Advanced Network Security

Lecture 3: Attacks and Mobile Networks

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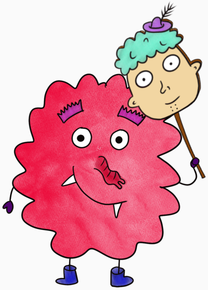
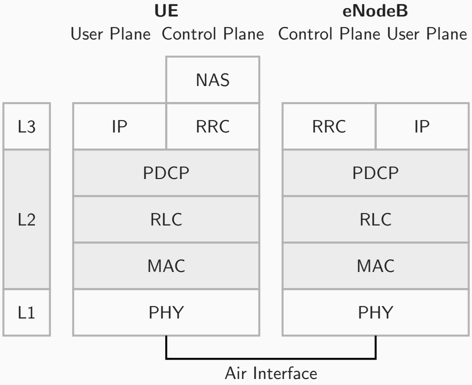
Last time...

- Why mobile network security is important
- Basics of mobile networks
  - Generic network setup
  - Long Term Evolution LTE
- Basic security goals
  - Confidentiality
  - Integrity
  - Availability
  - Privacy
- Mobile evolution



What was L2 again?

- **PDCP**: Transport of data with ciphering and integrity protection (RRC) and transport of IP packets.
- **RLC**: Transport PDCP data in different modes.
- **MAC**: Logical channels for RLC for multiplexing into into the physical transmission. Scheduling of within and between UEs.



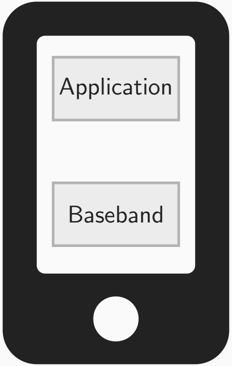
LTE Components

Component	LTE Acronym	LTE Component	Icon
Phone	**UE**	**User Equipment**	
Base Station	**eNodeB**	**Evolved Node B**	
Core Network	EPC	Evolved Packet Core	
Internet	IP Network	IP Network	

Focusing on the wireless connection:

- We focus on the **air interface** $\leftrightarrow$
- Another term for this is **radio access network**
- In LTE, the radio access network is called **E-UTRAN**

What happens in my phone?



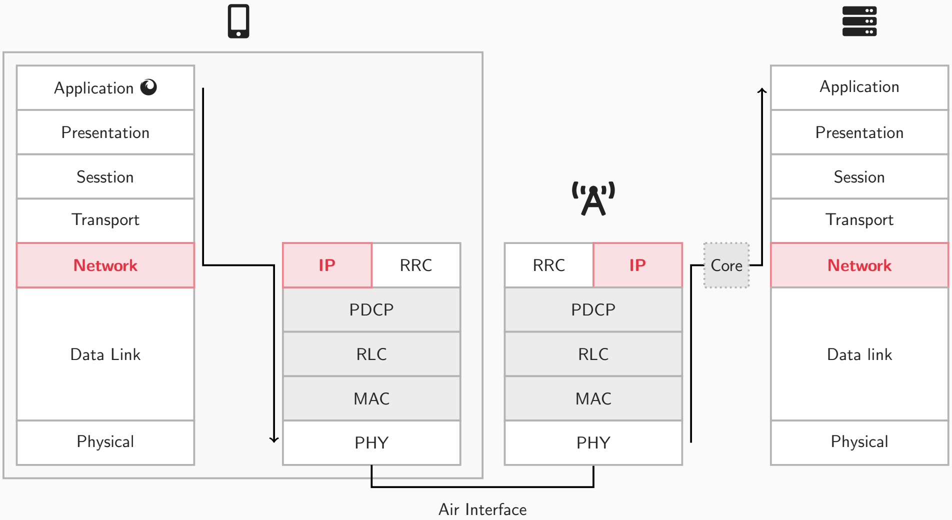
Application Processor

- The OS implements the network stack
- Standard Ethernet connection like WiFi

Baseband Processor

- The Baseband implements the modem
- Mobile data connection

Combining Stacks



Breaking LTE on Layer Two

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***Abstract*—Long Term Evolution (LTE) is the latest mobile communication standard and has a pivotal role in our information society: LTE combines performance goals with modern security mechanisms and serves casual use cases as well as critical infrastructure and public safety communications. Both scenarios are demanding towards a resilient and secure specification and implementation of LTE, as outages and open attack vectors potentially lead to severe risks. Previous work on LTE protocol security identified crucial attack vectors for both the physical (layer one) and network (layer three) layers. Data link layer (layer two) protocols, however, remain a blind spot in existing LTE security research.**

In this paper, we present a comprehensive layer two security analysis and identify three attack vectors. These attacks impair the confidentiality and/or privacy of LTE communication. More specifically, we first present a passive identity mapping attack that matches volatile radio identities to longer lasting network identities, enabling us to identify users within a cell and serving as a stepping stone for follow-up attacks. Second, we demonstrate how a passive attacker can abuse the resource allocation as a side channel to perform website fingerprinting that enables the attacker to learn the websites a user accessed. Finally, we present the aLTEr attack that exploits the fact that LTE user data is encrypted in counter mode (AES-CTR) but not integrity protected, which allows us to modify the message payload. As a proof-of-concept demonstration, we show how an active attacker can redirect DNS requests and then perform a DNS spoofing attack. As a result, the user is redirected to a malicious website. Our experimental analysis demonstrates the real-world applicability of all three attacks and emphasizes the threat of open attack vectors on LTE layer two protocols.

I. Introduction

The latest mobile communication standard LTE represents the daily communication infrastructure for billions of people in the world and has a pivotal role in our information society. LTE is designed to combine performance goals such as high transmission rates and low latency with a series of security features like formally proven mutual authentication, well-established encryption algorithms such as AES, and separated security domains. Besides casual use cases, LTE also has an emerging relevance for critical infrastructures and public safety communications [1]. Both scenarios are demanding towards a resilient and secure specification and implementation of LTE, as outages and open attack vectors potentially lead to severe risks. While the LTE specification considers a diverse set of security features, it can hardly predict all potential attacks, and it is even harder to cover sets of restrictions in real-world implementations.

