A Formal Analysis of 5G Authentication

CCS'18

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October 18, 2018

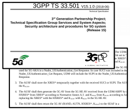
Designing Security Protocols

Smart people

e.g., IETF

Discussion

Standard



e.g., TLS

Release

Deployment

e.g., Banking

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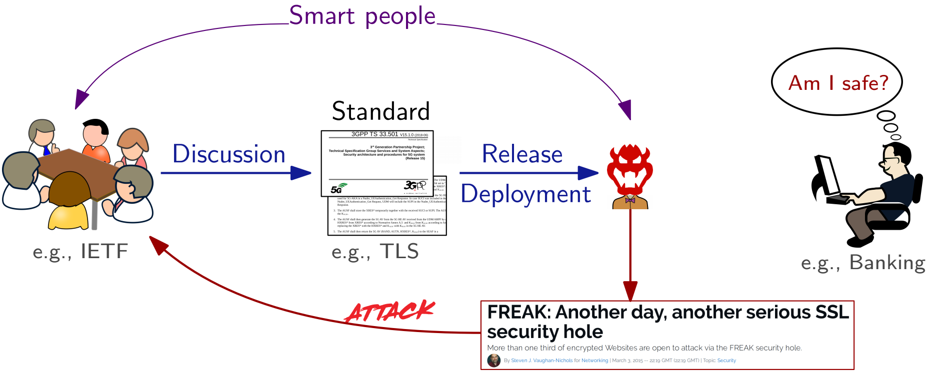

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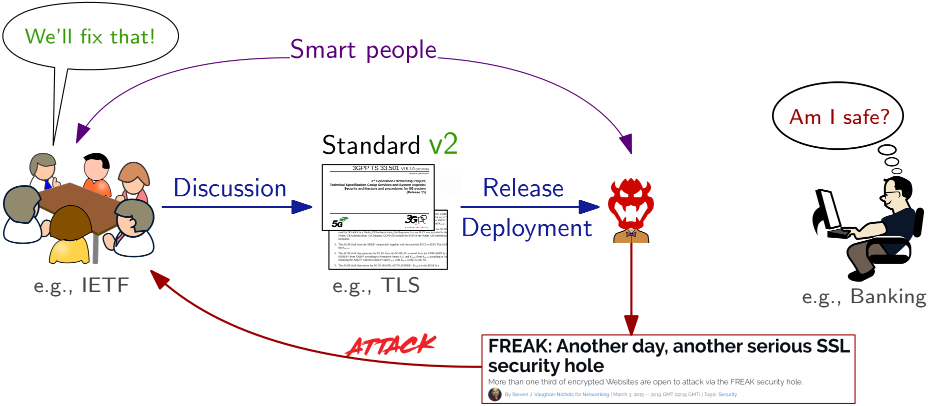

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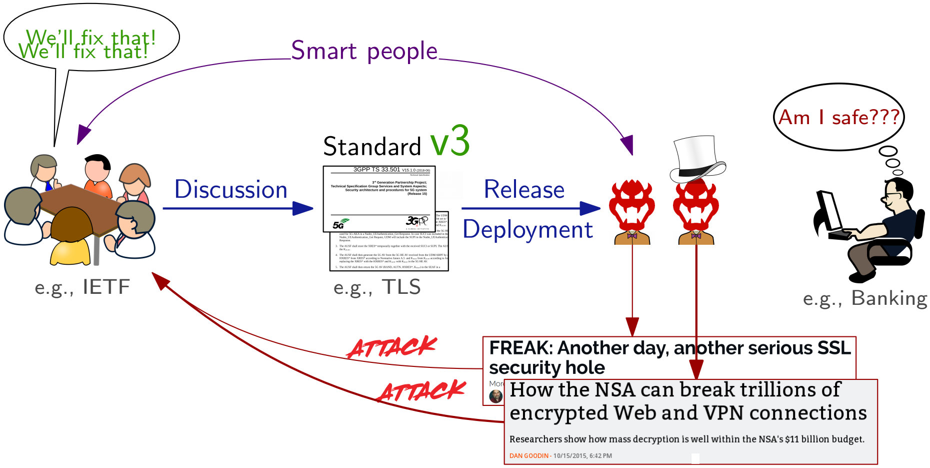

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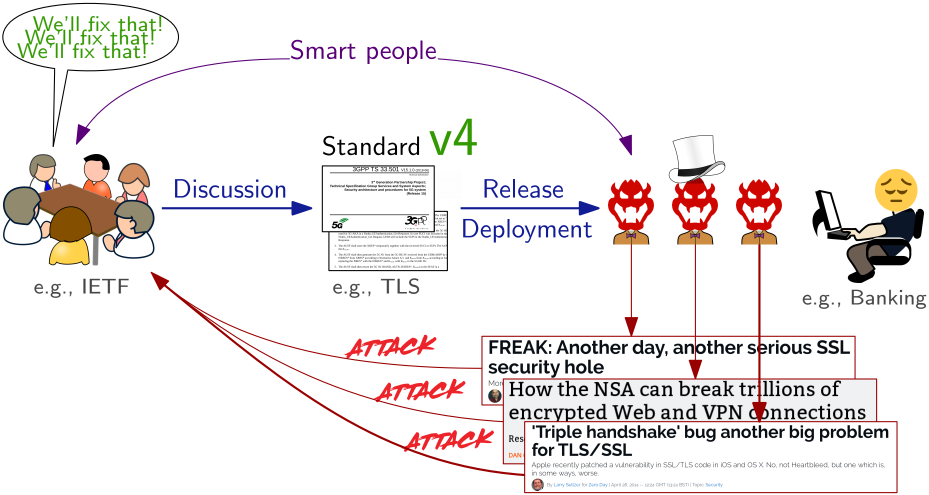

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Both are smart people

But asymmetric fight:
- weakest link
- active adversary exploiting insecure network
- concurrency + backward compatibility + ...

