# AdaptOver: Adaptive Overshadowing of LTE signals

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#### **Abstract**

We introduce AdaptOver, a new LTE signal overshadowing attack that allows an adversary to reactively and adaptively overshadow any downlink message between the network and the user equipment (UE). We demonstrate the impact of AdaptOver by using it to launch targeted Denial-of-Service (DoS) attacks on UEs.

We implement AdaptOver using a commercially available software-defined radio. Our experiments demonstrate that our DoS attacks cause persistent connection loss lasting more than 12 hours for a wide range of smartphones. DoS attacks based on AdaptOver are stealthier than attacks that relied on the use of fake base stations, and more persistent than existing overshadowing attacks, which caused connection loss of only up to 9 minutes. Given that AdaptOver can reactively overshadow any downlink message, its use is not limited to DoS attacks — it can be used for a wide range of other attacks, e.g., to extract the IMSI from a UE in a stealthier manner than traditional IMSI catchers. We consider AdaptOver to be an essential building block for many attacks against real-world LTE networks. In particular, any fake base station attack that makes use of spoofed downlink messages can be ported to the presented attack method, causing a much more reliable, persistent, and stealthy effect.

#### 1 Introduction

LTE was designed to provide cellular infrastructure that is robust against interference but is not necessarily suited for jamming-resilient communication. It is therefore not surprising that radio link between the base station (eNodeB) and user equipment (UE) is vulnerable to wireless jamming [12]. Given the lack of base station authentication, LTE is further vulnerable to fake base station attacks, leading to Denial-of-Service (DoS) [19], or man-in-the-middle (MITM) attacks [18]; in such an attack the UEs connect to the fake base station, resulting in an attacker being able to spoof any messages that are not authenticated/integrity-protected. Specifically, the fake

base station may cause DoS by replying to a service / attachment procedure with a reject [7, 8, 19], act as an IMSI catcher [8], or tamper with the keystream of the non-integrity protected user data [17, 18]. Although these attacks have a high impact, they require the attacker to remain active for long periods of time and to use high output power, risking detection by regulators and law enforcement agencies.

More recently, a new and more sophisticated attack method on LTE has emerged, based on message overshadowing [21]. In this attack, called SigOver, the downlink signal of a base station is overshadowed (i.e., replaced over-the-air) with a time and frequency synchronized attack signal of greater strength. In contrast to using (blanket) jamming or a fake base station, this attack requires far less power output (3dB vs 30dB) to achieve a high success rate in causing DoS for the UE. However, the design of SigOver allows the overshadowing only to be applied to channels with predictable scheduling, such as the Broadcast Control Channel (BCCH) and the Paging Control Channel (PCCH). Given this, SigOver can only cause DoS that is limited to a single cell and disconnects a UE from the network for at most 9 minutes. If the UE is in reach of other base stations, it will try to reconnect, requiring the attacker to mount the attack on all base stations in the vicinity of the victim UE simultaneously.

In this work, we introduce a novel attack technique called AdaptOver, that facilitates the overshadowing of *arbitrary* downlink messages and can interfere with any protocol procedure between any of the LTE components (the base station and the core network) and the UE, in an active connection. By design, AdaptOver is reactive and is coupled with a downlink decoder, making it able to react on downlink traffic. To successfully overshadow a message, AdaptOver needs to achieve only 1.8dB higher power than the legitimate signal. Although this seems like an improvement over SigOver, we can attribute this to differences in our experimental setups and therefore won't claim any advantage.

In order to demonstrate the impact of AdaptOver, we implemented a range of DoS attacks against multiple LTE connection establishment procedures. Our results show that by

overshadowing a single downlink (attach, service or authentication) message from the eNodeB and core network to the UE, AdaptOver is able to introduce persistent, >12 hours long, DoS (compared to a 9 minutes long DoS with existing overshadowing techniques). The attack does not depend on the number of base stations in the vicinity of the UE — the victim UE will not try to reconnect to any of the neighboring base stations. AdaptOver is able to DoS the UE at any time the phone re-establishes service after being idle for a while (which occurs in the worst case at most every 6 minutes when the user does not interact with the phone [1]), reboots, or the user toggles airplane mode.

The impact of AdaptOver is not limited to DoS attacks. AdaptOver can be used to manipulate LTE protocol procedures and leak information in a manner that is similar to fake base station attacks, but more surgically and stealthy. In [10], AdaptOver is used to enhance user tracking by exposing the persistent identifier (IMSI) of the user connecting to the network. This issue is known as *IMSI catcher* or *Stingray* attack. Traditionally, this attack requires setting up a fake base station with a high output power that lures victim UEs in the vicinity to connect to it. LTE is not designed to prevent this attack, but given the visibility of fake base stations, proposals have been made to detect them [3,4,11,14,16,20]. Using AdaptOver, the attacker can defeat techniques relying on detecting a fake base station and can thus expose the IMSI in a more stealthy manner.

In summary, we make the following contributions:

- We develop a reactive and protocol-aware attack, enabling the injection of downlink messages on the radio link at any point in time and on any communication layer of LTE.
- We demonstrate the impact of AdaptOver by implementing DoS attacks that are stealthier than prior attacks, which relied on the use of a fake base station, and more persistent (12h) than existing overshadowing attacks which caused connection loss of only up to 9 minutes.
- Finally, we discuss countermeasures that baseband manufacturers could implement to thwart the proposed DoS attacks.

The rest of the paper is organized as follows. In Section 2 we present the necessary background on LTE and previous work on signal overshadowing. In Section 3 we present our approach and showcase the Service Reject attack. Section 4 presents all ported attacks to AdaptOver and is followed by the evaluation in Section 5. Finally, countermeasures are discussed in Section 6.

