5G-Spector: An O-RAN Compliant Layer-3 Cellular Attack Detection Service

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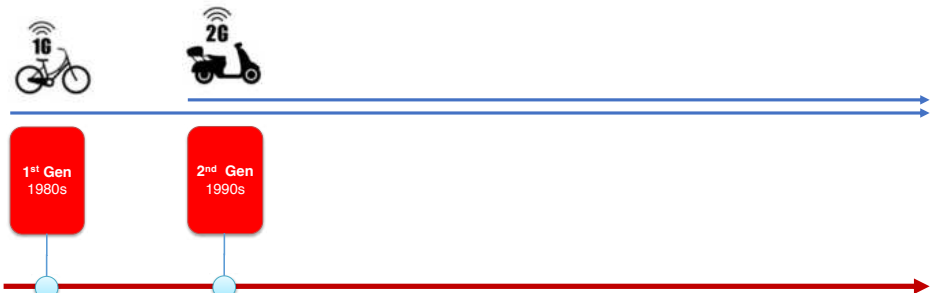
Evolution of Cellular Network

1st Gen
1980s

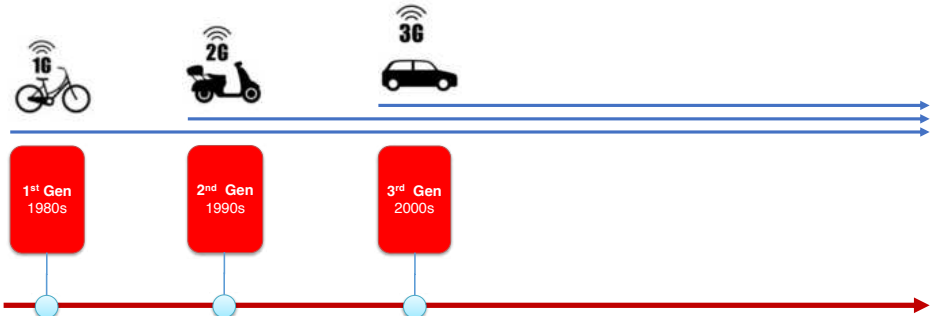
- **Analog Voice**
- **Very Low data rates**

Evolution of Cellular Network



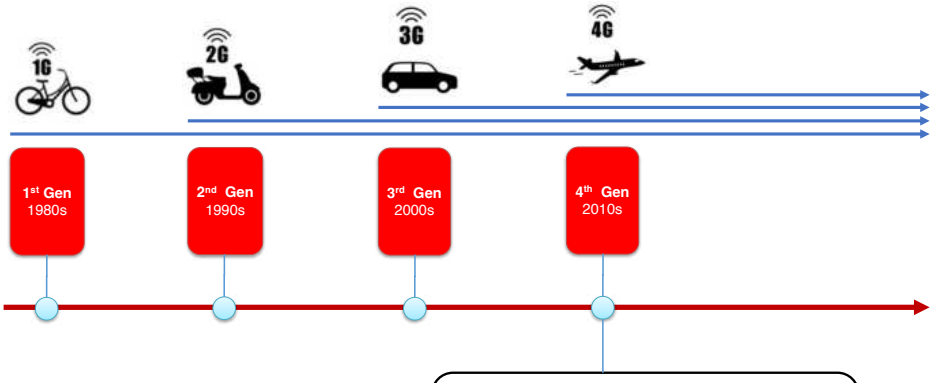
- **Digital Communication**
- **SMS (Short Message Service)**
- **GSM (Global System for Mobile Communications)**

Evolution of Cellular Network



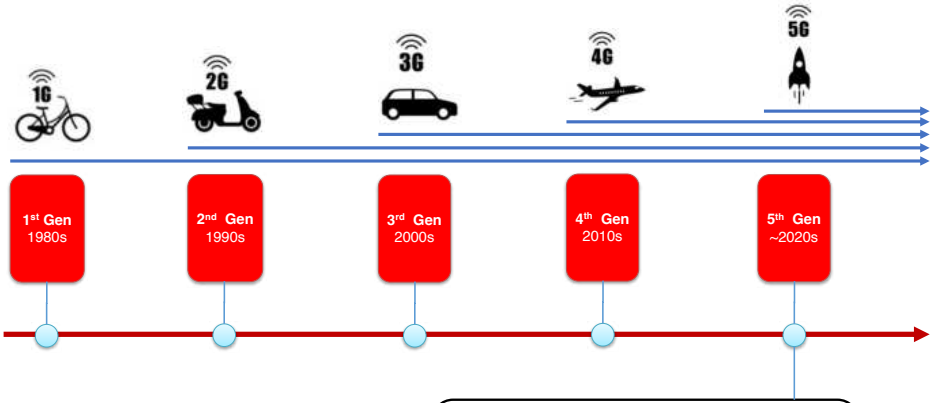
- **Mobile Internet (Kbps)**
- **Video Calls**
- **UMTS (Universal Mobile Telecommunications System)**

Evolution of Cellular Network



- High-Speed Data (Mbps)
- LTE (Long-Term Evolution) Standard
- Mobile Broadband

Evolution of Cellular Network



Why 5G is not Secure

Why do we care about 5G Security and Privacy?

Why 5G is not Secure

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The vulnerable cellular network standard

Why 5G is not Secure

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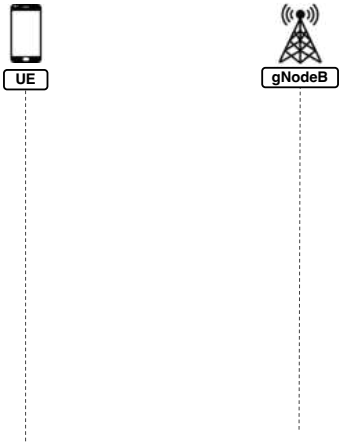

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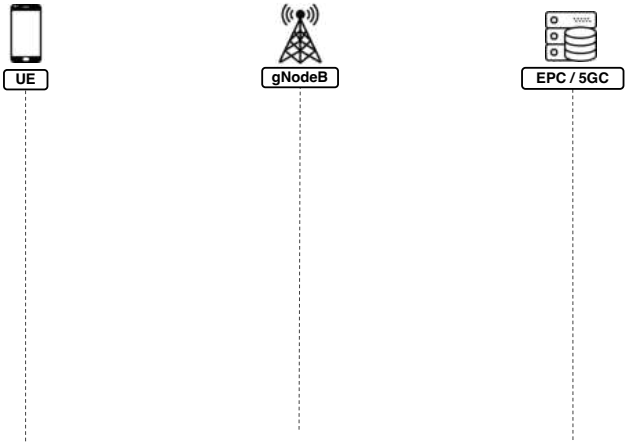

