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Practical Jamming of a Commercial 5G Radio System at 3.6 GHz

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Abstract

Fifth-generation (5G) mobile technology has attracted interest from armed forces worldwide due to its many new possibilities for communication. Military operations may face threats in the electromagnetic spectrum, such as intentional jamming of the radio signals. Insights into the effect of jamming are needed to assess operational scenarios in which 5G is safe for military use. This paper presents a study based on an experiment of radio jamming on a commercial 5G system typical for deployments in mobile operators' networks. The prime objectives of the study were to identify a commercial 5G radio system's response to jamming and determine the jamming signal power needed to disrupt the 5G communication. The 5G base station was equipped with a massive Multiple-Input Multiple-Output (MIMO) antenna operating at the 3.6 GHz frequency band. The analysis results showed that the 5G radio system managed to adapt to the jamming by lowering the modulation and coding order until a breaking point was reached at which the interfering signal overcame the UE signal in the uplink, leading to the 5G connection being terminated. The required level of jamming signal strength needed to disrupt the communication agreed with the results from theoretical studies.

Keywords: 5G New Radio; jamming; massive MIMO

1. Introduction

Mobile communications take an essential role in society and continually receive more interest among first responders and armed forces since they need secure, high-bandwidth, and cost-effective communications. Fifth-generation (5G) mobile technology brings several critical new possibilities for future military operations [6]. However, reliability and robustness against intentional attacks on communication are crucial concerns for adopting 5G technology in military operations. One such threat is radio jamming.

The 5G radio interface, New Radio (NR), enables new features like massive Multiple-Input Multiple-Output (MIMO) technology and a highly flexible structure of radio frames that might improve the robustness against jam-

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ming compared with previous generations, i.e., 2G, 3G, and 4G. However, 5G NR, as a civilian technology, was not explicitly designed to operate in a challenging RF environment. Before adapting 5G in military use cases, it is crucial to evaluate the vulnerabilities and possible disruptions to the radio communication system, which can help evaluate the threat level and the possibility of being jammed.

5G is a complex system, making it challenging for a theoretical study to consider all the different aspects of a real-world 5G system. Therefore, we conducted a jamming experiment targeting commercial 5G equipment to create a practical, real-life scenario. The experiment is, to our knowledge, the first to test jamming on a commercial 5G Base Station (BS) and off-the-shelf User Equipment (UE). The 5G system was equipped with a massive MIMO antenna operating on the 3.6 GHz frequency band in Time-Division Duplexing (TDD) mode, all relatively new in mobile communications. The 5G radio communication was exposed to barrage jamming, targeting the entire transmission bandwidth, and partial-band jamming, targeting the downlink synchronization signals.

The experiment's primary objective was to analyze how the commercial 5G radio system is affected by and responds to a jamming attack. The experiment's secondary objective was to identify the jamming signal power needed to disrupt the 5G radio communication and verify if the real-world results reasonably match the theoretical results from the literature.

The rest of the paper is organized as follows. Section 2 presents relevant theoretical studies related to jamming of 4G, 5G and massive MIMO. Section 3 describes the setup of our 5G jamming experiment. Section 4 introduces parameters used to analyze the 5G performance during jamming. Section 5 presents the experimental results, and Section 6 discusses the results. The conclusion is given in Section 7, and potential future work is suggested in Section 8.

2. Related work

Several theoretical studies have been conducted on the jamming effect on 5G radio communication. The authors in [10] present jamming threat assessments of 5G NR. When it comes to the jamming signal power needed to disrupt the 5G communication, the study suggests that if the received power from the jammer is equal to or stronger than the received power of the 5G signal (in physical control and data channels), a jamming attack will be successful. However, the study presents the calculations for 5G NR operating on Frequency-Division Duplexing (FDD) and remarks that TDD requires a separate analysis.

