Distributed and Mobile Message Level Relaying/Replaying of GNSS Signals

Malte Lenhart, Marco Spanghero, Panos Papadimitratos

Networked Systems Security Group, KTH Royal Institute of Technology, Sweden

BIOGRAPHY

Malte Lenhart received his B.Sc. in Information System Technologies from Technical University of Darmstadt, Germany, where he is currently pursuing his M.Sc. focused on IT security. He is currently writing his master thesis on GNSS security at the Networked Systems Security Group at the KTH Royal Institute of Technology, Stockholm, Sweden, under the supervision of Marco Spanghero and Panos Papadimitratos.

Marco Spanghero received his B.Sc. in Electronics Engineering from Politecnico of Milano and M.Sc. degree in Embedded System from KTH Royal Institute of Technology, Stockholm, Sweden. He is currently a Ph.D. candidate with the Networked Systems Security (NSS) group at KTH Royal Institute of Technology, Stockholm, Sweden. His research is concerned with secure positioning and synchronization.

Panos Papadimitratos is a professor with the School of Electrical Engineering and Computer Science (EECS) at KTH Royal Institute of Technology, Stockholm, Sweden, where he leads the Networked Systems Security (NSS) group. He earned his Ph.D. degree from Cornell University, Ithaca, New York, in 2005. His research agenda includes a gamut of security and privacy problems, with emphasis on wireless networks. He is an IEEE Fellow, an ACM Distinguished Member, and a Fellow of the Young Academy of Europe.

ABSTRACT

With the introduction of [Navigation Message Authentication (NMA)] future [Global Navigation Satellite Systems (GNSSs)] prevent spoofing by simulation, i.e., the generation of forged satellite signals based on publicly known information. However, authentication does not prevent record-and-replay attacks, commonly termed as meaconing. Meaconing attacks are less powerful in terms of adversarial control over the victim receiver location and time, but by acting at the signal level, they are not thwarted by [NMA]. This makes replaying/relaying attacks a significant threat for current and future GNSS. While there are numerous investigations on meaconing attacks, the vast majority does not rely on actual implementation and experimental evaluation in real-world settings. In this work, we contribute to the improvement of the experimental understanding of meaconing attacks.

We design and implement a system capable of real-time, distributed, and mobile meaconing, built with off-the-shelf hardware. We extend from basic distributed meaconing attacks, with signals from different locations relayed over the Internet and replayed within range of the victim receiver(s). This basic attack form has high bandwidth requirements and thus depends on the quality of service of the available network to work. To overcome this limitation, we propose to replay on message level, i.e., to demodulate and re-generate signals before and after the transmission respectively (including the authentication part of the payload). The resultant reduced bandwidth enables the attacker to operate in mobile scenarios, as well as to replay signals from multiple GNSS constellations and/or bands simultaneously. Additionally, the attacker can delay individually selected satellite signals to potentially influence the victim position and time solution in a more fine-grained manner. Our versatile test-bench, enabling different types of replaying/relaying attacks, facilitates testing realistic scenarios towards new and improved replaying/relaying-focused countermeasures in GNSS receivers.

I. INTRODUCTION

[GNSS] receivers are extensively used to provide precise location and time to a wide gamut of applications, including critical infrastructures. Due to the intrinsic lack of security in the [GNSS] civilian user segment, adversarial modification of [GNSS] provided [Position-Velocity-Time (PVT)] solutions is a concrete risk [1][2]. While military-grade [GNSS] signals are protected (to a certain extent) from spoofing, leveraging encrypted spreading codes, the structure and content of civilian signals, which are within the scope of this work, are publicly known and unprotected. Attackers can therefore spoof signals by simulating and transmitting signals that appear to originate from legitimate satellites. Simulation spoofing provides fine-grained control over the [PVT] solutions at the victim receiver that is misled to lock on them. Open-source software to simulate [Global Positioning System (GPS)] signals is publicly available [3], and an earlier work on an intermediate GPS spooper proved to be effective against civilian receivers, yielding a great level of control over the victim’s device with low detection probability [4].