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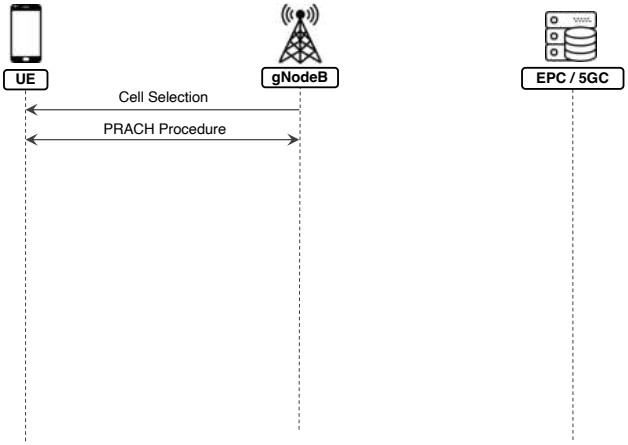

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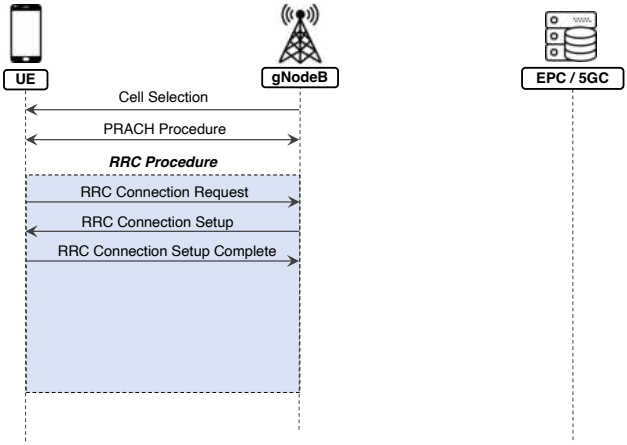

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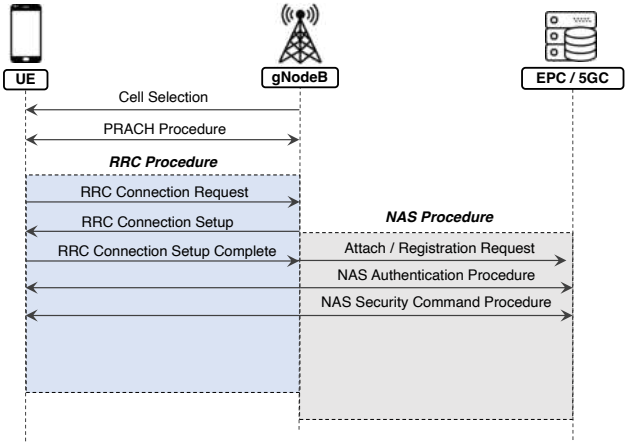

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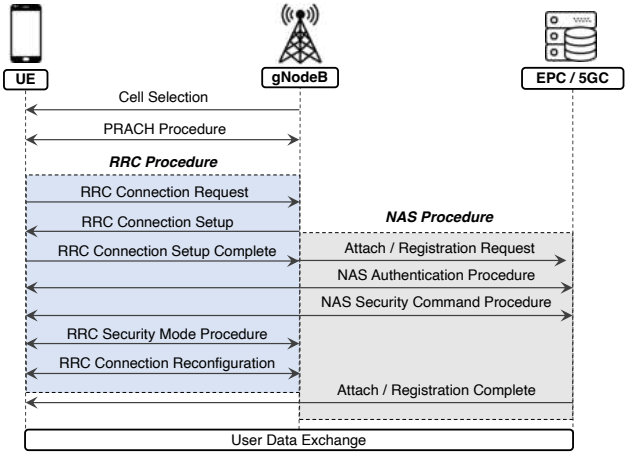
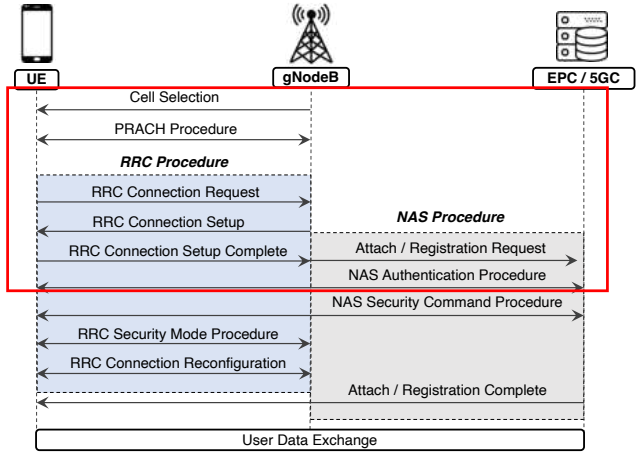
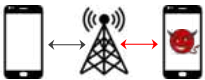


Why 5G is not Secure

Initial Messages Not Encrypted & Integrity Protected

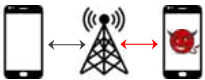


Threat Model



Adversary UEs

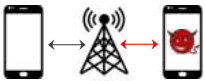
Threat Model



Adversary UEs

Man-In-the-Middle Attacker

Threat Model



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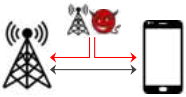
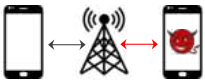


Signal Injector

Threat Model



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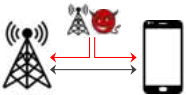
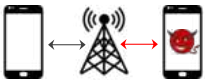


Signal Injector

USRP B210 ($2000)

Threat Model



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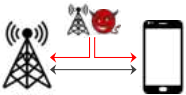


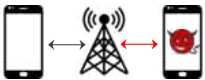
Signal Injector

USRP B210 ($2000)

+

Raspberry Pi ($80)

Threat Model



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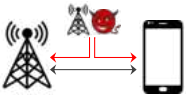

Signal Injector

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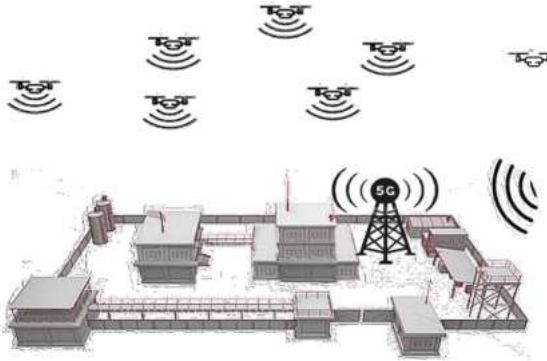
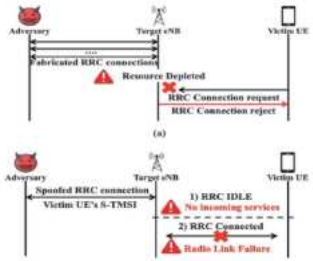
OpenAirInterface 5G (Free)

