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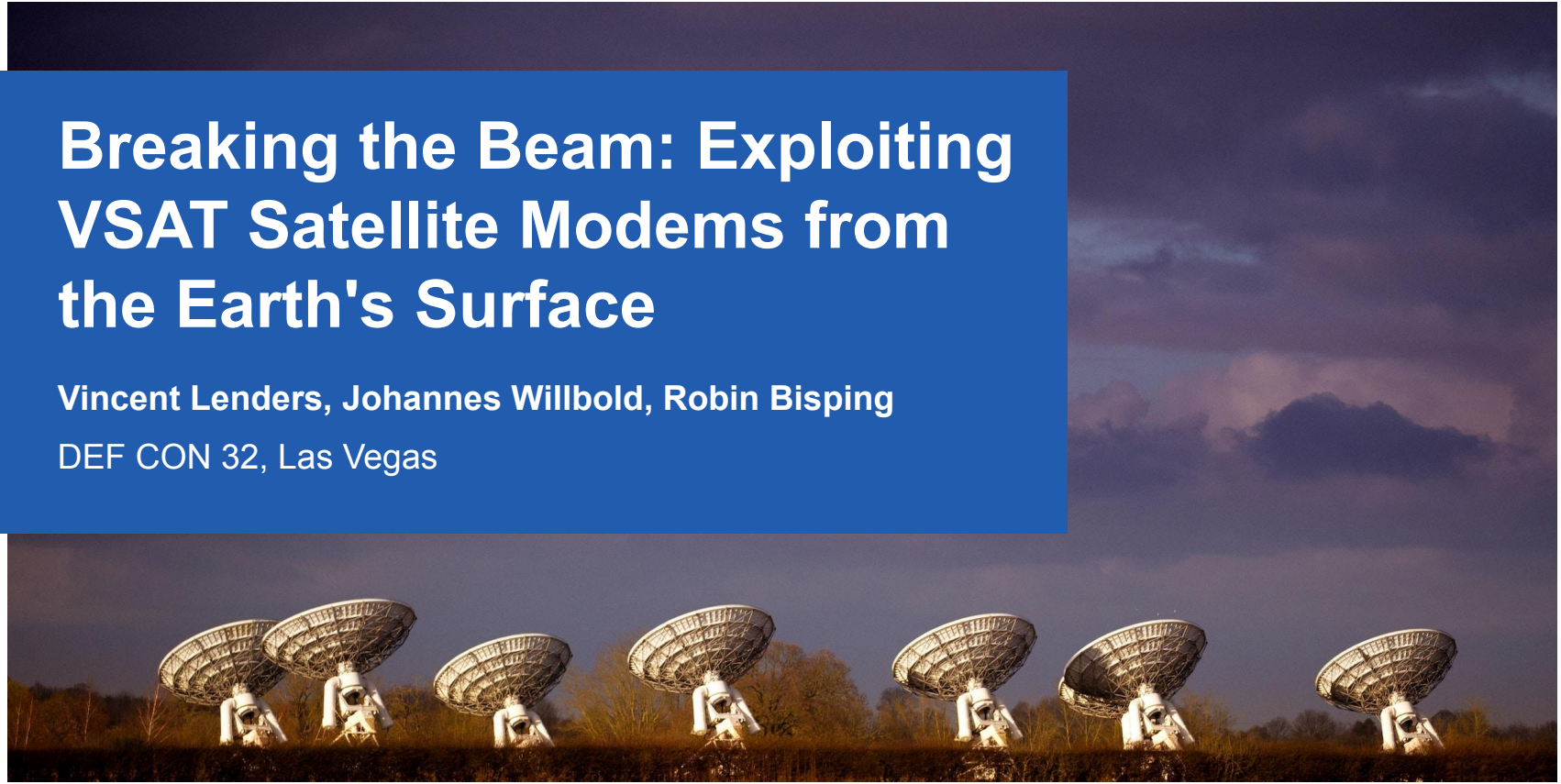
Breaking the Beam: Exploiting VSAT Satellite Modems from the Earth's Surface

Vincent Lenders, Johannes Willbold, Robin Bisping

DEF CON 32, Las Vegas



Ben Wicks / Unsplash

Introduction
About us

Vincent Lenders is a senior cybersecurity researcher with a strong focus on the security of wireless networks. He acts as the Head of Switzerland's Cyber-Defence Campus.



Johannes Willbold is a PhD student at the Ruhr University Bochum and researches the software security of space and satellite systems.



Robin Bisping is a graduate student of ETH Zurich and the Cyber-Defence Campus, where his research focused on the security of satellite systems.