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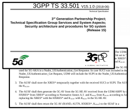
Standard v4



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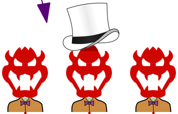

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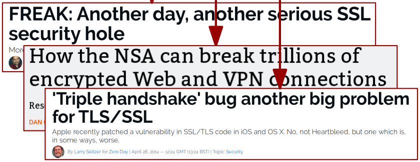

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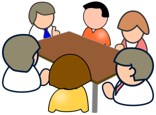

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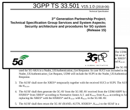

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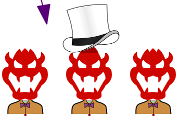

e.g., Banking

How can we help those guys?

FREAK: Another day, another serious SSL security hole

How the NSA can break trillions of encrypted Web and VPN connections

'Triple handshake' bug another big problem for TLS/SSL

Apple recently patched a vulnerability in SSL/TLS code in iOS and OS X. No, not Heartbleed, but one which is, in some ways, worse.

By Larry Seltzer for Zero Day | April 28, 2014 -- 12:24 GMT (13:24 BST) | Topic: Security

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???????

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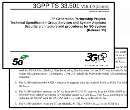

e.g., TLS

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ATTACK

Formal Verifier

$S \models P$?

Formal methods come to the **rescue**!

- Find errors and attacks **early** and **quickly**
- Establish **formal security guarantees**
- One must be **explicit** about **system spec.**, **environment spec.** (threat model), and **security goals**

5G Authentication

Mobile communication

- 4.8 billion unique users, 60% of world population has 4G
- next-gen 5G designed by 3GPP (as for 3G/4G); deployed in 2 phases
- Phase 1: frozen specification in 2018 and commercial service in 2020

Authentication

- Key protocol AKA: secure channel + authentication between  and 
- Different AKA protocols: 3G:AKA $\rightsquigarrow$ 4G:EPS AKA $\rightsquigarrow$ 5G:5G AKA

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5G AKA intended to improve security but:
Which security guarantees? Under which threat model/security assumptions?

Let's formally analyze 5G AKA!

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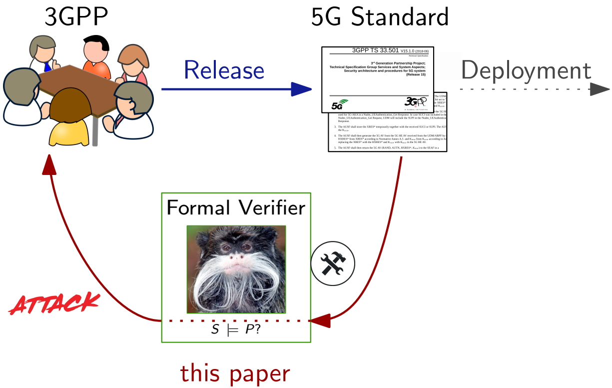

Formal Verification in the Symbolic Model

(also called Dolev-Yao model)

Cryptographic primitives assumed perfect

Security protocols encoded in a formal language (syntax + semantics)

Attacker = network (worst case scenario)

- eavesdrop: he learns all protocol outputs
- injections: he chooses all protocol inputs

Security properties encoded as reachability or equivalence properties

Sweet spot between precision and automation

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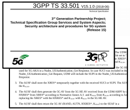
Automated Verification (tool):

- several efficient procedures and tools (but verification is undecidable)
- our tool of choice: Tamarin (the only one with the required features)

Process

5G Standard



≈700 pages, 4 docs.

Formalization →

Precise System Specification

- architecture and process spec.
- system assumptions and threat model (environment)
- security goals

Formalization

- implicit/unclear threat model and goals
- documents are often not self-contained

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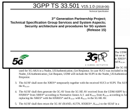
3GPP TS 33.501 V15.1.0 (2018-06)

3rd Generation Partnership Project;
Technical Specification Group Services and System Aspects;
Security architecture and procedures for 5G system
(Release 15)

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Property P

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- large, complex protocol with intricate state-machine
- encode security goals under many threat models

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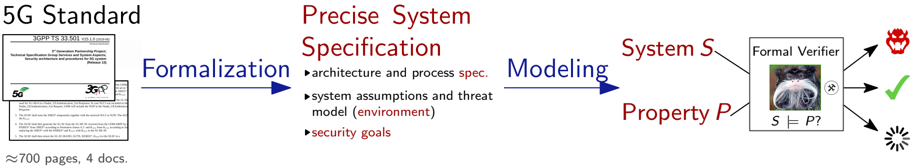

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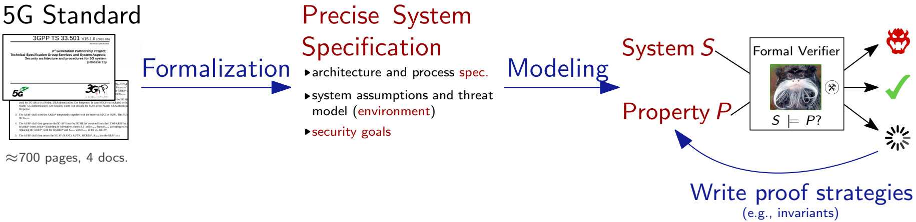

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- many features that make the verification
- need for proof strategies: sound by design, guide the proof search