Attack Scenarios

5G Base Station Distributed Denial-of-Service (DDoS) Attack Scenario

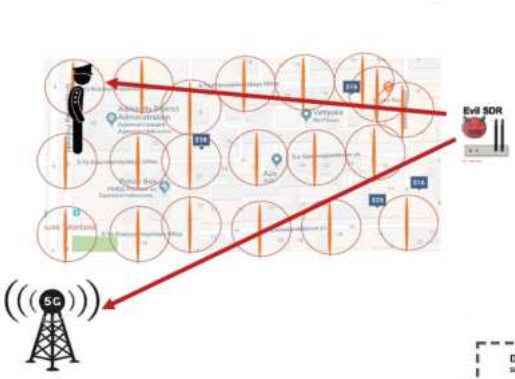


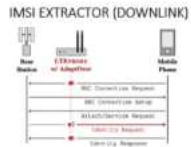


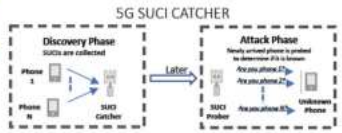
H. Kim, J. Lee, E. Lee and Y. Kim, "Touching the Untouchables: Dynamic Security Analysis of the LTE Control Plane," 2019 IEEE Symposium on Security and Privacy (SP), 2019.

Attack Scenarios

5G User Location Tracking Attack Scenario







Attack Scenarios

Can we fix the standards to eliminate these attacks?

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Currently very challenging due to numerous concerns

- Extremely Complicated Standard
- Backward Compatibility
- Performance and User Experience
- Overhead Constraint
- .....

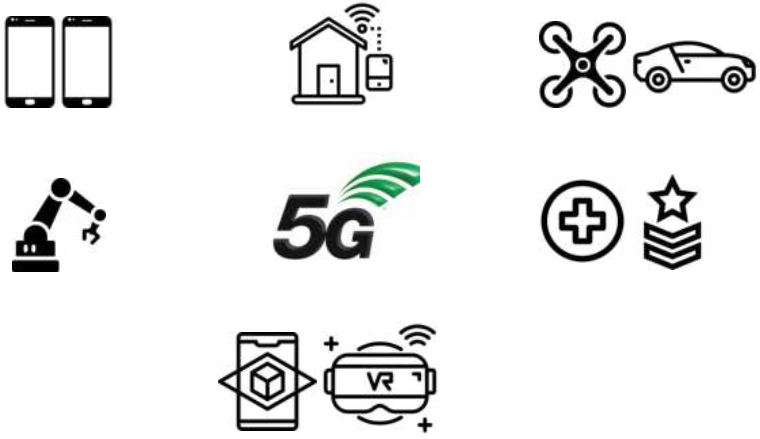
Attack Scenarios

~~Can we fix the standard body to eliminate these attacks?~~

~~Currently very challenging due to various concerns~~

How to defend against these attacks?

Our Key Insight: OpenRAN (O-RAN)



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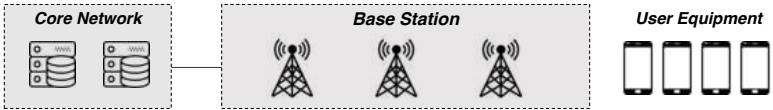
- Represent a new software-defined open cellular network architecture
- Founded in 2018 by O-RAN Alliance
- Adopted by 32 mobile network operator worldwide (as of 2/2024)

Deployments of O-RAN based technology and solutions from map.o-ran.org

Traditional RAN vs. Open RAN



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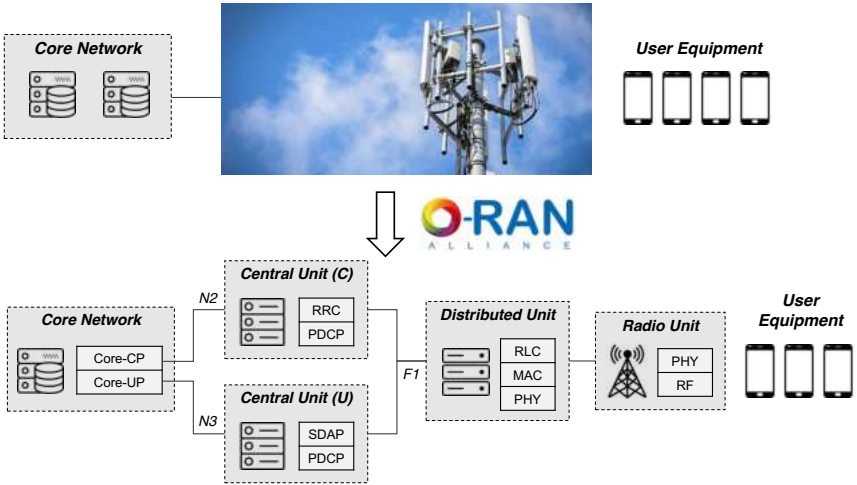

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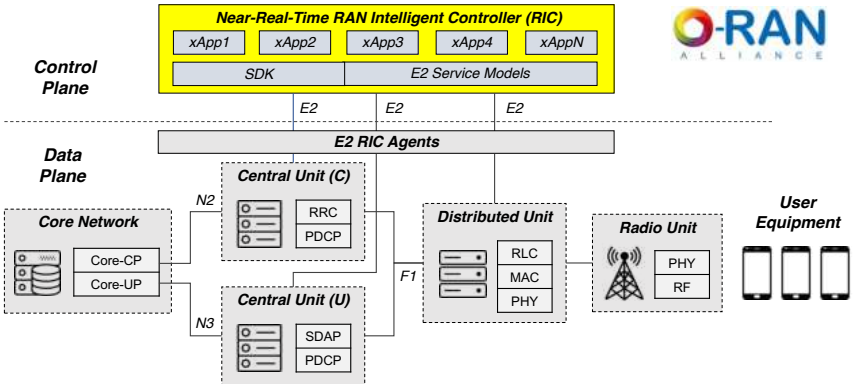