VSAT Satellite Communication

VSAT = Very Small Aperture Terminal

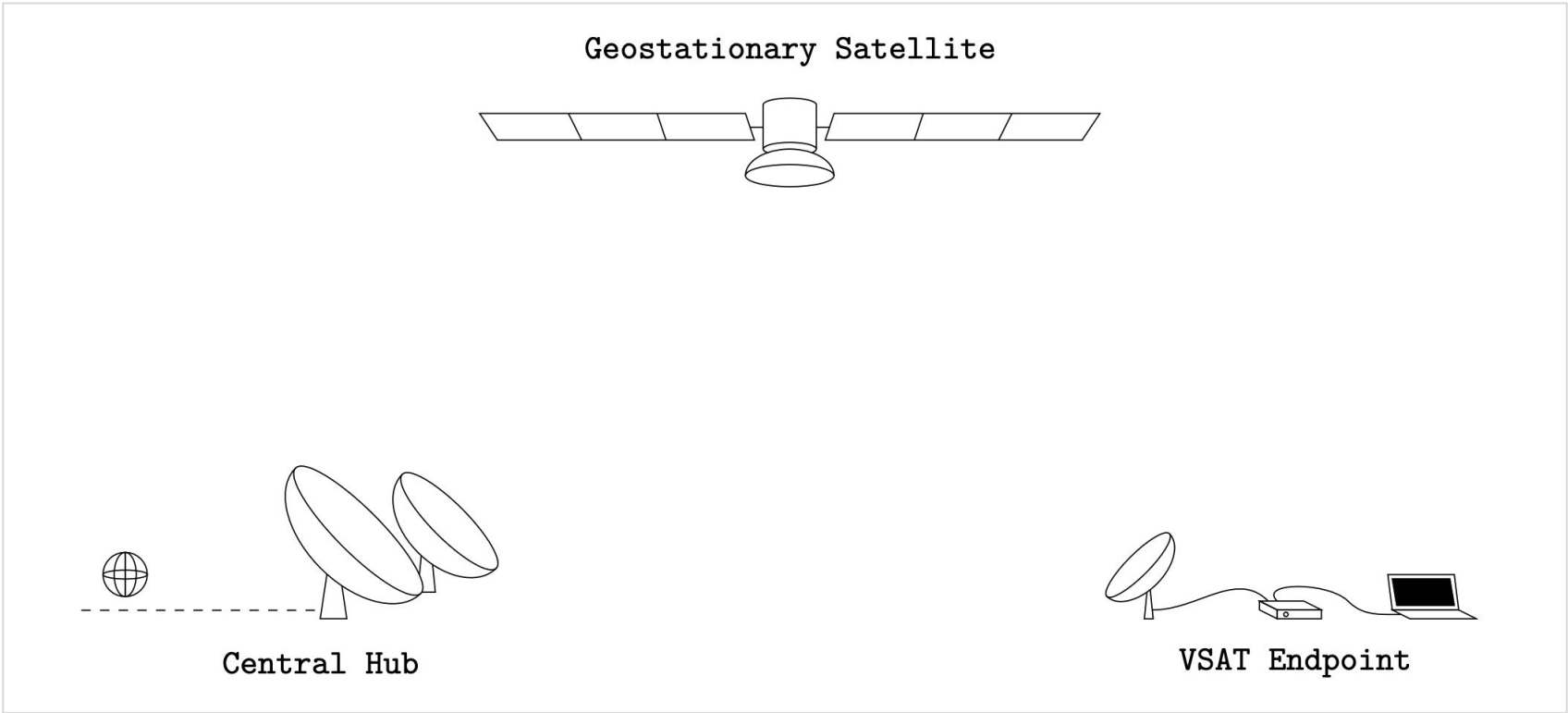


maritime VSAT

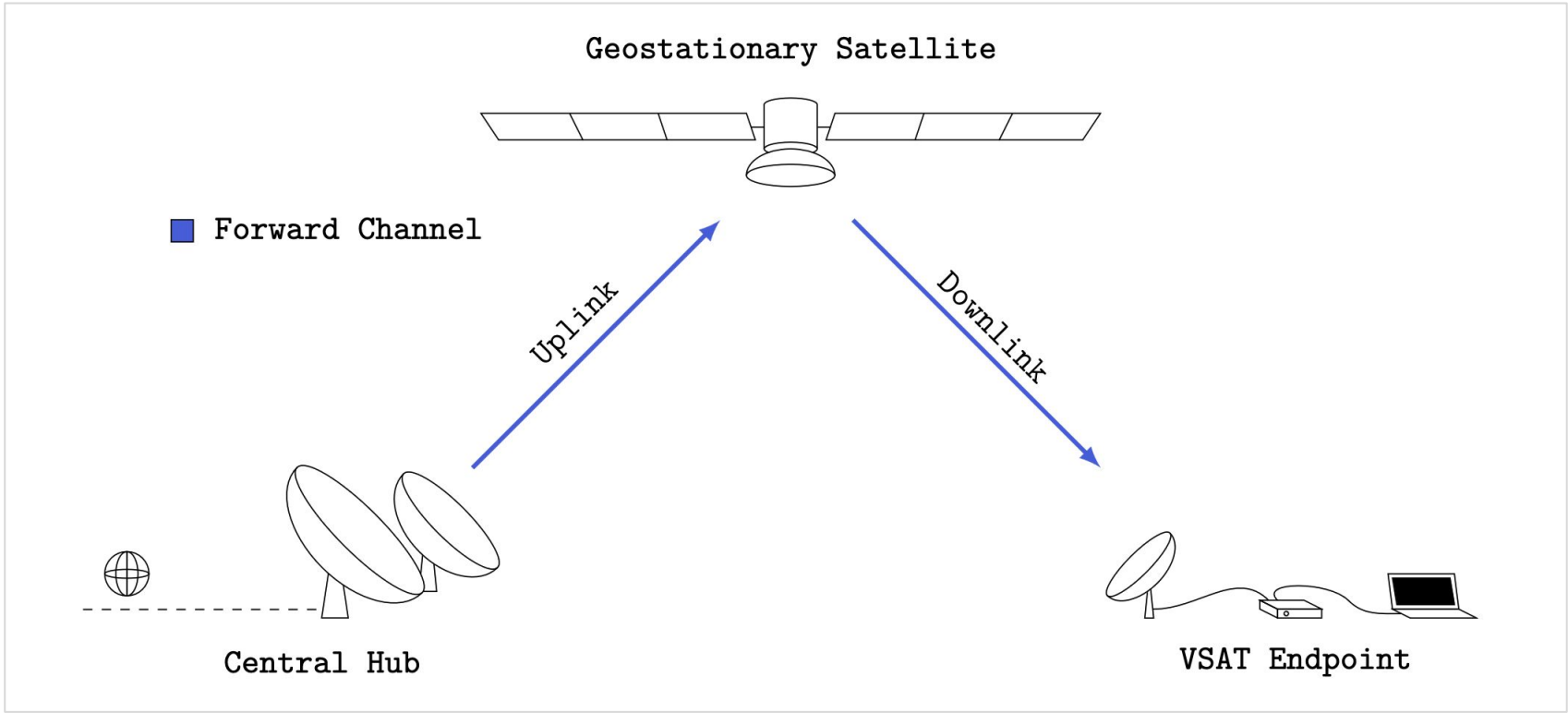


terrestrial VSAT

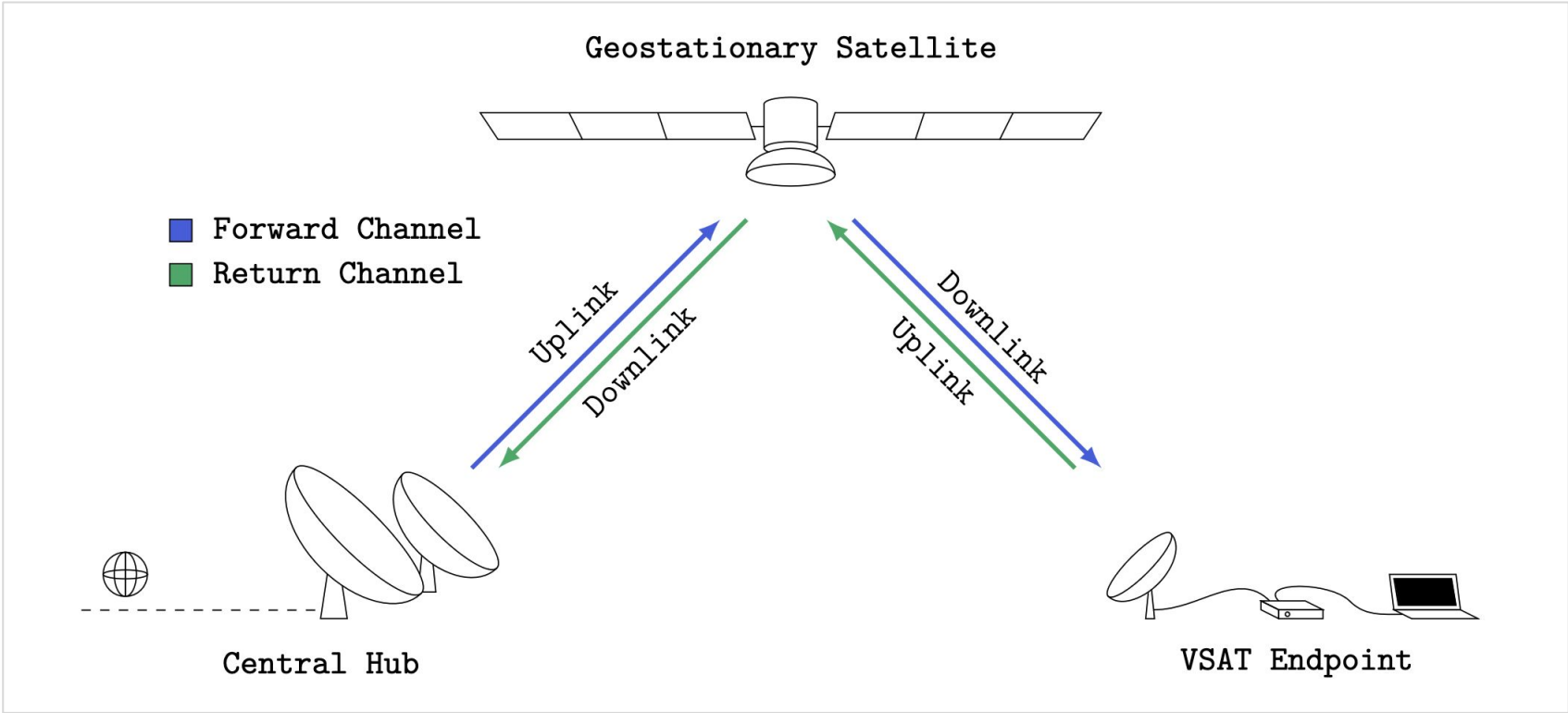
Background
VSAT Satellite Communication Systems