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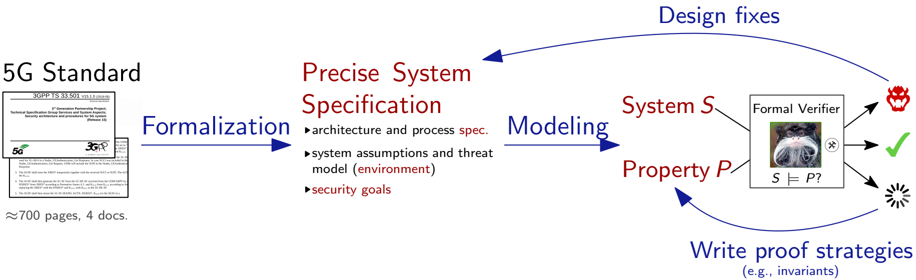

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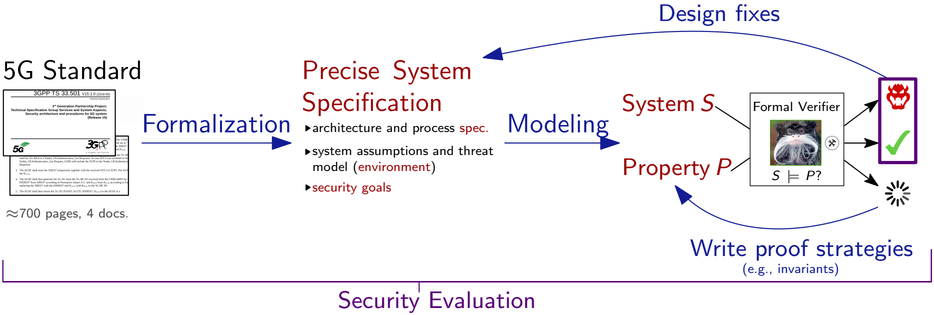

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Design fixes that are provably secure

Sec. Evaluation: attacks and fixes

Our Contributions

Formalization of the 5G standard

- Extract/Formally interpret security assumptions, goals and system spec.
- Identify key missing security goals + flaws in stated goals
- Propose fine-grained variants of goals (secrecy, authentication, privacy)

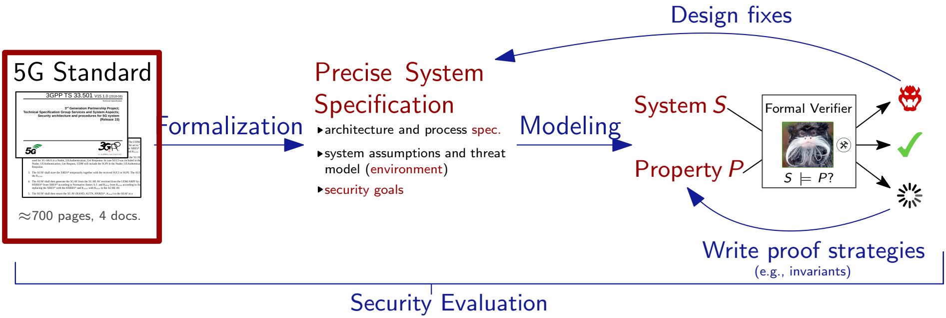
Formal model of 5G AKA amenable to automation

- First faithful model of an AKA protocol (challenges: loops, state-machine, scale, XOR)
- Dedicated proof strategies (in Tamarin)

Security Evaluation of 5G AKA

- Identify minimal assumptions required for each security goal to hold:
  - Authentication: critical properties are violated
  - Privacy: preserved for passive but broken for active
  - Secrecy: holds but not Perfect Forward Secrecy
- Explicit recommendations and provably secure fixes (also simplify)

Outline



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Write proof strategies
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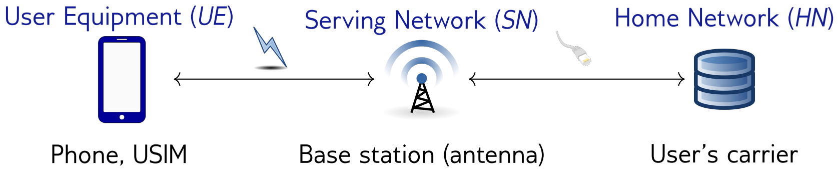
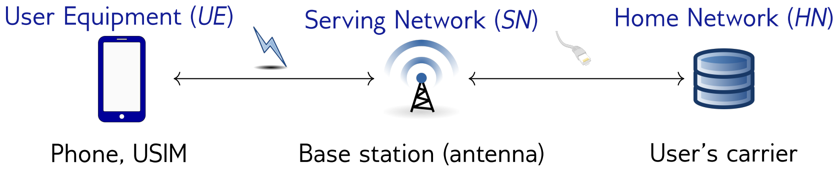
5G AKA



5G AKA designed to:

- **mutually authenticate** User Equipment with its Home Network (carrier)
- **establish session keys** btw. the User Equipment and its Serving Network

5G AKA



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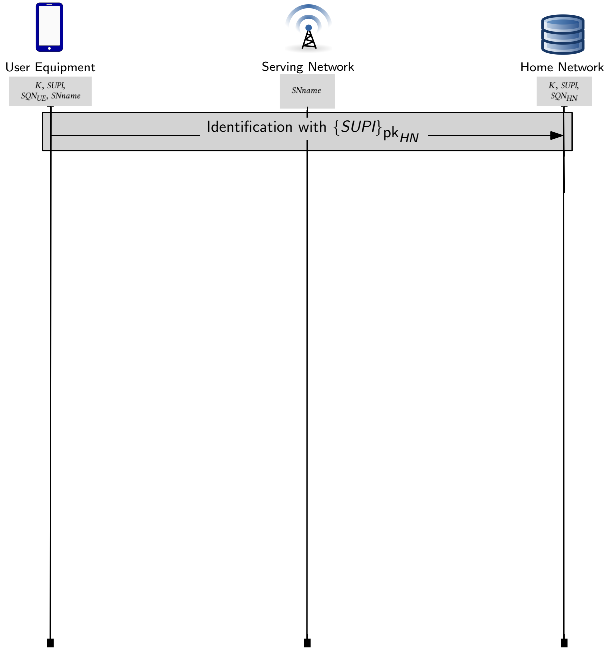
User Equipment (Phone with USIM) and Home Network **share**:

