause 5 has its own threat analysis. However, it is not immediately clear how the threats identified in those key issues are related to each other or to other known attacks that may have been mitigated in 5G.

This clause describes a taxonomy of attacks against 5G UEs over the radio interfaces, including the threats identified in clause 5 (highlighted in Figure X.2-1). Other threats that may have been mitigated by other security enhancements in 5G are also included here to show how the threats identified in this study are related to the overall landscape of attacks against 5G UE over the radio interfaces

The attack taxonomy is presented in the form of a tree structure to show the relationship among the attacks. For example, it shows that authentication relay attacks are a subset of Man-in-the-Middle (MITM) attacks. Note that the attack taxonomy tree itself is not an attack tree by classic definition.

This attack taxonomy allows understanding what attacks are possible, what attacks can be mitigated by a particular protection, and what attacks remain even with new security protections.

For example, this attack taxonomy can serve as a tool to track which countermeasures or solutions would need to be implemented together in order to mitigate those attack vectors with a high risk. We know that an attacker is not bound to one particular path of attack, but usually chooses whichever way is easiest to achieve its goal.

# B.2 Attack taxonomy

The attacks against 5G UEs over radio interfaces can be classified into two categories, active attacks and passive attacks. In active attacks, an attacker actively injects signal or messages to influence what UE would receive. In passive attacks, an attacker silently sniffs signals exchanged between a UE and a gNB.

For the convenience of reference, we assign a number to each attack in the attack taxonomy tree. In attack description, an active attack is prefixed with “A-“ and a passive attack is prefixed with “P-“. This can help distinguish an attack number from a clause number.

Editor Note: the attacks in Figure X.2-1 consists of threats identified in this TR and other threats that either have been addressed in 5G (e.g., with SUPI encryption and UPIP) or being studied in other TRs. How to further differentiate these types of threats in the Figure is FFS.

The root node of the attack taxonomy tree is the general category of all attacks under consideration. A leaf node is an actual attack. An intermediate node is a subcategory of attacks, an actual attack, or a step leading to another attack.



*Figure B.2-1- Taxonomy of attacks against 5G UEs over radio interfaces*

## B.2.1 Active Attacks

Active attacks can be classified into three categories: radio jamming, signal shadowing, and MIB/SIB attacks.

### B.2.1.1 Radio Jamming

Radio Jamming (A-1.1): The attacker jams the frequency band of broadcastings noise at the frequency that the gNB under attack. This can be done continuously, or “smart” at certain times only.

DoS (Type 1) (A-1.1.1): While the attacker is active, the UE is unable to camp on the attacked cell, due to lack of synchronization.

DoS of all gNBs (A-1.1.1.1): By broadcasting noise across in the spectrum of all reachable cells, the UE can’t synchronize with any 5G cell.

DoS (Type 3) (A-1.1.1.1.1): there is no 5G service for the attacked UE.

Downgrade-1 (A-1.1.1.1.2): this is the system level downgrade, and the UE is forced to camps on a 4G cell (potentially a cell under control of an attacker). This can lead to 4G attacks, such as identity request, or service reject for that network.

### B.2.1.2 Signal shadowing

Signal Shadowing (A-1.2)

Editor’s Note: refer to overshadow attack [23].

### B.2.1.3 Message attacks

Message attacks (A-1.3): By setting up a fake gNB, the attacker is able to spoof, replay, and tamper with control messages and data plane traffic under its control. The attack starts by spoofing or replaying MIB/SIB1.

Editor Note: how to further re-organize message attacks (A-1.3) is FFS.

MIB/SIB1 spoofing (A-1.3.1): The attacker can originate MIB/SIB1 and control completely the parameters in the MIB/SIB1.

Unicast message spoofing (A-1.3.1.1):

Spoofed identity request (A-1.3.1.1.1):

SUPI stealing (A-1.3.1.1.1.1)

Spoofed service reject (A-1.3.1.1.2):

Downgrade-1 (A-1.3.1.1.2.1): this is also a system level downgrade and the UE is forced to camps on a 4G cell (potentially a cell under control of an attacker). This can lead to 4G attacks, such as identity request, or service reject for that network.

