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DoLTEst: In-depth Downlink Negative Testing Framework for LTE Devices

CheolJun Park, Sangwook Bae, BeomSeok Oh, Jiho Lee, Eunkyu Lee, Insu Yun, and Yongdae Kim

LTE is Everywhere

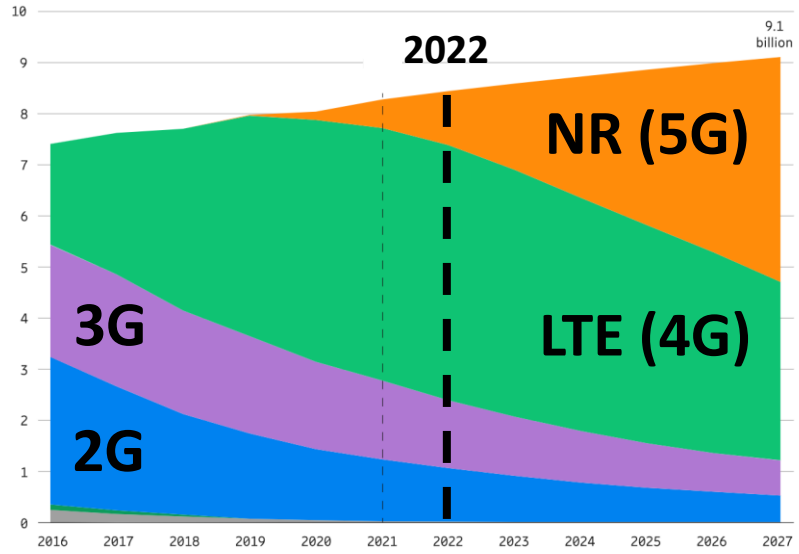
- > 22,000 LTE user devices from 990 manufacturers

Railway communication (LTE-R)

Industrial devices (LTE-M, NB-IoT)

Public safety services (PS-LTE)

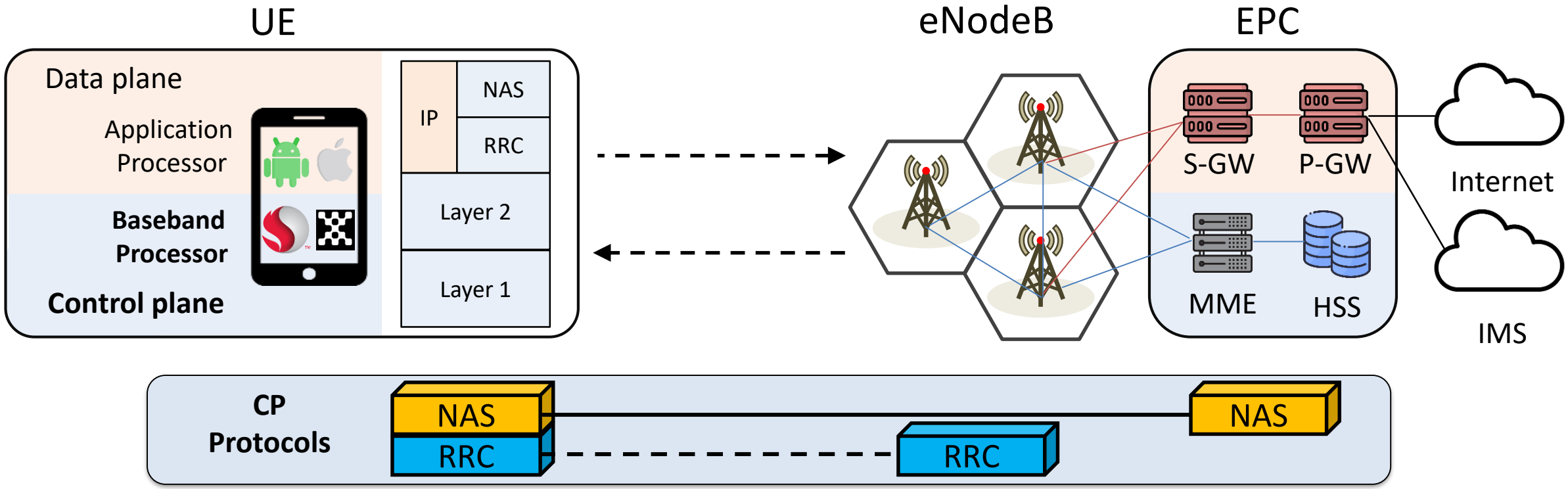
Vehicle communication (C-V2X)