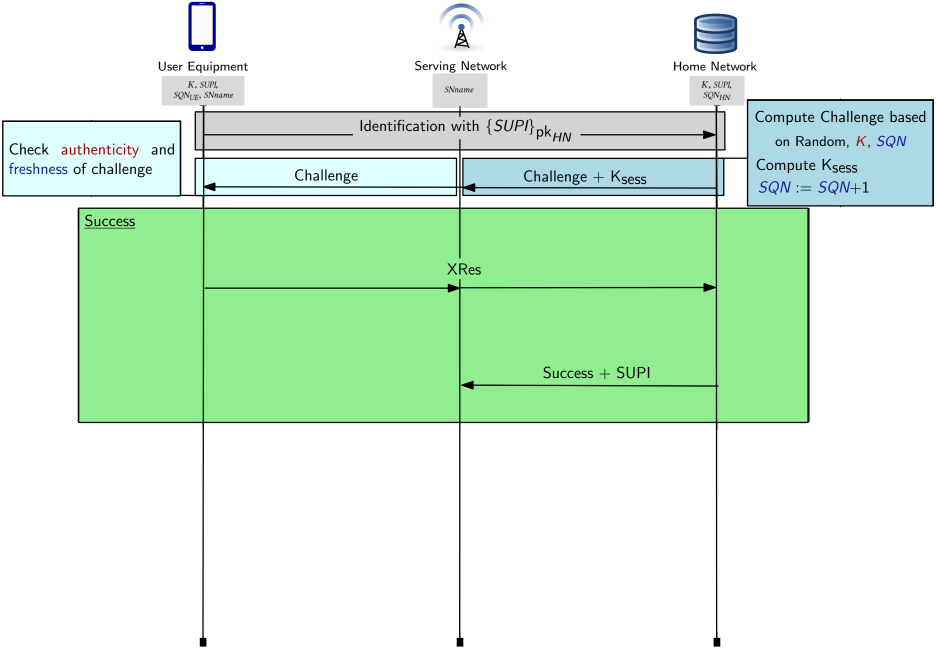
- a permanent *UE*'s **identifier** *SUPI* (for identification)
- a **symmetric key** K (shared secret)
- a **sequence number** *SQN* (for replay protection)

User Equipment knows the Home Network's **public key** pk_{HN}

5G AKA (cont.)


User Equipment
K, $SUPI$, SQN_{UE}, $SNname$
Serving Network
$SNname$
Home Network
K, $SUPI$, SQN_{HN}
Identification with $\{SUPI\}_{\mathrm{pk}_{HN}}$

5G AKA (cont.)


User Equipment
K, SUPI, SQN_UE, SNname
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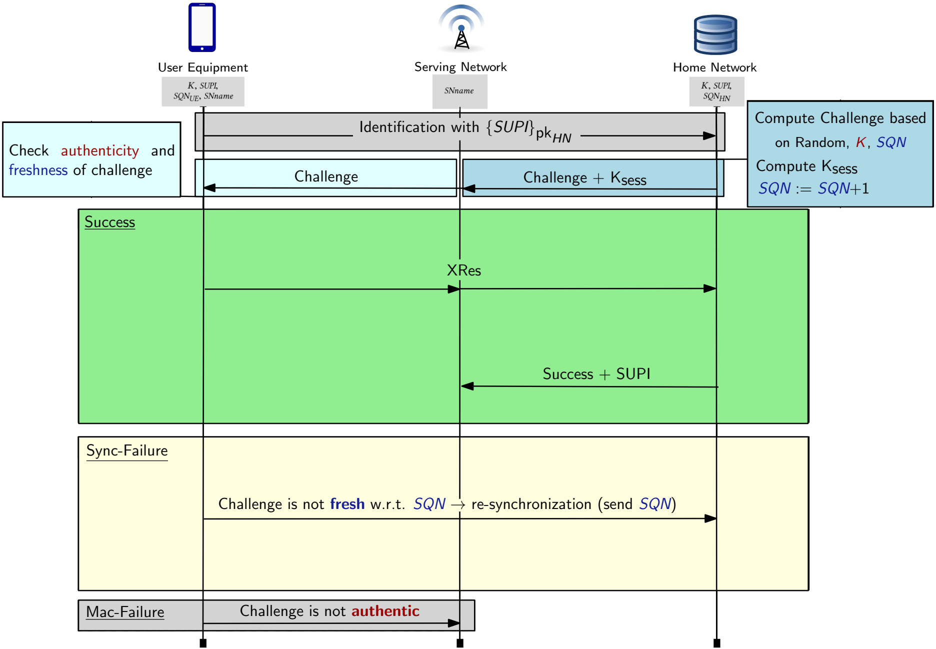
SNname
Home Network
K, SUPI, SQN_HN
Identification with {SUPI}pk_HN
Compute Challenge based on Random, K, SQN
Compute K_sess
SQN := SQN+1
Check authenticity and freshness of challenge
Challenge
Challenge + K_sess
Success
XRes
Success + SUPI