# 2 Background: LTE and Overshadowing

The following section presents the background knowledge required to understand the design of the AdaptOver attack.

Readers familiar with the internals of LTE may skip this part.

#### 2.1 LTE

An LTE network consists of 2 main components, the core network, called Evolved Packet Core (EPC), and the Radio Access Network (RAN), which includes a set of base stations called Evolved Node B (eNodeB) and user equipment (UE) devices, such as smartphones, routers, or Internet-of-Things (IoT) devices.

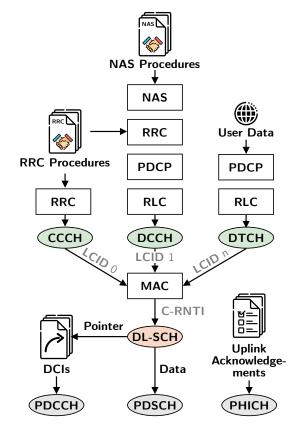


Figure 1: Overview over Downlink Channels and Layers

The wireless signal of LTE is structured as follows. In the time domain, the LTE signal consists of frames of 10ms duration, with each frame subdivided into 10 subframes of 1ms duration. Each subframe in LTE has the same basic structure and is independent from other subframes. In the frequency domain, the LTE signal is split into 72 to 1200 orthogonally placed sub-carriers, depending on the configured bandwidth of the cell.

The individual units of data to be transported are then modulated onto the allocated subcarriers and transformed using IFFT into the time domain. Allocations are defined with respect to the so-called resource grid, with the y-axis corresponding to the frequency domain sub-carriers and the x-axis to time domain slots. Each area of the (sub) grid is dedicated to a specific function. In this paper, we focus on the downlink.

In Figure 1, the bottom ovals (PDCCH, PDSCH, and PHICH) are downlink channels that have a designated area on the resource grid. How these channels are used to transport user and control data is explained in the next section.

#### 2.1.1 Channels and Layers

Physical Downlink Control Channel (PDCCH) At the beginning of a subframe is the Physical Downlink Control Channel (PDCCH). It contains Downlink Control Information (DCI) messages, which have two main purposes. First, they serve as metadata for the data carried in the rest of the subframe, indicating to which UE the data is destined, where the data is located in the resource grid, and how it is encoded. Second, DCI messages allocate uplink resources to a UE, specifying that a UE may send data at a specific time and frequency range on the uplink channel.

(Physical) Downlink Shared Channel (PDSCH / DL-SCH) Data encapsulated by the Medium Access Control (MAC) layer arrive in the form of transport blocks at the Downlink Shared Channel (DL-SCH). There, they are processed together with the Physical Downlink Shared Channel (PDSCH) processing chain and then placed on the resource grid. Any parameters used in processing, such as modulation scheme, precoding, or layer mapping, are put into a DCI message and sent alongside.

Radio Network Temporary Identifier (RNTI) Using Radio Network Temporary Identifiers (RNTIs), it is possible to carry data for different UEs in the same subframe. UE-specific messages are marked with their cell unique identifier called C-RNTI, while broadcast configuration messages use special RNTIs called System Information RNTI (SI-RNTI).

**Medium Access Control (MAC)** Within a UE, user data and control messages related to ongoing procedures are multiplexed and placed together on the DL-SCH. To distinguish different procedures, the MAC layer assigns each channel a logical channel ID (LCID).

**Physical HARQ Indicator Channel (PHICH)** 4 subframes after an uplink allocation has been sent via a DCI message, the data is sent by the UE. Another 4 subframes later, it is acknowledged via a 1-bit Hybrid Automatic Repeat Request (HARQ) message carried on the downlink on the PHICH. This serves as a low latency mechanism for detecting and correcting transmission errors on the uplink.

**Radio Resource Control (RRC)** RRC messages are passed between a UE and a base station and are used for connection management between the UE and the base station. In the connection establishment procedure (shown in

Section 2.1.2), the RRC Connection Request and RRC Connection Setup messages are carried on the Common Control Channel (CCCH). In the RRC Connection Setup message, the Dedicated Control Channel (DCCH) is configured, which carries all further RRC messages. When the connection has been established, user data is carried on the Dedicated Traffic Channel (DTCH).

Non-access Stratum (NAS) Messages that are exchanged between a UE and core network components, such as the Mobility Management Entity (MME) during connection establishment (see section 2.1.2) are carried on the NAS layer, where they are optionally encrypted and/or integrity protected. They are wrapped in an RRC message, which may be otherwise empty or contain a separate RRC message. The MME's purpose is to distribute paging messages, manage handovers and handle attachment and service procedures.

Radio Link Control (RLC) The RLC layer is used for segmentation, reliable transport, and in-order transmission. In the down- and uplink, each RLC segment sent is acknowledged. This is done by including the highest sequence number of the segment that was received successfully. Such acknowledgments can be carried on data segments as well.

**Packet Data Convergence (PDCP)** PDCP bears the responsibility for compression as well as security functions, such as integrity protection and encryption. Both integrity and encryption are optional for every message and may be enabled in the PDCP header.

#### 2.1.2 Procedures

When a UE attaches to a network, it executes the procedure as shown in Figure 2. Regardless if it has been merely idle, it first executes the base station attachment. After this attachment is done, the UE continues to start the core network attachment procedure, which will ultimately grant the UE network or telephony services.