An important difference between 4G and 5G is that 5G NR utilizes massive MIMO technology. By definition, a massive MIMO antenna can spatially separate multiple users because they have different radio channel properties [13]. A BS equipped with this type of antenna can then estimate and separate the different radio channels, thus, separating the users, which allows the simultaneous reception of radio signals from multiple users. Naturally, a question arises whether a massive MIMO antenna can distinguish a jamming signal's radio channel and, consequently, suppress the interference. The authors in [7] and [9] show that potentially, if the base station can accurately estimate the jamming signal and its radio channel, then a massive MIMO system can use this estimate to suppress the jamming signal significantly, making the system resilient to interference. However, simulated results in [7] show that with a regular massive MIMO system without interference estimation and suppression, the achievable data rate would drop to ~40% if the transmit power from the jammer was equal to the transmit power from the UE.

3. Experimental setup

The jamming experiment took place at Rygge Air Station operated by the Norwegian Armed Forces. The 5G infrastructure was provided through the 5G-VINNI project [4]. The experimental setup consisted of a 5G network, a smartphone equipped with a specialized mobile application for measurements, and a custom-built jammer. Barrage and partial-band jamming were applied.

3.1. 5G radio system, measurement equipment and jamming waveform

The network providing 5G coverage contained a BS equipped with 5G and 4G antennas and a 4G core network. The radio communication system operated on a Non-Stand Alone (NSA) architecture (a.k.a. Architecture Option 3

or E-UTRA-NR Dual Connectivity (EN-DC)), where the 5G channel was utilized as a user data carrier, while the 4G anchor managed the connection [1]. The 5G BS was equipped with two commercial massive MIMO antennas from Huawei, providing coverage in two sectors.

The UE was a smartphone Sony Xperia 1 II (XQ-AT51) equipped with a specialized mobile application, called QualiPoc from Rohde and Schwarz (R&S) [12], installed to measure, monitor, and store the physical layer parameters of the 5G communication. Test applications from Ookla [11] and iPerf3 [8] were used to generate as much data traffic as possible to measure the maximum capacity of the communication link speed. This paper refers to these measurements as speed tests, which were run manually several times at every measurement position and jamming setup.

The jammer consisted of a commercial high-bandwidth signal generator (Agilent N5183A), a commercial power amplifier (MILMEGA AS0204-100R), and a custom-made directional helix-type antenna. The jamming waveform was a frequency-modulated sinusoidal signal. The sweeping frequency of the modulated sinusoidal signal was set to 1 kHz, meaning that the sinusoidal waveform was sweeping back and forth across the targeted bandwidth 1000 times per second. The helix antenna radiated circularly polarised radio waves to be independent of the polarisation of the targeted 5G system. The antenna was mounted on a 10 meters high mast. The total output power of the jamming signal had three different settings, providing an Effective Isotropic Radiated Power (EIRP) of 33, 43, or 53 dBm.

Table 1 provides an overview of the parameters and configurations of the experimental setup. Fig. 1 shows the 5G BS and the trailer containing the jamming equipment and the antenna mast.

Table 1. Overview of the experimental setup.

Component	Feature	Setup
5G radio communication	Frequency band	n77/n78 (3.6 GHz, C band)
	Operational frequency	3.62–3.70 GHz
	Bandwidth	80 MHz
	Duplex	TDD
	Subcarrier spacing	30 kHz
	Slot configuration	DDDSU (4:1)
	Number of SSB beams	7 (default)
	Modulation	QPSK, 16QAM, 64QAM
	Max SU-MIMO streams	4 in downlink, 1 in uplink
	Architecture	NSA (Option 3, EN-DC)
	4G anchor band	B1 (2100 MHz)
5G base station	Tower height	24 meters
	Antenna	Huawei AAU5613
	Technology	Massive MIMO 64T64R
	Max EIRP	68 dBm
	Polarization	Cross (+45° and -45°)
User equipment	Smartphone	Sony Xperia 1 II (XQ-AT51)
	5G chipset	Qualcomm x55
	Measurement tool	R&S QualiPoc 20.3.69
	Max Total Radiated Power (TRP)	23 dBm
Jamming equipment	Antenna height	10 meters
	Jamming type	Barrage, partial-band
	Jamming waveform	FM sinusoidal signal
	EIRP	33/43/53 dBm
	Polarization	Circular