> 60% LTE subscription

LTE Network Architecture

- LTE service procedures are separated into **control plane** and user plane
  - Two main control plane protocols: **RRC, NAS**



Negative Testing

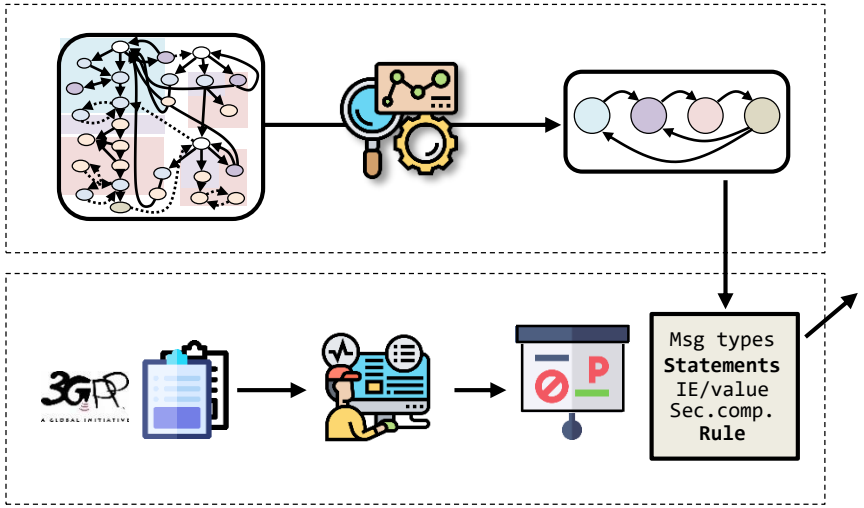
- Positive testing
  - Check if valid messages are correctly handled
- Negative testing?
  - Check if **invalid or prohibited messages** are appropriately handled
  - Among **993** test scenarios in conformance spec, only **14** cases are negative. [1] (3 RRC and 11 NAS)
  - Challenges
    - How do we enumerate all violating cases?
    - UE/Network state dependence
    - Spec is difficult to understand ➔ Oracle?

[1] 36.523, v15.5.0

Overview of Our Approach (DoLTEst)

