Radboud University

# Advanced Network Security

## Lecture 10: Decrypting Phone Calls

Harald Vranken, Katharina Kohls

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Open University Nijmegen
Radboud University Nijmegen

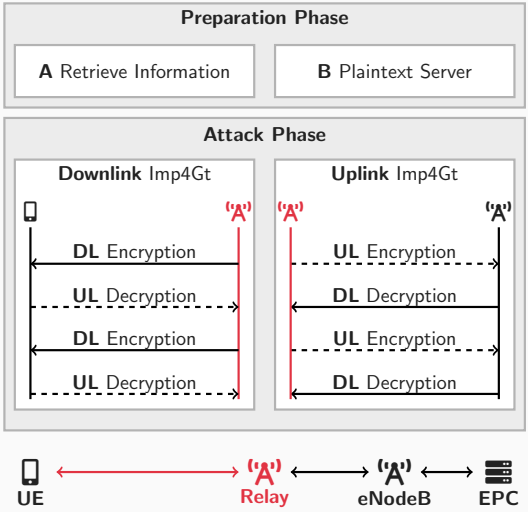
# Recap

(1) General introduction to mobile networks
- Terminology: UE, eNodeB, EPC
- Mobile protocol stack
- Security features

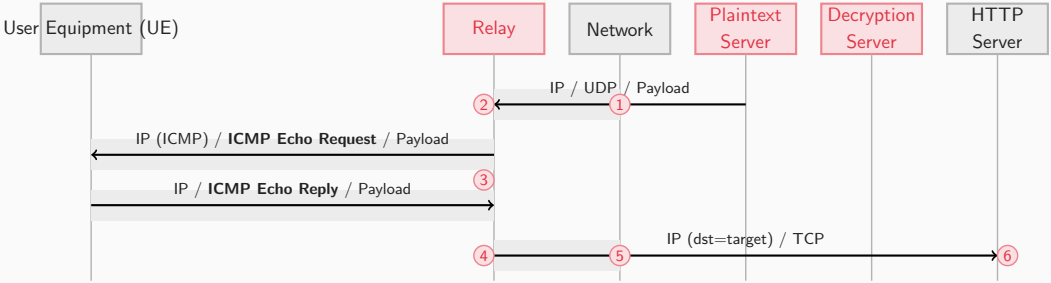
(2) Three layer-two attacks
- Website fingerprinting
- Identity mapping
- User data redirection

(3) Full impersonation in uplink and downlink direction
- Encryption and decryption oracle
- Ping reflection

# Attack Concept



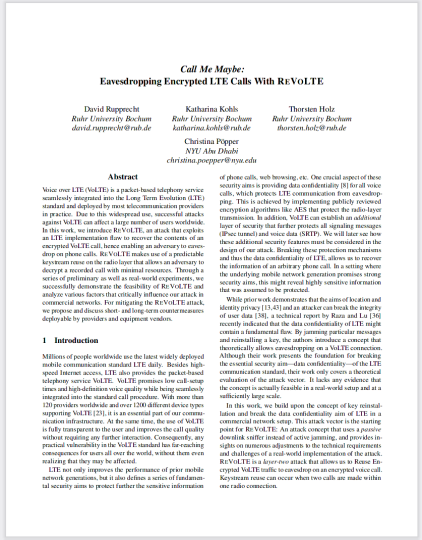
# HTTP Example



# HTTP Example

1. Inject payload to open port.
2. Intercept packet, change to `ICMP Echo Request`.
3. Send and receive the Ping for legitimate encryption and network context.
4. Forward encrypted packet, send in uplink direction.
5. Receive packet, decrypt, forward.
6. The packet arrives at the target server. It contains whatever we put in there!

# Call Me Maybe



***Call Me Maybe:***
**Eavesdropping Encrypted LTE Calls With REVOLTE**

David Rupprecht
*Ruhr University Bochum*
*david.rupprecht@rub.de*

Katharina Kohls
*Ruhr University Bochum*
*katharina.kohls@rub.de*

Thorsten Holz
*Ruhr University Bochum*
*thorsten.holz@rub.de*

Christina Pöpper
*NYU Abu Dhabi*
*christina.poepper@nyu.edu*

**Abstract**

Voice over LTE (VoLTE) is a packet-based telephony service seamlessly integrated into the Long Term Evolution (LTE) standard and deployed by most telecommunication providers in practice. Due to this widespread use, successful attacks against VoLTE can affect a large number of users worldwide. In this work, we introduce REVOLTE, an attack that exploits an LTE implementation flaw to recover the contents of an encrypted VoLTE call, hence enabling an adversary to eavesdrop on phone calls. REVOLTE makes use of a predictable keystream reuse on the radio layer that allows an adversary to decrypt a recorded call with minimal resources. Through a series of preliminary as well as real-world experiments, we successfully demonstrate the feasibility of REVOLTE and analyze various factors that critically influence our attack in commercial networks. For mitigating the REVOLTE attack, we propose and discuss short- and long-term countermeasures deployable by providers and equipment vendors.

## 1 Introduction

Millions of people worldwide use the latest widely deployed mobile communication standard LTE daily. Besides high-speed Internet access, LTE also provides the packet-based telephony service VoLTE. VoLTE promises low call-setup times and high-definition voice quality while being seamlessly integrated into the standard call procedure. With more than 120 providers worldwide and over 1200 different device types supporting VoLTE [23], it is an essential part of our communication infrastructure. At the same time, the use of VoLTE is fully transparent to the user and improves the call quality without requiring any further interaction. Consequently, any practical vulnerability in the VoLTE standard has far-reaching consequences for users all over the world, without them even realizing that they may be affected.