3.2. Jamming approach

Based on [14], we considered jamming in which a narrow frequency band of jamming energy is repeatedly swept over a relatively wide frequency band, and the sweep rate is high enough to accomplish its jamming task, to serve as a barrage or partial-band jamming. The barrage jamming targeted the entire 80 MHz bandwidth of the 5G system. The partial-band jamming targeted the part of the band carrying the Synchronisation Signals Block (SSB). The targeted

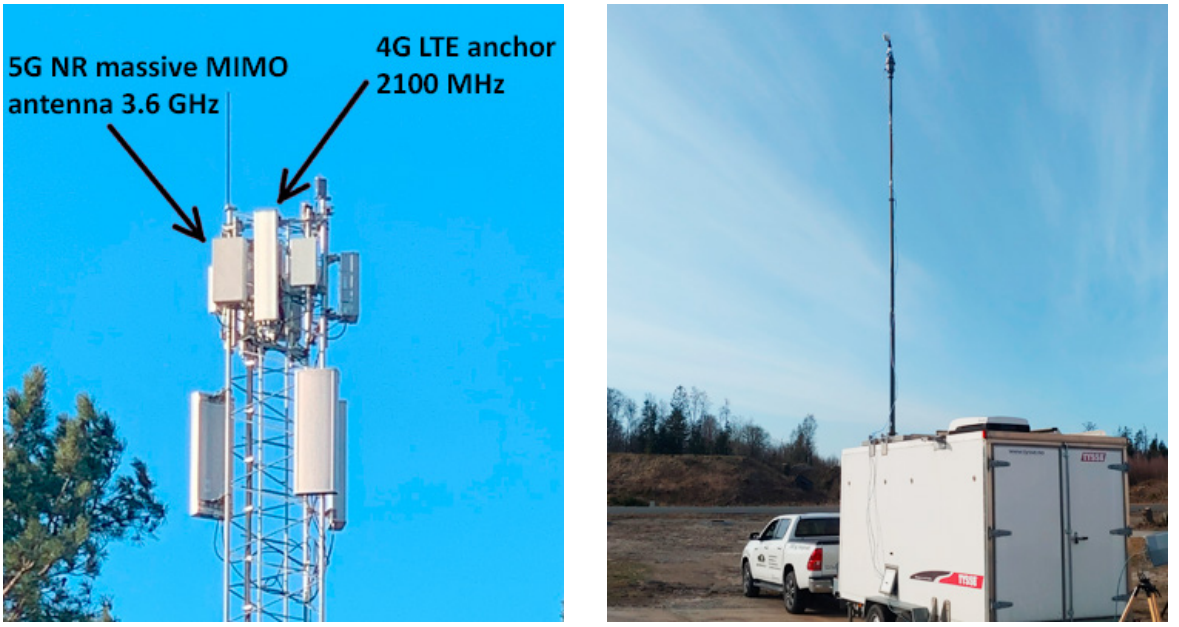

Fig. 1. (a) the 5G base station with a 4G anchor (photo: Kennet Nomeland/NDMA); (b) the jammer mounted on a trailer.

bandwidth was 7.2 MHz wide, with the center frequency at 3659.52 MHz. This paper refers to this type of partial-band jamming as SSB jamming since it aimed to interfere with the synchronization signals carried on the SSB.

The 5G radio communication on the 3.6 GHz frequency band operates in TDD mode. The uplink and downlink channels use the same frequency channel, making the separation of the uplink and downlink jamming difficult. However, we selected some specific measurement locations and jammer directions in order to separate the analysis of the jamming effect on the uplink and downlink as much as possible. Thus, we introduced uplink jamming and downlink jamming scenarios.

In the uplink jamming scenario, the jammer aimed to attack the BS. The directive jammer antenna was physically rotated to point its maximum gain towards the BS to disrupt the uplink signal. The jammer was always in Line-Of-Sight (LOS) with the BS. The UE received direct or indirect interference only from the side lobes of the jammer. Barrage jamming was applied in this scenario.

In the downlink jamming scenario, the jammer aimed to attack the UE. The jammer pointed directly towards the UE and had Non-Line-Of-Sight (NLOS) with the BS, making this setup more focused on the downlink jamming. Both the barrage jamming and the SSB jamming were applied in this scenario.