Base Station Attachment. After acquiring the cell configuration by decoding the System Information Block (SIB) messages sent on the Broadcast Control Channel (BCCH), the UE requests an uplink allocation on the Physical Random Access Channel (PRACH) with a PRACH Preamble. The eNodeB allocates a RNTI and the required uplink resources and signals this to the UE with the PRACH Response. The UE then initiates an RRC Connection Request, and receives the RRC Connection Setup message containing dedicated configuration for the UE. Finally, the UE confirms the connection using the RRC Connection Setup Complete message.

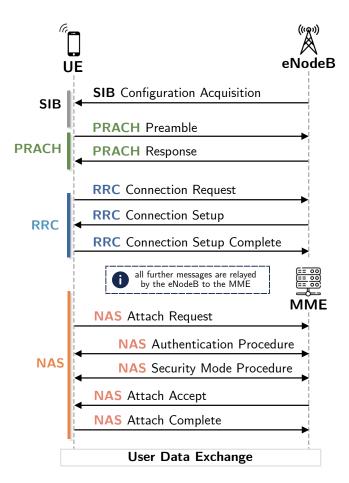


Figure 2: Full Attachment Procedure of a UE to a network

Core Network Attachment. After having established a connection with a base station using the RRC procedure described above, the UE starts the NAS attachment procedure. First, the UE sends its identifier with the NAS Attach Request to the MME. The MME and the UE will then perform the authentication and key exchange (AKA) procedure. The security of the channel is then activated in the security mode procedure. Finally, they conclude the successful attachment with a NAS Attach Accept and Complete message. Whenever the UE and the network do not exchange data for some time, the UE enters idle mode, detaching from the network. It may resume the connection by repeating the base station attachment procedure, followed by a NAS service request procedure, which is shown later in the context of an attack in Figure 3.

### 2.2 SigOver Attack

The authors of [21] showed a novel attack method called SigOver that replaces parts of the legitimate signal of an LTE base station (eNodeB) with one controlled by an attacker, using only commercially available software-defined radios

(SDR). They accomplished this by overshadowing parts of the signal with their attacker signal that achieves a higher power at the UE. Although these two signals collide, the stronger signal will still be decoded. This phenomena is called the *capture effect*.

Time & Frequency Synchronization. To be able to overshadow a signal, the attacker must send the signal with the correct timing and frequency alignment. To achieve this, the attacker first measures the offset between the generated frequency of the oscillator in the SDR and the real signal of the eNodeB. Then, he adjusts the frequency of the output signal accordingly, compensating for any inaccuracies of the internal oscillator of the SDR. To precisely align the timing of the signal, the attacker decodes the synchronization signals of the eNodeB (PSS and SSS) and aligns them with the output of the SDR. From these synchronization signals, the attacker may determine the starting point of the subframes the attacker aims to overshadow. Because the SDR used in the attack introduces a constant transmission delay between 5-20 microseconds (depending on the sampling rate), the attacker needs to instruct the SDR to start its transmission earlier to compensate the delay. However, this delay is constant and depending on the hardware model of the SDR, and can thus be measured and configured statically.

**PDSCH Overshadowing.** SigOver attacks the Physical Downlink Shared Channel (PDSCH). To overshadow the PDSCH channel, the PCFICH, PDCCH channel and reference signals that are used for channel estimation must be overshadowed as well, as they are all necessary to decode the PDSCH channel. With SigOver, those signals are generated by the attacker and sent along with the subframe.

Attacks enabled by SigOver. On the PDSCH channel, the cell broadcasts configuration messages in the form of System Information Blocks (SIB), and paging messages that are used to notify the UE of any incoming data or call. SIB paging messages are sent on a fixed schedule, with the SIB2 being sent at the 5th subframe of every 2nd frame and paging messages at the 9th subframe. SigOver showed that it is possible to achieve DoS of a single cell by enabling cell barring in the SIB2, with persistence of around 9 minutes after attack transmission is turned off. Furthermore, the researchers achieved selective DoS of a targeted UE by injecting paging messages containing the IMSI, albeit with no persistence, as the UE will immediately try to re-attach. Furthermore, they managed to perform downgrading via paging messages that are designed to force the UE to connect to a 3G network.

**Limitations of SigOver.** The design of SigOver allows the overshadowing only to be applied to channels with predictable scheduling, such as the Broadcast Control Channel (BCCH)

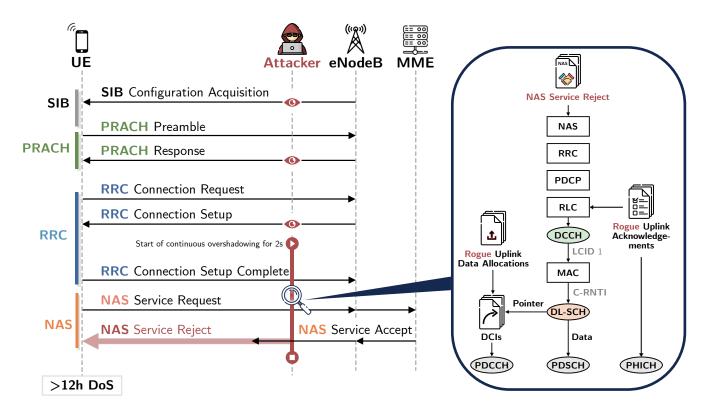


Figure 3: AdaptOver explained using Service Reject Attack. The attacker listens for the RRC Connection Setup message to start the attack. The attacker sends the NAS Service Reject on every subframe for 2 seconds, overshadowing the Service Accept with a Service Reject, causing a >12h DoS at the UE. During the attack, the attacker includes rogue uplink allocations and acknowledgments to allow the UE to send the NAS Service Request.

and the Paging Control Channel (PCCH). Therefore, SigOver can only be applied to paging and configuration acquisition procedures, leading to DoS that is limited to a single cell and results in a UE disconnecting for only 9 minutes. In reality, however, the UE is rarely in a situation with only one cell in reach, so it immediately switches over to the next available cell, requiring the attacker to mount the attack on all base stations in the vicinity of the victim as otherwise the DoS attack does not impact a UE in a real-world setting. Albeit still stealthier than a fake basestation attack, overshadowing signals on multiple downlink streams requires coordination and increases hardware costs as well as detectability.