5G AKA (cont.)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SQN := SQN+1
Success
XRes
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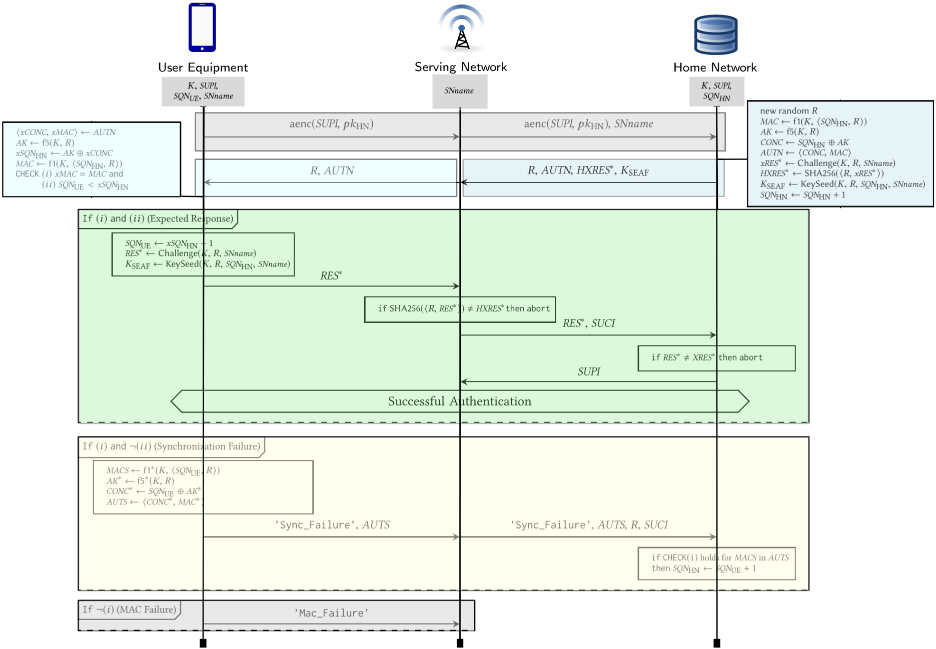
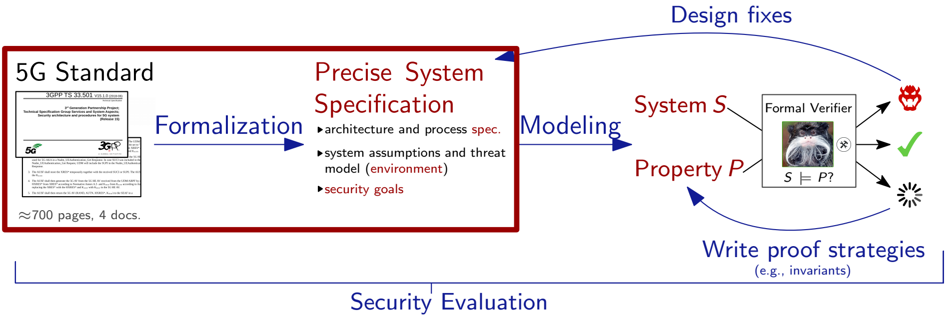
Sync-Failure
Challenge is not fresh w.r.t. SQN → re-synchronization (send SQN)
Mac-Failure
Challenge is not authentic

5G AKA (cont.)



User Equipment
K, SUPI, SQN_UE, SNname
Serving Network
SNname
Home Network
K, SUPI, SQN_HN
new random R
MAC ← f1(K, ⟨SQN_HN, R⟩)
AK ← f5(K, R)
CONC ← SQN_HN ⊕ AK
AUTN ← ⟨CONC, MAC⟩
xRES* ← Challenge(K, R, SNname)
HXRES* ← SHA256(⟨R, xRES*⟩)
K_SEAF ← KeySeed(K, R, SQN_HN, SNname)
SQN_HN ← SQN_HN + 1
aenc(SUPI, pk_HN)
aenc(SUPI, pk_HN), SNname
R, AUTN
R, AUTN, HXRES*, K_SEAF
⟨xCONC, xMAC⟩ ← AUTN
AK ← f5(K, R)
xSQN_HN ← AK ⊕ xCONC
MAC ← f1(K, ⟨xSQN_HN, R⟩)
CHECK (i) xMAC = MAC and
(ii) SQN_UE < xSQN_HN
If (i) and (ii) (Expected Response)
SQN_UE ← xSQN_HN + 1
RES* ← Challenge(K, R, SNname)
K_SEAF ← KeySeed(K, R, SQN_HN, SNname)
RES*
if SHA256(⟨R, RES*⟩) ≠ HXRES* then abort
RES*, SUCI
if RES* ≠ XRES* then abort
SUPI
Successful Authentication
If (i) and ¬(ii) (Synchronization Failure)
MACS ← f1*(K, ⟨SQN_UE, R⟩)
AK* ← f5*(K, R)
CONC* ← SQN_UE ⊕ AK*
AUTS ← ⟨CONC*, MAC*⟩
'Sync_Failure', AUTS
'Sync_Failure', AUTS, R, SUCI
if CHECK(i) holds for MACS in AUTS
then SQN_HN ← SQN_UE + 1
If ¬(i) (MAC Failure)
'Mac_Failure'