3.3. Measurement and jammer positions

Fig. 2 shows the selected measurement positions (M1–M9) and jammer positions (J1–J3). The figure also provides the cell sectors, the cell range, the LOS/NLOS propagation conditions between the UE and BS, and the jammer direction. At J1 and J2, the uplink jamming was applied as the jammer aimed directly towards the BS. The measurements were taken at M1–M4 with the jammer placed at J1 (Fig. 2a). With the jammer placed at J2, the measurements were taken at M5–M8 (Fig. 2b). With the jammer placed at J3, the downlink jamming was applied as the jammer aimed towards the UE at M9 (Fig. 2c).

4. Analysis parameters

We introduce the parameters used to measure the 5G performance and characterize the impact jamming had on radio communication.

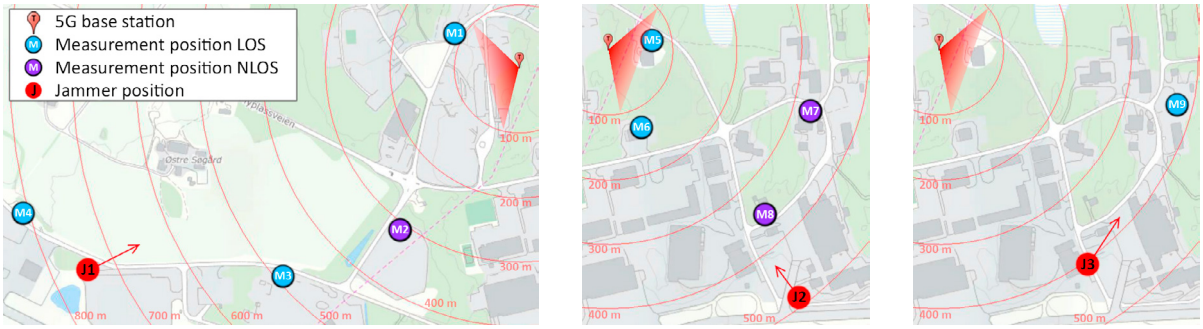

Fig. 2. (a) measurement positions M1–M4 and jammer position J1, uplink jamming; (b) measurement positions M5–M8 and jammer position J2, uplink jamming; (c) measurement position M9 and jammer position J3, downlink jamming.

4.1. 5G performance

The total user data throughput depends on the physical layer parameters settings like modulation scheme, coding rate, and order of MIMO streams. The throughput also depends on allocated radio resources and occurred transmission errors. Since the throughput value depends on several physical layer parameters that dynamically adapt to the radio environment, we selected the throughput as a primary performance indicator of the 5G communication. The registered throughput was measured at the physical layer.

The 5G performance measures like Modulation and Coding Scheme (MCS) index and retransmission rate were also insightful. The MCS index is an indicator of the modulation scheme and the code rate used for the data transmission, which is defined by Third Generation Partnership Project (3GPP) in [2] and can be translated into the exact values of the modulation scheme and coding rate. The retransmission rate is the percentage of the transport blocks that failed to be delivered correctly in uplink and needed to be transmitted from the UE again.

4.2. Jamming-to-uplink-signal (J/S) ratio

During the uplink jamming, the jammer transmitted its signal towards the BS and aimed to interrupt the signals arriving from the UE. We introduced a jamming-to-uplink-signal ratio (J/S) to characterize the jamming effect with respect to the received uplink signal. We defined the J/S ratio as a ratio of the jamming signal power at the BS and the UE signal power at the BS. The signal power that reaches the BS is defined by the transmit power (TRP or EIRP) and the Path Loss (PL) between the nodes. The J/S ratio in decibels can be expressed as:

$$J/S_{[dB]} = (EIRP_{Jammer} - PL_{Jammer\text{-}BS}) - (TRP_{UE} - PL_{UE\text{-}BS}) \quad (1)$$

The PL was calculated using the path loss exponent model and Rural Macro path loss model defined by 3GPP [3].