The introduction of authentication codes for civilian messages through Galileo [Open Service Navigation Message Authentication]...
In this work we focus on implementing practical replay/relay attacks at the signal and message level with colluding and distributed attacker nodes. Extending the basic (distributed) meaconing attack that replays an entire radio spectrum band, we show that replaying at message level reduces the required bandwidth. Our proposed approach demodulates legitimate signals and re-generates replicas used for spoofing. Our system is designed to replay/relay authenticated signals with small adaptations once they become publicly observable. Our modular test-bench is capable to launch one-to-many distributed replay attacks, enabling us to test attack effects on mobile victims using multiple network-connected colluding adversarial nodes.

The remainder of this paper is structured as follows: Section II discusses relevant related work and Section III presents the adversary model considered in this work. Sections IV and V present the proposed implementation for signal and message level replaying/relaying system, and the experimental setup used to demonstrate its effectiveness. Section VI evaluates our proposed design. Section VII concludes this work with a discussion of possible future developments.

II. RELATED WORK

GNSS receivers calculate the PVT solution based on visible satellites at a point in time. Due to transmitted power and attenuation over long distances between the satellite orbits and the Earth surface, the received power of the GNSS signals is in the order of $-180\,\text{dBm}$. For this reason, GNSS signals are susceptible to interference, adversarial overpowering, and environmental factors, such as multipath effects, shading, and weather. Moreover, simple detection schemes based on received signal power are of limited use, in terms of attack detection reliability and confidence [11]. To guarantee best service availability, GNSS receivers prioritize robustness and accuracy: this causes the receiver to lock onto the GNSS signals that show the highest signal-to-noise ratio, without considering their provenance. From an attacker perspective, this is favorable: once the receiver starts tracking a satellite, transmitting at a power advantage prevents the victim to switch back to tracking legitimate signals.

As the majority of commercial GNSS receivers lack fundamental security features, GNSS receivers are often victims of various attacks, notably jamming and spoofing. While jamming is well documented and more straightforward to detect, spoofing is harder to detect and attribute. This is especially true for advanced spoofing attacks, such as the Time Synchronization Attack (TSA), which lifts victims off legitimate satellite signals without relying on jamming to cause a loss of lock [11]. Without the sophistication of such advanced attacks, combined jamming and spoofing are likely to ‘capture’ commercial GNSS receivers, undetected, without triggering any alarm.

Existing work on replaying GNSS signals on the physical-layer mainly focuses on two attack types: Record-and-Relay, depicted in Figure 14 and meaconing, i.e., delayed retransmission in real-time, depicted in Figure 16. Record-and-Relay transceivers allow replicating realistic signal conditions in a controlled environment [12] [13]. From an attacker’s perspective, this technique can be used to replay a specific PVT solution at a later point in time and, if desired, at a different position. An attacker can ‘capture’ a victim receiver by jamming and replaying with sufficient signal power advantage [14]. This is possible even when the victim is able to track satellites in different frequencies (e.g., simultaneous tracking of GPS L1CA and L2CA) if the attacker replays all relevant bands, by employing wide-band front-ends or coherently sampling multiple bands. The Record-and-Relay approach is extensively demonstrated in literature [9] [15] [18] and is also applicable in the case of authenticated signals [10] [19] [20].

However, replaying systems provide only limited control on the receiver’s PVT solution. Furthermore, such systems generate up to 900 GB/h for a sampling frequency of 62.5 MS/s, sampling a single channel, requiring high speed disk arrays [12]. In addition, complex digitizers and front-ends are needed to guarantee low distortion of the sampled signals. These requirements can be relaxed by trading off signal quality of the recorded signal: narrow-band recording systems distort the signal characteristics, limiting the replay of second order effects.

Sampling frequencies as low as 1 MS/s, however, suffice for successful Record-and-Relay attacks, when combined with brief jamming intervals [21]. Also, storage requirements can be lifted if the recordings are streamed and replayed in real-time between inter-networked attacker nodes [21]. Such a setup can be used to replay GNSS signals over long distances, but is in practice limited by the available network bandwidth.

For authenticated signals, an attacker has to predict the security codes if trying to match the legitimate signal at chip level in...
real-time. If performed successfully, this attack is very effective and more flexible than a signal level replay. This attack, described in [10], allows an attacker to overtake a security-enhanced victim receiver, but it requires knowledge of the victim receiver’s initial state. Moreover, the attack complexity is beyond the capabilities of common attackers.