## 3 Adaptive Signal Overshadowing

AdaptOver is reactive and capable of modifying message flows and procedures between the UE and all LTE components, such as the base station or core network services. AdaptOver is capable of overshadowing any downlink channel with arbitrary data as well as decoding downlink channels, making it able to react to any downlink traffic.

We show that DoS attacks on LTE that required a fake base station can be ported to AdaptOver, enabling persistent (>12h long) DoS attacks at any time the phone reboots, toggles airplane mode, or, more frequently, re-establishes service after being idle for a while. Finally, we show how AdaptOver has been applied in [10] to create an IMSI catcher that is stealthier than existing traditional IMSI catchers relying on fake base stations.

Attacker model and assumptions. We consider the following attacker: (i) No knowledge of any keys and no physical access to components of the operator or the user equipment (UE). (ii) Capability to receive the downlink communication from the base station to the UE; no ability to decipher encrypted messages. (iii) Capability to send LTE signals to the UE such that the power of the attacker's signal at the UE is 3dB higher than the power of the signal transmitted by the base station. This can be achieved either by adjusting the transmission power or the location of the attacker's device.

We will show that these attacker capabilities are realistic and sufficient to add, alter and remove messages originating not only from the eNodeB, but also from core network components, such as the Mobility Management Entity (MME).

We illustrate the capabilities of AdaptOver in detail through

an example of the Service Reject Attack, which targets a UE while it re-establishes service after being idle. We discuss variants of this attack in Section 4.

### 3.1 Overview and Service Reject Attack

Service Request Procedure. Whenever a UE does not need to communicate, it may enter idle-mode to conserve energy, when directed to do so by the eNodeB. Exiting the idle mode is done by re-attaching to a base station with the PRACH and RRC procedure, followed by a Service Request to the MME, which is answered by a Service Accept message. According to [1,6], a UE is sent to idle mode after spending at most 60s without traffic. Our measurements in real networks of three different mobile operators corroborated this observation. Analysis of different traffic patterns done in [1] finds that a typical UE with light usage will enter a service request procedure approximately every 6mins. In theory, this can be shortened even further by forcefully terminating an active connection through jamming for an active connection, or by injecting a paging message with the TMSI or IMSI of the victim. This is, however, not required for AdaptOver to work and comes at the expense of higher detectability.

Service Reject Attack. The goal of our Service Reject attack is to overshadow the Service Accept that is sent by the MME and replace it with a Service Reject message with cause value 8 (i.e. *EPS services and non-EPS services not allowed*), as illustrated in Figure 3. According to Section 5.6.1.5 of 3GPP TS 24.301 [2], this will result in the UE considering the SIM card as invalid and unless the user retries, the UE will back off by more than 12 hours without trying to attach to the network. We validate the effect of the attack on different phones in Section 5.2. We show, for the first time, that such an attack can be done by message injection. Until now, such attacks were only shown to work when a UE is connected to an attacker's fake base station.

To schedule and reliably execute the Service Reject Attack, AdaptOver implements the following steps, depicted in Figure 3. First, in order to be able to schedule the injection of the Attack Reject message at a correct time and with the right parameters, AdaptOver implements a downlink decoder, which specifically listens and decodes the messages from the eNodeB as well as the MME. Upon receiving the RRC Connection Setup message, AdaptOver starts continuously injecting Service Reject messages on every subframe for the next 2 seconds. This is fairly conservative, experiments showed that injecting for a short duration of 50ms also sufficed, at a cost of slightly reduced reliability. AdaptOver places these messages on the PDSCH channel, therefore overshadowing all downlink messages sent by the eNodeB to the UE. In Section 3.2, we discuss in detail how our overshadowing implementation improves SigOver.

Main challenges. In LTE, the base station allocates the resource slots within which the UEs may send their data. Without such uplink allocations, no data will be sent by the UEs. If an attacker injects a Service Reject message too early, i.e., before the UE has been able to send a Service Request, the reject message will not be accepted by the UE and the attack will fail. Because AdaptOver temporarily overshadows all downlink messages for the targetted UE, uplink allocations from the eNodeB are lost during the attack.

To rectify this, an attacker could wait until the Service Request has been fully transmitted by the UE and acknowledged by the eNodeB. However, this presents us with two problems: (i) we need a real-time uplink decoder to determine when exactly the uplink transmission is complete, and (ii) the attacker has only very little time to start overshadowing because the response from the MME will usually be transmitted within a few milliseconds. Although in theory these challenges are not impossible to surmount, there is a more straightforward and robust solution implemented by AdaptOver, which can be readily executed on off-the-shelf SDRs.

AdaptOver does not wait until the request is transmitted and acknowledged. Instead, it begins transmission as soon as possible after the RRC Connection Setup is received on the downlink, as presented in Figure 3. Because transmission must begin before the next downlink message, the injection must happen with a latency of at most 8ms. During the attack, besides sending the Service Reject, AdaptOver also injects uplink allocations and acknowledgments, which makes sure that the UE sends its Service Request and thus accepts the Service Reject.

