

Towards Resilient 5G: Lessons Learned from Experimental Evaluations of LTE Uplink Jamming

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Abstract—Energy, water, health, transportation and emergency services act as backbones for our society. Aiming at high degrees of efficiency, these systems are increasingly automated, depending on communication systems. However, this makes these Critical Infrastructures prone to cyber attacks, resulting in data leaks, reduced performance or even total system failure. Beyond a survey of existing vulnerabilities, we provide an experimental evaluation of targeted uplink jamming against Long Term Evolution (LTE)'s air interface. Primarily, our implementations of smart attacks on the LTE Physical Uplink Control Channel (PUCCH), the Physical Uplink Shared Channel (PUSCH) as well as on the radio access procedure are outlined and tested. In exploiting the unencrypted resource assignment process, these attacks are able to target and jam specific UE resources, effectively denying uplink access. Evaluation results reveal the criticality of such attacks, severely destabilizing Critical Infrastructures, while minimizing attacker exposure. Finally we derive possible mitigations and recommendations for 5G stakeholders, which serve to improve the robustness of mission critical communications and enable the design of resilient next generation mobile networks.

I. INTRODUCTION

Nowadays, societies heavily depend on services provided by so-called Critical Infrastructures (CIs), including energy, water, health, transportation, public safety and communication systems. To improve efficiency and management of such infrastructures, comprehensive automation is pursued, necessitating an integration of Information and Communication Technology (ICT). Due to the lengthy and costly deployment of dedicated wired networks, harnessing (public) mobile communication technologies is widely regarded a suitable approach. Yet, ubiquitous connectivity eases access not only for authorized users, but also for malicious third parties. Cyber attacks on CI communication networks can severely degrade functionality and system stability. An attack, e.g. aimed at the power grid's ICT infrastructure, could trigger events leading to outages or blackouts [1]. Two major ways of disrupting a CI's wireless communication can be distinguished. On one side, so-called barrage jammers may be employed, which essentially obscure all user signals in a certain frequency range by using wideband noise. Such jammers are very effective in disrupting services and straightforward to implement. Yet, they can be detected and located with low effort, allowing authorities to stop the attack and hold attackers accountable. On the other side, smart jammers exploit inherent system properties such as protocol flaws, requiring less power. Thus, highly precise, covert attacks are enabled, only affecting target devices instead of an entire area or frequency band. Subsequently, attacks

cannot be recognized as easily. However, this class of jammers requires more advanced technological skills and knowledge. Hence, smart jammers are of major interest for groups with sufficient resources and technical capacities, which want to perform attacks, while staying hidden. Examples include hostile intelligence services or well-funded terrorist groups. Employed efficiently, smart jammers provide the means to secretly undermine critical, public infrastructures which depend on wireless communications.

It has to be emphasized that this publication is not intended as guideline for such groups, but rather serves to indicate vulnerabilities and derive mitigation strategies. Therefore, the main contributions of this paper can be summarized as below:

- General overview of possible attack vectors against current cellular mobile communication networks,
- Design of a smart jammer for issuing attacks on the Long Term Evolution (LTE) Physical Uplink Control Channel (PUCCH) and Physical Uplink Shared Channel (PUSCH), including corresponding evaluation results,
- Recommendations for improving CI communication systems, focusing on 5G developments.

The remainder of this paper is structured as follows: Section II provides a survey of key jammer properties and known attacks. It is followed by an overview of related work (Sec. III). Next, we introduce our smart uplink jammer (Sec. IV) and present evaluation results (Sec. V). Recommendations for increased resiliency are given in Section VI. Finally, Section VII provides a summary and an outlook on future work.

II. JAMMER PROPERTIES, POSSIBLE ATTACKS AND MITIGATIONS

This section provides an overview of key jammer properties and possible attack vectors in LTE infrastructures.

A. Jammer Properties

To disrupt radio communications, barrage jammers allow configuration of the used power level, bandwidth and duty cycle. Higher power levels increase the affected area and boost the impact on user signals, yet make the attacker more vulnerable to detection. Duty cycles indicate periods, in which the jammer is active. In contrast to barrage jammers, which are limited to the above mentioned properties, smart jammers provide the following additional parameters:

Synchronization: Synchronizing jamming to target signals maximizes an attack's impact, while minimizing visibility.