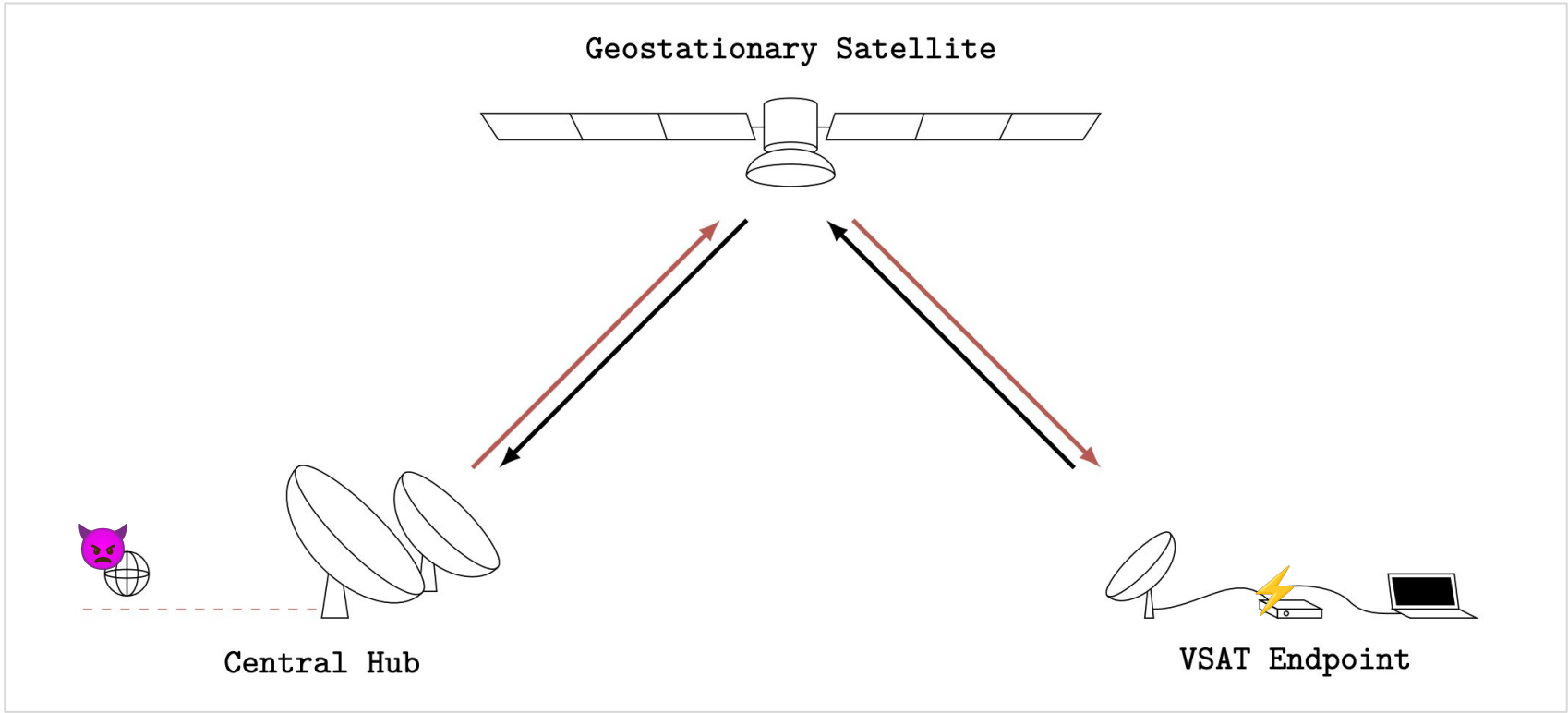
Background
VSAT Satellite Communication Systems