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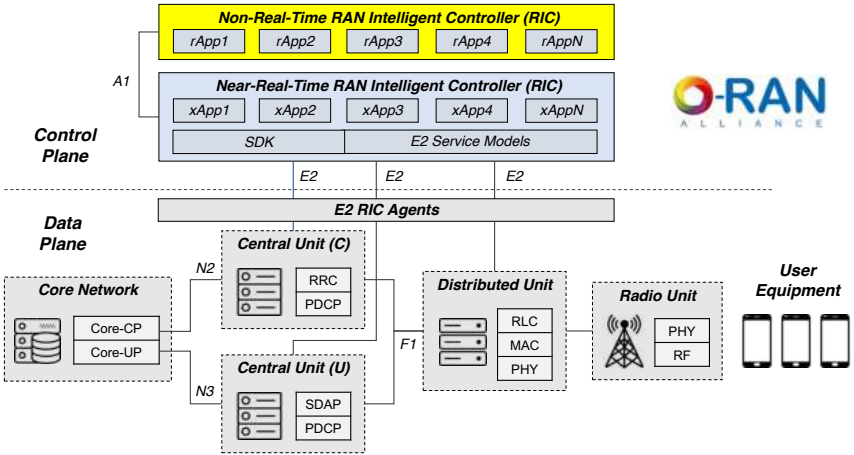

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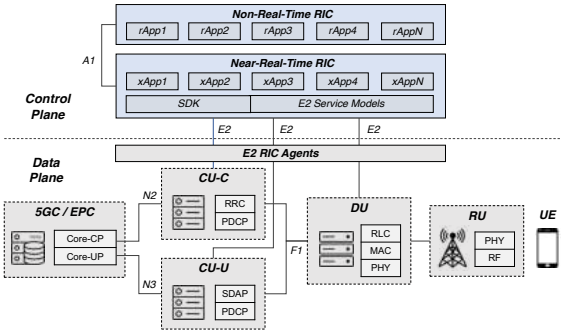
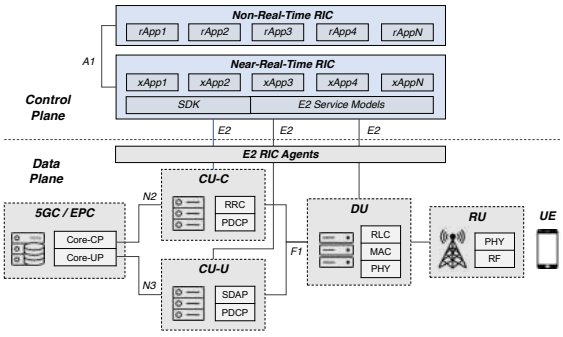


O-RAN's Key Capabilities

- Disaggregation

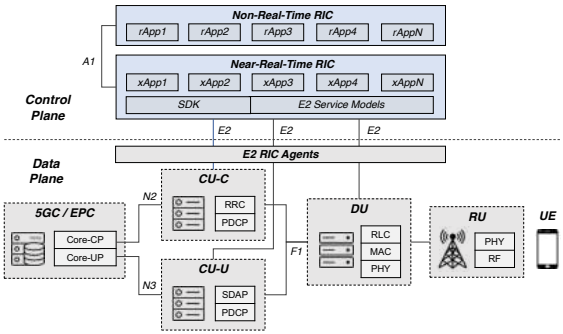
Traditional RAN vs. Open RAN



O-RAN's Key Capabilities

- Disaggregation
- Modularization (xApps / rApps)

Traditional RAN vs. Open RAN



O-RAN's Key Capabilities

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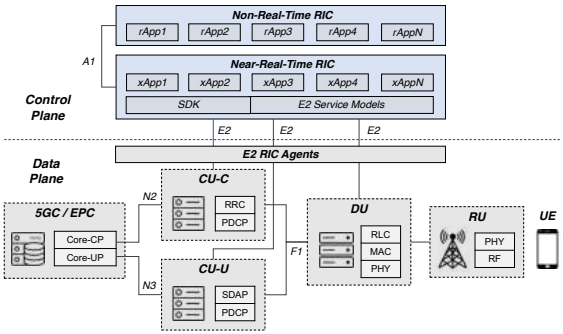

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- Interoperability
- Open Interfaces

Challenges and Solutions

Challenges

- **Visibility**: Telemetry from existing O-RAN service models are insufficient for security

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5G-Spector Solutions

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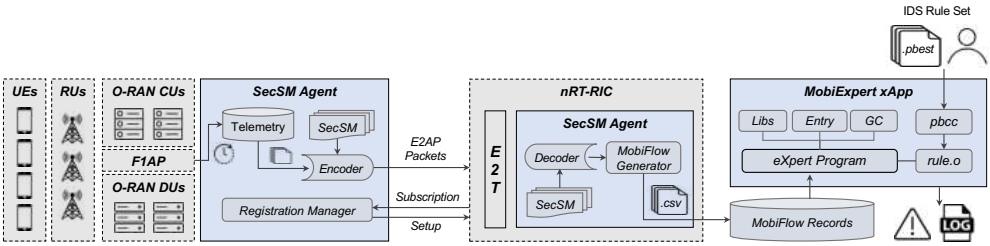
- **P-BEST** [LP99] w/ a decoupled architecture and efficient IDS programming language

5G-Spector Design



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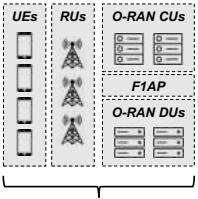

RAN Data Plane

- Open-sourced UE and RAN implementations (LTE / 5G)
- Simulation or commodity SDRs

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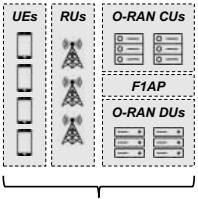

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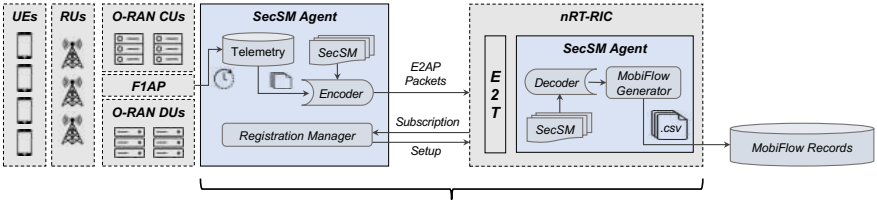

5G-Spector Control Layer

- xApp Registration and Subscription management
- Telemetry Report & Collection (**MobiFlow**)