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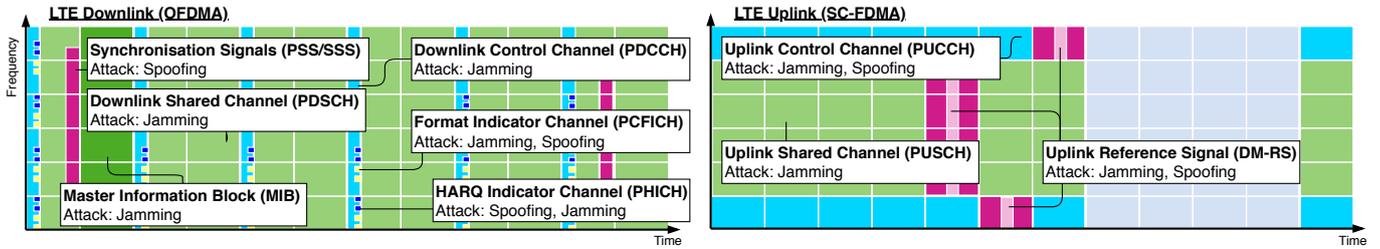


Figure 1: Overview of selected attack vectors, targeting the LTE down- and uplink

Eavesdropping: For the same reasons, gathering information about a target system before initiating an attack is beneficial. In LTE, this task is facilitated by the lack of Media Access Control (MAC) and Radio Link Control (RLC) encryption. Thus, subscribers may be de-anonymized [2] or User Equipment (UE) locations can be tracked [3]. In case of stationary UEs, e.g. in Smart Grids, a high level of channel awareness could be obtained and utilized by the attacker.

Placement: Due to their small form factor, smart jammers allow for arbitrary placement. Preferable locations may be close to the UE for downlink or near the evolved Node B (eNB) for uplink jamming. Thus, lower power levels can be employed, minimizing attack visibility. In contrast, high powered barrage jammers may be of significant size.

Directionality: Smart jammers may utilize highly directional antennas, focusing on specific targets. This increases range while decreasing power consumption, visibility and size.

B. Attack Vectors

LTE Radio Access Networks (RANs) can be attacked at the physical layer, physical channel and protocol level. Examples of each category are given below, summarized by Figure 1.

1) Physical Layer Attacks:

Cyclic Prefix Attack: As a key component of the Orthogonal Frequency-Division Multiplexing (OFDM) signal, the cyclic prefix prevents inter symbol interference and enables frequency domain equalization. To degrade radio performance, noise can be emitted during cyclic prefix transmission. Such an attack is considered highly effective as no specific mitigation is known, but it requires near perfect knowledge of the channel.

Synchronization Attack: In the course of a synchronization attack, the UE is prevented from receiving the Primary Synchronization Signal (PSS)/Demodulation Reference Signal (DMRS) (down-/uplink) by shifting the symbol timing peak. Here, the main challenge is locking onto the target signal.

Reference Signal Attack: Reference signal (pilot) attacks (Cell Specific Reference Signal (CRS)/DMRS) cause faulty channel estimations. Thereby, diverging conditions are assumed, limiting physical channel throughput. As downlink pilot signals are sparse, an attack requires a minimal duty cycle and transmission power. However, precise synchronization based on an analysis of channel conditions is required.

2) Physical Channel Attacks:

Physical Control Format Indicator Channel (PCFICH) Jamming: This method corrupts the channel format indicator. First, the jammer synchronizes to the cell, to receive and decode the Master Information Block (MIB). Next PCFICH elements are calculated and noise or a modulated signal is

transmitted on top of them. If the corrupted Control Format Indicator (CFI) is higher than the actual one, the UE tries to decode non-existent Downlink Control Informations (DCIs). In case the corrupted CFI is lower, the UE overlooks DCIs. For both scenarios, the first subframe slot's Physical Downlink Shared Channel (PDSCH) symbols are expected in the wrong location, causing errors in the corresponding transport blocks.

PDSCH Jamming: The PDSCH carries configuration as well as downlink user data. Hence, it allows targeting one or multiple UEs. Precise synchronization and DCI decoding are required to locate resources of a particular UE.