5. Results

5.1. The 5G system's response during jamming

The 5G radio system dynamically adjusts the physical layer parameters according to the radio channel quality to adapt to the radio environment and efficiently transmit data. As the channel was disrupted, the 5G system lowered the MCS to minimize the errors in signal decoding and demodulation. However, the 5G system often struggled to find the optimum settings for the physical layer parameters, which led to a high number of retransmissions and the 5G connection being terminated and downgraded to 4G.

We provide a typical example of the 5G system's reaction to the jamming experienced during the experiment. Fig. 3 shows the results of four consecutive speed tests conducted at the measurement position M5 without jamming (Fig. 3a) and during the uplink barrage jamming of 43 dBm (Fig. 3b). The 5G performance in the uplink is given in terms of throughput, MCS index, and retransmission rate.

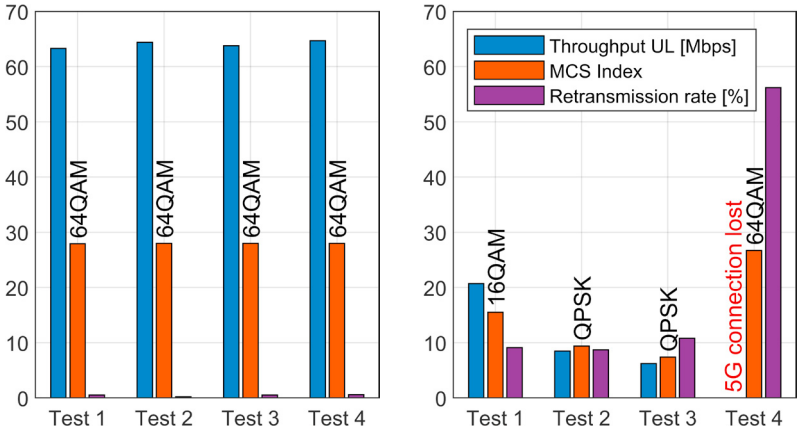

Fig. 3. The 5G system's (a) performance without jamming and (b) reaction to uplink barrage jamming.

Without any interference, as shown in Fig. 3a, the uplink throughput during the speed tests was stable and reached 65 Mbps, the maximum total capacity in the uplink. The MCS index was always at maximum, meaning that the 64QAM (Quadrature Amplitude Modulation) modulation scheme was used. The retransmission rate stayed below 1%.

When the interference was present, as shown in Fig. 3b, the throughput in the uplink was reduced and became highly varying from test to test until, at the start of the fourth speed test, the 5G connection was lost and went down to 4G. During Tests 1–3, the 5G system adapted to the contested radio channel by lowering the modulation order. A decent throughput with an acceptable level of retransmissions was achieved. During Test 4, the data transmission started on 64QAM, the retransmission rate went up to 56%, and the connection was lost. Many errors in data transmission suggest that the modulation order of 64QAM was too high in this contested RF environment, which led to the connection being terminated. Selecting the 64QAM modulation scheme on this disrupted radio channel was not a sufficient response from the 5G system.

The outputs of the speed tests were inconsistent in the presence of interference. The speed test with the highest throughput represented the 5G system's best adaptation to the contested RF environment compared with the outputs of the rest of the tests and, therefore, was considered optimal response to jamming. The 5G system's performance during Test 1 in Fig. 3b is an example of the optimal adaptation to 43 dBm jamming signal at the measurement position M5. In the rest of the result analysis, when measuring the effect of jamming at any given measurement position and jamming setup, we used the optimal 5G performance results, isolating the effect of physical layer parameters selection.

5.2. *Uplink jamming*

The relation between the J/S ratio and the 5G throughput gives a clear picture of the effect jamming has on the 5G radio communication. Plots, given in Fig. 4, show how the throughput in uplink and downlink decreased with the increasing J/S ratio. The results include three jamming signal power levels of uplink barrage jamming at a given measurement position. The throughput is given as zero if the jamming was too destructive to establish the 5G connection and take the measurements.

During the uplink jamming, the throughput in both uplink and downlink was reduced. Since the uplink and downlink channels were transmitted on the same frequency (TDD), the jamming signal also interfered, to some extent, with the downlink radio signal. Also, the downlink and uplink transmissions rely on each other because of the necessary control and feedback messages like Hybrid Automatic Repeat Request Acknowledgement (HARQ-ACK) that must be successfully received both ways.