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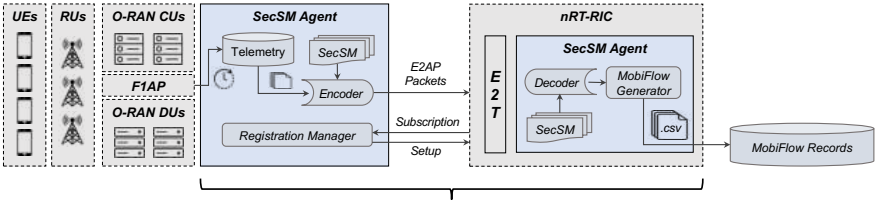

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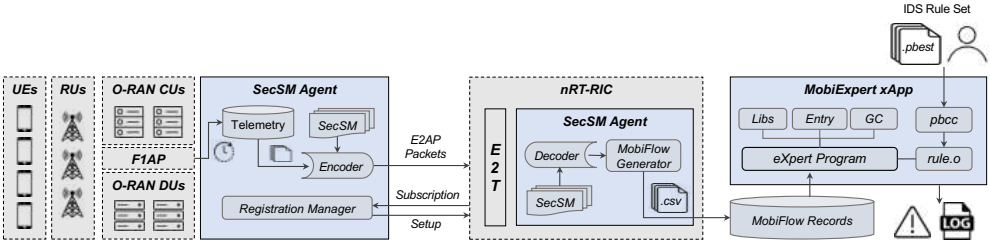

5G-Spector xApp Layer

- P-Best programming framework
- Attack signatures / rules integration
- Real-time alert notifications

Evaluation w/ Simulated Attacks and Variants

Attack	Layer	Exploited L3 Message	New	Detected
BTS RC Depletion	RRC	ConnectionRequest *(Fabricated)*	○	✓
Blind DoS	RRC	ConnectionRequest *(Replayed TMSI)*	○	✓
Downlink DoS	NAS	AuthRequest ← AttachReject	○	✓
	NAS	SecModeCmd ← AttachReject	●	✓
	NAS	AttachAccept ← AttachReject	●	✓
	NAS	AuthRequest ← ServiceReject	●	✓
	NAS	SecModeCmd ← ServiceReject	●	✓
	NAS	AttachAccept ← ServiceReject	●	✓
Uplink DoS	NAS	AttachReq ← AttachReq *(Invalid IMSI)*	○	✓
	NAS	ServiceReq ← ServiceReq *(Invalid MAC)*	●	✓
Uplink IMSI Extractor	NAS	AttachReq ← AttachReq *(Unknown TMSI)*	○	✓
Downlink IMSI Extractor	NAS	AuthRequest ← IdentityRequest *(IMSI)*	○	✓
	NAS	AuthRequest ← IdentityRequest *(IMEI)*	●	✓
	NAS	AuthRequest ← IdentityRequest *(TMSI)*	●	✓
	NAS	SecModeCmd ← IdentityRequest *(IMSI)*	●	✓
	NAS	AttachAccept ← IdentityRequest *(IMSI)*	●	✓
Null Cipher & Integrity	RRC	SecModeComplete ← SecModeFailure	○	✓
	NAS	SecModeComplete ← SecModeReject	●	✓

Table: All L3 cellular attacks and variants replicated and evaluated ($A \leftarrow B$ indicates message B overwrites A).

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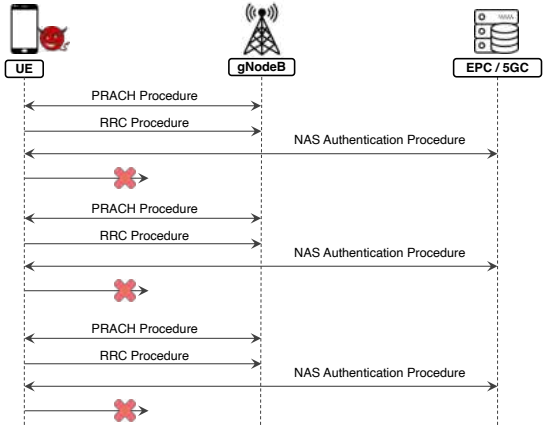
	NAS	AttachAccept ← AttachReject	●	✓
	NAS	AuthRequest ← ServiceReject	●	✓
	NAS	SecModeCmd ← ServiceReject	●	✓
	NAS	AttachAccept ← ServiceReject	●	✓
Uplink DoS	NAS	AttachReq ← AttachReq *(Invalid IMSI)*	○	✓
	NAS	ServiceReq ← ServiceReq *(Invalid MAC)*	●	✓
Uplink IMSI Extractor	NAS	AttachReq ← AttachReq *(Unknown TMSI)*	○	✓
Downlink IMSI Extractor	NAS	AuthRequest ← IdentityRequest *(IMSI)*	○	✓
	NAS	AuthRequest ← IdentityRequest *(IMEI)*	●	✓
	NAS	AuthRequest ← IdentityRequest *(TMSI)*	●	✓
	NAS	SecModeCmd ← IdentityRequest *(IMSI)*	●	✓
	NAS	AttachAccept ← IdentityRequest *(IMSI)*	●	✓
Null Cipher & Integrity	RRC	SecModeComplete ← SecModeFailure	○	✓
	NAS	SecModeComplete ← SecModeReject	●	✓

Table: All L3 cellular attacks and variants replicated and evaluated ($A \leftarrow B$ indicates message B overwrites A).

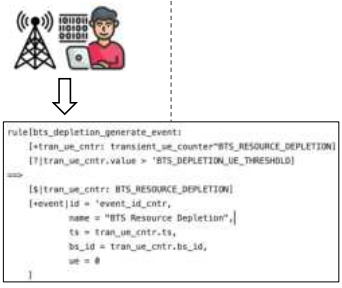
Evaluation w/ Simulated Attacks and Variants



BTS Resource Depletion Attack

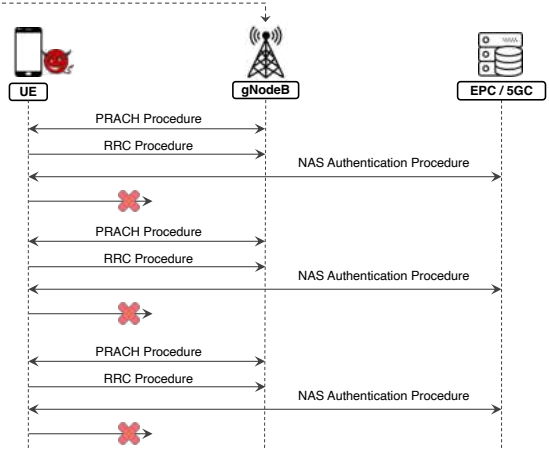
Kim et al. "Touching the untouchables: Dynamic security analysis of the LTE control plane."