Paging Jamming: Here PDSCH jamming is modified, by targeting paging channel Resource Blocks (RBs). The channel informs idle UEs of pending downlink data. If respective RBs are jammed, the UE is never notified of transmissions and remains idle. This attack reduces a jammer's duty cycle to predictable paging periods, relaxing DCI decoding requirements.

PUSCH Jamming: The purest version of PUSCH jamming is achieved by using a barrage of white noise on this channel. It is straightforward to implement, enabling Denial of Service (DoS) throughout an entire cell.

PUCCH Jamming: The PUCCH is located at the edge of the uplink bandwidth. Thus, it can be identified and jammed with low effort, affecting many UEs at once. The attack can lead to misinterpretation of received signals as scheduling requests, Hybrid Automatic Repeat Request (HARQ) (negative) acknowledgments, Channel Quality Indicators (CQIs) or Multiple Input Multiple Output (MIMO) precoding matrices, drastically reducing up- and downlink throughput. While some control data may be multiplexed into the PUSCH, use of the PUCCH enables higher cell capacities and data rates (e.g. via MIMO). Another advantage for the adversary is that the PUCCH power limit is commonly lower than the PUSCH power limit in order to reduce inter-cell interference.

UE Targeted Uplink Jamming: Since the entire uplink (both PUSCH and PUCCH) is slaved to the downlink with 4 ms delay, attackers can identify and target a particular UE's RBs. This is due to the nature of the PDSCH, which relies on obfuscation via Cyclic Redundancy Check (CRC) mask rather than proper encryption. An implementation and evaluation of such a jammer is detailed in Section IV. Given a DCI decoder, a target device's RBs can be found via its Radio Network Temporary Identifier (RNTI), obtainable by combining de-anonymization [3] with tools like C3ACE [4].

3) Protocol Attacks:

Cell Barring Spoofing: Rogue eNBs mimic real cells, barring UEs from connecting to specific cells by transmitting *cell-*

Barred and *intraFreqReselection* flags. Thus, UEs will ignore any cells on that frequency. Also, LTE requires UEs to ban cells from which System Information Blocks (SIBs) or MIBs are not received within a defined time frame. Hence, corrupting these blocks leads to barred cells for up to 300s as well [5].

Reject Spoofing: An identical rogue cell is created by synchronizing to a legitimate cell and mimicking its relevant parameters such as Public Land Mobile Network (PLMN) ID, tracking area, etc. Next, target UEs are forced from their original cell, and the rogue cell rejects subsequent reattachment attempts. Depending on the specific implementation, UEs may treat the PLMN as generally barred. Thus, this attack can be very efficient, yet requires significant effort.

III. RELATED WORK

In recent years, several publications have dealt with the analysis of different LTE vulnerabilities. An overview of various attack vectors against the LTE air interface is given in [6], estimating potential jammer to signal power ratios. Hussain et al. propose LTEInspector [7], which combines a symbolic model checker with a cryptographic protocol verifier. It is applied to analyze several different attacks, most of which are validated using a testbed set-up. Though commercial UEs are used for verification, evaluation is mainly focused on protocol implementations and core network signaling. Cyclic prefix and pilot jamming are evaluated for both up- and downlink in [8]. Measurements indicate that Orthogonal Frequency Division Multiple Access (OFDMA) is more resilient against these types of attack than Single-Carrier Frequency Division Multiple Access (SC-FDMA). A method for disrupting the PCFICH is introduced in [9], using simulations for validation. However, real-world measurements would be required for a comprehensive assessment. Also, 5G will mitigate the threat by removing the PCFICH. Labib et al. use radio frequency spoofing to impair synchronization and cell selection [10, 11]. Based on experiments with a software UE, enhancements to the aforementioned techniques are proposed. Simulations are performed in [12] to evaluate jamming against different PUCCH formats. Possible mitigations are discussed, e.g. foregoing PUCCH transmissions at the cost of limiting system capacity. DoS and de-anonymization (International Mobile Subscriber Identity (IMSI) catching) attacks are evaluated against commercial UEs in a laboratory by [13]. Yet, the employed eNB is not commercial grade. Rao et al. provide physical layer measurements on LTE resilience, considering attacks on different features of the OFDMA downlink signal [14]. However, the same open-source eNB and UE implementations are evaluated against each other. Thus, results cannot be generalized to commercial equipment.