Consequently, recent academic and non-academic work identified various potential vulnerabilities on different layers of the LTE protocol stack. On the network layer (layer three), passive or active attackers can either localize a user or deny the service and thus downgrade the phone to the insecure GSM network [2]–[4]. On the physical layer (layer one), LTE can be the target of jamming attacks that aim to deny the service [5]–[8]. As a matter of fact, the previous research efforts focused only on layer one or layer three protocols and—to the best of our knowledge—no security analysis of data link layer (layer two) protocols exists to date. This leads to a situation of uncertainty about potential security and privacy threats that arise from the specification or implementation flaws of the data link layer and its three protocols: Medium Access Control (MAC), Radio Link Control (RLC), and Packet Data Convergence Protocol (PDCP).

In this paper, we perform a security analysis of LTE on layer two and analyze these protocols for potential vulnerabilities. As a result, we introduce two passive attacks and one active attack that impair the confidentiality and privacy of LTE communication. Table I shows an overview of the attacks and their properties. We first focus on a passive adversary who can remain stealthy during an attack, i. e., being successful does not depend on any active interference with the network entities or protocols. Our first passive attack, the *identity mapping* attack, allows an adversary to map the user's temporary network identity (TMSI) to the temporary *radio* identity (RNTI). More specifically, we demonstrate how an attacker can precisely localize and identify a user within the cell, distinguish multiple transmission streams, and use this information as a stepping stone for subsequent attacks. One example for this is our second attack vector, the *website fingerprinting* attack. Website fingerprinting is known from other contexts like Tor [9], where traffic analysis reveals the browsing behavior of users despite Tor's onion encryption. In the context of LTE, we demonstrate a comparable information leak in the resource allocation: even though transmissions are encrypted, we can access plaintext information up to the PDCP and learn the transmission characteristics for individual users. This information is sufficient to distinguish accessed websites and de-anonymize a connection that is perceived to be secure due to encryption. Both attacks already harm user privacy separately, but they can be combined to an even stronger version of website fingerprinting, while solely depending on passive (downlink) sniffing.

We further introduce an active attack called aLTEr that exploits the missing integrity protection of LTE user data to perform a chosen-ciphertext attack. Our attack is based on the

Today:

Attacks and what you need to understand them

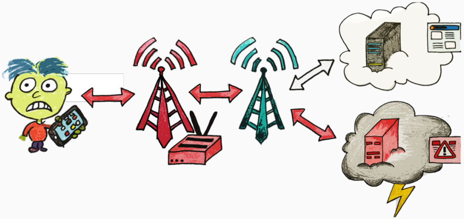
https://alter-attack.net

Three attacks against LTE L2:

(1) Website Fingerprinting

(2) Identity mapping

(3) User Data Redirection



Attack 1: Website Fingerprinting

Attack 2: Identity Mapping

Attack 3: User Data Redirection

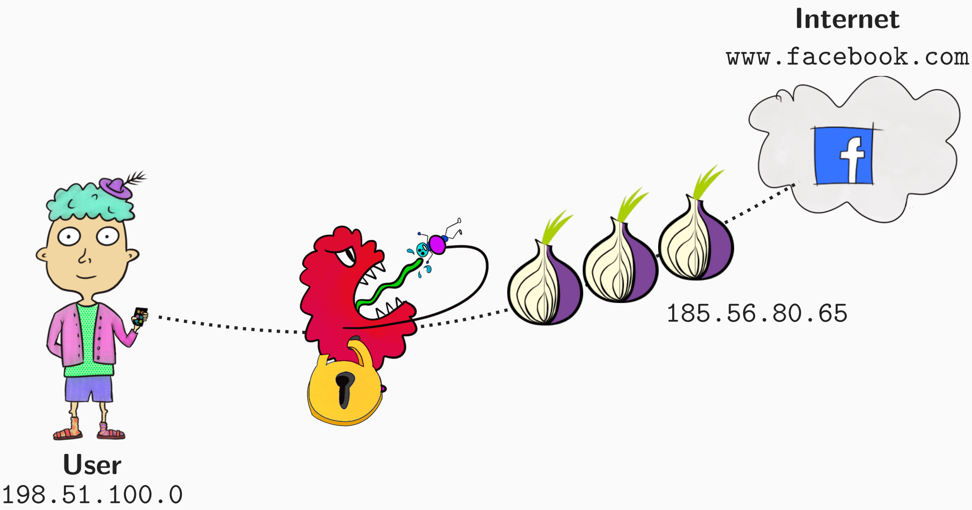
Summary

Attack 1: Website Fingerprinting

Required Background

- General concept of website fingerprinting (WF)
- Internet connection through LTE
- LTE metadata
- Basic attack setup and trace inspection

Website Fingerprinting: The Concept

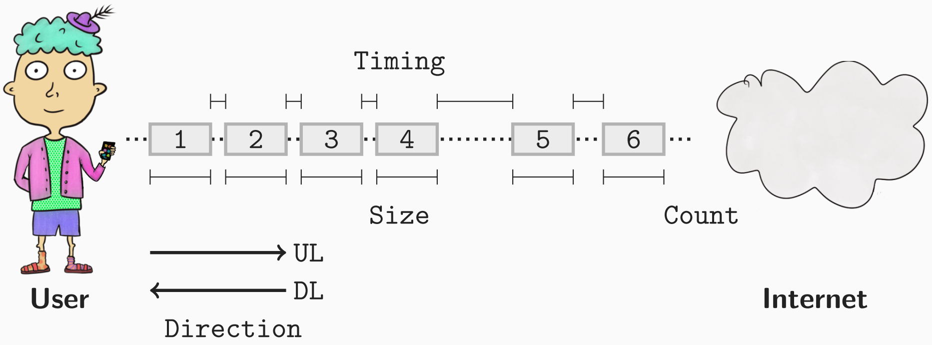


Website Fingerprinting: The Concept

Standard Internet Connection:

- User connects to a website
- IP address of user is sensitive
- Together with website they reveal Internet usage
- Attacker can monitor and learn sensitive data
- **Protection:** Encrypt transmissions

Metadata of Encrypted Traffic



Metadata of Encrypted Traffic

Encryption protects the content. Transmissions still reveal metadata:

- Measure the timing between packets
- Measure the sizes of packets
- Count packets
- Check the transmission direction

How do we get this metadata?