LTE not only improves the performance of prior mobile network generations, but it also defines a series of fundamental security aims to protect further the sensitive information of phone calls, web browsing, etc. One crucial aspect of these security aims is providing data confidentiality [8] for all voice calls, which protects LTE communication from eavesdropping. This is achieved by implementing publicly reviewed encryption algorithms like AES that protect the radio-layer transmission. In addition, VoLTE can establish an *additional* layer of security that further protects all signaling messages (IPsec tunnel) and voice data (SRTP). We will later see how these additional security features must be considered in the design of our attack. Breaking these protection mechanisms and thus the data confidentiality of LTE, allows us to recover the information of an arbitrary phone call. In a setting where the underlying mobile network generation promises strong security aims, this might reveal highly sensitive information that was assumed to be protected.

While prior work demonstrates that the aims of location and identity privacy [13, 43] and an attacker can break the integrity of user data [38], a technical report by Razaz and Lu [36] recently indicated that the data confidentiality of LTE might contain a fundamental flaw. By jamming particular messages and reinstalling a key, the authors introduce a concept that theoretically allows eavesdropping on a VoLTE connection. Although their work presents the foundation for breaking the essential security aim—data confidentiality—of the LTE communication standard, their work only covers a theoretical evaluation of the attack vector. It lacks any evidence that the concept is actually feasible in a real-world setup and at a sufficiently large scale.

In this work, we build upon the concept of key reinstallation and break the data confidentiality aim of LTE in a commercial network setup. This attack vector is the starting point for REVOLTE. An attack concept that uses a *passive* downlink sniffer instead of active jamming, and provides insights on numerous adjustments to the technical requirements and challenges of a real-world implementation of the attack. REVOLTE is a *layer-two* attack that allows us to Reuse Encrypted VoLTE traffic to eavesdrop on an encrypted voice call. Keystream reuse can occur when two calls are made within one radio connection.

**Today:**
**Decrypting VoLTE Calls**

`https://revolte-attack.net/`

# VoLTE: Voice over LTE


**VoLTE**

- uses a 4G *data* connection instead of the standard voice network to operate phone calls.
- has smaller packet headers and is more efficient than VoIP/LTE.
- device, firmware, and provider must all support VoLTE.

# VoLTE Networks


**Is this a thing?**

- 253 operators
- 113 countries

**Why is this a thing?**

- Better call quality
- LTE *security* features

https://gsacom.com/paper/gsa-announces-253-operators-investing-volte/

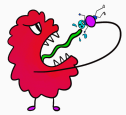
# Target and Keystream Call

**Target Call**

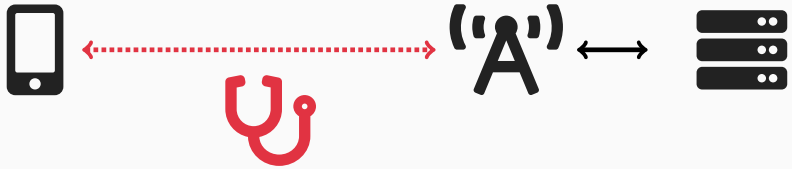
Record VoLTE Call

**Keystream Call**

Recover keystream!



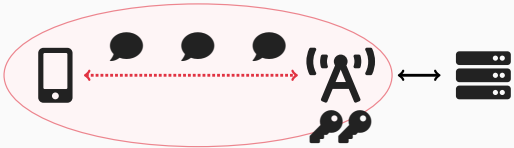
# Decrypting Encrypted Calls



**Call me Maybe**

- Record VoLTE phone calls → Wireless sniffer
- Exploit keystream reuse → Implementation flaw
- Decrypt recorded call → Attack goal

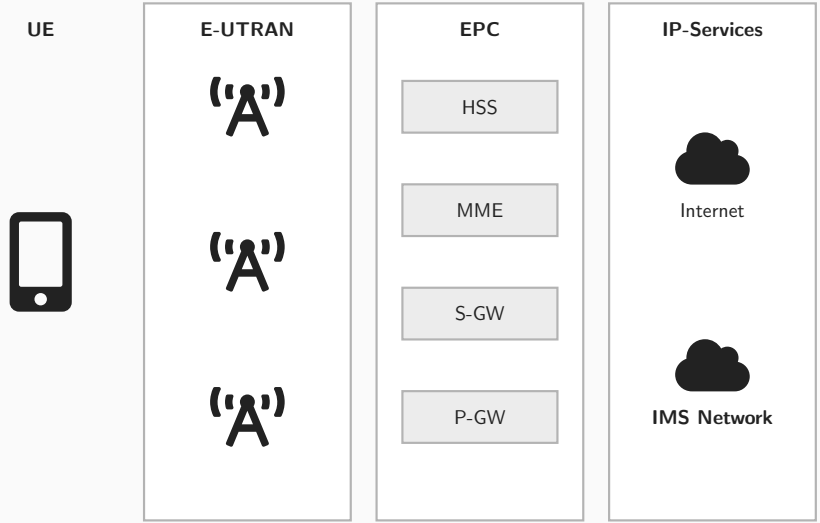
# Attack Challenges



- **Wireless sniffer:** Be in the same radio cell, record traffic between UE and eNodeB.
- **Keystream reuse:** Call is encrypted. If the *same* keystream is used again, we can decrypt the call.
- **Challenges:** Everything that happens in the wireless transmission of voice data.