For this injection, we have leveraged components from srsLTE [15] from their eNodeB implementation and adapted them to our needs. We achieve a latency of less than 6ms between receiving a downlink message and starting the overshadowing.

As a side-effect, the uplink allocations sent by AdaptOver are most likely different from the ones sent by the base station. Thus, the base station may not be able to decode the Service Request sent by the UE and will thus not continue with the re-attachment procedure, making the attack even more robust.

## 3.2 AdaptOver Components

The following section goes over all components of AdaptOver and how they interact. (i) The downlink decoder continuously decodes the low- and high-level messages sent by the base station. It is used to inform the time and frequency offset of the overshadowing, to configure the encoding and parameters of the messages, and to trigger the start of the attack. (ii) After the attack is triggered, the Message Encoding component encodes and packages the attack messages such that the UE decodes them properly. (iii-iv) During the attack, control messages are injected continuously that modify the reliable transport mechanisms. This is done so that the victim UE suc-

cessfully transmits its request. Otherwise, it will not accept the attacker's response. (v) Messages are continuously output by placing them on the PDSCH channel, overshadowing the real downlink. This is done by a SigOver-inspired implementation, to which we make some significant improvements.

- (i) **Downlink Decoder.** Decoding data on the downlink is a task every UE has to implement. We repurpose open-source components from srsLTE [15] that already provide synchronization and signal acquisition from the base station. In our implementation, we specifically listen for *PRACH Response* messages from the base station. This message carries the Radio Network Temporary Identifier (RNTI) to the UE, which will identify all further messages on the PDSCH. All further messages on the PDSCH are then decoded independently in parallel for each UE and may serve as a trigger for further actions, such as starting an attack.
- (ii) Message Encoding. We again use components of srsLTE [15] to encode the desired messages from the NAS procedure level down to the physical layer, as shown in Figure 3. Using configuration messages obtained by our downlink decoder (i), we configure the layers the message needs to pass through.
- (iii) Uplink Allocation. In LTE, the base station allocates the UEs resource slots when they may send their data. Without such uplink allocations, no data can be sent by the UE, and a subsequent Service Reject would not be processed. As the original allocations from the eNodeB are overshadowed by the attacker, the attacker needs to send those allocations as well. We have leveraged components from srsLTE and send the uplink allocations at the first subframe of every frame, as indicated in Figure 4. We use an internal buffer to store the sent allocations, as the HARQ acknowledgments (which are sent 8 subframes later) depend on it.

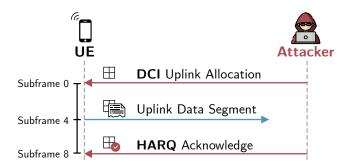


Figure 4: In every frame, a DCI Uplink Allocation and its corresponding HARQ Acknowledgement are sent at specific subframes. The UE transmits data on subframe 4, but it is not received by anyone, because the attacker does not listen to it and the original eNodeB most likely did not send the same allocation.

(iv) Reliable Transport Modification. The UE needs to have its request fully transmitted and acknowledged before it accepts a response to it. Because the attacker also overshadows acknowledgments for the uplink data, the attacker needs to include acknowledgments in the overshadowing. In LTE, acknowledgments are carried in 2 distinct layers; MAC and RLC.

(RLC) The RLC layer uses acknowledgments with sequence numbers in both up and downlink directions. It may also split messages into multiple segments, which are then carried over multiple subframes. To acknowledge an Attach Request, an acknowledgment must therefore be sent for the highest segment number of the complete request. As our attacker model does not assume a decoding capability of the uplink, the attacker does not know this highest segment number but can limit it to a narrow range. At the start of each connection, the RLC sequence numbers start at 0. The attacker sends acknowledgments for all sequence numbers in increasing order from the interval  $[0, \Delta]$ , with  $\Delta$  as the maximum amount of segments the message might be split up in. In our experiments, we discovered that  $\Delta \leq 8$  suffices for all tested smartphone models. As shown in Figure 5, during the attack, we increment the sequence number by one every 250ms and send the RLC acknowledge at every subframe, together with the NAS Service Reject message.

(MAC) In the MAC layer, acknowledgments for the previous transport block sent by the UE are carried in the Physical Channel Hybrid ARQ Indicator Channel (PHICH) exactly 8 subframes after the uplink allocation. As shown in Figure 4, our attacker sends the acknowledgments at every frame on subframe 8, after having sent an uplink allocation in the first subframe. HARQ acknowledgments carry a 1-bit ACK/NACK with no sequence number and depend on the location of the corresponding uplink acknowledgment in the LTE resource grid, which is looked up in the buffer created in (iii).

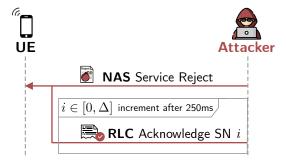


Figure 5: At every subframe, an RLC Acknowledge is sent together with the NAS Service Reject attack payload. The highest sequence number is not known and guessed by increasing the sequence number by one every 250ms or after 250 subframes.

(v) Overshadowing. Overshadowing LTE requires precise frequency and time synchronization, which has been explored by SigOver. AdaptOver makes several key improvements. First, messages can be sent at every subframe, as opposed to only on a single subframe. Second, high-level messages are encoded less than 1ms before transmitting them to the radio device, which enables a highly reactive system. Third, multiple messages may be transmitted on the PDSCH channel at the same time, enabling parallel attacks on multiple victim UEs. Finally, each PDSCH channel to the UE is modulated adaptively according to the configuration messages decoded from the downlink, just before starting the attack. These configuration messages include physical channel parameters that are dedicated to each UE. While overshadowing the PDSCH, both SigOver and AdaptOver must also overshadow the PD-CCH to carry control messages. As a side-effect, any legitimate control messages destined to the UE, including uplink allocations, are overshadowed as well.