III. ADVERSARY MODEL

Distributed replaying adversaries can overcome range boundaries imposed by the physical antenna cables length in classic meaconing, but they are less robust due to external factors such as network availability. Provided that the attacker has access to network connectivity, it is possible to split the adversarial replaying device into two colluding nodes, typically operated by the same adversary. In particular, an attacker can sample GNSS signals in one position and relay these to a replaying node located in a different position, where the signals are replayed towards a targeted victim. In order to setup such a successful real-time signal level replay, the attacker needs to deploy two or more interconnected colluding nodes with a GNSS radio front-ends (Figure 2a). Although effective and relatively straightforward to setup, signal level replay/relay is limited by external factors (e.g., network connection quality) and it is further limited by the amount of data exchanged between nodes. Such an attacker has to replay the entirety of the selected spectrum, without being able to filter specific satellites. Thus, it can potentially be defeated by antenna-based countermeasures that determine the Angle of Arrival (AoA) of received satellite signals. Deploying multiple Adversarial Transmitter (ATX) nodes does not help the signal level replayer, as all satellites would suspiciously appear to originate from multiple sources, beyond expected multipath effects.

(a) Distributed 1-to-many attack: each ATX node replays the received spectrum to capture a different victim receiver.

(b) Distributed 1-to-many colluding attack: multiple synchronized nodes replay different subsets of the available satellites to a single victim. This attack configuration can potentially defeat AoA spoofing detection.

Figure 2: Different possible distributed replaying/relaying attack setups.

To overcome this limitation, we enhance the basic meaconing attacker. First, the Adversarial Receiver (ARX) node processes the available GNSS signals in real-time to obtain navigational information, authentication bits, signal properties, and satellite messages. To significantly reduce network utilization, only these relevant parameters regarding the GNSS signals are relayed to the ATX nodes. At the ATX node, GNSS signals based on relayed signal- and message-properties are re-generated. This approach adds latency compared to replaying on signal level, but it enables a much broader set of attacks. Both approaches work
on GNSS authenticated signals, but not on fully encrypted signals, as demodulation and parameter extraction is not possible without access to the secret spreading codes.

When operating on message level, an attacker can further operate in a more synchronized and distributed configuration, as depicted in Figure 3B. By demodulating individual satellite signals, she is able to distribute a chosen subset of satellite signals to one or multiple ATX nodes in the proximity of the victim receiver. The victim receiver(s) obtain(s) the superposition of the re-generated attacker signals, together with the weaker, legitimate GNSS signals. Such a distributed attacker can reconfigure the satellite assignment and distribution at run-time, thus compensating network congestion, node failure (or capture) or other attack degrading factors. This orchestrated attack approach potentially increases attack effectiveness against AoA detection.

Due to the achieved compression by operating at message level, requirements on the connectivity between the ARX and ATX nodes can be relaxed. In fact, assuming that each node can access cellular infrastructure, this attack is suited for adversarial nodes connected to mobile cellular networks. The distributed adversary is capable of positioning the ARX node close to the victim receiver. By using highly directional antennas and proper shielding, the attacker can avoid self spoofing effects. This allows the attacker to use legitimate GNSS signals for time-synchronization of the colluding nodes. After capturing the victim receiver by jamming and overpowering, the attacker has full control on the victim’s PVT solution, either by introducing selective delays to satellite streams, and/or by initiating movement with the adversarial ARX node. In a more advanced setting, the attacker can position its ARX node close to the true victim position initially. This avoids sharp discontinuities in the victim PVT solution.

In the scope of replay attacks, we distinguish receivers operating in cold start mode (i.e., not locked to legitimate satellites) and those which already obtained a PVT fix. After a cold start, the receiver performs a search of satellites in view, called acquisition. During acquisition, a receiver is relatively easy to spoof, as it will lock onto the strongest satellite signals, which, due to proximity advantage, are those of the attacker. In contrast, a receiver already locked to legitimate signals keeps tracking these, unless the attacker forces a loss of lock by jamming, before initiating the spoofing attack. As victim receiver we consider an advanced general purpose Commercially off the Shelf (COTS) multi-GNSS receiver that features anti-jamming and anti-spoofing capabilities. Additionally, we consider both static and mobile spoofing scenarios in different environments (i.e., open sky and urban setting).