Evaluation w/ Simulated Attacks and Variants



```
rule[bts_depletion_generate_event:
    [+tran_ue_cntr: transient_ue_counter="BTS_RESOURCE_DEPLETION]
    [?|tran_ue_cntr.value > 'BTS_DEPLETION_UE_THRESHOLD]
==>
    [$|tran_ue_cntr: BTS_RESOURCE_DEPLETION]
    [+event]id = "event_id_cntr,
            name = "BTS Resource Depletion",
            ts = tran_ue_cntr.ts,
            bs_id = tran_ue_cntr.bs_id,
            ue = 0
    ]
```

P-BEST IDS Signature in 5G-Spector



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Evaluation w/ Simulated Attacks and Variants

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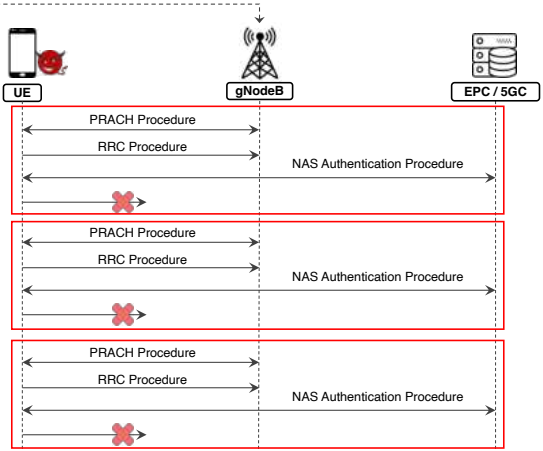
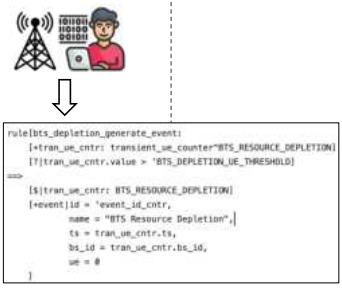
P-BEST IDS Signature in 5G-Spector



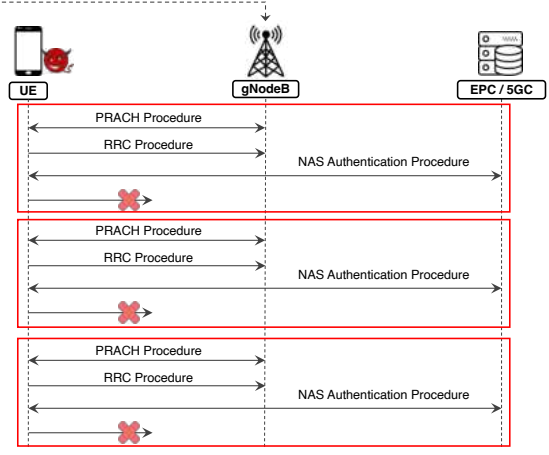
BTS Resource Depletion Attack

Kim et al. "Touching the untouchables: Dynamic security analysis of the LTE control plane."

Evaluation w/ Simulated Attacks and Variants



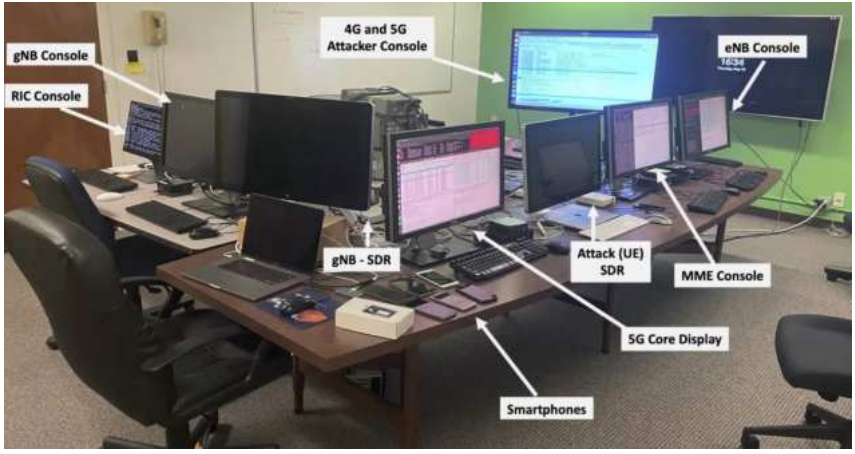
P-BEST IDS Signature in 5G-Spector



BTS Resource Depletion Attack

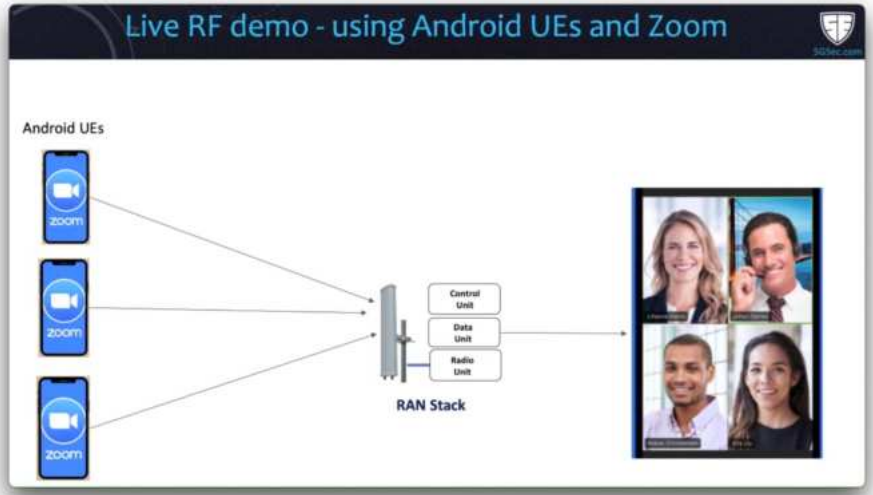
Kim et al. "Touching the untouchables: Dynamic security analysis of the LTE control plane."