# Attack Challenges

# VoLTE Infrastructure



# VoLTE Infrastructure

- User, making a phone call
  - Make initial call
  - Answer a subsequent call
- Radio cell
  - Set the codec and ROHC
  - Apply security measures
- Packet-switched phone call through the IMS
  - Transport protocols

- Home Subscriber Service (HSS)
- Mobility Management Entity (MME)
- Serving Gateway (S-GW)
- PDN Gateway (P-GW)

# Challenges

**Performance**

- **Codecs and comfort noise**
- **Robust header compression**
- **Radio data bearers**

**IP Multimedia Subsystem (IMS)**

- Control and media planes
- Packet-switched architecture

**Security**

- Radio-layer encryption
- Additional AKA
- Secure Real-Time Transport Protocol (SRTP)

**Multimedia Codec**

transforms signals between different representations with either optimizing the data consumption or the quality.

**Three possible codecs:**

(1) Enhanced Voice Services (EVS)[1]

(2) Adaptive Multi-Rate (AMR)

(3) Adaptive Multi-Rate Wideband (AMR-WB)

[1] https://www.3gpp.org/news-events/1639-evs_news

### Optimization Methods

- Comfort Noise
  - Save data in periods where the calling partner is silent.
  - Comfort noise is generated through a *seed*.
  - Seed is smaller, transmitted on lower frequency.
  - **Example:** AMR-WB uses 40bit over 160ms, actual voice uses 477bit every 20ms.
- Transcoding occurs when calling partners use different codecs.
  - **Example:** Radio-layer problems enforce a downsampling.

# Why are codecs relevant for us?

**We will eavesdrop a phone call, everything is encoded by the applied multimedia codec.**

**What we need to know:**

- What codec was applied?
- How can we reconstruct the information?
- How to handle comfort noise?
- How to handle transcoding?

**Robust Header Compression (ROHC)**

is a technique to save bits in the headers of IP, TCP, UDCP, and RTP packets. The compression saves bandwidth by removing redundancies from packet headers with the same connection endpoints.

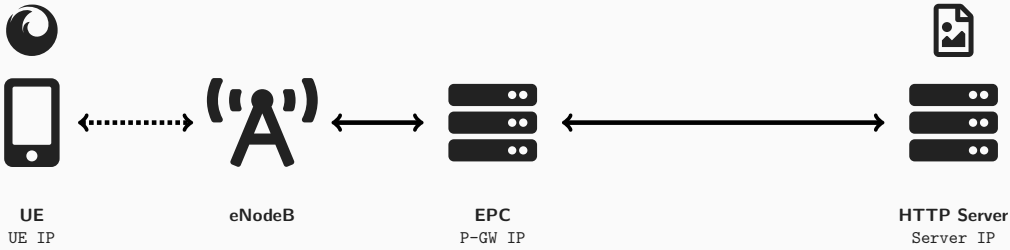
**What we need:**

(1) Addressing packets in a mobile connection

(2) Involved protocols

(3) Protocol headers and redundant information

# Robust Header Compression (ROHC)




*What protocols are involved?*

*What header fields remain the same?*

# Protocol Headers

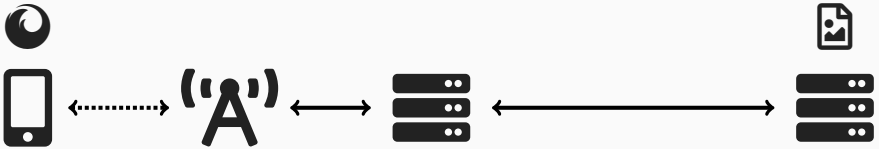
**IPv4 Header**

| Version | IHL | Type of Service | Total Length | |
|---|---|---|---|---|
| Identification | | | Flags | FragmentOffset |
| Time to Live | | Protocol | Header Checksum | |
| Source IP Address | | | | |
| Destination IP Address | | | | |
| Options | | | | Padding |

**UDP Header**

| Source Port | Destination Port |
|---|---|
| Length | Checksum |
| Data | |

# Redundant Information



# Robust Header Compression (ROHC)

**Remove Redundancy:**

- Send the first packet with all header information included
  $\rightarrow$Both sides learn relevant and static information.
- In the following packets, remove all headers that do not change.

**The eNodeB activates ROHC profiles:**

- Profile 1: compress RTP, UDP, IP headers;
  only transmit RTP data with ROHC header.
- Profile 2: compress UDP, IP; only transmit UDP payload with ROHC header.

# Why is ROHC relevant?

**ROHC compresses the transmitted packets and influences the data that we can eavesdrop.**

**What we need to know:**

- What kind of compression is enabled?
- What information do we lose?
- When does this occur?

# Radio Data Bearers

**Radio Bearers**

- Signaling Radio Bearers SRB
- **Dedicated Radio Bearers DRB**

**Idle and Active Connections**

- Inactivity triggers `idle` mode
- Active radio connections use a dedicated radio bearer
- Logical link of UE and eNodeB
- Define transmission requirements

| Bearer | Purpose | Bearer ID |
|---|---|---|
| DRB1 | Internet | 1 |
| DRB2 | SIP (IMS) | 2 |
| DRB3..32 | RTP | 3..32 |

- DRB1: Standard Internet connection
- DRB2: Signalling traffic for the IMS
- DRB3..32: Phone calls, is immediately removed after the call

# Why are Bearers relevant?

**We will later exploit a keystream reuse. Using the same bearer ID contributes to keeping the same keystream.**

**What we need to know:**

- How does the eNodeB pick the bearer ID?
- Does the bearer ID stay the same?