## 4 Other Attacks Based on AdaptOver

In this section, we present different attacks that use the capabilities of AdaptOver. We focus on DoS attacks that target the availability of the LTE system with high persistence, very low power requirements, and detectability. To achieve this goal, we are, similarly to the presented Service Reject attack in Section 3.1, modifying a response from the MME on the wireless channel by overshadowing the response. Other than the specific message being injected during the attack, the procedure and components of AdaptOver are identical to the presented Service Reject attack.

We provide a summary of an IMSI catcher attack based on AdaptOver, introduced in [10].

### 4.1 Attach Reject

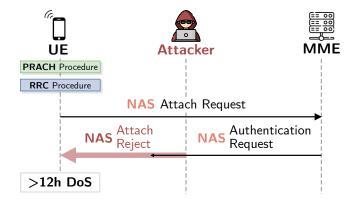


Figure 6: Attach Reject Attack - The attacker replaces the NAS Authentication Request with a NAS Attach Reject, causing a DoS of more than 12 hours at the UE.

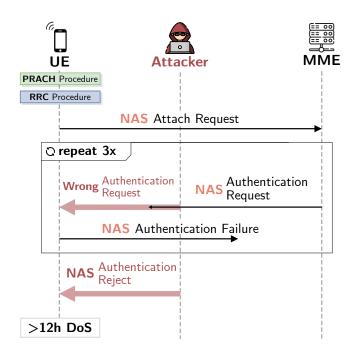


Figure 7: Authentication Reject Attack - After the Authentication Request is sent 3 times, a NAS Authentication Reject message is injected by the attacker, causing a DoS of more than 12 hours at the UE.

As shown in Figure 6, the UE first sends an Attach Request message to the MME. Using AdaptOver, the attacker replaces the benign response of the MME on the wireless channel with an Attach Reject message. This causes the UE to consider the inserted SIM as invalid and thus a DoS at the UE. When not interacted with, the UE will not re-connect for more than 12 hours. We executed this attack with 20 different smartphone models from 10 different vendors and observed the same result for all of them. Refer to Section 5.3 for the detailed experimental procedure and results.

### 4.2 Authentication Reject Attack

In Figure 7, the procedure flow that leads to an authentication reject is shown. It induces a failure to authenticate the MME at the UE by sending a wrong Authentication Request three times. Afterwards, according to 3GPP TS 24.301 [2], the network may terminate the procedure with an Authentication Reject message sent to the UE. We evaluated the effect of the authentication reject message in the UEs by implementing the attack with AdaptOver. We observed that for almost all smartphone models tested, after retrying for at most 2 times, no further re-connection attempt has been logged for more than 12 hours after the attack stopped.

The attack can also be executed by waiting until the UE has sent the (correct) Authentication Response, but by this time the UE has installed the correct session keys, which might help

identify our rogue Authentication Reject. Therefore, attacking the procedure as shown is preferable.

**Limitations.** Although we demonstrate the high impact of the Authentication Reject attack, the practical applicability of it remains rather low, because the same procedure can be attacked one step earlier with the Attach Reject attack demonstrated in section 4.1 and requires considerably more engineering.

## 4.3 IMSI Catcher based on AdaptOver

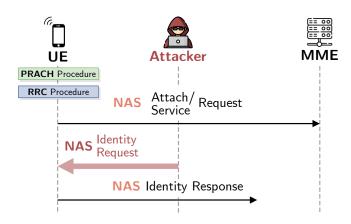


Figure 8: IMSI Catcher built using an Uplink Sniffer and AdaptOver. After the attacker records a Service or Attach Request that is sent by the victim UE, the attacker injects the NAS Identification Request message, causing the UE to disclose its IMSI in plaintext.

IMSI catchers [8] enable an attacker to set up a fake base station, to which UEs connect and leak their IMSI (persistent identifiers). Because of the design of LTE, preventing IMSI catchers fully is not feasible. 5G addresses this attack vector, however, downgrade attacks remain a major issue until LTE is fully phased out.

Related work [10] shows that an IMSI catcher can be implemented by combining AdaptOver with a custom made LTE uplink sniffer and defeat existing IMSI catcher detection techniques. This is because the detection of IMSI catchers mainly relies on recognizing the presence of fake base stations [3,4,11,14,16,20]. We briefly summarize it below and illustrate it in Figure 8.

In the attack, the adversary injects using AdaptOver an Identity Request message after the base station sent the RRC Connection Setup message. No matter if the UE has sent an Attach or Service Request message, as per the 3GPP TS 24.301 [2], the UE will respond with its IMSI in plain text. This response is then captured by the uplink sniffer of the attacker, as shown in [10].

### 5 Experimental Evaluation

In this section, we first present our experimental hardware setup, and will then show our evaluation of our three DoS attacks implemented in AdaptOver. We summarize the results for all three DoS attacks in Table 1.

Finally, we present our evaluation about the power requirements and range of AdaptOver.

## 5.1 Hardware Setup



Figure 9: Experimental Setup

To evaluate our attacks in a realistic setting, we set up a private LTE network in a shielded environment, using the commercially available Amarisoft Callbox Mini as the base station and core network. To execute our attacks, we used a Lenovo T490 notebook, connected to an Ettus Research USRP B210 software-defined radio. To aid with debugging, we used a Lenovo X230T notebook to decode the downlink using our implementation, srsUE from srsLTE [15] to act as a UE, and finally installed QCSuper [13] on some of the phones to validate the reception of the messages.