Evaluation w/ OTA Attacks

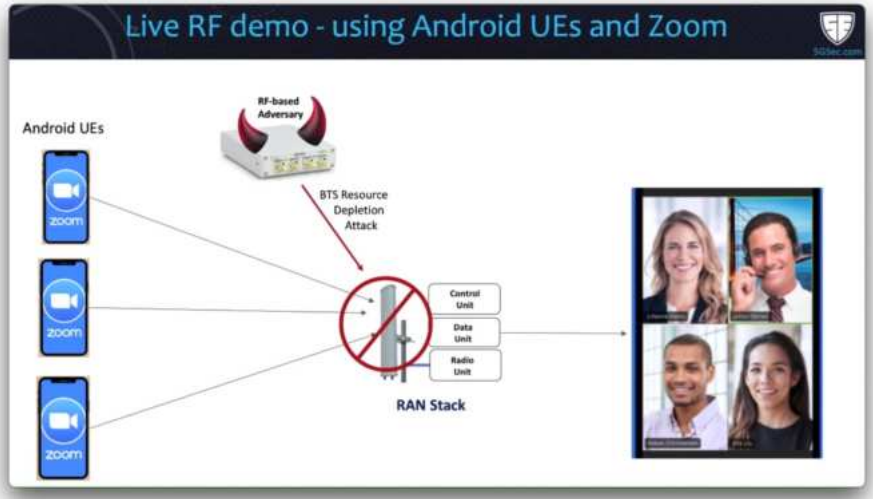


Our 5G Network Testbed at the Computer Science Lab of SRI International.

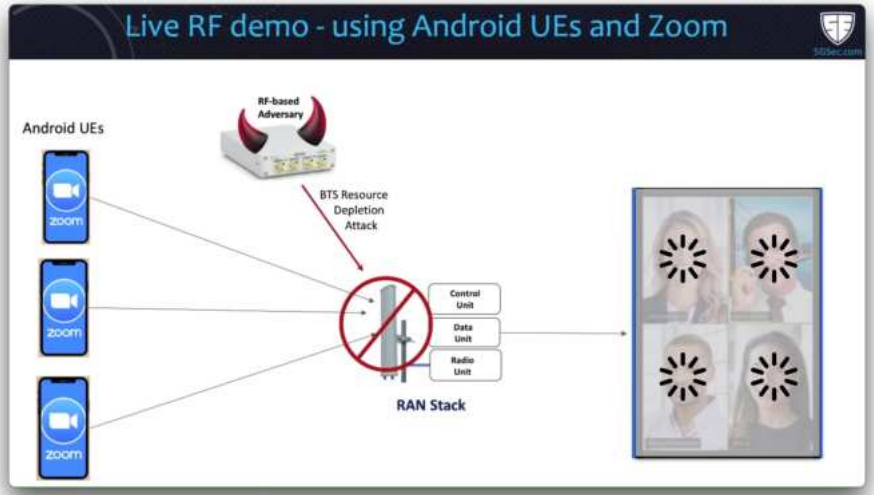
Evaluation w/ OTA Attacks



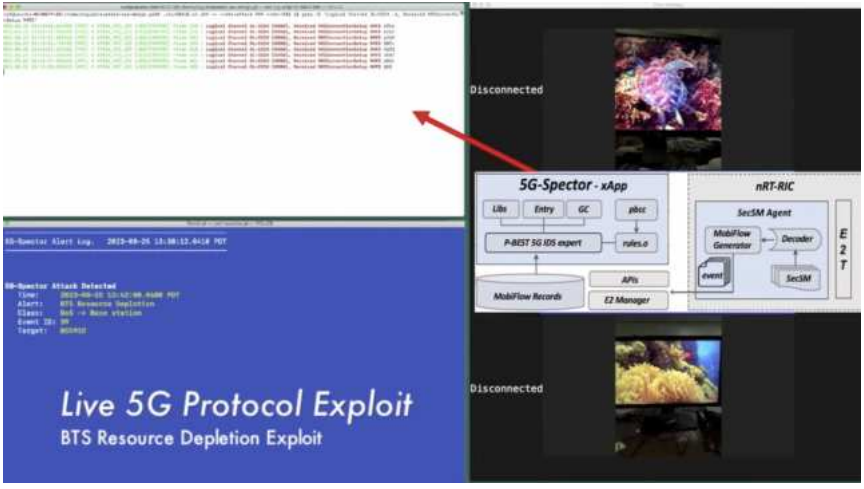
Evaluation w/ OTA Attacks



Evaluation w/ OTA Attacks



Evaluation w/ OTA Attacks



Demo video available at https://www.5gsec.com/post/5g-spector-demo

Evaluation w/ Real-World Datasets

Name	Ref	UE	Time(s)	#Pkt.	#MF	#Sess.	B	Event
BT-1	[LPY+16]	LG LS660	10,597	4,164	1,810	113	✓	0
BT-2	[LPY+16]	LG G3 VS985	514	3,803	173	15	✓	0
BT-3	[LPY+16]	LG G3 VS985	489	3,766	158	15	✓	0
BT-4	[LPY+16]	Galaxy S5	764	2,996	154	13	✓	0
BT-5	[LPY+16]	LG G3 VS985	16,324	26,548	1,217	114	✓	0
BT-6	[LPY+16]	Galaxy S5	1,459	2,803	97	13	✓	0
BT-7	[LPY+16]	Galaxy S5	2,053	4,794	448	27	✓	0
BT-8	[LPY+16]	Galaxy S5	6,387	2,839	1,435	113	✓	0
			.....					
AT-1	[EAW+]	N/A	1	632	61	11	✗	0
AT-2	[EAW+]	N/A	1	482	53	8	✗	0
AT-3	[EAW+]	N/A	1	626	59	6	✗	0
			.....					

Table: Evaluation results using real-world benign cellular traffic.

Evaluation w/ Real-World Datasets

Name	Ref	UE	Time(s)	#Pkt.	#MF	#Sess.	B	Event
BT-1	[LPY+16]	LG LS660	10,597	4,164	1,810	113	✓	0
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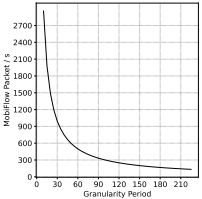
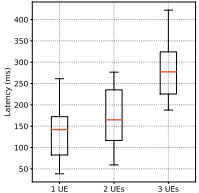
			.....					

Table: Evaluation results using real-world benign cellular traffic.

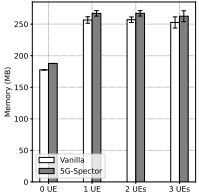
Evaluation of Performance and Overhead



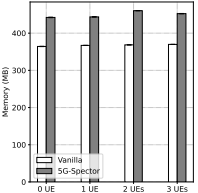
(a) Throughput.



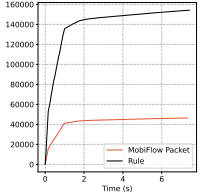
(b) Latency.



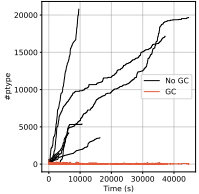
(a) RAN MEM.