1. Manual spec. analysis

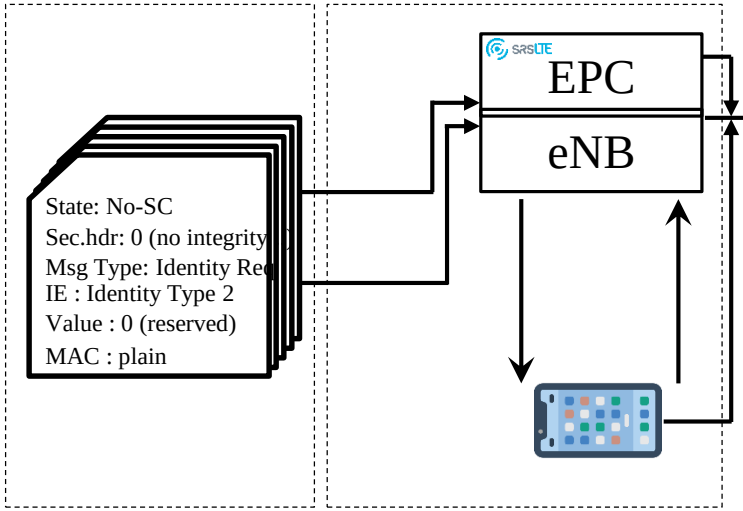
① Define new security-abstracted states



② Construct *guidelines*

2. Test case generation & OTA testing

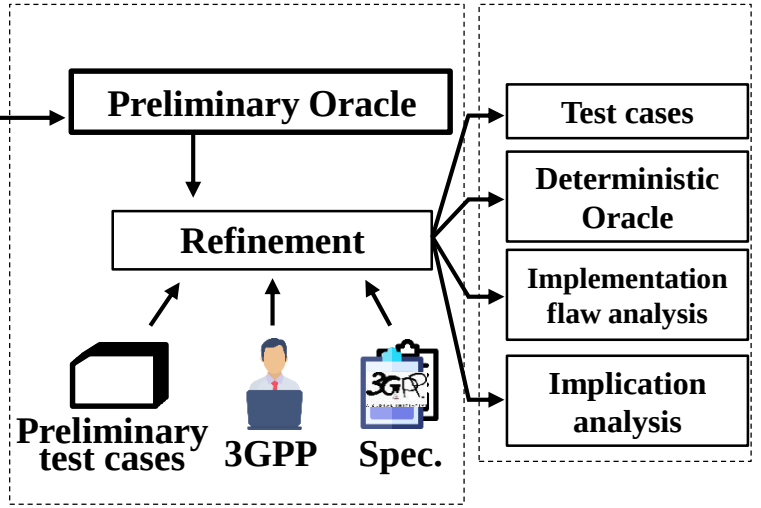
③ Generate test cases



④ Open-source LTE stack based over-the-air device testing

3. Manual post-analysis

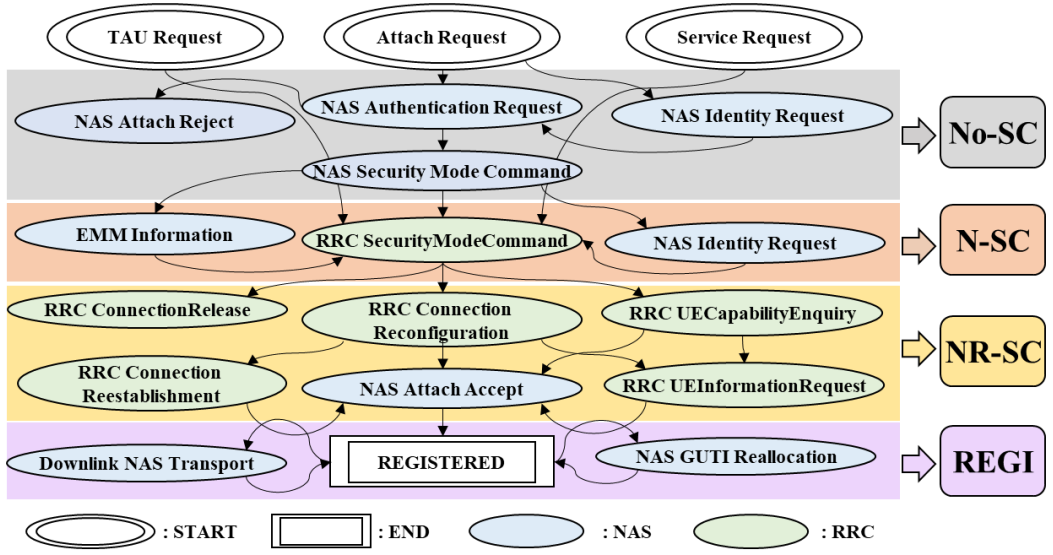
⑤ Deviant behavior analysis

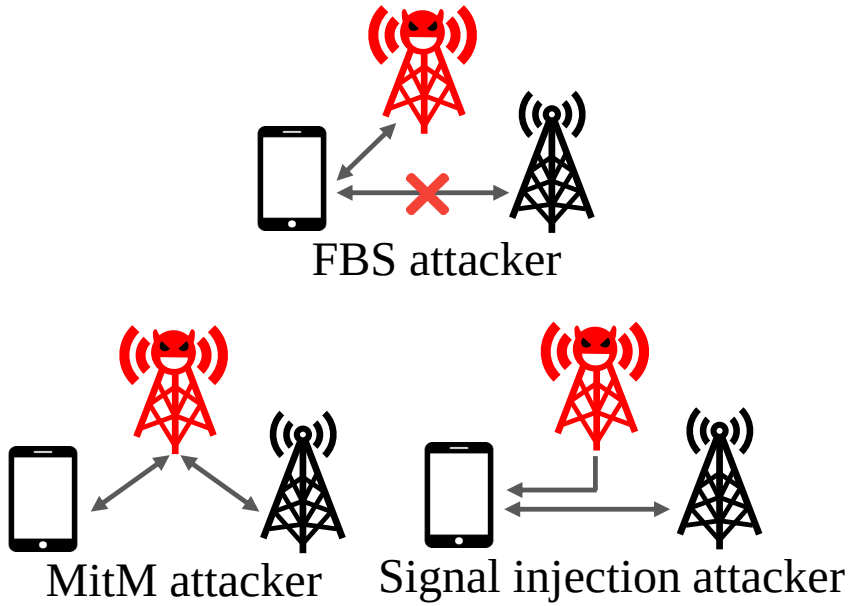


⑥ Flaw& implication analysis, oracle refinement

Security Abstracted States

- Re-define the existing implicit UE states as **new security abstracted states**
- Advantages
  - Reflecting **advanced LTE attacks**
  - **Reduce** total number of test cases





Test Case Generation

- Goal: Generating test messages that are **invalid or prohibited by specification**
  - We found every **statement** related with message authentication[1,2]
  - Addressing ambiguities in the spec: over-approximation

Protocol	Guideline					MAC	Reference	# of test cases for each state	Page #
	No.	State	Security Header Type	Message Type	IE				
RRC	1	*	N/A	RRCConnectionReconfiguration	drb-ToAddModList: {...}	*	A.6, 5.3.1.1 in [7]	2	68p
	2	*	N/A	RRCConnectionReconfiguration	srb-ToAddModList: {SRB2}	*	A.6, 5.3.1.1 in [7]	2	39p
	3	*	N/A	RRCConnectionReconfiguration	measConfig: {...}	*	A.6, 5.5.5.1 in [7]	2	68p