Outline



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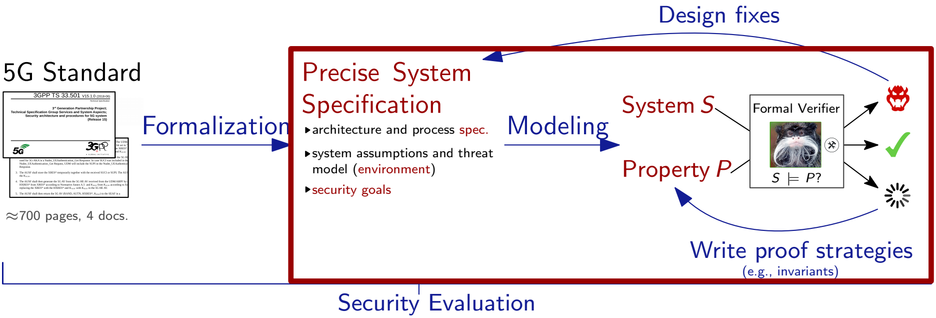

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Formal Modeling

System ~500LoC

- full state-maching with re-synchronization, precise modeling of XOR and counter SQN (only Tamarin can handle all that)
- + optional key-confirmation
- for unbounded number of *UEs, SNs,* and *HNs,* and unbounded sessions

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Threat Model & Security Goals ~1000LoC, 124 lemmas

- powerful Dolev Yao: control all the network
- wide-range of formal security goals (including secrecy, authentication, privacy)
- + many compromise scenarios in order to identify minimal assumptions

  $\rightsquigarrow$ strongest possible adversary model

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Proof Strategies ~1000LoC, ~ 5 hours computation time

- complex state-changes + loops $\rightsquigarrow$ automatic: / manual: impractical
- proof strategies: lemmas + heuristics that guide the proof search

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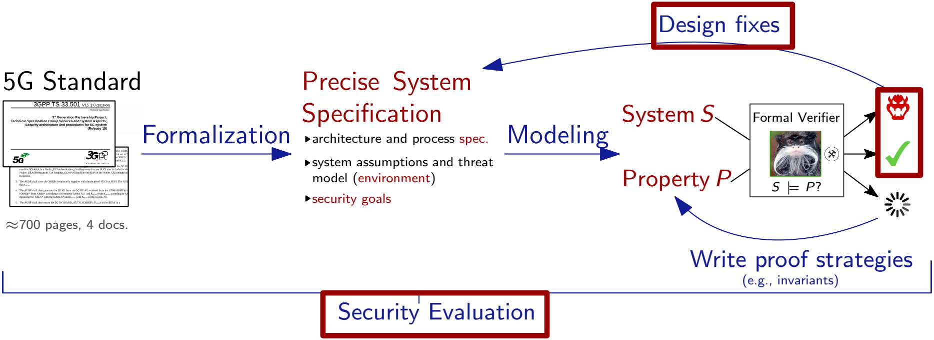
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Results

More than just 👹/✓?

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YES! For instance for *authentication:*

- Different perspectives ... (who obtains guarantees, about whom?)

Pair of parties

Point of view	*UE*		*SN*		*HN*	
Partner	*SN*	*HN*	*UE*	*HN*	*UE*	*SN*

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More than just /✓?

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Pair of parties

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Partner	*SN*	*HN*	*UE*	*HN*	*UE*	*SN*
Agreement						
on K_{sess}						
on *SUPI*						
on *SNname*						
Weak agree.						

Authentication properties

Results

More than just /✓?

YES! For instance for *authentication:*

- Different perspectives … (who obtains guarantees, about whom?)
- with different kinds of agreement properties … (identities?, data?, replay?)
- under different attacker models. (*e.g.* what can be compromised?)

Pair of parties

Point of view	*UE*				*SN*				*HN*			
Partner	*SN*		*HN*		*UE*		*HN*		*UE*		*SN*	
Agreement	NI	I	NI	I	NI	I	NI	I	NI	I	NI	I
on K_{sess}	✗	✗	…	…	✗	✗	…	…	…	…	…	…
on *SUPI*	-	-	-	-	-	-	…	-	-	-	-	-
on *SNname*	-	-	…	-	-	-	-	-	…	-	-	-
Weak agree.	✗		$\neg K$		…		…		…		…	

Authentication properties

Minimal assumption

Results: Authentication: Attack 1

Attack 1

(on explicit goal given in the spec.)

makes *SN* think it is talking to another UE ($\neq$ *SUPI*)

How?

- $SN \xleftarrow{\text{Challenge}+\text{K}_{\text{sess}}} HN$ and $SN \xleftarrow{\mathit{SUPI}} HN$ are not bound together!
- : interleave two sessions and swap two *SUPI*

Remark: In an earlier draft (v0.7.1), *SUPI*, K_{sess} sent together $\rightsquigarrow$ ✓

(we detected the introduced flaw when updating our models)

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Fix

Either:

- explicitly assume a binding channel *SN-HN* (= binding message−session)
- cryptographically bind the messages together

Results: Authentication: Attack 2

We re-verify all authentication properties when attack 1 is fixed:

Point of View	UE	SN
Partner	SN	UE
Weak agreement	$[\neg K \wedge \text{key-conf} \wedge \neg \text{ch}]$	$[\neg K \wedge \neg \text{ch}]$

Key-confirmation is required!

However, key-confirmation is not mandatory in the standard!

(subsequent procedures?)

Results: Authentication: Attack 2 (cont.)

Attack 2 (on explicit goal given in the spec.)

can impersonate a *SN* towards *UEs* without key-conf (not mandatory)

How?

- *SNname* is not included in the MAC sent by *HN* that comes with the challenge

Results: Authentication: Attack 2 (cont.)

Attack 2

(on explicit goal given in the spec.)

can impersonate a *SN* towards *UEs* without key-conf (not mandatory)

How?

- *SNname* is not included in the MAC sent by *HN* that comes with the challenge

Fix

Either:

- mandatory key-confirmation, required in one direction only ($UE \leftarrow SN$)
- add *SNname* to the MAC sent by *HN* (key-confirmation not required then)

Remark: our fixes reduce the number of roundtrips required to get security!