IV. IMPLEMENTATION
To demonstrate the effectiveness of the advanced distributed relay/replay attacker, we develop a mobile test bench with ARX and ATX nodes built from COTS hardware. A BladeRF 2.0 Software Defined Radio (SDR) is used as radio front-end to receive and transmit GNSS signals. Each node is connected to and powered by a laptop computer used to process the GNSS information. A reference GNSS receiver is used to record the true trajectory of the attacker ARX node, as well as to provide a precise clock discipline.

For the ARX node (Figures 3A and 3B), the signal from an active GNSS antenna is split between the reference receiver and the ARX node’s SDR. A low noise amplifier is connected in series to the SDR front-end, to increase the sensitivity of the sampling receiver and to compensate for the power signal reduction caused by the splitter. The reference receiver (u-blox LEA-6T) is configured to output navigation and time information. A consumer grade laptop (Dell XPS 15) samples the GNSS signal in real-time, and depending on the replay mode, it extracts signal parameters. These parameters, or the raw signal samples, are relayed over an LTE connection (LTE Cat 12 with a maximum theoretical transfer speed of 600 Mbit/s), provided by the attached cellular module. Due to limitations imposed by the cellular carrier, mobile phones are not provided with a public IP, required for routing data to the ATX node. We therefore route all network traffic through a Virtual Private Network (VPN) hosted at the KTH Royal Institute of Technology.

Similarly, the ATX node is connected to the same type of SDR cellular module and processing laptop. The signal received from the ARX node is re-transmitted via the ATX SDR combined with the legitimate GNSS signals and received at the victim.
receiver (u-blox Zed-F9P). A calibrated Temperature Controller Oscillator (TCXO) is used at the ATX node’s radio for precise clock discipline. Experimental observations show that this is required in cold climates for precise RF tuning. The block diagrams and utilized hardware for the ATX are shown in Figures 3b and 4b.

**Signal level replay** is performed by sampling the GNSS spectrum (in our case, we limit the replay to the GPS L1 band, due to available hardware constraints) at 1 MS/s sample rate and 1 MHz bandwidth. GNU Radio [22] flows are used to handle the SDRs signal sampling and I/Q correction. The sampled data is transferred to the ATX node via a TCP socket. Figure 5 outlines the structure of the signal level relayer. The baseband signals from the SDR are transmitted with 16 bit quantization and converted back at the ATX node. A programmable gain stage provides control of the amplification level. Raw IQ samples obtained from the ATX node are stored to disk for analysis and validation purposes.

**Message level replay** is performed by transmitting only relevant signal parameters, required to re-create the baseband signal at the ATX node. A schematic overview is depicted in Figure 6. It is built upon three existing open-source projects: GNSS-SDR [23], GNU Radio and GPS-SDR-SIM [3].

The ARX node uses the open-source software GNSS receiver GNSS-SDR. Recently added stream capabilities are used to extract useful parameters. The transmitted signal parameters include the Time of Week (TOW) (to synchronize multiple

---

**Figure 4:** Prototypes used for experimental evaluation of the proposed relaying/replaying schemes.

**Figure 5:** Signal level relaying/replaying data flow.
message streams), the PVT position and time, send out at specific time intervals. Other parameters, such as estimates of pseudorange, Doppler frequency shift, code-phase and Carrier-to-Noise parameters for each satellite, are not yet used in this implementation phase, to not add additional measurement uncertainty. Instead, these parameters are generated by simulation. Furthermore the navigation message bits are forwarded from ARX to ATX so that the authentication bits can be inserted into the generated navigation messages, as soon as they become perceivable for GNSS receivers. The ‘intermediate receiver spoofer’ described in [H] uses a similar set of signal parameters (estimates of code-phase, Doppler frequency shift and carrier-phases) and PVT solution, to align the spoofed signals to the legitimate ones, which in turn enables advanced TSA attacks. Our relaying/replaying implementation additionally forwards observed unpredictable authentication bits, which by design introduces a delay into the system and prevents synchronization to the legitimate signals to a degree necessary for TSA. The difference in evaluated attack target, i.e., authenticated signals, determine which parameters are necessary and which attack features are achievable.

The ARX node flow is depicted in Figure 7. Each GNSS-SDR output stream is received, de-serialized in its own dedicated block, from which the the contained messages are forwarded to an assembly block, synchronizing and combining the different message streams. Custom GNU Radio out-of-tree blocks are used for message passing, communication, as well as signal generation and streaming from and to the SDRs. This approach helps us to the software modular, and to integrate the different replaying components easily. A separate distribution block with knowledge of the number of ATX nodes and the respectively assigned satellites, filters the message objects, so that each node only receives the intended satellite parameters. The alternative design, in which each ATX node decides which satellites to replay, was discarded due to the higher configuration effort.