### 5.2 Service Reject Attack Evaluation

We carried out the service reject attack, described in section 3.1, in a shielded environment using our AdaptOver implementation. To that end, we first connected the smartphones to the network regularly and waited until they entered idle mode. We then started the attack and interacted with the smartphones, such that they may exit the idle mode and enter the service request procedure, which we then attacked with our AdaptOver attack, sending a Service Reject message.

**Results.** Only the iPhone X reconnected by itself after nearly 10h. All other tested smartphones did not re-connect within 12 hours. For most of the models, either toggling flight mode or restarting was enough to re-establish a connection. For the LG Nexus 5X, it required the re-insertion of the SIM

	Service Reject			Atta	Attach Reject			Authentication Reject		
Phone	Duration <sup>1</sup>	Action <sup>2</sup>	$GUI^3$	Duration <sup>1</sup>	Action <sup>2</sup>	$GUI^3$	Duration <sup>1</sup>	Action <sup>2</sup>	GUI <sup>3</sup>	
Pixel 2	>12h	R		> 12h	R		> 12h	R		
Pixel 3a	>12h	T		> 12h	T		> 12h	T		
Huawei P20 Pro	>12h	T		> 12h	T		> 12h	T		
Huawei P30	>12h	T		> 12h	T		>12h	T		
Huawei P30 Lite	>12h	T		> 12h	T		> 12h	T		
Samsung Galaxy A8	>12h	T		> 12h	T		> 12h	T		
Samsung Galaxy S10	>12h	T		> 12h	T		> 12h	T		
LG Nexus 5X	>12h	S		> 12h	R		> 12h	R		
iPhone 6S	>12h	R		> 12h	R		> 12h	R		
iPhone 7	>12h	T		> 12h	T		> 12h	T		
iPhone 8	>12h	T		> 12h	T		> 12h	T		
iPhone 11	>12h	T		> 12h	T		> 12h	T		
iPhone 11 Pro	>12h	T		> 12h	T		> 12h	T		
iPhone X	9.78h	T		> 12h	T		> 12h	T		
HTC U12+	>12h	T		> 12h	T		> 12h	T		
OnePlus 7T Pro	>12h	T		> 12h	T		> 12h	T		
Xiaomi Mi 9	>12h	T		> 12h	T		> 12h	T		
Xiaomi Mi Mix 3 5G	>12h	T		> 12h	T		> 12h	T		

<sup>&</sup>lt;sup>1</sup> Duration until the UE re-established a connection by itself

Table 1: Attack Results for DoS Attack carried out by AdaptOver

card to restore connectivity. Furthermore, some of the smart-phones displayed a message on the phone, indicating a problem with the SIM card. A selection of those messages is shown in Figure 10, with similar messages shown on the Huawei P30, Samsung Galaxy S10, and LG Nexus 5X.

### 5.3 Attach Reject Attack Evaluation

Using the design from section 3, we implemented the Attach Reject attack using AdaptOver. We first put the UEs in flight mode, after which we started the attack, and then turned flight mode off for each UE, triggering an attachment procedure and therefore our attack. After a few minutes, we turned off the attack. Using the logs from the Amarisoft Callbox Mini, we verified that there were no further connection attempts from the UE since the first Attach Reject.

**Results.** None of the phones tried to re-establish a connection to the network within 12 hours. In Table 1, the results are listed for each tested smartphone.

### 5.4 Authentication Reject Attack Evaluation

To evaluate the effect of our Authentication Reject attack, we implemented the attack in AdaptOver. We first put the UEs in flight mode, after which we started the attack, and then turned flight mode off for each UE, triggering an attachment procedure and therefore our attack. After each phone was subjected to the attack, the attacker was turned off and the phones left alone.

**Results.** All tested phones did not re-connect within 12 hours. Table 1 summarizes the results, including the remedial actions necessary. For the Huawei P30, it was necessary to send the Authentication Reject message twice for the attack to succeed, as it replied to the first Authentication Reject again with an Authentication Failure.

### 5.5 Power Requirements

To evaluate the required power for an attack to work, we executed the attack in a shielded environment, with the attacker and the eNodeB both at exactly 1m distance from the

<sup>&</sup>lt;sup>2</sup> Action that will re-connect the phone immediately, **T**: Toggle flight mode, **R**: Restart phone, **S**: Reinsert SIM Card

<sup>&</sup>lt;sup>3</sup> Whether an indicator on the GUI is present

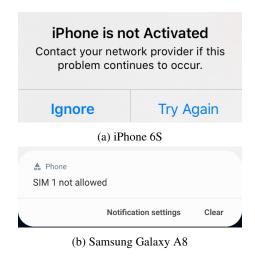


Figure 10: GUI indicators of smartphones subjected to the Service Reject attack

UE. Then, we changed the output gain of the attacker and measured how many overshadowed messages were decoded correctly from the attacker vs how many were from the legitimate eNodeB. Messages that could not be decoded at all were discarded. Then, we connected the output of both eNodeB and attacker to a Keysight oscilloscope and measured the power difference in dB. Although we found that a relative power advantage (J/S) of 1.8dB is sufficient to achieve a 100% attack success rate, which is an improvement from [21], this could be due to differences in the experimental setups. Table 2 shows the measurements of J/S and the corresponding success rate. Both the standard-deviation  $(\sigma_{J/S})$  and the mean  $(\mu_{J/S})$  are listed.