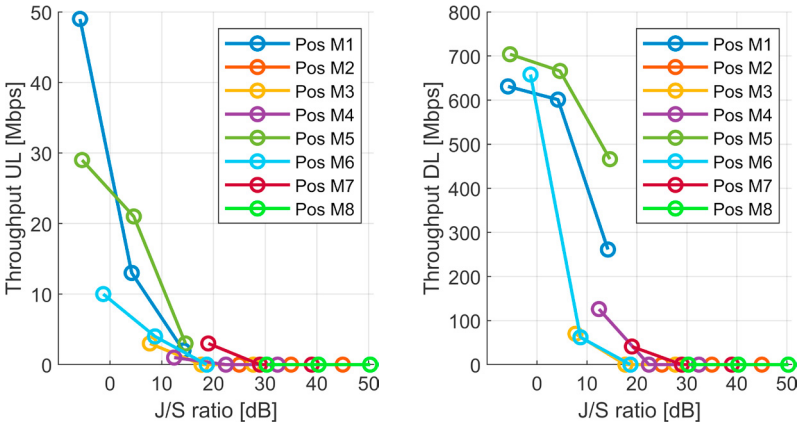

Fig. 4. Uplink jamming impact on (a) the uplink throuhput and (b) the downlink throughput.

In Fig. 5, the plot of the decreasing uplink throughput as the J/S ratio increases is supplemented with (1) a logistic curve fit function to provide a model for the drop in throughput caused by jamming and (2) a threshold line that separates a jammed radio channel that could not provide any service from a radio channel that managed to provide services to some extent. In this paper, we call this threshold value of the J/S ratio, at which a jamming signal became too destructive for a 5G system to work, a Breaking Point (BP). We identified the BP to be 5 dB, which means that if the jamming signal that reached the BS was higher than the uplink signal at the BS by 5 dB or more, the jamming attack was successful. The radio channel is considered tolerable with a J/S ratio less than 5 dB since the 5G system could adapt and operate with reduced stability and throughput.

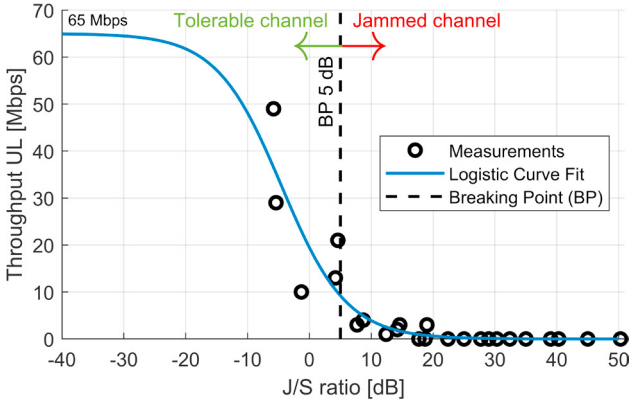

Fig. 5. Uplink throughput versus J/S ratio plotted with a logistic curve fit function and the Breaking Point (BP), which separates a tolerable channel from a jammed channel.

5.3. Downlink jamming

Fig. 6 shows how the 5G performance was influenced by the different jamming types and signal power levels during the downlink jamming.

The barrage jamming with high power was the most effective in disrupting the 5G communication as no service could be delivered when the jamming of 53 dBm EIRP was applied.

In the case of the SSB jamming, the jamming power was concentrated on the synchronization signals. However, this type of jamming signal was not enough to completely disrupt the synchronization and break the 5G connection. The 5G system managed to operate with reduced throughput during the SSB jamming.

Fig. 7 shows the results of Synchronisation Signal Signal-to-Noise and Interference Ratio (SS-SINR) measurements at M9. The distribution of the SS-SINR is given in box plots.