	4	*	N/A	RRCConnectionReconfiguration	mobilityControlInfo: {...} securityConfigHO: {...}	*	A.6, 5.6.5.1 in [7]	2	918p, 72p
	5	*	N/A	RRCConnectionRelease	...	*	A.6 in [7]	2	918p
	6	*	N/A	SecurityModeCommand	integrityProtection: {EIA1, EIA2, EIA3}[c]	*	A.6, 5.3.1.2 in [7]	10	70p
	7	*	N/A	UECapabilityEnquiry	...	*	A.6, 5.6.3.2 in [7]	2	230p
	8	*	N/A	counterCheck	...	*	A.6 in [7]	2	918p
	9	*	N/A	UEInformationRequest	...	*	A.6, 5.6.5.2 in [7]	2	919p
	10	*	N/A	DLInformationTransfer	...	*	A.6 in [7]	2	918p
NAS	11	*	*	Identity Request	Identity Type2: {IMSI}[c]	*	4.4.4.2 in [4]	124	50p, 51p
	12	*	*	Security Mode Command	integrityProtAlgorithm: {EIA1, EIA2, EIA3}[c]	*	4.4.4.1, 4.4.4.2 in [4]	155	50p
	13	*	*	GUTI Reallocation Command	...	*	4.4.4.2 in [4]	31	50p, 51p
	14	*	*	EMM Information	...	*	4.4.4.2 in [4]	31	50p, 51p
	15	*	*	Downlink NAS Transport	...	*	4.4.4.2 in [4]	31	50p, 51p
	16	*	*	Attach Reject	EMM cause:{#25}	*	4.4.4.2, 5.5.1.2.5 in [4]	31	50p, 51p, 129p
	17	*	*	Attach Accept	...	*	4.4.4.2 in [4]	31	50p, 51p

[1]: TS. 24.301, [2]: TS. 36.331

Example

Specification	**Except the messages** … **below**, no NAS signalling messages shall be processed by the UE… unless the network has **established secure exchange of NAS** messages… … - **Identity Request** ((if requested identification parameter is **IMSI**)