# Challenges

**Performance**

- Codecs and comfort noise
- Robust header compression
- Radio data bearers

**IP Multimedia Subsystem (IMS)**

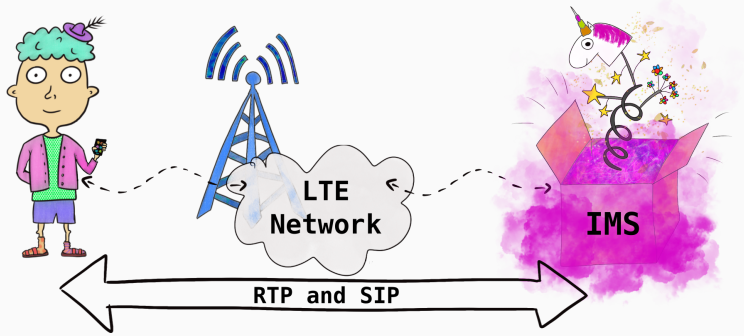
- **Control and media planes**
- **Packet-switched architecture**

**Security**

- Radio-layer encryption
- Additional AKA
- SRTP

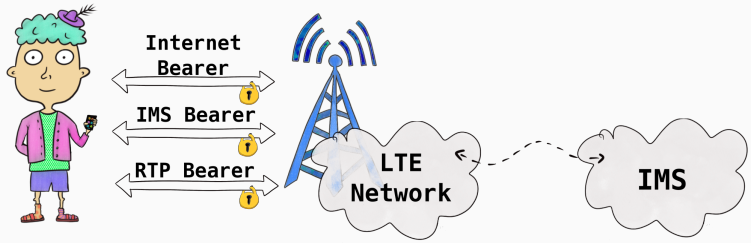
# IP Multimedia Subsystem (IMS)

# IP Multimedia Subsystem (IMS)



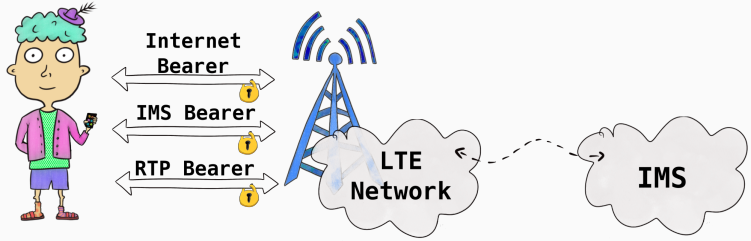

- **IMS:** Generic system for IP-based multimedia
- **RTP:** Transport audio and video via IP
- **SIP:** Build and control communication session

# Radio Bearers




| Bearer | Purpose | Bearer ID |
|---|---|---|
| DRB1 | Internet | 1 |
| DRB2 | SIP (IMS) | 2 |
| DRB3..32 | RTP | 3..32 |

# Why is the IMS relevant?




**What we need to know:**

- RTP bearer is the most important for our attack.
- Two security features are relevant:
  (1) RTP versus SRTP
  (2) Bearer ID as input for the keystream generation.

# Challenges

**Performance**

- Codecs and comfort noise
- Robust header compression
- Radio data bearers

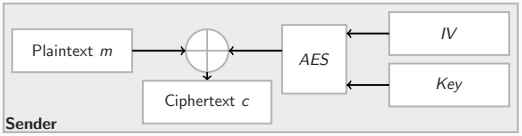
**IP Multimedia Subsystem (IMS)**

- Control and media planes
- Packet-switched architecture

**Security**

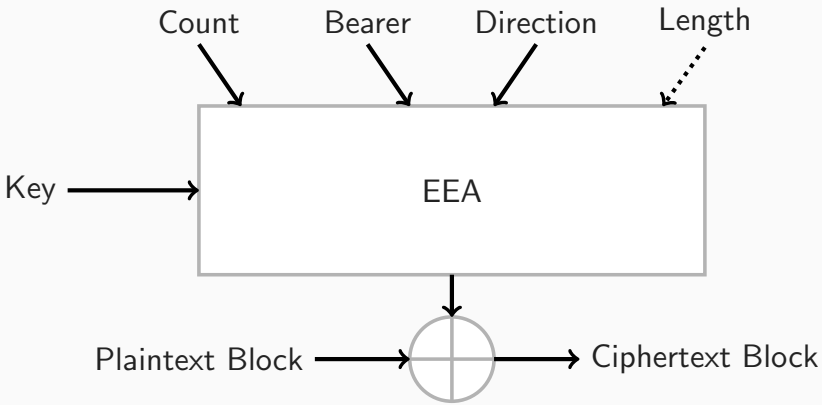
- **Radio-layer encryption**
- **Additional AKA**
- **SRTP**