Service hijacking (A-1.3.1.1.2.1.1)

Fake SMS (A-1.3.1.1.2.2)

Other attacks (A-1.3.1.1.2.3)

Downgrade-2 (A-1.3.1.1.2.2): this is a service level downgrade, and the UE is forced to use a service of lower grade. For example, the UE may be forced to fall back to circular switch for a voice call.

DoS (Type 4) (A-1.3.1.1.2.3):

SIB2-9 spoofing (A-1.3.1.2):

Fake PWS (A-1.3.1.2.1):

MIB/SIB1 replay (A-1.3.2): The attacker is replaying the MIB/SIB1 of a legitimate gNB. The UE can communicate with the false gNB (attacker), but the parameters of air interface are copied from a legitimate gNB which may or may not be tampered with.

MITM (A-1.3.2.1)

Tampering (A-1.3.2.1.1)

Tampering CP/UP (A-1.3.2.1.1.1)

Linkability (A-1.3.2.1.1.1.1)

DoS (Type 2) (A-1.3.2.1.1.2)

aLTEr/IMP4GT (A-1.3.2.1.1.3)

Other attacks (A-1.3.2.1.1.4)

Relaying (A-1.3.2.1.2)

Authentication relaying (A-1.3.2.1.2.1)

Location poisoning (A-1.3.2.1.2.1.1)

MIB/SIB1 modification (A-1.3.3):

DoS (Type 1) (A-1.3.3.1):

Downgrade-3 (A-1.3.3.1):

## B.2.2 Passive Attacks

### B.2.2.1 Uplink Sniffing

SUPI stealing (P-2.1.1)

### B.2.2.2 Downlink Sniffing

User tracking (P-2.2.1)

Other data sniffing (P-2.2.2)

REVOLTE ((P-2.2.2.1)

Editor’s Note: descriptions of more active attacks are FFS

## B.2.3 Passive Attacks

Passive attacks can be classified into sniffing of uplink radios and downlink radios.

P-2.1 Uplink sniffing – an attacker sniffs the radio sent by the UE in the uplink channel.

P-2.1.1 IMSI/SUPI stealing – an IMSI/SUPI sent by a UE to the network can be stolen if it is not encrypted.

P-2.2 Downlink sniffing – an attacker sniffs the radio sent by the network in the downlink channel.

Editor’s Note: descriptions of more passive attacks are FFS

# B.3 Discussion

Editor’s Note: discussion is FFS

Annex C (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 |
| 2020-08 | SA3#100-e | S3-202150 |  |  |  | S3-201555,  S3-201636,  S3-201635r1(revised to S3-202223),  S3-201592r5(revised to S3-202161),  S3-201637r3(revised to S3-202226),  S3-201638r2(revised to S3-202227),  S3-202009r1(revised to S3-202108),  S3-202016r3(revised to S3-202142),  S3-202026r1(revised to S3-202109) | 0.10.0 |
| 2020-10 | SA3#100bis-e | S3-202740 |  |  |  | S3-202603r4 (revised to S3-202782),  S3-202467  S3-202542,  S3-202543,  S3-202558,  S3-202691,  S3-202699  S3-202717  S3-202718,  S3-202719,  S3-202720,  S3-202737  S3-202738 | 0.11.0 |
| 2020-11 | SA3#101-e | S3-203447 |  |  |  | S3-202866,  S3-202893r2  S3-203310r1  S3-202983r3(revised to S3-203364)  S3-203158  S3-203160  S3-203007  S3-203008r1(revised to S3-203452) | 0.12.0 |
| 2020-12 | SA3#101-e |  |  |  |  | Review by EditHelp and MCC | 0.12.1 |
| 2021-01 | SA3#102-e | S3-210778 |  |  |  | S3-210150  S3-210212  S3-210518  S3-210131r2(revised to S3-210783)  S3-210132r2 (revised to S3-210784) | 0.13.0 |
| 2021-03 | SA3#102bis-e | S3-211345 |  |  |  | S3-211028, S3-211116, S3-211235, S3-211261, S3-211329 | 0.14.0 |
| 2021-05 | SA3#103-e | S3-212351 |  |  |  | S3-211522  S3-212358  S3-212356  S3-212357  S3-212283 | 0.15.0 |
| 2021-08 | SA3#104-e | S3-213244 |  |  |  | S3-212677r1  S3-212520  S3-213210  S3-213238  S3-213240  S3-213241  S3-213242  S3-213243 | 0.16.0 |