In comparison to related work, this publication evaluates further aspects of the LTE air interface, considering the impact on end-to-end connectivity of commercial grade equipment.

IV. TARGETED UPLINK JAMMING: CONCEPT, IMPLEMENTATION AND EVALUATION SCENARIO

Within this section, we introduce our approaches to jamming and describe the scenario and measurement setup.

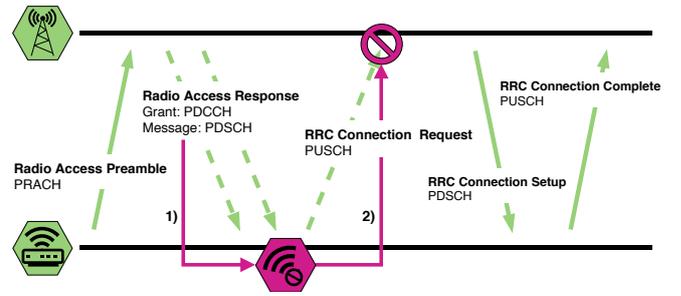


Figure 2: Principle of the PRATTLE attack

A. Smart Uplink Jamming Concepts

1) *PUSCH/PUCCH Jammer:* Our jammer, implemented on top of srsLTE [15], disturbs the LTE PUSCH and PUCCH respectively. To perform the attack, we synchronize the device with a cell, decode the Physical Downlink Control Channel (PDCCH) and transmit on RBs, originally assigned to the target UE. Building on the UE implementation in srsLTE, the jammer imitates the victim device. Upon activation, the jammer jumps to the Radio Resource Control (RRC) Connected State immediately, utilizing the provided target RNTI. Afterwards, the jammer is able to transmit on top of the UE's assigned RBs. No other radio access or scheduling requests are issued and RRC remains nearly unchanged.

2) *Physical Radio Access Termination in LTE (PRATTLE):* Besides the above described jammers, an attack on the radio access procedure is devised, referred to as PRATTLE. It targets the first PUSCH message of one or several UEs. The attack is structured as shown in Figure 2: 1) The jammer continuously monitors the PDCCH for Radio Access Response Grants. 2) RRC Connection Requests, identified by grants, are jammed repeatedly. 3) Due to this attack, the UE fails the complete procedure and retries until a maximum number of attempts (6 to 200) is reached. After that, the corresponding cell is to be treated as barred for up to 300 s [5]. In the following, however, only the former two attacks are evaluated.

3) *Critical Infrastructure Jamming Scenario:* To evaluate the developed uplink jammer's effectiveness, we consider a Smart Grid scenario. Such CIs possess well-defined requirements, as specified by e.g. the International Electrotechnical Committee (IEC)'s standard 61850 [16], which are extremely challenging regarding reliability and latency. Moreover, cyber attacks on power grid ICT infrastructures may be of severe consequences, endangering all dependent systems. Attackers profit from the static nature of grid assets, allowing for optimal target localization and jammer placement. We specifically consider IEC 61850 based Wide Area Monitoring Protection and Control (WAMPAC) systems, regularly transmitting measurement data between Smart Grid substations.

B. Experimental Measurement Setup

Measurements are performed within our laboratory as shown in Figure 3, in isolation from public radio networks. For this purpose, the UE under test is placed in a shielding box and connected to the eNB via a box-internal antenna. UE uplink and jammer signal are combined and fed to the eNB. For synchronization, the downlink signal of a commercial,