Background
VSAT Satellite Communication Systems

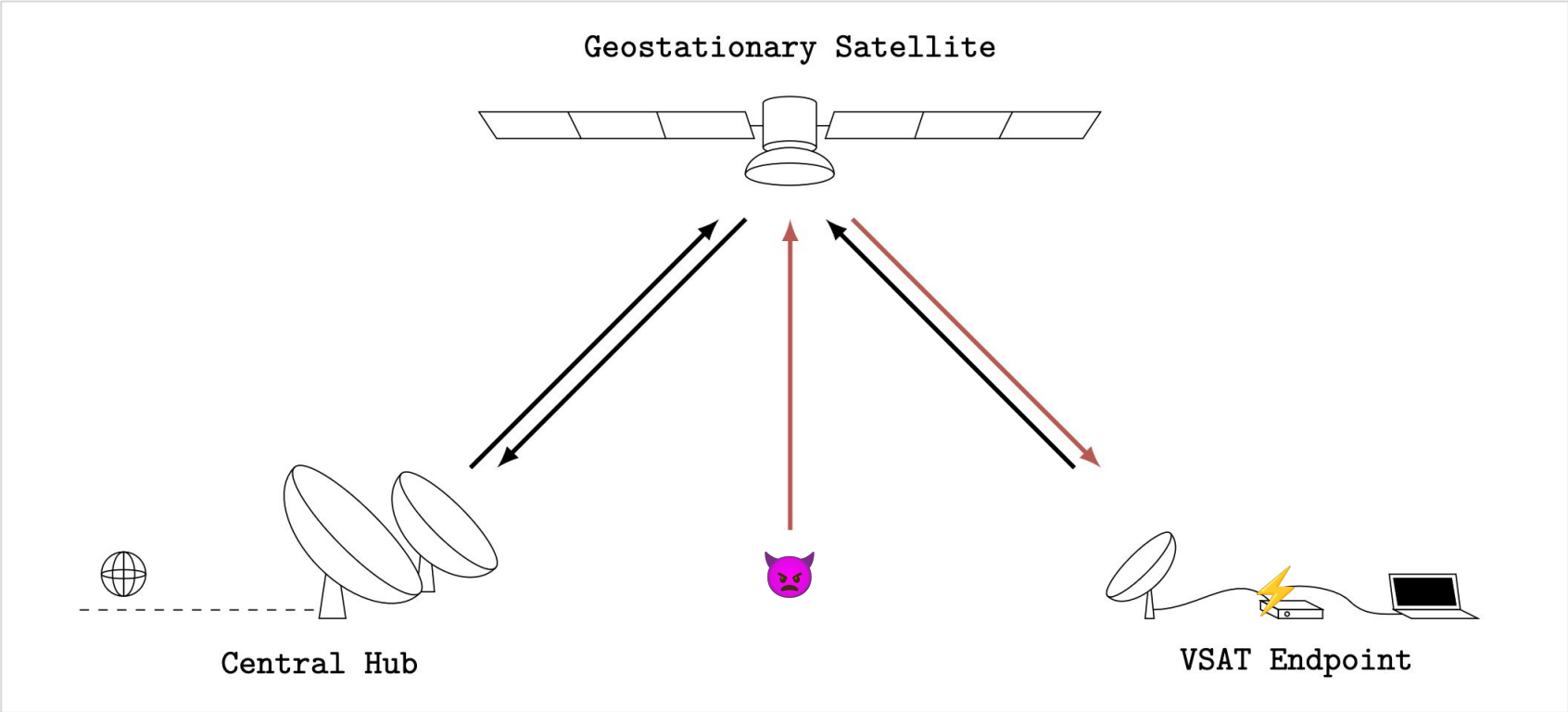


Threat Models
1) Attacking the Central Hub



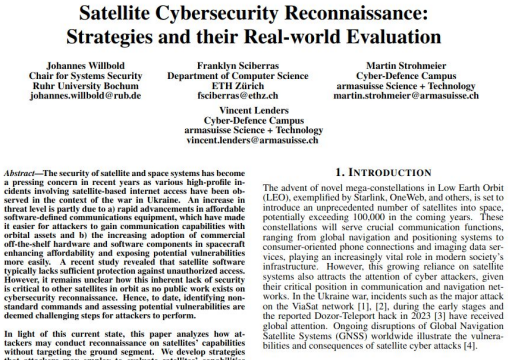

Businessweek
The Satellite Hack Everyone Is Finally Talking About
As Putin began his invasion of Ukraine, a network used throughout Europe—and by the Ukrainian military—faced an unprecedented cyberattack that doubled as an industrywide wake-up call.
By Katrina Manson
Illustrations by Jordan Speer
1 March 2023 at 00:01 GMT+1
https://www.bloomberg.com/features/2023-russia-viasat-hack-ukraine/

Threat Models
2) Attacking the Satellites



Threat Models
Our previous Work on Attacking the Satellites

IEEE Aerospace 2024



Satellite Cybersecurity Reconnaissance: Strategies and their Real-world Evaluation

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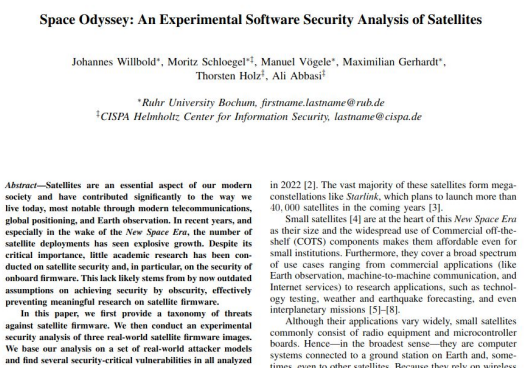
***Abstract*—The security of satellite and space systems has become a pressing concern in recent years as various high-profile incidents involving satellite-based internet access have been observed in the context of the war in Ukraine. An increase in threat level is partly due to a) rapid advancements in affordable software-defined communications equipment, which have made it easier for attackers to gain communication capabilities with orbital assets and b) the increasing adoption of commercial off-the-shelf hardware and software components in spacecraft enhancing affordability and exposing potential vulnerabilities more easily. A recent study revealed that satellite software typically lacks sufficient protection against unauthorized access. However, it remains unclear how this inherent lack of security is critical to other satellites in orbit as no public work exists on cybersecurity reconnaissance. Hence, to date, identifying non-standard commands and assessing potential vulnerabilities are deemed challenging steps for attackers to perform.**

In light of this current state, this paper analyzes how attackers may conduct reconnaissance on satellites' capabilities without targeting the ground segment. We develop strategies

1. Introduction

The advent of novel mega-constellations in Low Earth Orbit (LEO), exemplified by Starlink, OneWeb, and others, is set to introduce an unprecedented number of satellites into space, potentially exceeding 100,000 in the coming years. These constellations will serve crucial communication functions, ranging from global navigation and positioning systems to consumer-oriented phone connections and imaging data services, playing an increasingly vital role in modern society's infrastructure. However, this growing reliance on satellite systems also attracts the attention of cyber attackers, given their critical position in communication and navigation networks. In the Ukraine war, incidents such as the major attack on the ViaSat network [1], [2], during the early stages and the reported Dozor-Teleport hack in 2023 [3] have received global attention. Ongoing disruptions of Global Navigation Satellite Systems (GNSS) worldwide illustrate the vulnerabilities and consequences of satellite cyber attacks [4].

IEEE S&P 2023



Space Odyssey: An Experimental Software Security Analysis of Satellites

Johannes Willbold*, Moritz Schloegel*‡, Manuel Vögele*, Maximilian Gerhardt*,
Thorsten Holz‡, Ali Abbasi‡

*Ruhr University Bochum, firstname.lastname@rub.de
‡CISPA Helmholtz Center for Information Security, lastname@cispa.de

***Abstract*—Satellites are an essential aspect of our modern society and have contributed significantly to the way we live today, most notable through modern telecommunications, global positioning, and Earth observation. In recent years, and especially in the wake of the *New Space Era*, the number of satellite deployments has seen explosive growth. Despite its critical importance, little academic research has been conducted on satellite security and, in particular, on the security of onboard firmware. This lack likely stems from by now outdated assumptions on achieving security by obscurity, effectively preventing meaningful research on satellite firmware.**

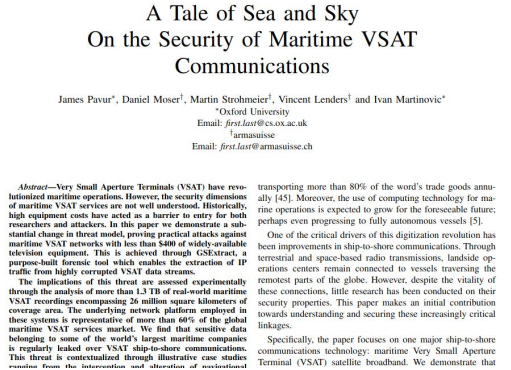
In this paper, we first provide a taxonomy of threats against satellite firmware. We then conduct an experimental security analysis of three real-world satellite firmware images. We base our analysis on a set of real-world attacker models and find several security-critical vulnerabilities in all analyzed

in 2022 [2]. The vast majority of these satellites form mega-constellations like *Starlink*, which plans to launch more than 40,000 satellites in the coming years [3].