Finally, after transmission over the Internet, the signal is re-generated at the ATX node, by feeding the extracted signal parameters, navigation messages and authentication payload to an adapted version of the open-source GPS simulator GPS-SDR-SIM. Incorporating a signal simulator into a replay system sounds contradictory at first glance, but it reduces the development effort required to model Doppler-shift effects and to maintain code-phases between satellites. In the proposed implementation, the signal simulator is only used to recreate the physical-layer signal, while the underlying information is obtained from the ARX node.

Figure 6: Message level relaying/replaying signal and message flow.

Figure 7: Message passing in GNU Radio: de-serialization, assembly and distribution.
V. EXPERIMENTAL SETUP

The victim GNSS receiver is located in a fixed position $\text{LOC}_{\text{start}}$ (Figure 8a). The ARX node is placed near the victim, initially passive. It is connected to the victim receiver via a power combiner and RF cables to adhere to regulatory restrictions regarding protected frequency bands. The mobile ARX node is mounted on a vehicle (Figure 8b). Initially, it is near the victim as well, so that for all nodes and the victim receiver the ground truth location at $t = t_0$ is $\text{LOC}_{\text{start}3D} = [17.957016 \; E; 59.402846 \; N]$. Both the ARX node and the victim are monitored using a reference GNSS receiver throughout the experiment. Similarly, the network throughput between attacker nodes is measured for the duration of the attack.

At the start of each experiment, the victim receiver and ARX node start from cold-start mode and start by acquiring and tracking satellites to derive a legitimate PVT solution. After few minutes, at $t_j = t_0 + 200\, s$, the attacker jams the victim receiver to cause a loss of lock on the legitimate satellites. Successful jamming can be achieved in approximately $15\, s$, so that, at $t_r = t_0 + 215\, s$, the attacker starts replaying GNSS signals. These are directly streamed from the ARX node in the case of signal level replay, for message level replay signal parameters are extracted before streaming. Due to the higher Signal-to-Noise Ratio (SNR) of the replayed signals, the victim receiver will, with high likelihood, track the adversarial signals. We observed that at approximately $t_{\text{adv3D}} = t_0 + 300\, s$, the victim receiver usually derives a new PVT fix corresponding to the attacker’s signals. Once the victim locks on the replayed signal, the ARX node starts moving physically: this, essentially, generates a spoofed PVT trajectory, so that the victim appears to be moving alongside the ARX node.

![Diagram](image)

**Figure 8:** Experimental setup for attacking a static victim receiver using a moving ARX node.

Figure 9 shows the predefined trajectory used for the relay/replay attack in this experiment. We perform relay experiments in an urban environment and rely on cellular 4G networks to transmit the relay signal between the adversarial sampler and the transmitter. All experiments are conducted in the surrounding area of the KTH Royal Institute of Technology campus in Kista (Stockholm). The location used for testing is situated in a position that offers favorable 4G connection, with coverage offered by Tele2 Sweden network.

VI. EVALUATION

Signal level relaying/replaying measurements show that the attacker can successfully 'capture' the victim receiver and impose a PVT solution based on the relayed/replayed signal. Figure 10 shows the attack phases observed at the victim receiver, initially obtaining a fix based on legitimate signals. During the $15\, s$ jamming period it looses lock. This is visible approximately $200\, s$ into the recording. After the jamming phase, the replay signals overpower the legitimate signals in view. The receiver adapts to the new signals and eventually acquires a new fix, based on the initial position of the ARX node. The stability of the new fix is dependent on the ability of the attacker to consistently replay GNSS signals. Once the ARX node starts moving on the predefined path, the victim receiver seemingly follows this change in position and velocity as shown in Figure 11a and Figure 11b respectively.
Additional confirmation of the successfully attack can be obtained by observing raw signal characteristics. In particular, SNR changes correspond to the different attack phases: significant drops in signal quality during jamming and initial replay signal injection phases, as shown in Figure 12a. The SNR bias between reference receivers at the adversarial sampler (Figure 12b) and the victim (Figure 12a) is due to a mismatch between the receiver’s internal gain. Due to limitations of the available hardware, SNR measurements were not acquired directly at the adversarial sampler, but in a separate receiver. This receiver used a mobile phone embedded antenna located on the car’s dashboard, in contrast to the sampler’s high performance, high gain antenna placed on the rooftop, accounting for the SNR differences.