Results: Secrecy and Privacy

Secrecy(K_{sess}, K) holds but not PFS(K_{sess})

Privacy: The *UE*'s identifier *SUPI* remains **secret** (with honest *SN*/*HN*)

- defeats IMSI-catchers but
- **insufficient** to ensure **untraceability** with an active: Attack 3
- fix requires major redesign ☹

$\leadsto$ new 5G tracking device ("5G-Stingray") coming?

Conclusion

Contributions: Formalization of the 5G standard + Tamarin model with proof techniques + comprehensive security evaluation

5G AKA standard:

- definitely lacks explicit assumptions and security goals ☹
- meets core properties after easy fixes/+assumptions ☺
- improves privacy over 3G/4G, but still suffers from traceability attacks ☹

We have an ongoing discussion with 3GPP and GSMA: they will modify the standard.

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Future work:

- verify and formally compare other variants of AKA (3G, 4G, EAP-AKA' in 5G)
- follow the development of 5G (*e.g.* phase 2)
- more precise/efficient verification of privacy

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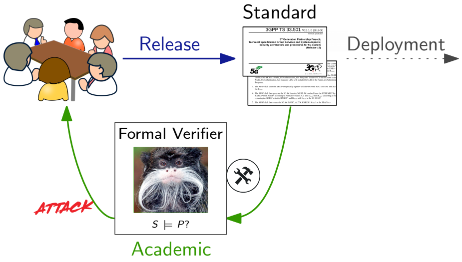
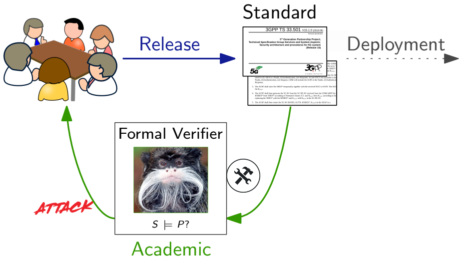
Others' future work: Formal Methods are a powerful tool! They are now mature enough for the real-world. ☺ Let's use them! ☺

Now:


Standard
Release
Deployment
3GPP TS 33.501
Formal Verifier
$S \models P$?
ATTACK
Academic

Now:


Release
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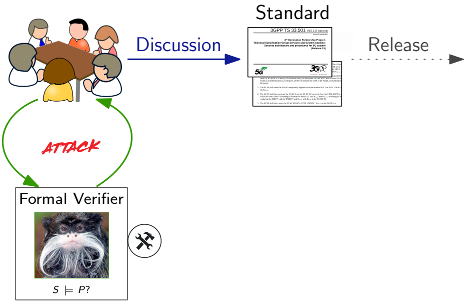
Ideally:


Discussion
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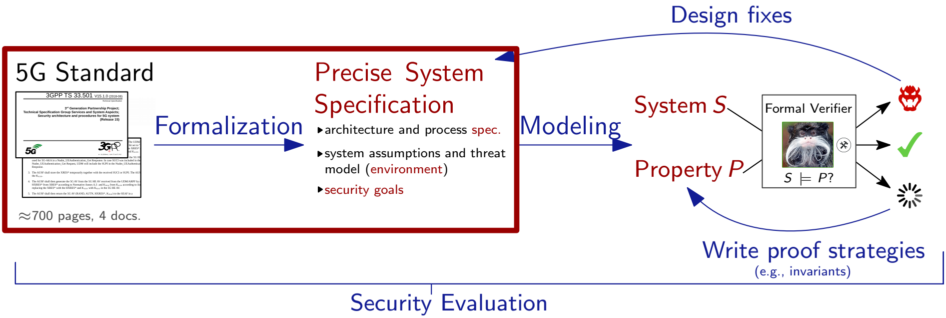
Backup Slides

Outline



Design fixes
5G Standard
3GPP TS 33.501 V15.1.0 (2018-06)
3rd Generation Partnership Project;
Technical Specification Group Services and System Aspects;
Security architecture and procedures for 5G system
(Release 15)
≈700 pages, 4 docs.
Formalization
Precise System Specification
architecture and process spec.
system assumptions and threat model (environment)
security goals
Modeling
System S
Property P
Formal Verifier
S ⊨ P?
Write proof strategies
(e.g., invariants)
Security Evaluation

Formalization

Goal: build a precise specification of the system (protocol), environment (*e.g.* threat model), and security goals

Example of imprecision in the standard and our interpretation:

Assurance [that the subscriber] is connected to a serving network that is authorized by the home network. [...] This authorization is 'implicit' in the sense that it is implied by a successful authentication and key agreement run.

$\leadsto$

Subscriber must obtain non-injective agreement on SNname with its Home Network after key confirmation.

Formalization

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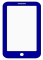
$\rightsquigarrow$

Subscriber must obtain non-injective agreement on SNname with its Home Network after key confirmation.

Takeaways

- critical security goals are missing (implicit?): *e.g.* injective agreement on the key seed
- some stated goals are two weak: no assurance that the authenticated party participated to the current session
- unclear system assumption (*e.g.* on channels) and threat model (notably for privacy)

Authentication: definitions



Point of view	*UE*		*SN*		*HN*	
Partner	*SN*	*HN*	*UE*	*HN*	*UE*	*SN*

Authentication depends on the perspective and the expected agreement:
What guarantees does *UE* obtain regarding *HN*?

(*HN*'s identity, *HN*'s view on the session)

Authentication: definitions

Point of view	UE		SN		HN	
Partner	SN	HN	UE	HN	UE	SN
Weak agree.	? ?	? ?		[...]		

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weak agreement	agreement on *HN*'s and *UE*'s ids (mutual auth.)