Small satellites [4] are at the heart of this *New Space Era* as their size and the widespread use of Commercial off-the-shelf (COTS) components makes them affordable even for small institutions. Furthermore, they cover a broad spectrum of use cases ranging from commercial applications (like Earth observation, machine-to-machine communication, and Internet services) to research applications, such as technology testing, weather and earthquake forecasting, and even interplanetary missions [5]–[8].

Although their applications vary widely, small satellites commonly consist of radio equipment and microcontroller boards. Hence—in the broadest sense—they are computer systems connected to a ground station on Earth and, sometimes, even to other satellites. Because they rely on wireless

IEEE S&P 2020



A Tale of Sea and Sky
On the Security of Maritime VSAT Communications

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***Abstract*—Very Small Aperture Terminals (VSAT) have revolutionized maritime operations. However, the security dimensions of maritime VSAT services are not well understood. Historically, high equipment costs have acted as a barrier to entry for both researchers and attackers. In this paper we demonstrate a substantial change in threat model, proving practical attacks against maritime VSAT networks with less than $400 of widely-available television equipment. This is achieved through GSExtract, a purpose-built forensic tool which enables the extraction of IP traffic from highly corrupted VSAT data streams.**

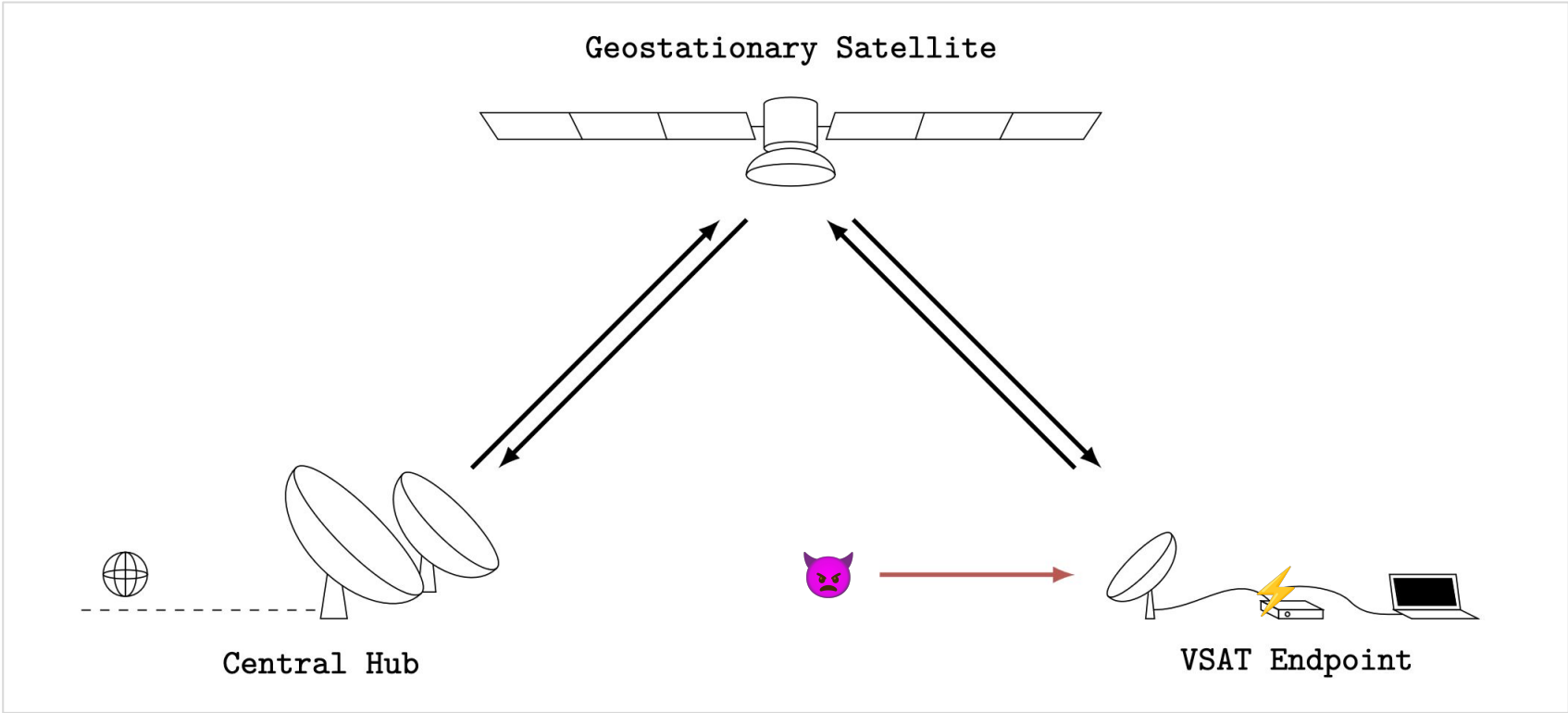
The implications of this threat are assessed experimentally through the analysis of more than 1.3 TB of real-world maritime VSAT recordings encompassing 26 million square kilometers of coverage area. The underlying network platform employed in these systems is representative of more than 60% of the global maritime VSAT services market. We find that sensitive data belonging to some of the world's largest maritime companies is regularly leaked over VSAT ship-to-shore communications. This threat is contextualized through illustrative case studies

transporting more than 80% of the world's trade goods annually [45]. Moreover, the use of computing technology for marine operations is expected to grow for the foreseeable future; perhaps even progressing to fully autonomous vessels [5].

One of the critical drivers of this digitization revolution has been improvements in ship-to-shore communications. Through terrestrial and space-based radio transmissions, landside operations centers remain connected to vessels traversing the remotest parts of the globe. However, despite the vitality of these connections, little research has been conducted on their security properties. This paper makes an initial contribution towards understanding and securing these increasingly critical linkages.

Specifically, the paper focuses on one major ship-to-shore communications technology: maritime Very Small Aperture Terminal (VSAT) satellite broadband. We demonstrate that

Threat Models
3) Attacking the VSAT Endpoint



Attacking the VSAT Endpoint
Contributions of this Work

- We **reverse engineer** a VSAT modem (Newtec MDM2200 from iDirect) and its communication protocol stack down to the physical layer