Because of the large amount of data transferred between the attacker’s nodes, network quality is important to guarantee a successful attack. From the performed experiment we observe that a minimum speed of 27.5 Mbit/s is required for the signal level replay to succeed. This is slightly lower than the calculated 32 Mbit/s for a complex signal at 1 Mps sampling rate and 16 bit quantization. If this requirement is not met, we observe that the replay radio buffer is not able to receive enough data from the sampler to produce valid GNSS signals (Figure 13a), causing a temporary loss of lock in the victim receiver.

During the tests we observed certain locations with degraded LTE coverage where the throughput of the cellular connection was sub-optimal. This event is visible at \( t = 11:14:15 \) in Figure 10. If the replay is interrupted for prolonged periods (in the order of the jamming period), it is possible that the attacker loses control over the victim receiver. On the other hand, as the network interruptions are temporary, the intermittent replay action results in jamming of the victim until a stable throughput is not restored. If the throughput is not impacted drastically, the non-continuous sample stream causes enough signal interference with the legitimate signals, that the victim does not regain lock on the latter. Possibly, such issue could be solved by focusing on rate constant transmission instead of minimal latency by sample buffering at the ATX node. Further investigation in this direction is ongoing.
Message level relaying/replaying experimentation brought up two major problems: for one, the reliable tracking and extracting of GNSS signals and parameters with the SDR and the software receiver at the ARX node, and secondly, the generation of realistic spoofing signals at the ATX node.

While tracking the legitimate GNSS signals to extract the required signal parameters with GNSS-SDR, we observed a high level of instability, presumably caused by the SDR clock. We found that the LimeSDR experienced significantly less loss of locks on legitimate satellites, compared to the BladeRF 2.0 SDR, even when configured with an externally disciplined clock. Constant loss of lock reported by GNSS-SDR when working with the BladeRF as front-end, can, among others, indicate problems in frequency stability due to oscillator imprecision. This effect is further amplified due to the cold temperature during our outdoor experiments. We therefore relied on the LimeSDR, featuring a more robust clock circuitry for our experiments. We are currently investigating possible causes by evaluating the radio’s performance in sampling rate and frequency stability.

At the ATX node, we experienced a significant degradation in signal quality, when attempting to generate signals in real-time from a moving ARX node. Investigation into the signal regeneration component showed that PVT X,Y,Z offsets between simulation steps greater than 20 m prevent demodulation in the victim receiver.\(^2\) By tuning GNSS-SDR parameters (especially by employing carrier smoothing in the Observables block and using a more precise PVT implementation for mobile receivers), we were able to reduce the position offsets below 1 m. This proved to be sufficient for the victim receiver to lock onto ATX signals, but introduced additional computation load for the ARX node.

\(^2\)At the current state, it is unclear whether this is caused by the inability of the victim receiver to track the resulting rapidly varying constellation, or if ATX signals are rejected based on internal spoofing countermeasures.
Our message level replayer 'captured' the victim GNSS receiver as depicted in Figure 14. The victim position successfully follows the position of the ARX node, although with lower accuracy than in the signal level replay. Figure 14b shows that the speed of the victim receiver is in principle also determined by the ARX speed, with accuracy limited by the precision in signal reconstruction. The signal regeneration fails in places where the PVT solution error at the ARX node increases. This is one possible reason why the depicted attack in Figure 14 fails in the middle of the ARX path. Other plausible causes are degraded signal reception due to environmental shadowing, the ARX node speed, as well as mechanical effects due to a speed bump in the exact location where the attack fails. In our ongoing work, we investigate improvements on accuracy, e.g., more precise signal feature extraction, or by incorporating signal parameters, such as carrier-to-noise ratios into the signal regeneration. The SNR of the relayed/replayed signals do not match the one measured at the ARX node, as can be seen in Figure 15a (ATX SNR) and Figure 15b (legitimate signal SNRs). As only a subset of the satellites, as selected by the adversary, are relayed/replayed, characteristic satellites which disappear from view during the recording, are not visible in the replayed signals. Temporary SNR degradation in Figure 14a are due to PVT loss at the ARX node or to outages in the network.