Authentication: definitions

Point of view	*UE*				*SN*		*HN*	
Partner	*SN*		*HN*		*UE*	*HN*	*UE*	*SN*
Agreement	NI	I	NI	I				
on K_{sess}	?	?	?	?				
on *SUPI*	?	?	?	?		[...]		
on *SNname*	?	?	?	?				
Weak agree.	?	?	?	?				

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weak agreement	agreement on *HN*'s and *UE*'s ids (mutual auth.)
(NI) non-injective agreement on K_{sess}	agreement on *HN*'s and *UE*'s ids and K_{sess}

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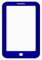

Point of view	*UE*				*SN*		*HN*	
Partner	*SN*		*HN*		*UE*	*HN*	*UE*	*SN*
Agreement	NI	I	NI	I				
on K_{sess}	?	?	?	?		[...]		
on *SUPI*	?	?	?	?				
on *SNname*	?	?	?	?				
Weak agree.	?	?	?	?				

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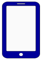

Point of view	*UE*				*SN*		*HN*	
Partner	*SN*		*HN*		*UE*	*HN*	*UE*	*SN*
Agreement	NI	I	NI	I				
on K_{sess}	✗	✗	$\neg K \wedge$k-c	$\neg K \wedge$k-c				
on *SUPI*	wa	×	wa	×		[...]		
on *SNname*	wa	×	[$\neg K \wedge$k-c]	×				
Weak agree.	[✗]		$\neg K$					

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Minimal security assumption:

- $\neg K$: no reveal of long-term key
- k-c: requires key-confirmation
- $\neg$ch: requires secure channel *SN*-*HN*
- (also compromise of sk_{HN}, *SUPI*, *SQN*)

Authentication: definitions

Point of view	UE				SN				HN			
Partner	SN		HN		UE		HN		UE		SN	
Agreement	NI	I	NI	I	NI	I	NI	I	NI	I	NI	I
on K_{sess}	✗	✗	$\neg K \wedge$k-c	$\neg K \wedge$k-c	✗	✗	¬ch	$\neg K \wedge \neg$ch	$\neg K$	$\neg K$	¬ch	¬ch
on *SUPI*	wa	×	wa	×	wa	×	[¬ch]	×	wa	×	×	×
on *SNname*	wa	×	[$\neg K \wedge$k-c]	×	wa	×	wa	×	[$\neg K$]	×	wa	×
Weak agree.	[✗]		$\neg K$		[$\neg K \wedge \neg$ch]		¬ch		$\neg K$		¬ch	

Authentication depends on the perspective and the expected agreement:
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- (also compromise of sk_{HN}, *SUPI*, *SQN*)

Authentication: all results

Point of view	*UE*				*SN*				*HN*			
Partner	*SN*		*HN*		*UE*		*HN*		*UE*		*SN*	
Agreement	NI	I	NI	I	NI	I	NI	I	NI	I	NI	I
on K_{sess}	✗	✗	$\neg K \wedge$k-c	$\neg K \wedge$k-c	✗	✗	¬ch	$\neg K \wedge \neg$ch	$\neg K$	$\neg K$	¬ch	¬ch
on *SUPI*	wa	×	wa	×	wa	×	[¬ch]	×	wa	×	×	×
on *SNname*	wa	×	[$\neg K \wedge$k-c]	×	wa	×	wa	×	[$\neg K$]	×	wa	×
Weak agree.	[✗]		$\neg K$		[$\neg K \wedge \neg$ch]		¬ch		$\neg K$		¬ch	

After fixing Attack 1 (binding):

Point of View	*UE*		*SN*	
Partner	*SN*		*UE*	
Agreement	NI	I	NI	I
on K_{SEAF}	$\neg K \wedge$key-conf$\wedge \neg$ch	$\neg K \wedge$key-conf$\wedge \neg$ch	$\neg K \wedge \neg$ch	$\neg K \wedge \neg$ch
Weak agreement	[$\neg K \wedge$key-conf$\wedge \neg$ch]		[$\neg K \wedge \neg$ch]	

Other Results

Secrecy:

Point of view	*UE*	*SN*	*HN*
K_{sess}	$\neg K \wedge \neg\text{ch}$	$\neg K \wedge \neg\text{ch}$	$\neg K \wedge \neg\text{ch}$
PFS(K_{sess})	✗	✗	✗
SUPI	$\neg sk_{\text{HN}} \wedge \neg\text{ch}^*$	–	$\neg sk_{\text{HN}} \wedge \neg\text{ch}^*$
K	$\varnothing$	$\varnothing$	$\varnothing$

*: no dishonest SNs (violated otherwise)

Other Results

Secrecy:

Point of view	*UE*	*SN*	*HN*
K_{sess}	$\neg K \wedge \neg \mathsf{ch}$	$\neg K \wedge \neg \mathsf{ch}$	$\neg K \wedge \neg \mathsf{ch}$
PFS(K_{sess})	✗	✗	✗
SUPI	$\neg sk_{\mathrm{HN}} \wedge \neg \mathsf{ch}^*$	–	$\neg sk_{\mathrm{HN}} \wedge \neg \mathsf{ch}^*$
K	$\emptyset$	$\emptyset$	$\emptyset$

*: no dishonest SNs (violated otherwise)

Privacy:

- *SUPI* remains confidential, even against active attackers and hence also against passive attackers.
- 5G AKA thus defeats previous active IMSI-catcher attacks
- We also have modelled a weak, passive attacker and have automatically proven that he cannot trace subscribers.
- active attackers are realistic threats for most use cases. We have (automatically) found that 5G AKA suffers from a traceability attack in that setting.