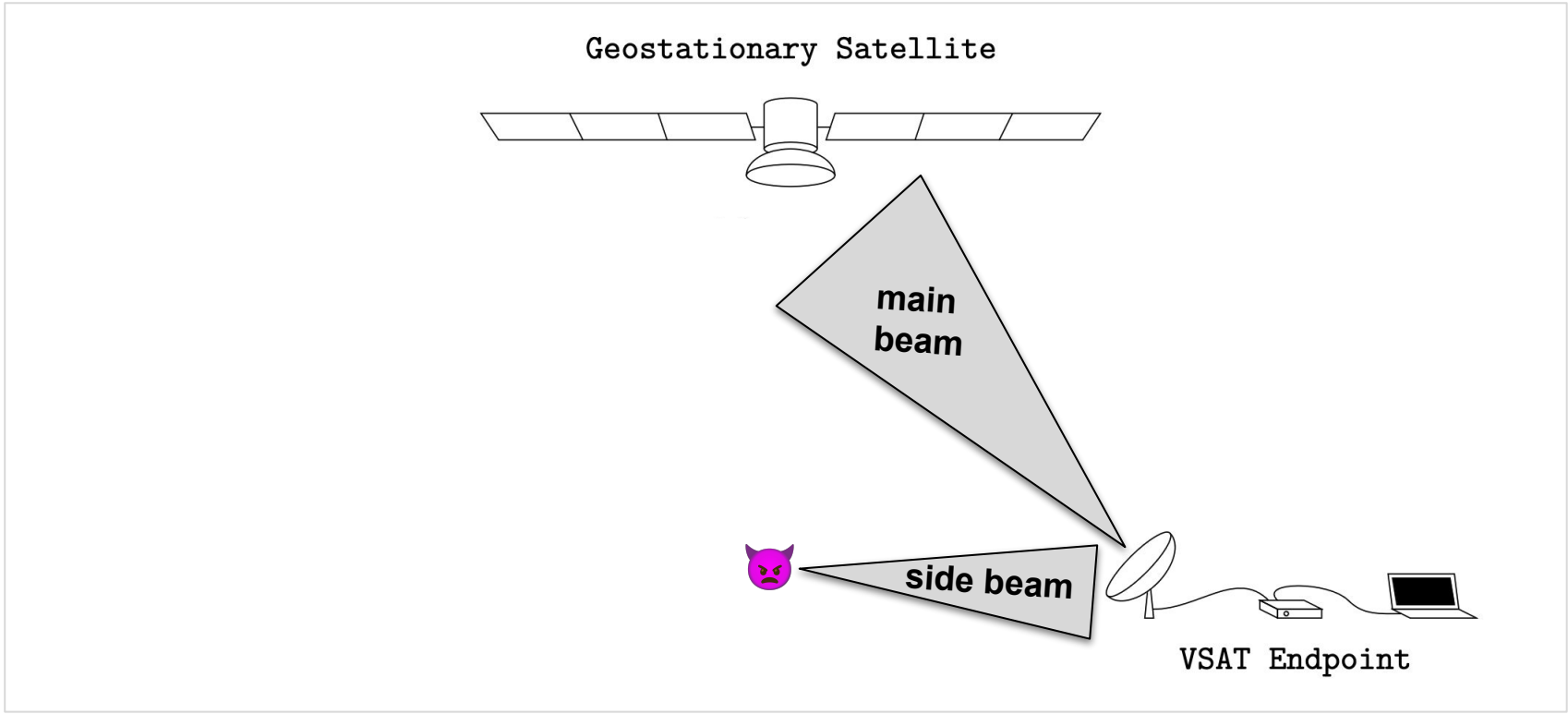
- We find **new vulnerabilitie**s in the control plane of the modem including
  - a WebUI code injection attack
  - a vulnerability in the software update signaling process for unauthenticated privileged RCE

- We develop **three over-the-air wireless attacks** leveraging control-plane traffic authentication bypasses and the discovered vulnerabilities to
  - reset the modem
  - update a malicious firmware
  - obtain a remote admin shell

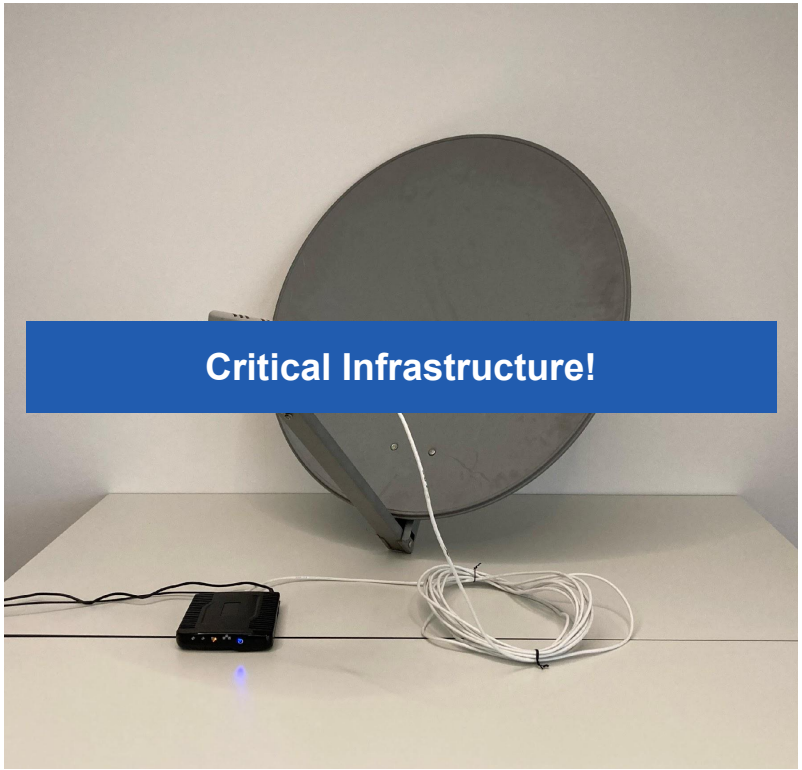
- We demonstrate the feasibility to **break the beam** by launching theses attacks using off-the-shelf software-defined radio equipment from the earth’s surface.

Breaking the Beam

Injecting signals around the main beam of the VSAT endpoint antenna



Case Study
Newtec MDM2200



Centers of Excellence in the U.S., Belgium & Singapore serve the unique needs of each region

5000 hubs deployed supporting over half million modems

#1 Ranking in maritime market – trusted by **8 of the 9 leading service providers** – connecting seafarers and vessels worldwide amongst cruise, oil and gas, commercial shipping and fishing industries

#1 Ranking in aero with 44% market share – linking thousands of passengers, cockpit and ground support crew across **3,000+ commercial planes and business jets**

#1 Ranking in media and broadcast market – enhancing live broadcast capabilities for more than 5 years, enabling more than **3 billion people to watch TV every day**

Leading the digital transformation of the ground segment through strategic partnership with Microsoft Azure and the DIFI consortium

Leading industry collaboration and unified standardization to enable the integration of **5G over satellite**

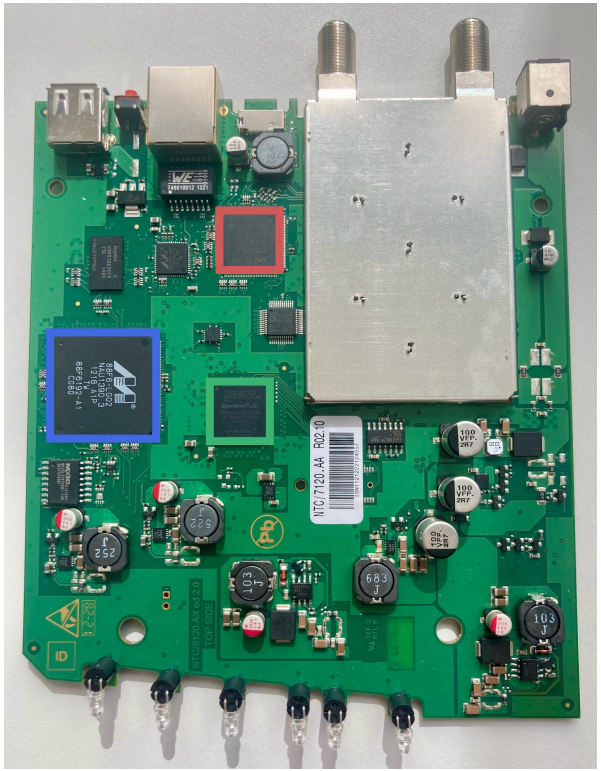
Global leader in government and defense – **#1 ranking in U.S. DoD VSAT** and relied on by 21 of 28 EU nations and 19 of 29 NATO member states

https://www.idirect.net/wp-content/uploads/2020/01/2022-Corporate-Factsheet-US.pdf