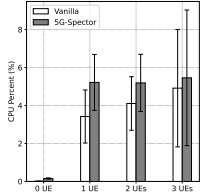
(b) RIC MEM.



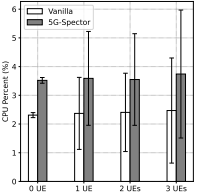
(c) Speed.



(d) GC Performance.

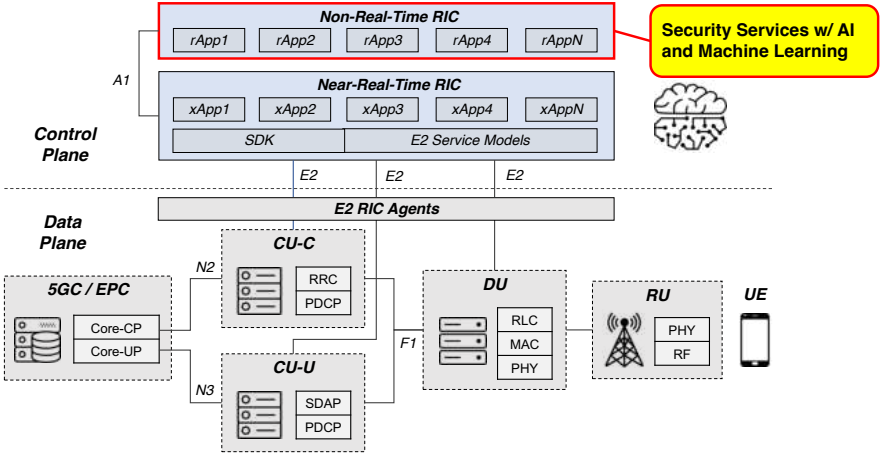


(c) RAN CPU.

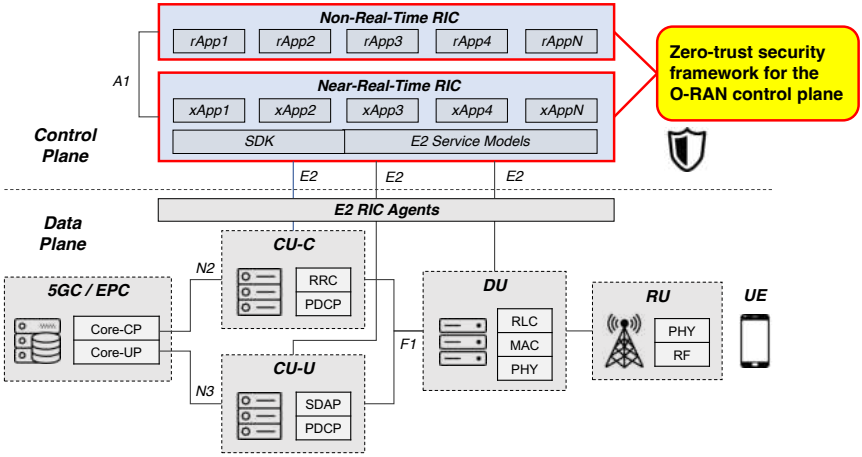


(d) RIC CPU.

Future Work


Non-Real-Time RIC
rApp1
rApp2
rApp3
rApp4
rAppN
Security Services w/ AI and Machine Learning
A1
Near-Real-Time RIC
xApp1
xApp2
xApp3
xApp4
xAppN
SDK
E2 Service Models
Control Plane
E2
E2
E2
E2 RIC Agents
Data Plane
CU-C
N2
RRC
PDCP
5GC / EPC
Core-CP
Core-UP
DU
RLC
MAC
PHY
RU
PHY
RF
UE
F1
CU-U
N3
SDAP
PDCP

Future Work


Non-Real-Time RIC
rApp1
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rAppN
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Near-Real-Time RIC
xApp1
xApp2
xApp3
xApp4
xAppN
SDK
E2 Service Models
Zero-trust security framework for the O-RAN control plane
Control Plane
E2
E2
E2
E2 RIC Agents
Data Plane
CU-C
N2
5GC / EPC
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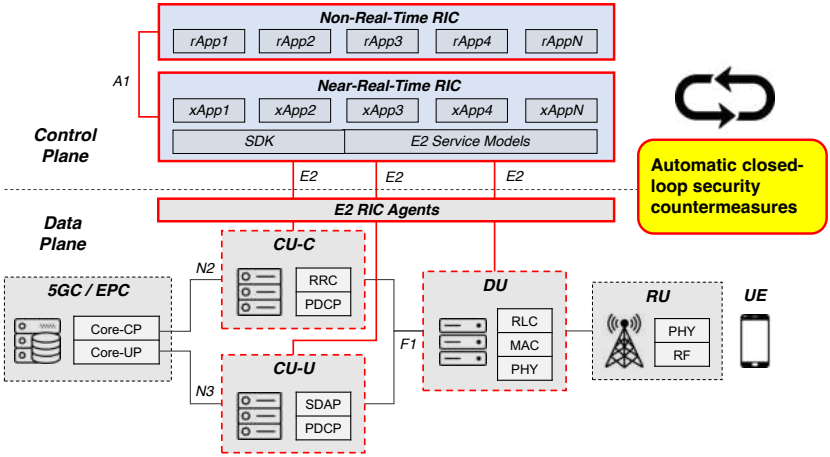
Core-CP
Core-UP
DU
RLC
MAC
PHY
RU
PHY
RF
UE
F1
CU-U
N3
SDAP
PDCP

Future Work


Non-Real-Time RIC
rApp1
rApp2
rApp3
rApp4
rAppN
A1
Near-Real-Time RIC
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xApp2
xApp3
xApp4
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E2 Service Models
Control Plane
E2
E2
E2
E2 RIC Agents
Data Plane
Automatic closed-loop security countermeasures
CU-C
N2
5GC / EPC
RRC
PDCP
Core-CP
Core-UP
DU
RLC
MAC
PHY
RU
PHY
RF
UE
F1
CU-U
N3
SDAP
PDCP

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Radio Access Network

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Security Enhanced
Radio Access Network

Paper QR Code

5G-Spector Full paper (NDSS'24):
https://web.cse.ohio-state.edu/~wen.423/papers/5G-Spector-NDSS24.pdf

5G-Spector Source Code: https://github.com/5GSEC/5G-Spector

5G-Spector Demo Video: https://www.5gsec.com/post/5g-spector-demo

My personal homepage: https://web.cse.ohio-state.edu/~wen.423/

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