- Can either be measured (timing, packet counts)
- Is part of the header information (size)
- Or is visible in the connection (direction)

The amount of metadata depends on the protocols, physical link, and optional security measures

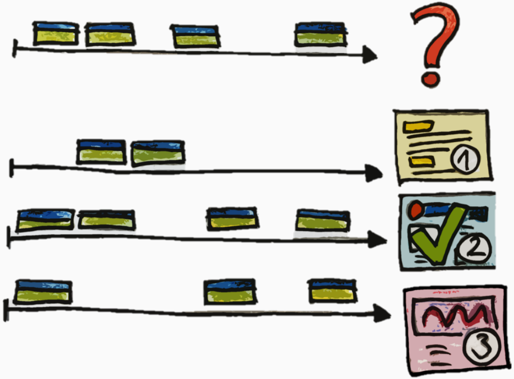
Classification Attack

Preparation

- Attacker pre-records requests and responses to n websites
- Repeats each website several times
- Results in a labeled data set

Classification Attack

- Record traffic of victim
- Compare trace with pre-recorded data
- Highest similarity $\rightarrow$ guess



Trace Data Set

abc.net.au	bootstrapcdn.com	daum.net	flightaware.com	ietf.org	men
aboutads.info	boston.com	debian.org	flipkart.com	ifeng.com	mes
abs-cbn.com	brainly.com	dell.com	forbes.com	ign.com	met
academia.edu	breitbart.com	denverpost.com	fortune.com	ikea.com	met
addthis.com	britannica.com	detik.com	foxnews.com	ilovepdf.com	mgi
addtoany.com	businessinsider.com	deviantart.com	free.fr	imdb.com	mia
adp.com	bustle.com	dictionary.com	freepik.com	imgur.com	mic
adsrvr.org	buzzfeed.com	digg.com	ft.com	imore.com	mir
akismet.com	buzzfeednews.com	digicert.com	gamespot.com	indeed.com	mit
alibaba.com	cafemom.com	discordapp.com	genius.com	independent.co.uk	mlb
aliexpress.com	ca.gov	doi.org	getpocket.com	instagram.com	moa
allegro.pl	cam.ac.uk	domainmarket.com	gfycat.com	instructables.com	mom
altervista.org	cambridge.org	dotomi.com	giphy.com	instructure.com	moz
amazonaws.com	canva.com	douban.com	github.com	intel.com	msn
amazon.com	carfax.com	doubleclick.net	github.io	intuit.com	mys
ameblo.jp	cars.com	doubleverify.com	gizmodo.com	iso.org	mys
americanexpress.com	casalemedia.com	douyu.com	glassdoor.com	issuu.com	mys
ampproject.org	cbc.ca	dribbble.com	globo.com	jianshu.com	nam
androidcentral.com	cbslocal.com	dropbox.com	gmail.com	jimdo.com	nas
android.com	cbsnews.com	dropcatch.com	gmw.cn	jquery.com	nat
answers.com	cbssports.com	drudgereport.com	gnu.org	kayak.com	nat
apache.org	cdc.gov	drugs.com	go.com	khanacademy.org	nbc
aparat.com	change.org	duckduckgo.com	godaddy.com	kickstarter.com	nbc
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arstechnica.com	china.com.cn	economist.com	gravatar.com	legacy.com	new
ask.com	chouftv.ma	ed.gov	grid.id	lenovo.com	new
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avast.com	cmu.edu	elsevier.com	hbr.org	littlethings.com	nic
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bankofamerica.com	columbia.edu	epa.gov	healthline.com	livejournal.com	nin
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bet365.com	coursera.org	evernote.com	hotels.com	mailchimp.com	off
bet9ja.com	cpanel.com	exelator.com	hotstar.com	mail.ru	oke
bidswitch.net	craigslist.org	facebook.com	howstuffworks.com	manoramaonline.com	ok.
bilibili.com	crashlytics.com	fandom.com	howtogeek.com	mapquest.com	onl
bing.com	creativecommons.org	fantasypros.com	hp.com	mashable.com	onl
bit.ly	criteo.com	fastcompany.com	huanqiu.com	mathtag.com	ope
blackboard.com	csdn.net	fastly.net	hubspot.com	mayoclinic.org	ope
blogger.com	custhelp.com	fc2.com	huffpost.com	mediafire.com	ora
bloomberg.com	dailycaller.com	fedex.com	hugedomains.com	medicalnewstoday.com	ore
bobshideout.com	dailydot.com	finance101.com	hulu.com	medicinenet.com	otv
bonappetit.com	dailykos.com	findagrave.com	ibm.com	medium.com	oup

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1-513-exit.csv	1-92-exit.csv	2-444-exit.csv	3-132-exit.csv	3-563-exit.csv	3-9-client.csv
1-514-client.csv	1-930-client.csv	2-445-client.csv	3-133-client.csv	3-564-client.csv	3-9-exit.csv
1-514-exit.csv	1-930-exit.csv	2-445-exit.csv	3-133-exit.csv	3-564-exit.csv	
1-515-client.csv	1-931-client.csv	2-446-client.csv	3-134-client.csv	3-565-client.csv	

State of the Art

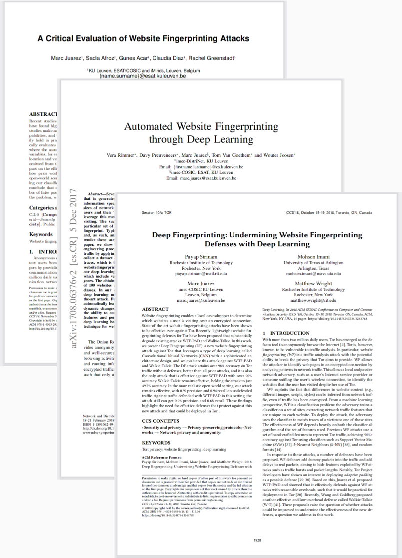
Attack Techniques

- Machine learning:
  Make sense of metadata
- Deep learning:
  Automatic feature generation