# Radio-Layer Encryption

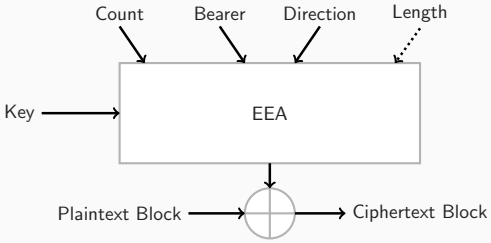



- PDCP applies the encryption algorithm EPS Encryption Algorithm (EEA).
  - EEA1: Snow3G
  - EEA2: AES in counter mode
  - EEA3: ZUC
- Plaintext gets XOR-ed with keystream
- Keystream blocks are generated individually for each plaintext block

# Keystream Generation



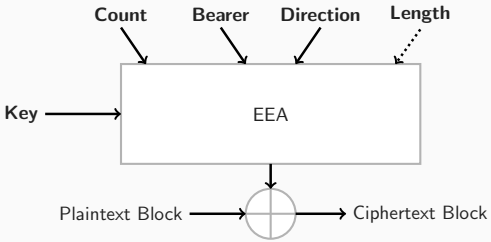
# Keystream Generation




- **Key** Use plane key, established for each new radio connection.
- **Count** PDCP sequence number + PDCP hyperframe number
- **Bearer** Bearer identity
- **Direction** Uplink or downlink
- **Length** Length of the keystream block (does not influence the keystream generation)

# Why is the keystream generation relevant?

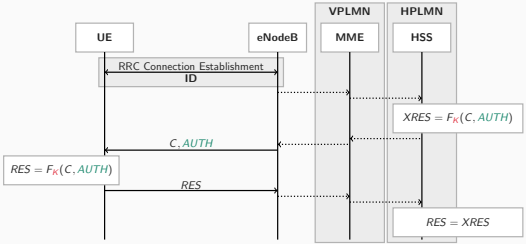
**We need to reconstruct the keystream to decrypt a recorded call.**




**What we need to know:**

- Do these inputs change over multiple connections?
- What influences changes?

# VoLTE AKA




- UE and Evolved Packet Core (EPC) use the AKA for mutual authentication.
- The IMS is a new component in this setting. It also uses mutual authentication.
- To achieve this, the User Equipment (UE) needs to go through a *second* AKA.

# Second AKA

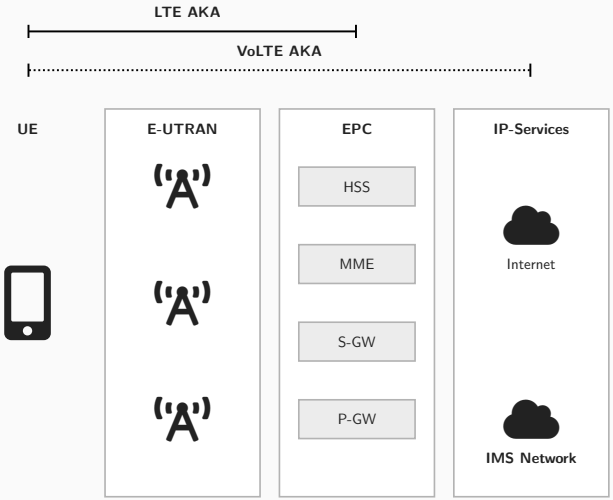
**Initial Authentication and Key Agreement (AKA)**

- Initial AKA authenticates UE and EPC
- After that, all traffic is encrypted.

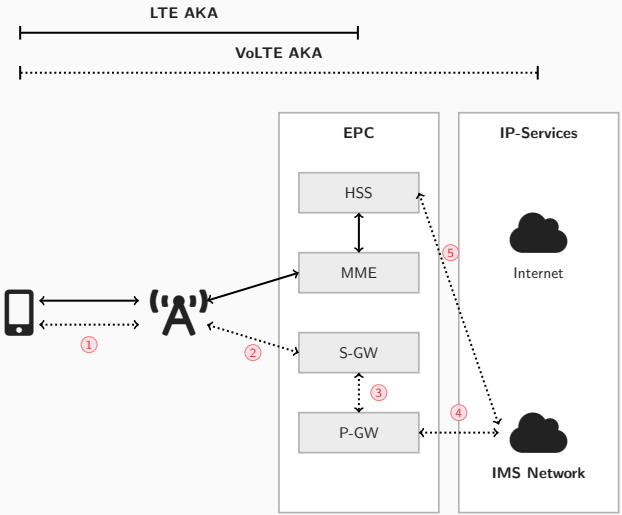
**VoLTE AKA**

- When the UE wants to make a VoLTE call, it establishes mutual authentication with the IMS.
- A second AKA takes place.
- All messages use the already authenticated LTE connection.

# VoLTE AKA

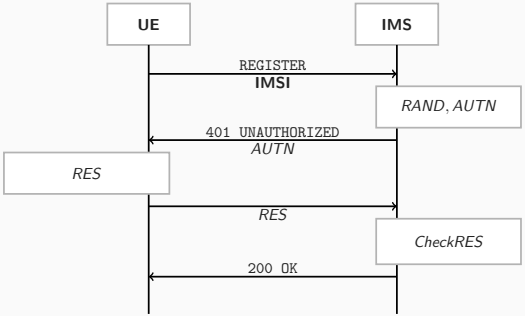

LTE AKA
VoLTE AKA
UE
E-UTRAN
EPC
IP-Services
HSS
MME
S-GW
P-GW
Internet
IMS Network

# VoLTE AKA


LTE AKA
VoLTE AKA
EPC
IP-Services
HSS
MME
S-GW
P-GW
Internet
IMS Network
1
2
3
4
5

# VoLTE AKA

1. Radio connection between UE and eNodeB
2. VoLTE traffic is treated as user plane data $\rightarrow$ handled in Serving Gateway (S-GW).
3. PDN Gateway (P-GW) receives traffic and forwards it to the IP network.
4. IMS checks whether user is allowed to receive service.
5. Checks identity at HSS.