Guideline

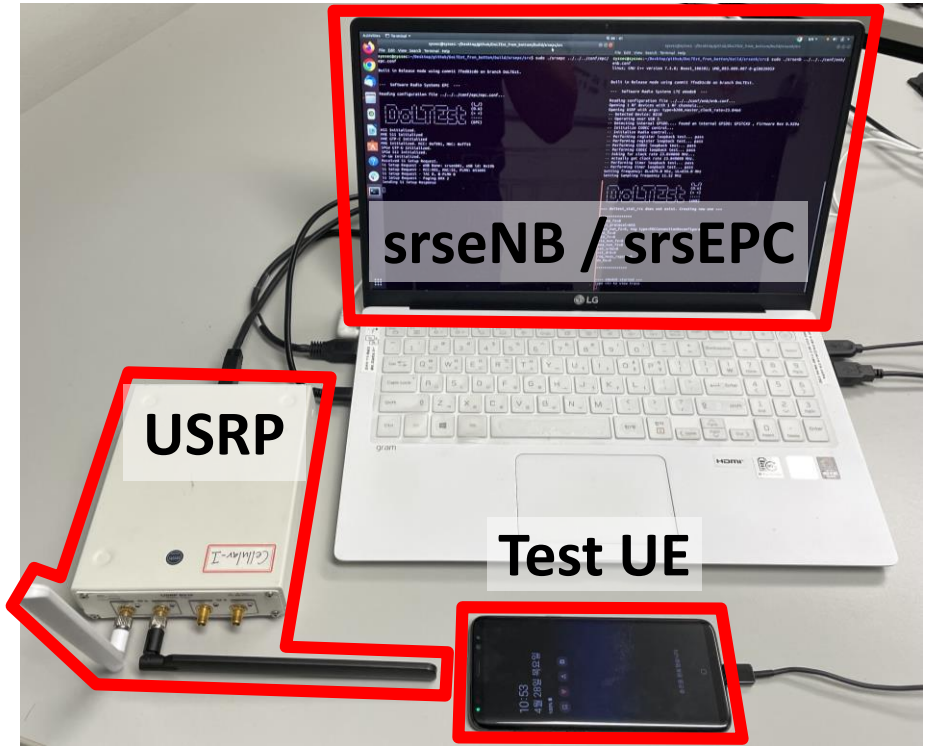
State	Security Header Type	Message Type	IE	Value	MAC
*	*	**Identity Request**	Identity Type 2	**not IMSI**	*