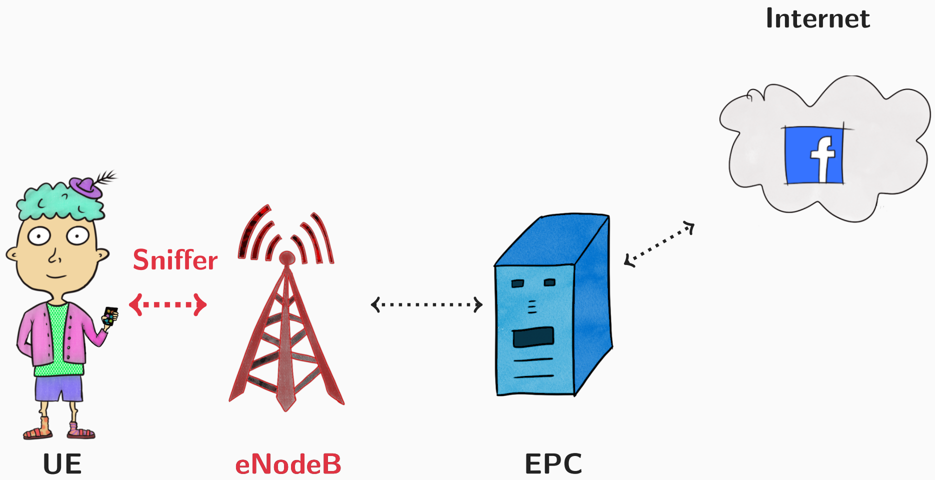
Evaluation

- Pre-recorded data sets are always too small
- Scientific evaluation is unrealistic

Not relevant for the exam!



Website Fingerprinting on LTE



Mobile Data Connection

- Radio connection between UE and eNodeB
- eNodeB connects to core network
- Forwards website request

How do we get the attack traffic?

- **Option 1**: Malicious eNodeB records all traffic
  What happens when the eNodeB is malicious?
- **Option 2**: Wireless sniffer monitors radio connection
  What's the difference to wire tapping?

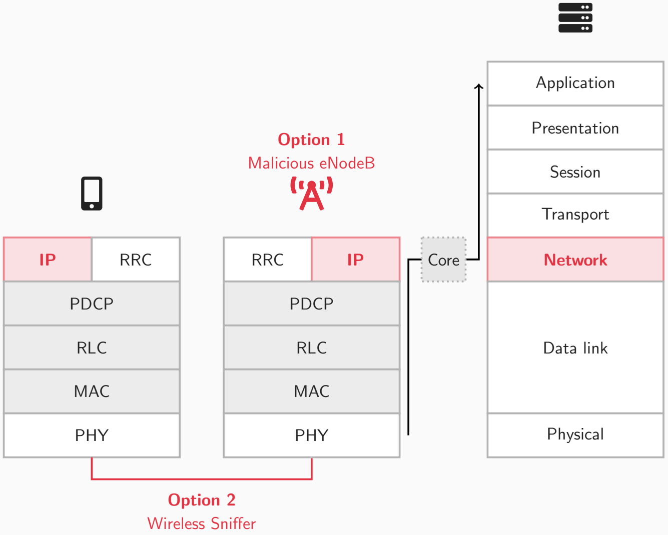
Last Week: Website Request over LTE

Option 1: **eNodeB**

- Access to L1-L3
- LTE encryption

Option 2: **Sniffer**

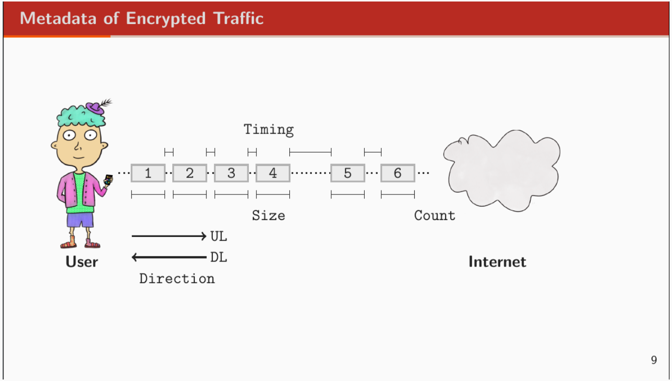
- Access to air interface
- Only transmissions



Recall: Metadata

- timing
- count
- direction
- ...

Metadata in LTE?

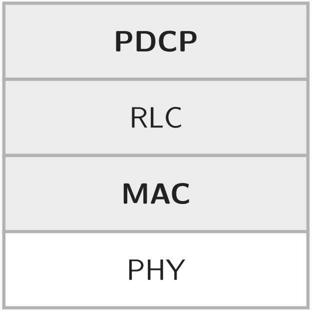


Where do we get the metadata?

- The PDCP sub-layer gives us the *data*
- The MAC sub-layer gives us *identifiers*

Challenge:

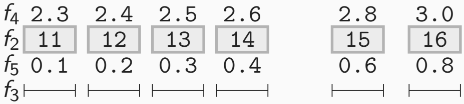
- Physical transmission applies *encoding*
- Option 1: We directly get decoded information in the eNodeB
- Option 2: We must decode the recordings first



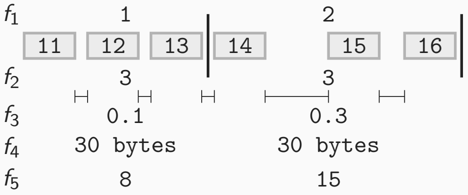
Raw Information

Uncompressed information from traffic

f_1	`rnti`	RNTI
f_2	`seq`	PDCP Sequence Number
f_3	`len`	PDCP Packet Length
f_4	`abs`	Absolute Timestamp
f_5	`rel`	Relative Timestamp