**VoLTE AKA Protocol**

- The VoLTE AKA uses SIP.
- UE sends *IMSI* for identification at the HSS.
- Caller and callee both authenticate.

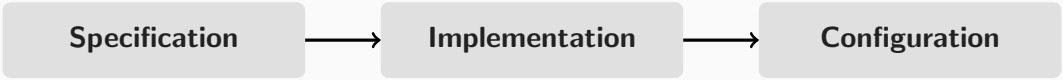
**SRTP**

The SRTP adds encryption, message authentication and integrity, and replay attack protection to RTP.

**SRTP Security**

- SRTP would add an additional layer of encryption.
- This encryption happens on higher layers of the protocol stack.

**VoLTE security measures are optional.**
**It is up to the provider to configure these features.**




**Define things on paper**

Things are flawed by definition.

Update specification 😳

**Transform it into code**

All devices with this implementation are flawed.

Patch implementation ☹

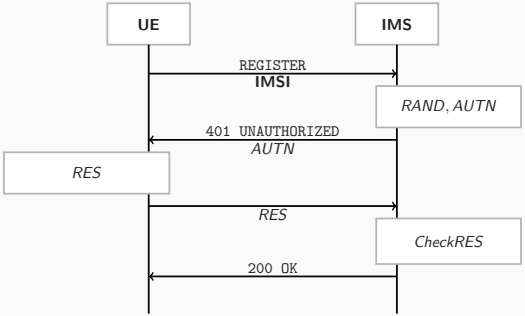
**Fine-tune the live network**

Local network has a flawed configuration.

Patch configuration 😇

# Why is the VoLTE AKA relevant?

**The second AKA and SRTP enable additional encryption.**




**What we need to know:**

- How often does the network apply the second VoLTE AKA?
- How often is SRTP used for an additional layer of encryption?

# Challenges

**We record a call and reconstruct the keystream from a second call.**
**These are the challenges:**

**Performance**: How codecs & compression affect traffic.

**IMS**: RTP bearer as main data transportation.

**Security**: VoLTE AKA and encryption through SRTP.

# Challenges: Summary

**We record a call and reconstruct the keystream from a second call.**
**These are the challenges:**

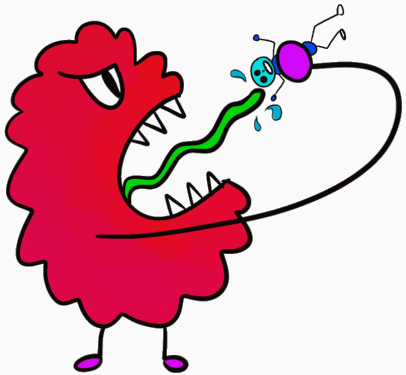
- **Attack:** Decrypting VoLTE calls by exploiting a keystream reuse.
- **We need to consider**:
  (1) Performance: Codecs and compression and how this affects traffic
  (2) IMS: Data bearers and the RTP bearer as main data transportation.
  (3) Security: VoLTE AKA and encryption through SRTP.
- **Next:** Understanding the ReVoLTE attack

# Challenges: Exam Examples

- What is Robust Header Compression?
- Why do we need to consider ROHC and codecs for the attack?
- What do we exploit for the ReVoLTE attack?
- Why does SRTP influence the attack?
- Why does VoLTE use a second AKA?
- What protocol is used for the VoLTE AKA?

# Attack

# Call me Maybe!



(1) Unclear specification

(2) Keystream reuse

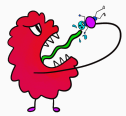
(3) Wireless sniffing

(4) Decrypt calls

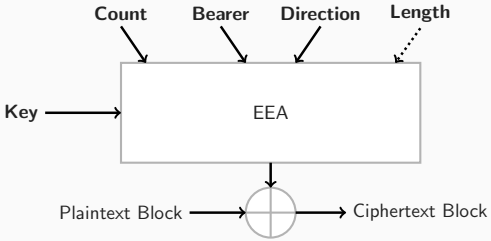
# Target and Keystream Call

Target Call

Keystream Call



# Stream Cipher

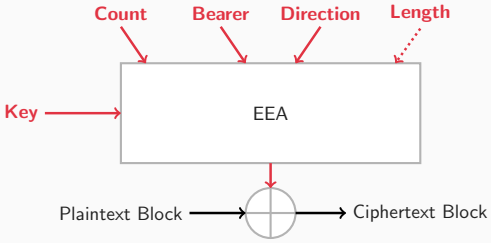



**Stream Cipher**

- **Key:** VoLTE user traffic key
- **Count:** Sequence number of packets
- **Bearer:** Bearer identity
- **Direction:** Uplink or downlink
- **Length:** Keystream block length