Compared to signal level replay, message level replay introduces processing delays in the ARX and ATX nodes. The ARX node processes individual satellites before distributing data to the ATX nodes, which rely on the PVT solution calculated at the ARX node to generate spoofing signals. Without custom optimization, the GNSS-SDR implementation for processing navigation messages and telemetry introduces a 600 ms delay (a full navigation sub-frame). Notably, further optimization in GNSS-SDR can optimize and reduce this latency, e.g., streaming the navigation message bit or word wise. This would, however, require a higher degree of synchronization between the colluding adversaries, as well as better error correction. Further improvements on the replay latency are out of the scope of this work and are left for future work. The only resulting difference caused by a longer processing delay from an attackers point of view, is the length of the required jamming phase until the receiver’s time
uncertainty allows acceptance of the spoofed signals [14].

We highlight the bandwidth reduction achieved by the message level replay: Figure 13b shows how the required throughput for the ARX to ATX peaks at 15 KB/s. This brings it well within reach of most cellular plans, thereby increasing the flexibility of distributed relay/replay in highly mobile scenarios, possibly with both the attacker and the victim moving.

VII. CONCLUSION

We demonstrated the capabilities of a network-based GNSS relay/replayer, that operates at signal level and at message level. We developed an experimental setup that can be used for future research on relay/replay spoofing countermeasures. Its modular design allows different attacker/victim configurations. By basing the attacker on COTS devices, we facilitate replication by researchers to investigate detection schemes with legitimate and upcoming authenticated GNSS signals. An attack demonstration on COTS hardware furthermore stresses the present day risk for spoofing incidents.

Our results show that signal level replay over a mobile network is feasible, provided that the wireless ARX/ATX connection has sufficient throughput. With high-end consumer grade cellular connectivity, as the data plan used in our experiments, this is a realistic assumption, especially with the further deployment of fast cellular technologies. Our successful message level relay/replay attack design, by overcoming bandwidth limitations, demonstrate that replaying attacks, especially by colluding networked attackers, pose a versatile threat to the security of GNSS.

In addition to addressing open questions discussed in Section VI, we plan to include recently introduced authenticated Galileo OS-NMA signals into our experiments. Our test-bench has been designed with the integration of authenticated signals in mind, requiring only minor adaptation in the ARX node, and custom re-generation units for each targeted GNSS band. Another avenue for future work is the inclusion of more advanced attack types. Message level relaying/replaying allows to attack multiple GNSS bands simultaneously, and allows integrating more advanced attacks, e.g., introducing selective delays to specific satellite streams.

ACKNOWLEDGEMENTS

This work was supported in part by the SSF SURPRISE cybersecurity project and the Security Link strategic research center.

REFERENCES

[1] “Spoofing in the black sea: What really happened?” accessed: 2021-11-26. [Online]. Available: https://www.gpsworld.com/spoofing-in-the-black-sea-what-really-happened/

[2] “GNSS jamming and spoofing: Hazard or hype?” accessed: 2021-11-26. [Online]. Available: https://space-of-innovation.com/gnss-jamming-and-spoofing-hazard-or-hype/

[3] T. Ebinuma, “Osqzss/gps-sdr-sim,” accessed 2021-10-29. [Online]. Available: https://github.com/osqzss/gps-sdr-sim

[4] T. E. Humphreys, B. M. Ledvina, M. L. Psiaki, B. W. O’Hanlon, and P. M. Kintner, “Assessing the spoofing threat: Development of a portable GPS civilian spoofer,” in Proceedings of Proceedings of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2008), vol. 2, 2008, pp. 2314–2325.

[5] I. Fernández-Hernández, V. Rijmen, G. Seco-Granados, J. Simon, I. Rodríguez, and J. D. Calle, “A Navigation Message
Authentication Proposal for the Galileo Open Service,” NAVIGATION, Journal of the Institute of Navigation, vol. 63, no. 1, pp. 85–102, March 2016.

[6] J. M. Anderson, K. L. Carroll, N. P. DeVilbiss, J. T. Gillis, J. C. Hinks, B. W. O’Hanlon, J. J. Rushanan, L. Scott, and R. A. Yazdi, “Chips-Message Robust Authentication (Chimera) for GPS Civilian Signals,” Proceedings of the 30th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2017), vol. 4, pp. 2388–2416, 2017.