LTE Metadata: Compressed Information



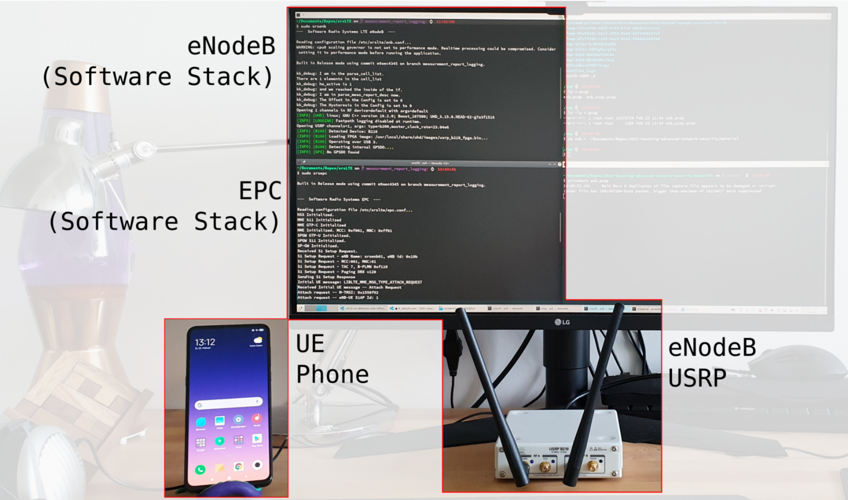
Compressed Information

Aggregated in windows of 500ms length

f_1	`win`	Window Index
f_2	`cnt`	Num. Packets in Window
f_3	`iat`	Avg. Inter-Arrival Time
f_4	`byt`	Tot. Data in Window
f_5	`seq`	Avg. Sequence Number

Demo:
Controlling your own LTE setup

Demo: Measurement Setup



Demo: Malicious eNodeB

If you want to follow along or repeat this later:

- With SDR: Ettus USRP B2x0/B205mini/X3x0, LimeSDR, bladeRF
- Clone, install dependencies, build
- Without SDR: Docker version, integrated channel model

Setting this up is annoying!

Detailed steps can be found in the work sheet, if you get stuck just ask.

Requirements and Preparations

```
# clone, install dependencies, build
# plugin SDR, antennas, ...
sudo srsepc # start EPC in terminal 1
sudo srsenb # start eNodeB in terminal 2
```

Demo:
Inspecting LTE PCAPs
and finding the RNTI

RNTI

stands for Radio Network *Temporary* Identifier. They are used to differentiate between multiple connected UEs.

Why do we need the RNTI?

- MAC sub-layer manages active radio connections
- Every active connection has its own RNTI
- There are many different types of RNTI
- For now we just treat this as a unique and temporary identifier

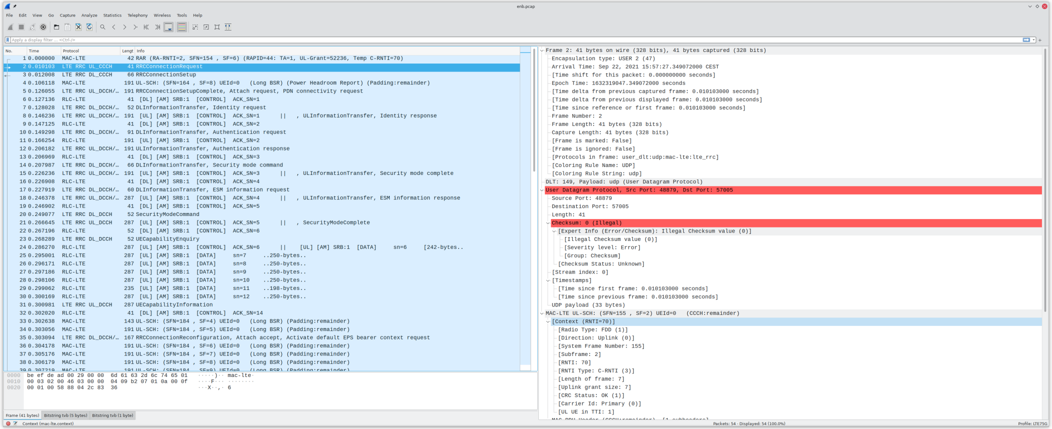
PDCP

transport the control plane and user plane data and can apply features like header compression, ciphering, or integrity protection.

Why do we look at PDCP packets?

- They transport the main data
- It's the data we see on the air interface or in the eNodeB
- We can derive several traffic features that relate to the transmission

Demo: Finding PDCP Traffic



Demo: Finding PDCP Traffic

What did you recognize?

- With the right decoding we see TCP packets.
  To make life easier the encryption is disabled.
- `Context (RNTI=70)`
  This is the same RNTI as in the initial MAC packet.
- What are we looking at? `RRCConnectionRequest`
- Later: `RAR`

Website Fingerprinting: Summary

- **Problem**: Traffic is encrypted but metadata leaks information.
- **Metadata**: Timings, frequencies, sizes, directions, . . .
- **WF**: Classification attack where pre-recorded data set is compared to attack trace.
- **WF on LTE**: Monitor traffic in eNodeB or at air interface
- **Features**: RNTI, PDCP, timing.
- **Demos**: Finding information in PCAP traces, try this at home!

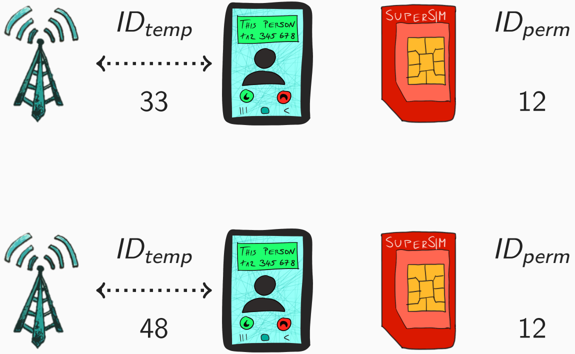
Website Fingerprinting: Exam Examples

- Recall the protocol stack. Where is the air interface? Why is there an IP-layer in the stack? What's the difference between the UE stack and the eNodeB stack? What is the control plane, what is the user plane?
- What protocols are part of the second layer in the LTE stack?
- Name examples of LTE metadata information, this can be either raw information or compressed information.
- What is the tool we used to take a closer look at PCAP traces?
- In the context of WF, what is the RNTI used for? What kind of RNTI do we see in the MAC packets of the eNodeB trace?
  We'll learn more about this in the next part.