**Same** input generates **same** keystream!

# Input and Output

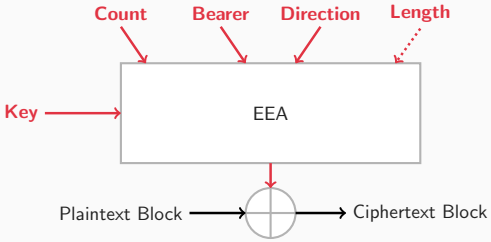



**Same** input generates **same** keystream!

$$(Plain_A \oplus Keystream) \oplus (Plain_B \oplus Keystream) = (Plain_A \oplus Plain_B)$$

$$(Plain_A \oplus Plain_B) \oplus Plain_B = Plain_A$$

# Reconstructing the Plaintext




Adversary has control over $\boldsymbol{Plain_B}$

$$(Plain_A \oplus Keystream) \oplus (\boldsymbol{Plain_B} \oplus Keystream) = (Plain_A \oplus \boldsymbol{Plain_B})$$

$$(Plain_A \oplus \boldsymbol{Plain_B}) \oplus \boldsymbol{Plain_B} = Plain_A$$

# Roadmap

**Two Attack Components:**

(1) VoLTE data encrypted with a *stream cipher* 😳

(2) Keystream *reuse* 😳

# Attack Concept

(1) **Target Call**

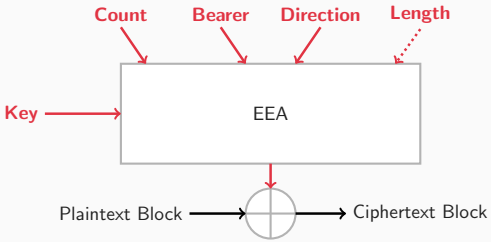
- User makes a phone call
- Adversary monitors encrypted traffic
- Waits until call ends

(2) **Keystream Call**

- Call the victim
- Talk for same duration
- Monitor traffic

(3) **Reconstruct First Call**

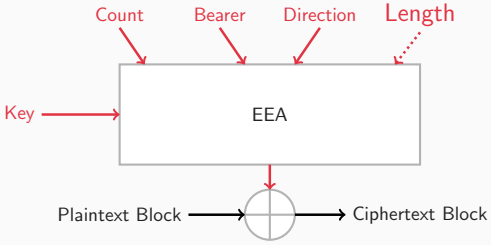
# Keystream Generation




- **Key:** VoLTE user traffic key
- **Count:** Sequence number of packets
- **Bearer:** Bearer identity
- **Direction:** Uplink or downlink
- **Length:** Keystream block length

**Step-by-step check of all inputs for the keystream**

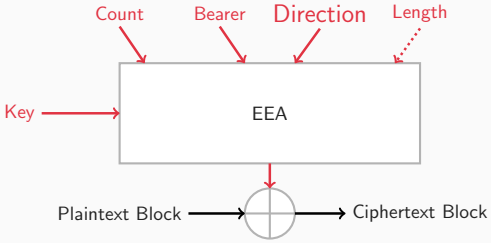
# Length




**Length**

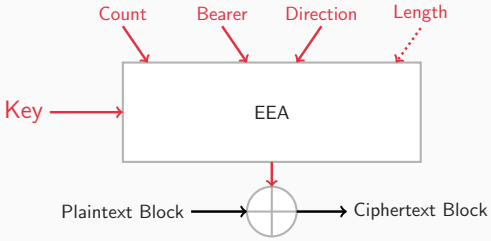
- Keystream block length.
- Does not influence the keystream generation.
- *Does not change the keystream.*

# Direction



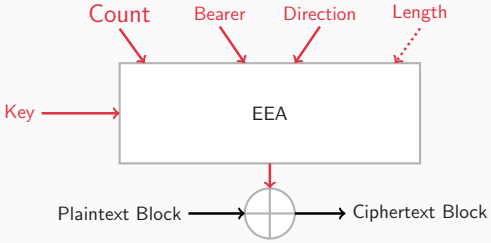

**Direction**

- Defines the direction of the traffic.
- Can either be uplink or downlink traffic.
- We monitor traffic in both directions.
- *Does not change the keystream.*




**Key**

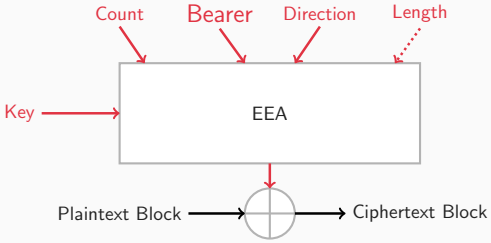
- Use plane key $k_{up}$
- Established for each new radio connection.
- If we manage to stay in the same session, $k_{up}$ does not change.
- *Does not change the keystream.*




**Count**

- Count consists of the PDCP sequence number and the PDCP hyperframe number.
- For each new call, the count will be reset
- *Does not change the keystream.*

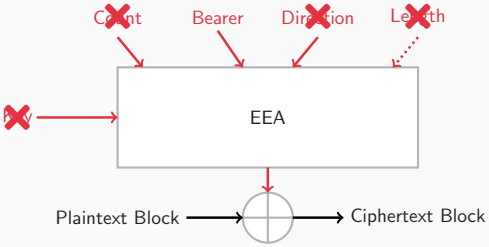
# Bearer ID




**Bearer ID**

- Bearer ID for the RTP bearer can be in range 2..32
- If a new Bearer ID is used, the keystream changes.
- If the same Bearer ID is reused, it is an *implementation flaw.*
- *Might not change the keystream.*