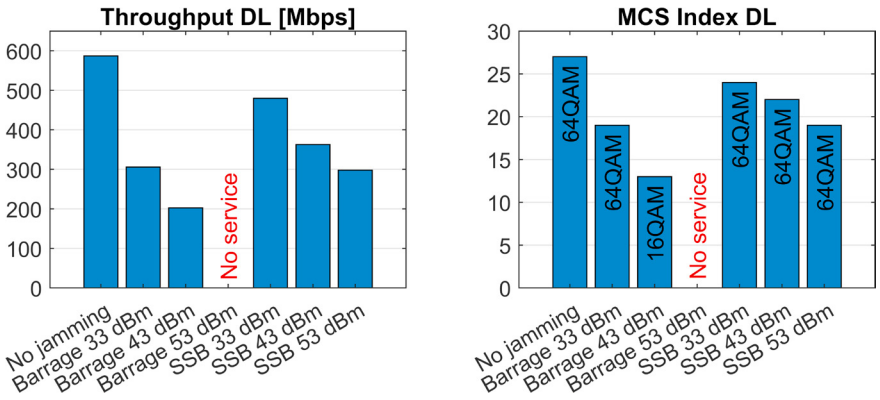

Fig. 6. Reduction of (a) downlink throughput and (b) MCS index at M9 during the downlink jamming.

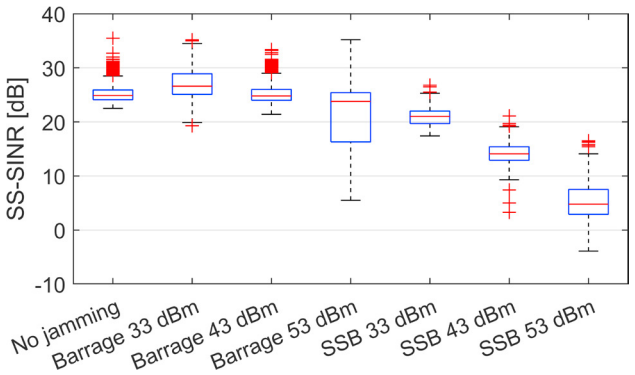

Fig. 7. Distribution of SS-SINR at M9 during the downlink jamming.

Higher jamming signal power and targeted SSB jamming led to a more substantial decrease in SS-SINR. The SSB jamming with the highest EIRP of 53 dBm reduced the SS-SINR, on average, by 20 dB. Even in this case, the SS-SINR was, on average, as low as 5 dB, the 5G data transmission was stable.

6. Discussion

This section summarises the experiment results and discusses how these results can assess the vulnerabilities and threat level of using 5G NR in a contested RF environment.

6.1. The 5G system's response to jamming

A 5G radio system is designed to dynamically adjust the physical layer parameters for optimal operation in various radio channel conditions. The system's ability to automatically adapt to a poor radio channel can be advantageous against interference.

In the experiment, when the adaptation to the disruptions was successful, the user data could be transmitted with a lower modulation and coding scheme and, hence, reduced throughput. However, the results also showed that the 5G radio system often struggled to find the optimal parameters for the communication, and the 5G connection was terminated and downgraded to 4G.

The 5G radio communication in the experiment operated in NSA, meaning that some part of the higher layer signaling went through the 4G radio channel instead of the 5G radio channel. However, from the radio perspective, the data transmission on the 5G radio channel is alike whether the architecture is NSA or Stand Alone (SA). Therefore, the 5G resilience to jamming of a SA system is expected to be similar to NSA.

The NSA architecture provided redundancy because the communication could be switched to the undisrupted 4G channel. However, in a case of a tactical 5G bubble operating on SA with no available 4G channels to switch to, a 5G system would be forced to stay on a disrupted radio channel, continuously attempting to find optimal physical layer settings. If the 5G system is not entirely jammed (below the BP), it can be expected to successfully adapt to the challenging RF environment and operate with reduced performance.

6.2. Vulnerable uplink

In TDD, where the uplink and downlink are transmitted on the same frequency band, the barrage jamming affects both uplink and downlink channels. Nevertheless, the jammer is more likely to direct its attack towards the BS, knowing that it can affect the uplink channels of all users in the cell, while the downlink jamming disrupts only the users that are in the jammer's range. Also, the attacker is aware that the uplink signal power is minimal compared with the downlink signal power and thus easier to contest.