Attack 2: Identity Mapping

Required Background

- Identifiers
- Connection establishment
- Uplink and downlink sniffer



Match IDs

$$ID_{temp} \rightarrow ID_{perm}$$

Temporary and Permanent Identifiers

From permanent to temporary... or from critical to uncritical

- IMSI: Lifelong identifier, does not reset
- TMSI: Semi-permanent random ID, can be reset if needed
- RNTI: Temporary ID, updated with every new session

We'll see more details about IMSIs, TMSIs, and RNTIs later in this lecture. For now this is enough.

Attack Concept

ID_{temp}

ID_{temp}

...

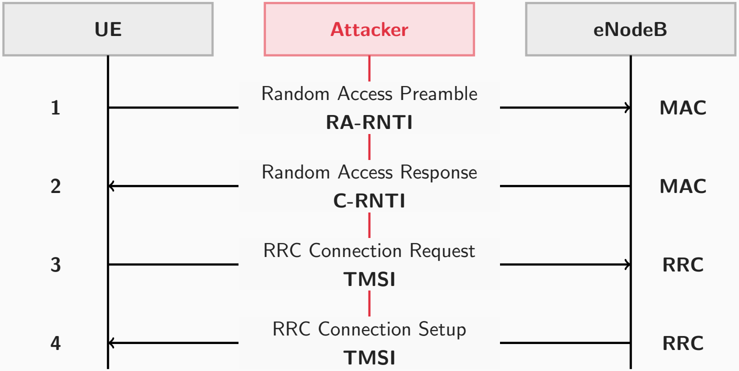
ID_{perm}

ID_{perm}

Monitor Communication

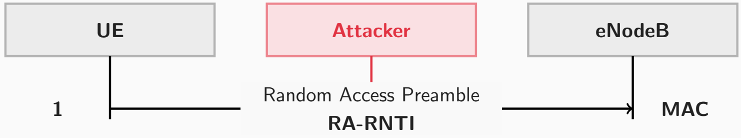
- Connection establishment exchanges messages between the UE and the eNodeB
- They're first addressed using the RNTI
- Later when everything is in place, they can switch to the TMSI
- Recording both, the $ID_{temp} = RNTI$ and the $ID_{perm} = TMSI$, is the goal
- **Allows to match the identifiers!**

Identity Mapping Attack



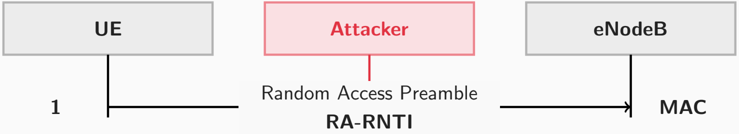
Different types of RNTI exist:

- **RA-RNTI**: Random Access RNTI. Used for PRACH Response.
- **C-RNTI**: Cell RNTI. Used for the transmission to a specific UE after RACH.
- P-RNTI: Paging RNTI. Used for Paging Message.
- SI-RNTI: System Information RNTI. Used for transmission of SIB messages
- T-CRNTI: Temporary C-RNTI. Mainly used during RACH
- SPS-C-RNTI, TPC-PUCCH-RNTI, TPC-PUSCH-RNTI, M-RNTI, CC-RNTI, G-RNTI, SC-RNTI, SL-RNTI, SC-N-RNTI, eIMTA-RNTI



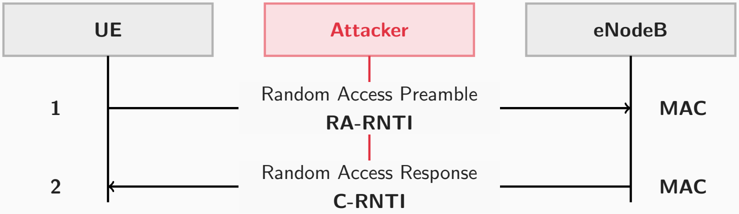
Random Access Preamble

- UE determines the value of the RA-RNTI
- $RA-RNTI = 1 + t_{id} + 10 * f_{id}$
- t_{id} is the index of the first subframe of the specified PRACH
- f_{id} is the index of the specified PRACH
- Physical Random Access Channel: UE requests uplink resources from eNodeB



Random Access Preamble (Simplified)

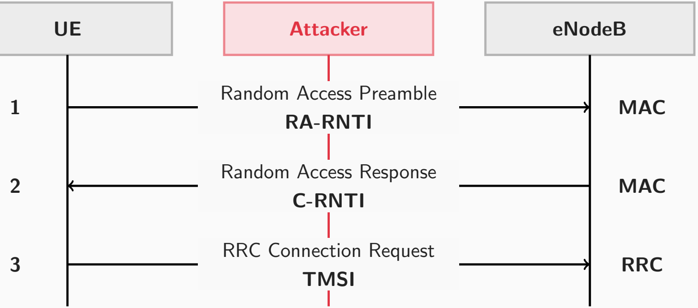
- UE determines the value of the RA-RNTI
- **There are only ten possible RA-RNTIs**
- $RA - RNTI \in [1..10]$



Random Access Response

- eNodeB assigns the C-RNTI
- Contention resolution: assign a temporary unique value
- Avoid collisions (requesting resources at the same time)
- 16-bit $C - RNTI \in [1..65523]$

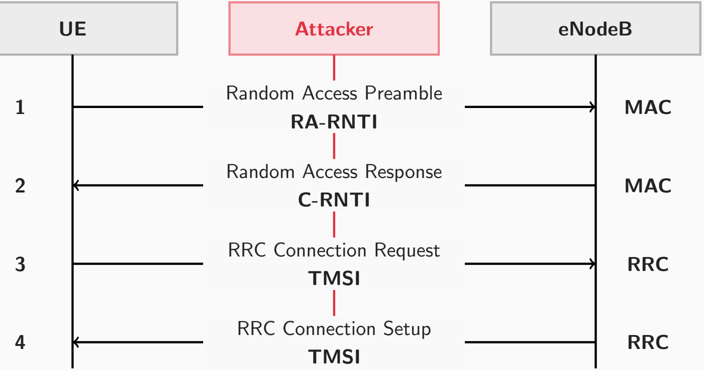
Uplink Sniffer



RRC Connection Request

- UE requests the connection and sends its TMSI
- **Match between C-RNTI and TMSI**

Downlink Sniffer



RRC Connection Setup

- eNodeB setups the connection
- **Match between C-RNTI and TMSI**

TMSI and IMSI

TMSI

Temporary Mobile Subscriber Identity, randomly assigned temporary identity. For security reasons, the TMSI is a placeholder for the unique IMSI of a user. It can be updated after a certain time period.