# Keystream Checklist




- **Key:** VoLTE user traffic key ☹
- **Count:** Sequence number of packets ☹
- **Bearer:** Bearer identity??
- **Direction:** Uplink or downlink ☹
- **Length:** Keystream block length ☹

**What happens to the Bearer ID?**

# Target and Keystream Call

RRC Security Mode Command

$k_{up}$

**Target Call**

Reset **Count**

Set **Bearer ID**

**Keystream Call**

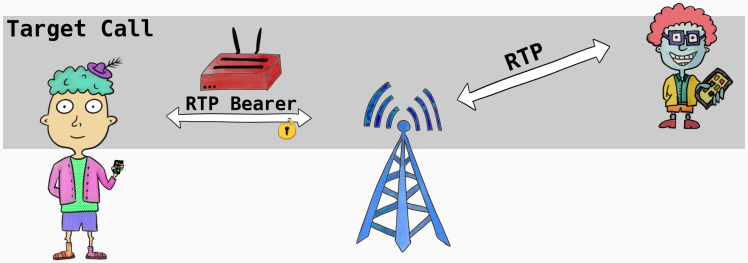
Reset **Count**

Set **Bearer ID**

3/15 eNodeBs increase the Bearer ID

**12/15** eNodeBs **reuse** the same keystream

# Conducting the Attack



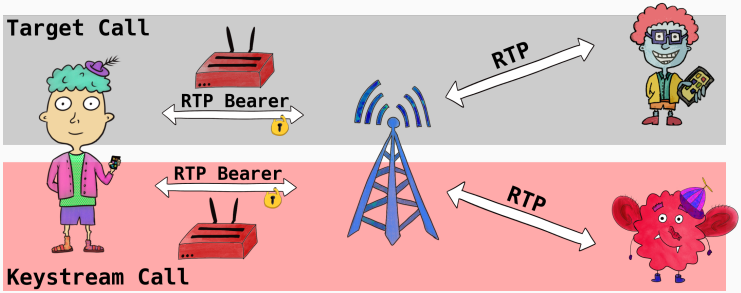

**Target Call**

(1) Victim places call

(2) Adversary monitors RTP bearer: Encrypted voice data

(3) Passive sniffer in the same radio cell

# Conducting the Attack




**Keystream Call**

(1) Adversary calls victim immediately after target call

(2) Again, record RTP bearer *with same bearer ID*

(3) Reconstruct plaintext of first call

# Reconstructing the Plaintext

$$(Plain_A \oplus Keystream) \oplus (\boldsymbol{Plain_B} \oplus Keystream) = (Plain_A \oplus \boldsymbol{Plain_B})$$
$$(Plain_A \oplus \boldsymbol{Plain_B}) \oplus \boldsymbol{Plain_B} = Plain_A$$

**Controlling $\boldsymbol{Plain_B}$:**

- $\boldsymbol{Plain_B}$ is the keystream call
- We replay something we know
- Example: Recorded conversation

**Remember the Challenges?**

- Avoid comfort noise
- Anticipate the codec
- Only works without SRTP

# Attack: Summary

**How the keystream reuse happens and how we conduct the attack.**

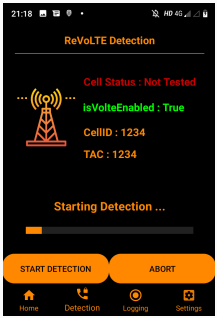
- **Keystream Generation**:
  - Direction and length are not really relevant.
  - User plane key remains the same for a session.
  - Count is reset, as defined in the specification.
  - Last remaining input: Bearer ID
- **Attack:** Record target call, place keystream call, reconstruct plaintext of first call.

# Attackt: Exam Examples

- What is the critical component that causes the keystream reuse?
- How could we fix this attack vector?
- Is the ReVoLTE attack something that could happen in the real world?
- Can you remember the technical challenges we discussed in the beginning? Does everything make a little more sense now?
- Why is there a subsequent keystream call?

# Results

- **Implementation flaw**
- Specification was ambiguous, this is resolved now
- Providers can patch the flaw if known




www.revolte-attack.net

# Acronyms

| | |
|---|---|
| **AKA** | Authentication and Key Agreement |
| **eNodeB** | Evolved NodeB |
| **EEA** | EPS Encryption Algorithm |
| **EPC** | Evolved Packet Core |
| **E-UTRAN** | Evolved Universal Terrestrial Radio Access |
| **HPLMN** | Home PLMN |
| **HSS** | Home Subscriber Service |
| **IMS** | IP Multimedia Subsystem |
| **MAC** | Medium Access Control |
| **MCC** | Mobile Country Code |
| **MME** | Mobility Management Entity |
| **MNC** | Mobile Network Code |
| **NAS** | Non-Access Stratum |
| **P-GW** | PDN Gateway |
| **PCRF** | Policy and Charging Rules Function |
| **PDCP** | Packet Data Convergence Protocol |
| **PDN** | Packet Data Network |
| **PHY** | Physical Layer |
| **RA-RNTI** | Random Access RNTI |
| **RLC** | Radio Link Control |
| **RNTI** | Radio Network Temporary Identity |
| **ROHC** | Robust Header Compression |
| **RRC** | Radio Resource Control |
| **RTP** | Real-Time Transport Protocol |
| **S-GW** | Serving Gateway |
| **SIP** | Session Initiation Protocol |
| **SRTP** | Secure Real-Time Transport Protocol |
| **UE** | User Equipment |
| **VPLMN** | Visiting PLMN |