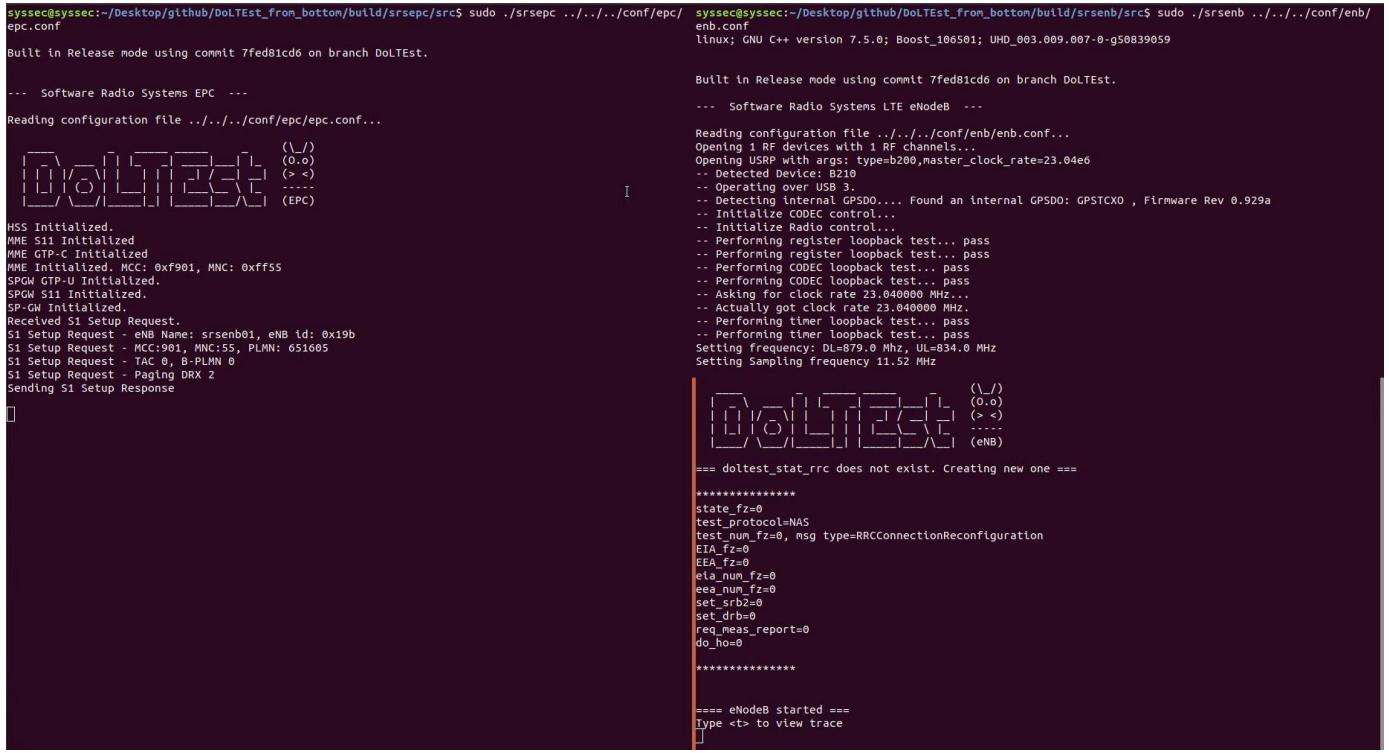
Over-approximation

No-SC	0 (no integrity protected)	Identity Request	Identity Type 2	0 (reserved)	plain
…	…	…	…	…	
No-SC	1 (no integrity protected)	Identity Request	Identity Type 2	2 (IMEI)	random
…	…	…	…	…	
No-SC	3 (integrity protected with…)	Identity Request	Identity Type 2	3 (IMEISV)	random
N-SC	3 (integrity protected with…)	Identity Request	Identity Type 2	3 (IMEISV)	plain

Implementation

- We edited srsLTE (9,234 LoC) to send total 1,848 test messages
  - State control + Test message generation
- Available on: https://github.com/SysSec-KAIST/DoLTEst





Results

- Tested **43** cellular devices from **five** major baseband manufacturers
  - Qualcomm, Exynos, MediaTek, HiSilicon, and Intel
- Discovered **26** implementation flaws, of which **22** were new

Type of flaw for handling: S*- Security header type, M*- Message type, I*- IE/value

Protocol	Message	State					Implication	Studied?
		No-SC	**N-SC**	**NR-SC**	**REGI**	All		
RRC	RRCConnectionReconfiguration	I1(2)†, I1		M2		-	AKA bypass (I1), Location leak (I1,M2)	[36], [52]
	RRCConnectionRelease	-		M2		-	Redirection attack (M2)	[41]
	SecurityModeCommand	I2†,I3		-		-	Eavesdropping (I2,I3)	[48]
	UECapabilityEnquiry	-		M2		-	Information leak (M2)	[53]
	CounterCheck	M1		M2		-	Information leak (M2)	-
	UEInformationRequest	M1†		M2		-	Location leak (M1,M2)	[52]
	DLInformationTransfer	-		M2		-	-	-
NAS	Identity Request	I2,I3	-			S1,S2(2)	Information leakage (S1,S2,I2,I3)	[43]
	Security Mode Command	I3	-			-	Eavesdropping (I3)	[48]
	GUTI Reallocation Command	-				S1	Identity spoofing (S1), Denial-of-Service (S1)	[36]
	EMM Information	-	S1			-	NITZ spoofing (S1)	[45]
	Downlink NAS Transport	-			S1	-	SMS phishing (S1)	[43]
	Attach Reject	S2,I2	-			S1	Denial-of-Service (S1,S2,I2)	[52]
	Attach Accept	-				-	-	-