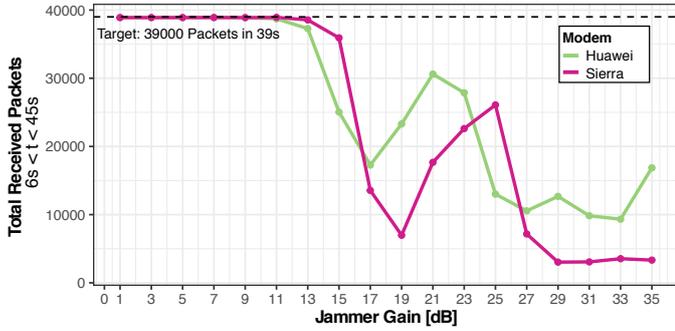


Figure 5: PUSCH jammer impact under different jammer gains

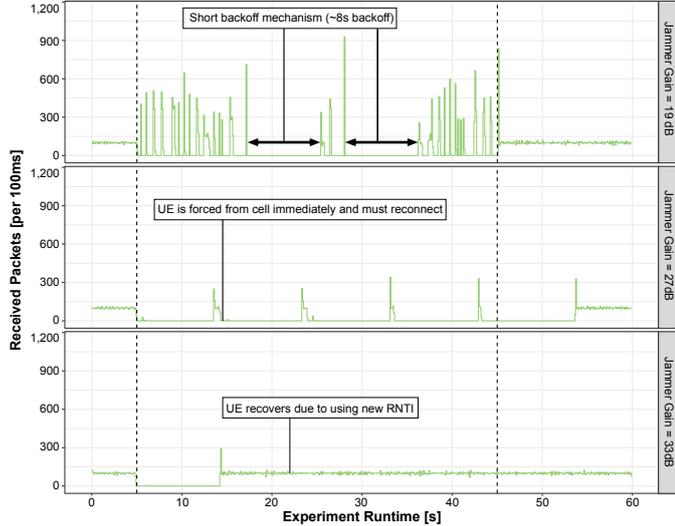


Figure 6: Detailed UE behavior under PUSCH jamming

eNB connectivity and attempts to reconnect using its previous RNTI. Thus, the jammer is able to continue its attack as soon as the UE reconnects. After failing the radio access procedure several times, the UE enters a back off period of (in this case) 8 s. With higher gains (middle of Figure 6), the UE is forced from the cell immediately after radio access ($\ll 1$ s), as its signal is significantly weaker than the jammer's. The bottom part of Figure 6 is specific to the Huawei device. At a very high jammer gain of 33 dB the connection is disrupted in a way, which causes the UE to assume a complete connection loss. Hence, it starts an entirely new connection, utilizing a different RNTI and sending an RRC Connection Request instead of an RRC Reestablish Request. In this way the UE shakes off the jammer, achieving stable transmission after 14 s.

Repeating experiments with the Sierra Wireless UE show behavior similar to the Huawei modem. However, the Sierra Wireless handset does not recover in any case. Also, the UE's back off period increases with the number of failures (up to: Sierra 22 s, Huawei 12 s), i.e. at higher jammer gains. In several cases it even refuses to connect for up to 300 s. This indicates that the cell barring timer is used to exclude the eNB from its list of selectable cells.

A. Uplink Jamming Mitigations

An uplink jamming attack may be identified by the eNB on basis of up- and downlink channel conditions diverging signi-

ficantly from each other as well as from historical data. Our evaluations using the Huawei device already point to a possible mitigation strategy. It was shown that switching the RNTI allows to render the attack ineffective, requiring the attacker to re-identify the UE. Hence, new, unpredictable RNTIs should be assigned on both connection and reconnection attempts. Yet, since control channels in LTE are not encrypted, this is not a sustainable option. Beyond that, eNBs should assign more robust modulation and coding schemes more quickly and allow critical UEs a higher transmit power.

VI. RECOMMENDATIONS FOR 5G STANDARDIZATION AND DEPLOYMENT

In the following we provide recommendations for 5G stakeholders organized by standardization and deployment aspects.

A. Standardization of 5G Mobile Networks

As a major aspect of 5th Generation of Cellular Mobile Communication (5G) new radio, beamforming increases resilience against jamming. However, there are still several shortcomings, which should be addressed by future 5G releases. Though 5G finally supports encryption and integrity protection of Signalling Resource Bearer (SRB) > 0 and Dedicated Resource Bearer (DRB) [17, 18], null encryption is still acceptable [18]. Even if encryption is applied, the air interface is not secured until after the UE successfully completes the entire attach procedure [18].