[7] “FCC fines operator of GPS jammer that affected Newark airport GBAS,” accessed: 2021-11-26. [Online]. Available: https://insidegnss.com/fcc-fines-operator-of-gps-jammer-that-affected-newark-airport-gbas/

[8] M. Coulon, A. Chabory, A. Garcia-Pena, J. Vezinet, C. Macabiau, P. Estival, P. Ladoux, and B. Roturier, “Characterization of Meaconing and its Impact on GNSS Receivers,” in Proceedings of Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020), September 2020, pp. 3713–3737.

[9] P. Papadimitratos and A. Jovanovic, “GNSS-based Positioning: Attacks and Countermeasures,” in IEEE Military Communications Conference (IEEE MILCOM), San Diego, CA, USA, November 2008, pp. 1–7.

[10] T. E. Humphreys, “Detection Strategy for Cryptographic GNSS Anti-Spoofing,” IEEE Transactions on Aerospace and Electronics Systems, vol. 49, no. 2, pp. 1073–1090, April 2013.

[11] D. Schmidt, K. Radke, S. Camtepe, E. Foo, and M. Ren, “A Survey and Analysis of the GNSS Spoofing Threat and Countermeasures,” in ACM Computing Surveys, vol. 48, May 2016, pp. 1–31.

[12] I. Ilie, R. Hini, J. S. Cardinal, D. Blood, and D. Fortin, “Record and Playback System for GNSS: What You Need to Know for Successful Testing,” Proceedings of 24th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2011), pp. 2009–2021, 2011.

[13] S. Hickling and T. Haddrell, “Recording and Replay of GNSS RF Signals for Multiple Constellations and Frequency Bands,” Proceedings of Proceedings of the 26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013), pp. 1907–1918, 2013.

[14] P. Teunissen and O. Montenbruck, Springer Handbook of Global Navigation Satellite Systems, P. Teunissen and O. Montenbruck, Eds. Springer, 2017.

[15] J. Chen, S. Zhang, H. Wang, and X. Zhang, “Practicing a Record-and-Replay System on USRP,” in SRIF 13: Proceedings of the second workshop on Software radio implementation forum, ser. Srif ’13. New York, NY, USA: Association for Computing Machinery, 2013, pp. 61–64.

[16] R. Blum, D. Dötterböck, and T. Pany, “Investigation of the Vulnerability of Mobile Networks Against Spoofing Attacks on their GNSS Timing-receiver and Developing a Meaconing Protection,” Proceedings of the 2019 International Technical Meeting of The Institute of Navigation (ION GNSS+ 2019), pp. 345–362, 2019.

[17] A. Brown, J. Redd, and M. Dix, “Open Source Software Defined Radio Platform for GNSS Recording, Simulation,” in Proceedings of the 26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013), September 2013.

[18] P. Papadimitratos and A. Jovanovic, “Protection and Fundamental Vulnerability of GNSS,” in IEEE International Workshop on Satellite and Space Communications (IEEE IWSSC), Toulouse, France, October 2008, pp. 167–171.

[19] D. Maier, K. Frankl, R. Blum, B. Eissfeller, and T. Pany, “Preliminary assessment on the vulnerability of NMA-based galileo signals for a special class of record & replay spoofing attacks,” 2018 IEEE/ION Position, Location and Navigation Symposium (PLANS), pp. 63–71, 2018.

[20] G. Caparra, S. Ceccato, N. Laurenti, and J. Cramer. “Feasibility and Limitations of Self-spoofing Attacks on GNSS Signals with Message Authentication,” Proceedings of the 30th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2017), vol. 6, pp. 3968–3984, 2017.

[21] M. Lenhart, M. Spanghero, and P. Papadimitratos, “Relay/replay Attacks on GNSS Signals,” WiSec 21: Proceedings of the 14th ACM Conference on Security and Privacy in Wireless and Mobile Networks, pp. 380–382, 2021.

[22] “GNU Radio Website,” accessed 2021-10-29. [Online]. Available: http://www.gnuradio.org

[23] C. Fernández-Prades, J. Arribas, P. Closas, C. Avilés, and L. Esteve, “GNSS-SDR: An open source tool for researchers and developers,” in Proceedings of 24th International Technical Meeting of the Satellite Division of the Institute of Navigation 2011 (ION GNSS+ 2011), vol. 2, September 2011.