$\mu_{J/S}$	$\sigma_{J/S}$	Success Rate		
-2.049 dB	0.627	0%		
-1.1202 dB	0.675	1.325%		
-0.117 dB	0.665	30.625%		
0.639 dB	0.619	96.825%		
1.870 dB	0.641	100%		
2.559 dB	0.733	100%		

Table 2: Summary of Overshadowing Success Rate and Resulting J/S

**Resulting Attack Range.** Based on the 3dB number, we can establish the maximum distance  $d_{Attacker}$  of the attacker to the UE in relation to the distance from the UE to the base station  $d_{\leftrightarrow}$  and the output power of the attacker  $P_{Attacker}$  and the base station  $P_{eNodeB}$ . Assuming a free space path loss model, we get:

$$d_{Attacker} \le d_{\leftrightarrow} \cdot 10 \left( \frac{P_{Attacker} - P_{eNodeB} - 3dB}{20} \right) \tag{1}$$

Due to regulations, testing this outside a shielded environment is not feasible. If we conservatively assume a transmit power, including any antenna gains, of 40dBm for the eNodeB and 20dBm for the attacker, we can get an idea of how large the attack radius is, as shown in Table 3.

$d_{\leftrightarrow}$	<b>Downlink</b> max d <sub>Attacker</sub>
100m	7.1m
500m	35.4m
1km	70.8m

Table 3: Estimated Attack Range for an attacker transmit power of 20dB. The basestation emits its downlink signal with a power of 40dB.  $d_{\leftrightarrow}$  denotes distance between UE and basetation. max  $d_{Attacker}$  is the distance between attacker and victim UE.

#### 6 Countermeasures

In the following section, we're discussing possible countermeasures to the presented AdaptOver DoS attacks and how to implement them.

#### 6.1 Retry Mechanism

Guaranteeing availability in LTE is not possible, as the wireless channel can always be sufficiently disturbed such that communication is impossible. However, this requires a high output power and constant transmission of the attacker, while our attacks induced a persistent denial-of-service with comparatively low power. However, our attacks were only successful because the smartphones did not try to re-establish a connection, even after several hours.

Our recommendation to the baseband developers is thus to retry establishing a connection more often, no matter the cause of failure. This will force the attacker to attack its victim continuously, requiring a larger time and resource investment. Ideally, the cost and effectiveness of an attacker deploying AdaptOver should be similar to a regular noise jamming attack. The downside to this approach is that the retry requests of UEs that do not have a legitimate reason to connect to the network will increase the load on the core network with their continued attempts. To balance these opposing needs, we propose implementing the retry mechanism as an exponential back-off, spacing retries to avoid congestion on the core network.

### 6.2 Detection

Detecting the AdaptOver attacks on lower layers is not difficult, as we are continuously overshadowing the downlink with identical information to blank out any legitimate downlink traffic, presenting a highly identifiable characteristic. On a higher layer, separating a legitimate rejection from a bogus one could be possible by identifying the absence of a message authentication code. In [5], Echeverria et al. tried to identify an attach, service or authentication reject attack originating from a fake base station, but other than the presence of the reject message, they could not identify any characteristic that would clearly separate the attack from a legitimate rejection.

### **6.3** Integrity Protection

When requiring integrity of messages between participants, a message authentication code (MAC) is added to the message, proving to the recipient that it has not been tampered with. None of the messages we sent contained such a valid MAC, as our attacker model excluded the attacker's knowledge of the shared key between UE and the operator. However, our attacks succeeded nonetheless. The technical specification of 3GPP [2] requires that non-integrity protected messages should not be accepted by the UE after it has established an authenticated session. Clearly, this was not implemented correctly, but can easily be corrected with the retry measure proposed in section 6.1.

### 7 Related Work

Fake Base Station Attack Detection. Fake base station attacks require a considerably larger power output as an overshadowing attack, as shown by SigOver [21]. Due to their high power output and the requirement to continuously broadcast their configuration, fake base station attacks are highly detectable, as has been explored by numerous works [3, 4, 11, 14, 16, 20]. In these works, the authors detect fake base stations due to their unusual broadcast configuration, location, or other indicators. In [5], the authors do not use lower layer indicators to detect the presence of a fake base station, but rather rely on the protocol trace of the interaction with the fake base station.

Fake Base Station Attack Impact. Despite their high detectability, fake base station attacks are of high impact and have been shown to be useful for both DoS and MITM attacks. In [17, 18], the authors managed to manipulate regular user traffic, using a fake base station as a MITM. In [9], the authors investigated the implementation of multiple real-world MMEs, uncovering many implementation defects of operators leading to DoS and SMS phishing. In this paper, we have focused on denial-of-service attacks enabled by the 3GPP standard, and thus used NAS reject attacks. The principle of

these NAS authentication, attach, and service reject attacks have been covered in [7, 8, 19], all using a fake base station.

Downlink Overshadowing. Signal overshadowing in LTE has first been discussed by SigOver [21]. In SigOver, the authors implemented a DoS attack using IMSI paging and SIB overshadowing. They further implement a signalling storm, network downgrade and coarse-grained tracking attack against LTE. Our work significantly builds and improves upon their work, enabling interactive and adaptive attacks on higher layer procedures, which result in more persistent DoS attacks. This work has been used in [10] to create a highly covert IMSI extractor, enabling persistent tracking over an abritrarily long period of time.

#### 8 Conclusion

In this paper, we developed and implemented a new attack method against LTE called AdaptOver. We implemented three DoS attack variants capable of denying LTE service of all tested current smartphones across multiple base stations over more than 12 hours. We proposed simple and effective countermeasures to the DoS attacks, which are implementable by baseband vendors without any changes to the standard.

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