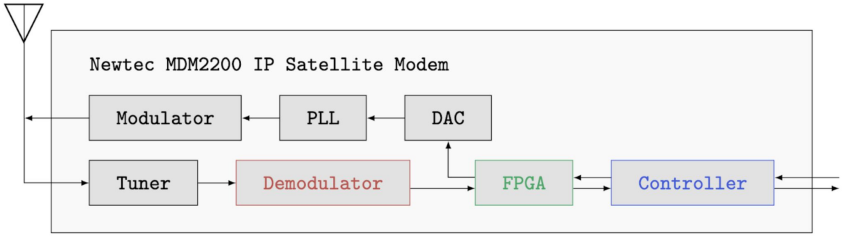
Reverse Engineering

- The modem abstracts the signal processing complexity behind a **network interface**.
- The firewall **accepts all incoming traffic** on this interface.

Reverse Engineering Communications
Information Gathering



- Hardware components provided hints about the protocol stack.
- Open source intelligence: Tech sheets, specifications



Reverse Engineering Communications
Information Gathering

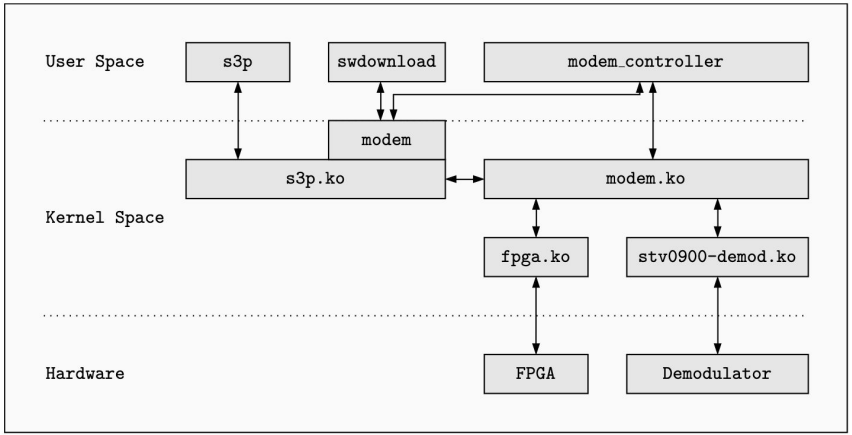
Modem diagnostics

- Confirmed protocol assumptions
- Useful tool while implementing our attacker

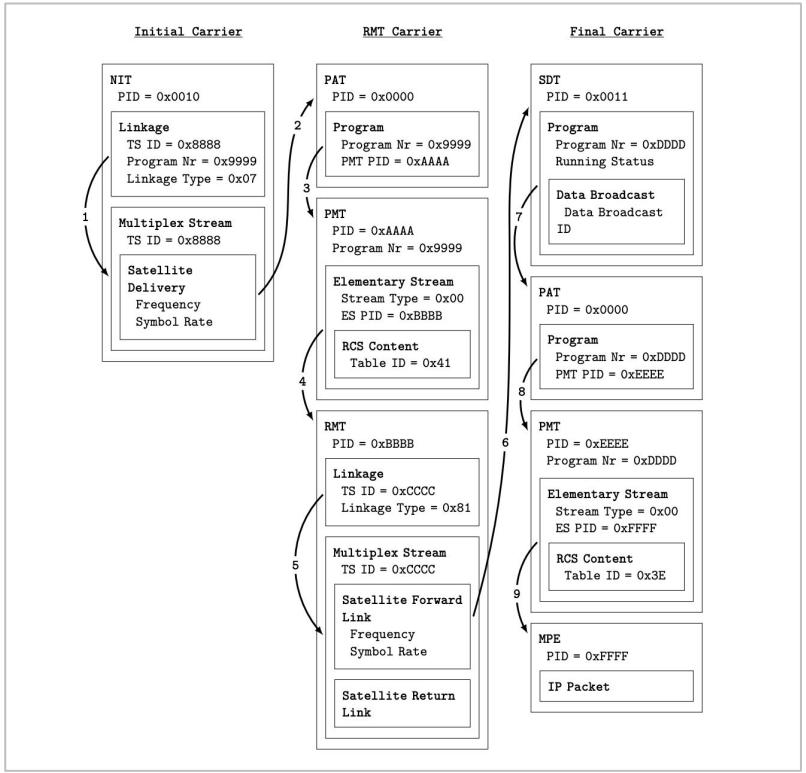
```
==============================
3. Internal modem driver states
==============================
Modem_data:
-----------
INITIAL CARRIER
  Initial carrier selection
  Select_initial_carrier_counter - 0
  NIT - network information table
                table_id                        : 0
                section_length                  : 0
                interactive_network_id  : 0
                version_number                  : 0
                current_next_indicator  : 0
                section_number                  : 0
                last_section_number             : 0
                sections_received               : 0
                Linkage_descr_valid 0
                Sat_del_valid 0
RMT CARRIER
  Rmt carrier selection - select_nit_ts_method
  Rmt carrier selection - selected_NIT_linkage_descr.  0
  Rmt carrier selection - selected_NIT_TS_id_ref           0
  PAT1 - on RMT carrier
                table_id                        : 0
                section_length                  : 0
                interactive_network_id  : 0
                version_number                  : 0
                current_next_indicator  : 0
                section_number                  : 0
                last_section_number             : 0
                sections_received               : 0
                pmt_pid_valid: 0
                rcs_pmt_pid_valid: 0
                rcs_mpe_pmt_pid_valid: 0
  PMT-1 - on RMT carrier
                table_id                        : 0
                section_length                  : 0
                interactive_network_id  : 0
                version_number                  : 0
                current_next_indicator  : 0
                section_number                  : 0
                last_section_number             : 0
                sections_received               : 0
```