S3

Studied?: Attacks using the message type was previously studied, †: Previously reported

Findings

- Manufacturer-dependent flaws
  - 5 NAS integrity bypass @ every **Qualcomm BP**
  - 2 RRC integrity bypass @ every **Exynos BP**

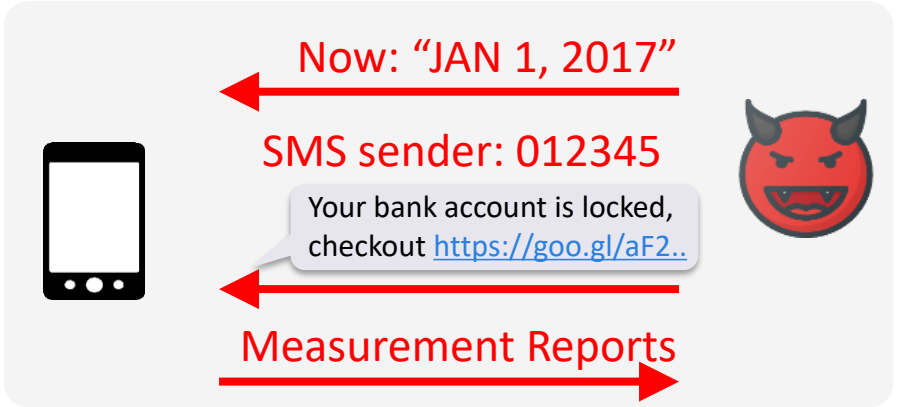
- Device-specific flaws
  - Null integrity algorithm (EIA0) and measurement report b/f security activation @ Galaxy S10 (**Exynos**)
  - AKA bypass @ iPhone 6s (**Qualcomm**)

- Others
  - Integrity bypass for NAS Identity Request message @ every **MediaTek/Exynos** BP and some **Qualcomm** BP

CVE-2019-2289, CVE-2021-30826, SVE-2021-20291 (CVE-2021-25516)

Attacks

- Network identity and time zone spoofing
- SMS injection
- Eavesdropping and manipulating data traffic
- Location leakage
- Also, device fingerprinting



Baseband	Device	Message				
		#1	#2	#3	#4	#5
Intel	Apple iPhone XS	·	·	·	A_5	·
Qualcomm	Xiaomi Mi Mix 2	·	A_2	A_4	A_5	A_3
Exynos	Samsung Galaxy S10	A_1	·	A_4	A_5	·
MediaTek	LG K50	·	·	A_4	A_6	·
HiSilicon	Huawei Mate 20 Pro	·	A_3	·	A_5	·

What else?

- **Old bug reappearing**
  - Null integrity check is an old (early-LTE) bug
  - However, it suddenly re-appeared on brand-new device, Galaxy S10 (Exynos)
- **New bug after firmware patch**
  - After patching to the latest firmware, new bug appeared
  - Galaxy S8 (Qualcomm), iPhone 6s (Qualcomm)

- MediaTek PSRT --- Did not replied to my bug reports for years.
  - Contacted multiple times for multiple bugs over multiple papers. (12/20, 05/21, 01/22, ...)
  - Just received one response for another paper. None for this.
  - Also, they decided to not to give a CVE for no reason.

Conclusion

- **Only a few negative test cases** in the conformance specification

- **DoLTEst**: a negative testing framework for finding non-standard-compliant bugs in UE
  - Tested 43 devices and found 26 implementation flaws
  - Brand-new device, firmware patch can bring a new logical bugs
  - **Open-sourced**: https://github.com/SysSec-KAIST/DoLTEst

- We recommend 3GPP to **include much more negative test cases on the conformance test specification**

Thank You!

- Questions?
- You can reach us:
  - CheolJun Park : fermioncj@kaist.ac.kr (@cheoljun_p)
  - Sangwook Bae: baesangwook89@gmail.com (@baesangwook89)
- KAIST SysSec Lab (Prof. Yongdae Kim)