IMSI

International Mobile Subscriber Identity, uniquely identifies every mobile user. It is *not* the identifier of the SIM card, but still part of the profile.

The TMSI is used for security reasons!
It can be reset if compromised. The IMSI cannot be reset.

Identification Attack: Summary

- **Challenge**: Learn the identifier of a specific user.
- **Problem**: C-RNTI is different in every new session
- **Solution**: Try to learn the TMSI! It's temporary but is rarely updated.
- **Uplink**: Monitor the RRC Connection Request.
- **Downlink**: Monitor the RRC Connection Setup
- **Result**: Match C-RNTI to TMSI $\rightarrow$ Identity!

Identification Attack: Exam Examples

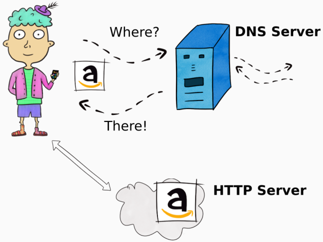
- Sketch the principle of the Identity Mapping Attack (draw the protocol, know everything in bold font)
- What is the difference between the RA-RNTI and the C-RNTI?
- What is the difference between the C-RNTI and the TMSI?
- Explain what the TMSI is. Why is the TMSI used instead of the IMSI?
- Explain what the IMSI is.

Attack 3: User Data Redirection

User Data Redirection?

DNS requests simplified:

- User wants to visit a site
- Asks the DNS Server for directions
- DNS server looks around
- Responds
- User contacts HTTP Server



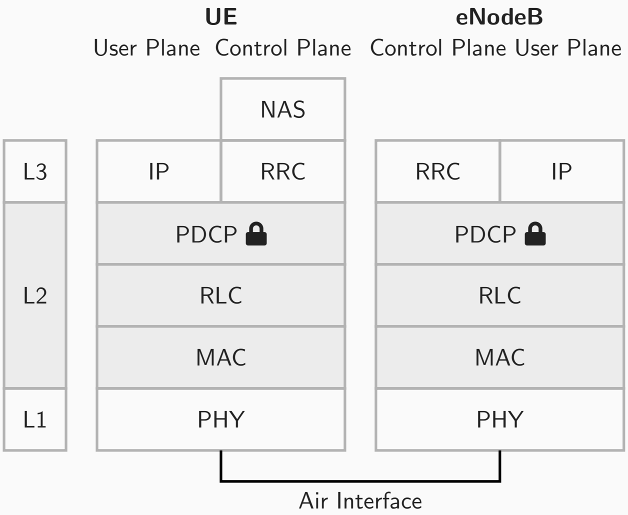
Three Attack Components

(1) **Plaintext Modification**

(2) DNS Spoofing

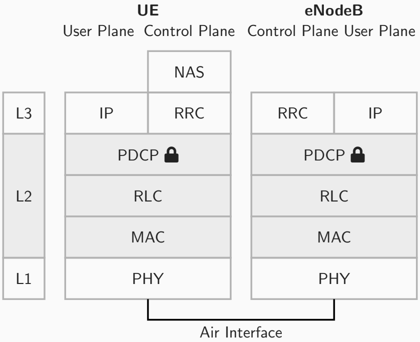
(3) Man-in-the-Middle

Plaintext Modification



Plaintext Modification

Feature	Control Plane	User Plane
Encryption	✓	✓
Integrity Protection	✓	✗



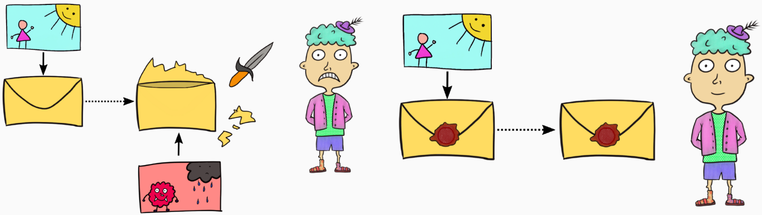
There is no integrity protection for user plane traffic!

Integrity?

Data Integrity

Nobody fiddled with the data:

- Original message arrives at the recipient
- Not changed along the way



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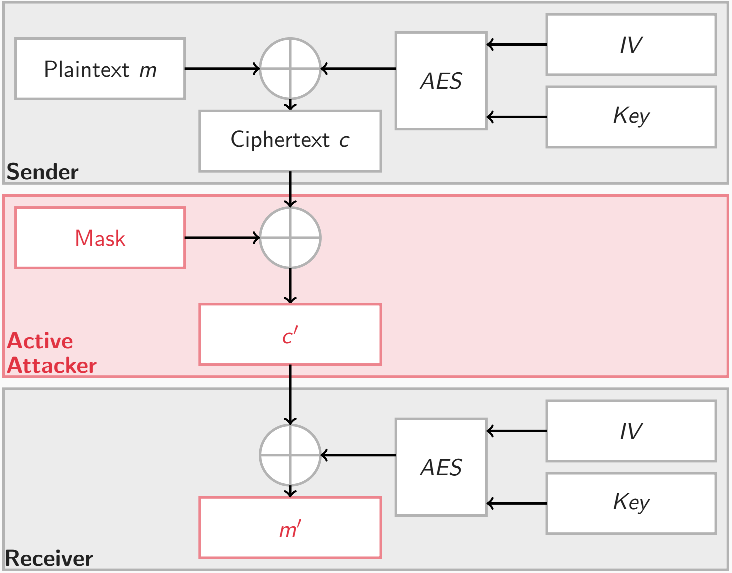
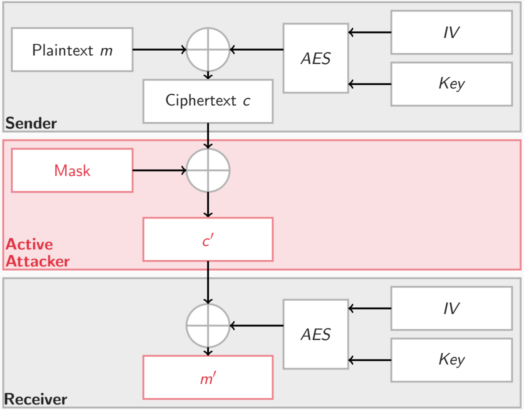
Known-Plaintext Attack



Known-Plaintext Attack

- PDCP encrypts IP packet
- Stream cipher: AES in counter mode
- XOR manipulation mask *m*
- Deterministic manipulation
- Manipulation remains undetected...
  But why?