1) *Mitigating Cell Barring and Reject Spoofing Attacks:* According to the 5G RRC standard [17] intra-frequency barring is still applied without verifying broadcasted barring information. Such cell impersonation attacks could be prevented through the use of verification schemes for cell configuration (either for all UEs or those required by CI). Therefore, the following mechanism may be employed, using signatures applicable to both LTE and 5G: 1) Operators generate public/private key pairs of reasonable size (e.g. 2048 bit). 2) Operators provision public keys in the Subscriber Identity Modules (SIMs). 3) Operators sign hashes of concatenated MIB and scheduled SIB contents with their private keys 4) Base stations broadcast the signature in dedicated SIBs. 5) UEs receive all periodic SIBs, tentatively applying their settings, then verify the signature using the public key. 6) If verification succeeds, settings are committed (including intra-frequency cell barring), otherwise the settings are ignored and the cell is treated as malicious. While this approach prolongs the cell search, it precludes barring spoofing and reject attacks.

2) *Mitigating Uplink Jamming Attacks:* As in LTE, the 5G PDCCH is not encrypted. Hence findings still apply (with few limitations). A simple means of increasing the computational load for the attacker is scrambling the entire DCI with a sequence derived from the destination RNTI, rather than just scrambling the CRC (as in LTE). To compensate for limited DCI entropy, an RNTI hopping scheme can be employed at 5G base stations by periodically reconfiguring the RNTI, once encryption for SRB1 [17] is established. Thus, the probability of an attacker learning the RNTI during its lifetime is reduced.

Besides, some general measures can be used to improve the

resilience of 5G. Providing the standard in a machine readable format would facilitate (automatic) identification of critical flaws. Lightweight, mutual authentication and encryption for the air interface should be introduced. Open, less complex, single-purpose protocols, such as Internet protocols, should be preferred to highly flexible solutions with many optional, potentially vulnerable extensions. Also, legacy compatibility with insecure mechanisms and protocols is to be avoided.

B. 5G System Operation for Critical Infrastructures

To identify irregularities in system operation, 5G mobile network operators should deploy advanced monitoring systems. Rogue and impersonated eNBs can be identified with this method. Beamforming antennas allow to increase SNR, suppress interference signals and restrict jammer placement options, thus enhancing resilience. Distributed beamforming techniques such as Coordinated Multi Point (CoMP) provide more robust radio links by receiving signals from multiple eNBs. Secure reallocation schemes for temporary IMSI mitigate de-anonymization. Disallowed or limited null-ciphering protects user data and improves overall security.

Prior to deployment, CI operators ought to check coverage to ensure UEs are offered high signal strength connections via more than one eNB, providing mobile network redundancy. Location specific connection properties should be considered during UE installation, e.g. directed antennas may be employed under line-of-sight conditions. Operators should procure UEs, which support higher MIMO schemes for spatial redundancy. Locking SIMs into tracking areas mitigates rogue eNBs with different area codes. Also, SIM cards without voice services prevent de-anonymization through call-repetition and downgrade attacks, i.e. forcing UEs into insecure and slow 2G/3G cells. CI utilities and mobile network providers can improve attack detection by continuously exchanging performance data, e.g. via secure APIs. Also, appropriate layer 4 protocols help reduce the impact of jamming.

VII. CONCLUSION AND OUTLOOK

Within this paper we provide an overview of relevant cyber attacks on mobile communication networks, endangering the stability of CIs. In particular, we present our concept for disrupting uplink communications on the LTE PUSCH of a Smart Grid ICT infrastructure. Corresponding experimental evaluations demonstrate the attack's effectiveness. The jammer is shown to significantly reduce throughput, forcing the UE to back off or even crash. Moreover, our analysis also indicates potential mitigations such as the application of scrambled or encrypted DCIs. Recommendations to mobile network and CI operators as well as to standardization bodies are derived, revealing a path towards secure and resilient 5G. Key improvements involve beamforming and massive MIMO. In future work, we aim at broadening the evaluation to further equipment. Also, the public radio access termination attack, described in Section II, is to be implemented and analyzed in detail. For mitigation, we plan to develop a robust, lightweight DCI encryption/scrambling strategy to counter eavesdropping, which serves as basis for attacks such as those presented here.

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