The results showed that the jamming signal power received at the BS needed to be only 5 dB higher than the uplink signal power received at the BS to achieve a successful jamming attack. According to the logistic curve fit model in Fig. 5, for a J/S ratio of 0 dB and 5 dB, the throughout was reduced to 30% and 14% of the maximum capacity, respectively. The jammer power needed to disrupt the 5G connection complies with the 5G threat assessment results found in [10].

The BS in the experiment was equipped with a commercial massive MIMO antenna. The beamforming provided relatively high transmit power and may have improved the robustness against jamming in the downlink. However, when it comes to the uplink, the utilization of a regular massive MIMO technology showed no additional resilience to jamming in the signal reception. The reduction in throughput complies with the calculations presented in [7], which state that the capacity of a regular massive MIMO system would be reduced to ~40% and ~12% of the maximum capacity at a J/S ratio of 0 dB and 5 dB, respectively.

5G NR needs both an uplink channel and a downlink channel to function to transmit data in any of those directions. The uplink channel is more easily disrupted than the downlink channel and, hence, the weak link among the two.

6.3. Smart jamming

The synchronization signals appeared to be relatively robust against simple interfering signals of the barrage and partial-band jamming. A smart jammer can exploit the knowledge about 5G NR and attack the vital spots of radio communication to increase the jamming efficiency. A jamming signal specifically designed to disrupt the synchronization signals' correlation or spoof the system with fake synchronization signals would be more efficient. Designing this type of smart jammer is feasible since the design of the 5G channels and signals is defined in open standards.

7. Conclusion

We conducted a radio jamming experiment on a commercial 5G system operating on a 3.6 GHz frequency band, creating a real-life attack scenario. The 5G radio system responded to the contested RF environment by lowering the modulation and coding scheme and operating with reduced capacity when the jamming signal was tolerable. However, the results also showed that, in some cases, the 5G radio system struggled to find the optimal parameters for the communication under workable conditions. When the interference was too destructive, leading to many errors in data transmission, the 5G session was terminated, and the connection tended to go down to an uninterrupted 4G channel. Because of the limited User Equipment (UE) output power, we consider the Base Station (BS) an attractive target and the uplink transmission a vulnerable 5G radio communication component. The regular commercial massive MIMO antenna showed no additional resilience in the uplink signal reception, meaning that the ability to multiplex radio channels spatially was not utilized to counteract interference. When the barrage jamming signal power received at the BS was at least 5 dB higher than the UE signal power received at the BS, the 5G connection could not provide tolerable service, indicating a successful jamming attack. This breaking point of 5 dB, at which the 5G radio communication was no longer possible, is in line with the theoretical studies in the literature. The partial-band jamming targeted at the synchronization signal block did not affect the downlink synchronization significantly.

8. Future work

As an output of the experience gained during the jamming experiment, we propose some jamming mitigation measures for future studies.

It is difficult for a communication system with low output power to compete with a jammer transmitting a strong interfering signal. More resilience to uplink jamming can be achieved by boosting the transmit power at UE. High Power User Equipment (HPUE) was introduced in 4G, allowing the uplink transmit power to be higher than the default of 23 dBm in some specific bands. Studies on increasing the uplink transmit power in some exceptional military use cases and bands should be considered and might, in the future, be added to the 3GPP standards. Increased uplink power would be beneficial only if it is not causing any additional issues like increased inter-user or inter-cell interference.

The results from the experiment showed that a regular commercial massive MIMO antenna had no advantage against the uplink jamming signal. The BS had no setup to estimate and suppress the uplink jamming signal. The jamming suppression would require some resource elements dedicated to the jamming channel estimation and digital signal processing techniques to filter out the interference. The analysis in [7] and [5] show that, ideally, it is possible to obtain a massive MIMO system that is completely resilient to the jamming signal independently of the jamming power. Aspects of implementing such techniques are worth further investigation.

Some military applications such as blue force tracking and messaging services might work even if the radio link is unstable and the throughput is highly reduced. The tolerance for transmission errors might be high as long as the radio link completes the task. A 5G radio system could be optimized at the physical layer to handle these challenging radio environments. For example, supporting increased tolerance for high retransmission rates before terminating the connection could give the 5G system more time to adapt and provide reduced but tolerable service quality.

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