No user plane integrity protection 👎

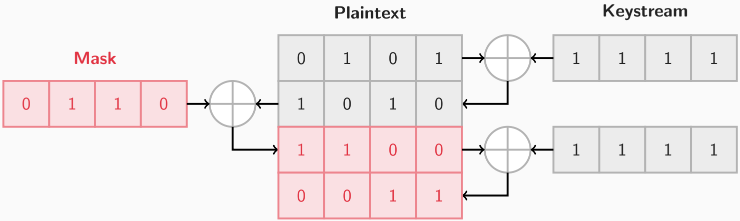


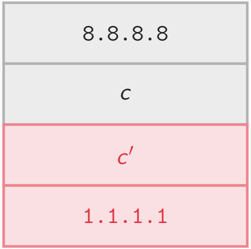
How can we achieve this?

Three Attack Components

(1) Plaintext Modification ✔
(2) **DNS Spoofing**
(3) Man-in-the-Middle

Manipulation Mask

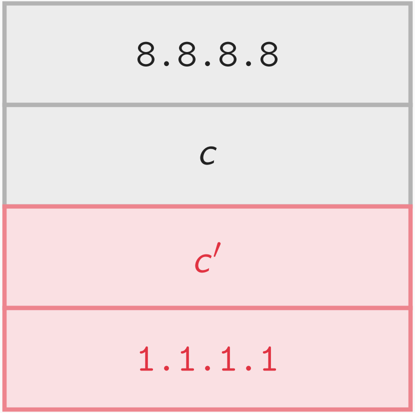




Example: DNS Spoofing

Spoofing DNS Requests

- Why do we know the plaintext? Providers have standard DNS resolvers!
- Prepare a mask that flips bits like we need it
- Add the mask to create the manipulated c'
- Receiver recovers plaintext $m' \neq m$

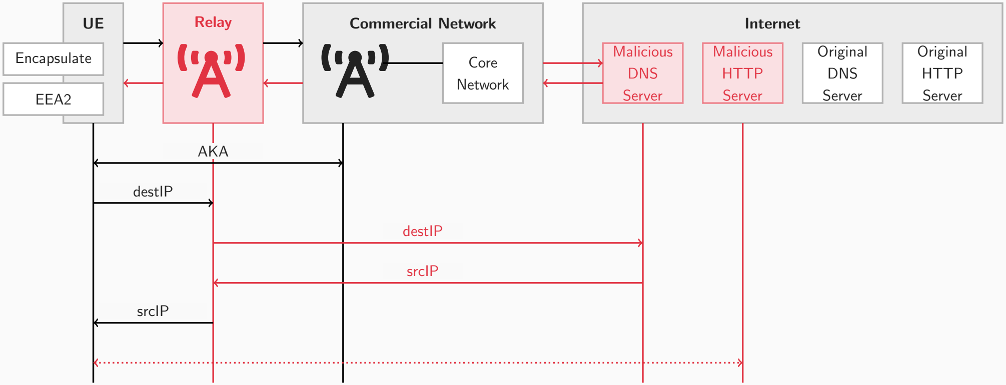


How can we achieve this?

Three Attack Components

(1) Plaintext Modification ✔
(2) DNS Spoofing ✔
(3) **Man-in-the-Middle**

The aLTEr attack



Bringing it all together:

(1) UE and eNodeB conduct AKA (authentication and key agreement) → Connection is established and ready to use

(2) UE sends website request including the `destIP` of the Original DNS Server

(3) Malicious eNodeB recognizes the request and replaces it with a new `destIP` of the Malicious DNS Server

(4) Malicious DNS server responds with address of Malicious HTTP Server

(5) Malicious eNodeB recognizes response and replaces the malicious `srcIP` with the one of the intended DNS server `srcIP`

(6) UE now has spoofed response and sends website request to the Malicious HTTP Server. **Unrecognized because of missing integrity protection!**

Three Attack Components

(1) Plaintext Modification ✔
(2) DNS Spoofing ✔
(3) Man-in-the-Middle ✔

Summary

Three L2 Attacks

(1) Website Fingerprinting
- Metadata information in LTE
- Classification attack

(2) Identity Mapping
- Temporary and permanent identifiers
- Matching them by passive sniffing

(3) User Data Redirection
- Known-plaintext attack
- Man-in-the-middle
- DNS spoofing

Acronyms

AKA	Authentication and Key Agreement
C-RNTI	Cell Radio Network Temporary Identity
eNodeB	Evolved NodeB
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access
EPLMN	Equivalent PLMN
GUTI	Globally Unique Temporary Identifier
HPLMN	Home PLMN
HSS	Home Subscriber Service
IMSI	International Mobile Subscriber Identity
LTE	Long Term Evolution
MAC	Medium Access Control
MCC	Mobile Country Code
MME	Mobility Management Entity
MNC	Mobile Network Code
NAS	Non-Access Stratum
P-GW	PDN Gateway
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PHY	Physical Layer
PLMN	Public Land Mobile Network
RAP	Random Access Preamble
RA-RNTI	Random Access RNTI
RLC	Radio Link Control
RNTI	Radio Network Temporary Identity
RRC	Radio Resource Control
S-GW	Serving Gateway
S1AP	S1 Application Protocol
SCTP	Stream Control Transmission Protocol
VPLMN	Visiting PLMN
SDR	Software Defined Radio
TMSI	Temporary Mobile Subscriber Identity
UE	User Equipment