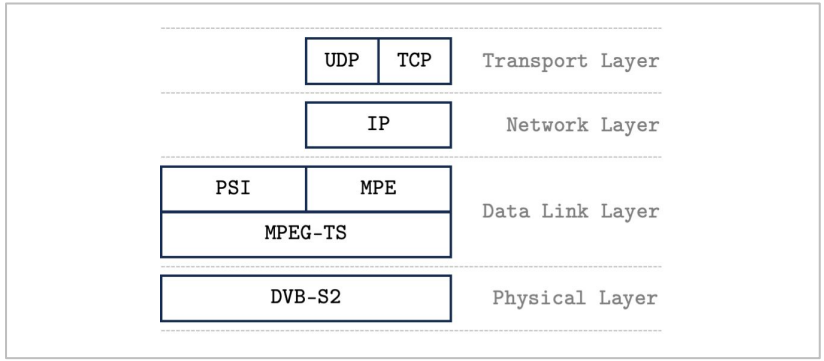
Analyzing binaries

- We had extracted the firmware
- Binaries contained debugging symbols



Protocols
DVB-RCS / Sat3Play

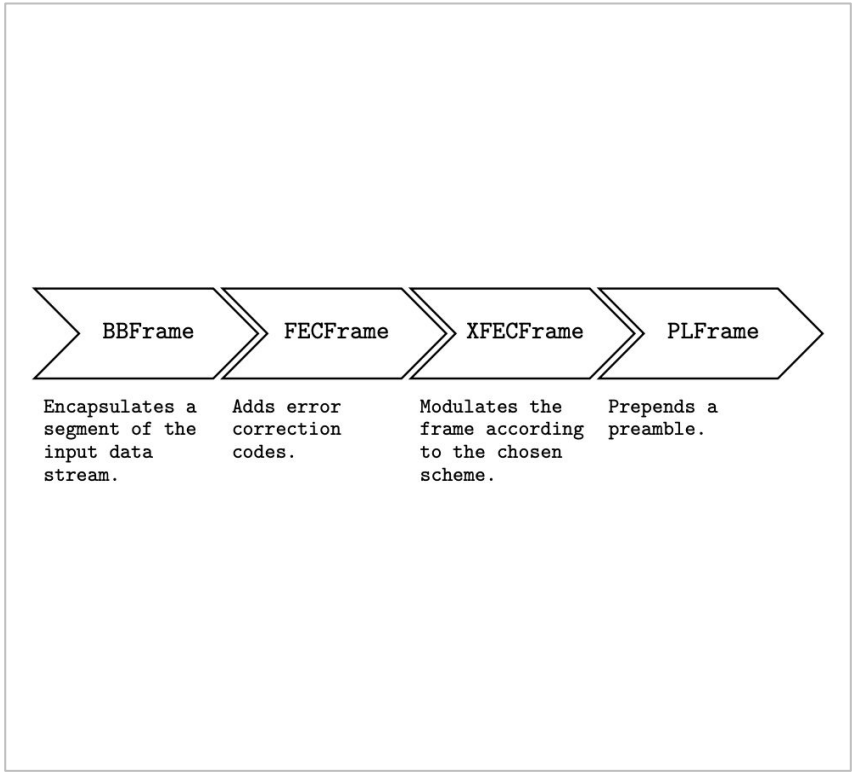




- **DVB-RCS** provides a **standardized framework for satellite communication**.
- **Security is optional**.

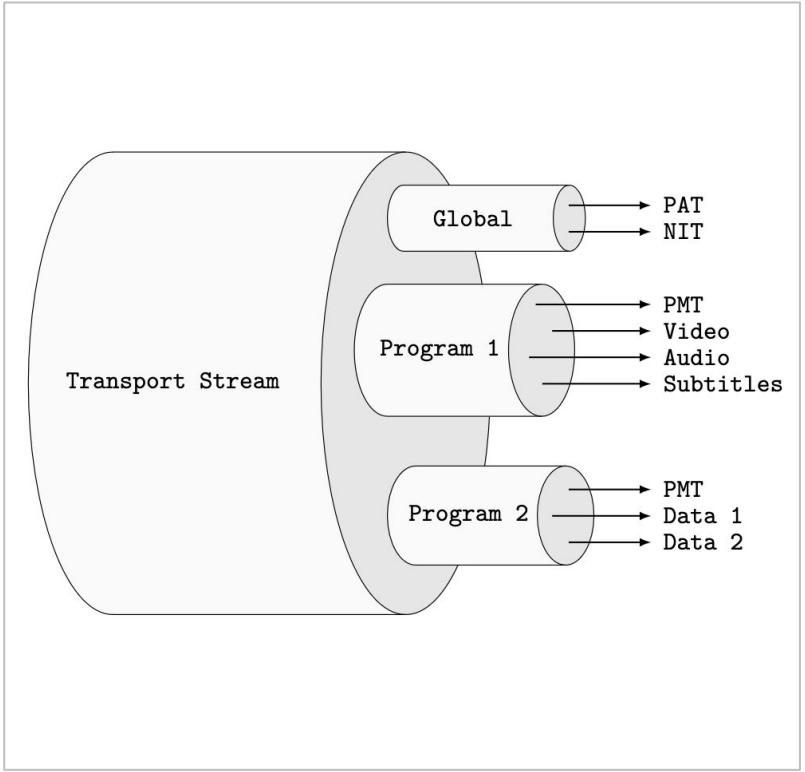
- **S3P** is Newtec's **proprietary implementation of DVB-RCS**.
- It deviates from DVB-RCS in several respects.

Protocols
DVB-S2



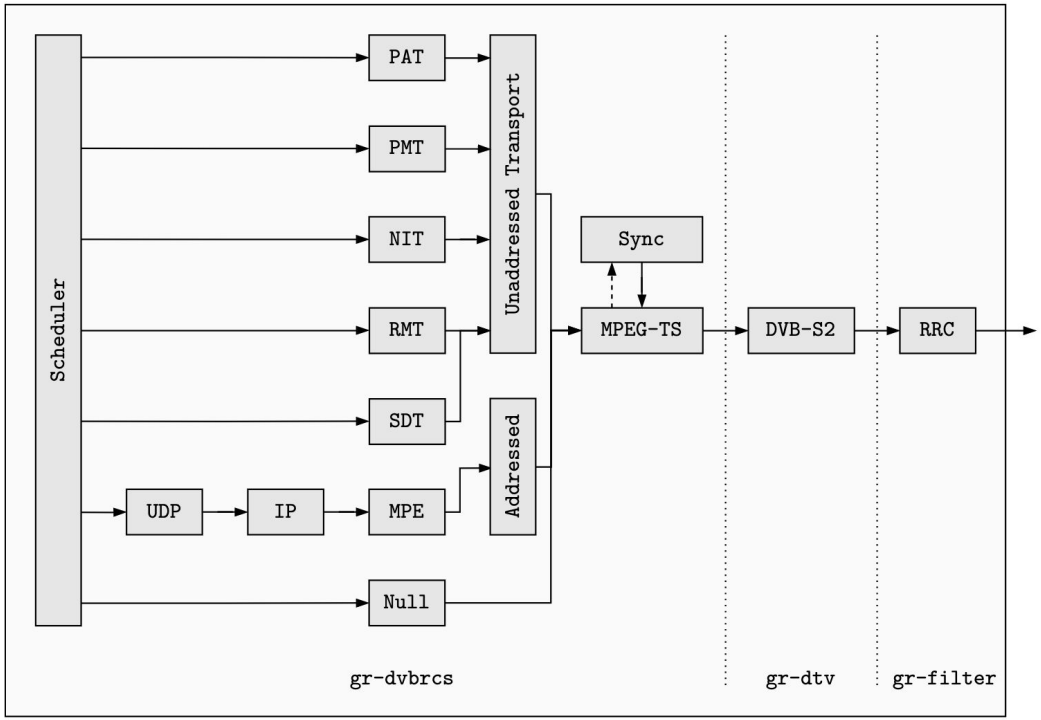
- Support for **multiple modulation schemes**, such as QPSK, 8PSK, and 16APSK.
- Employs BCH and LDPC **error correction codes**.

Protocols
MPEG-TS



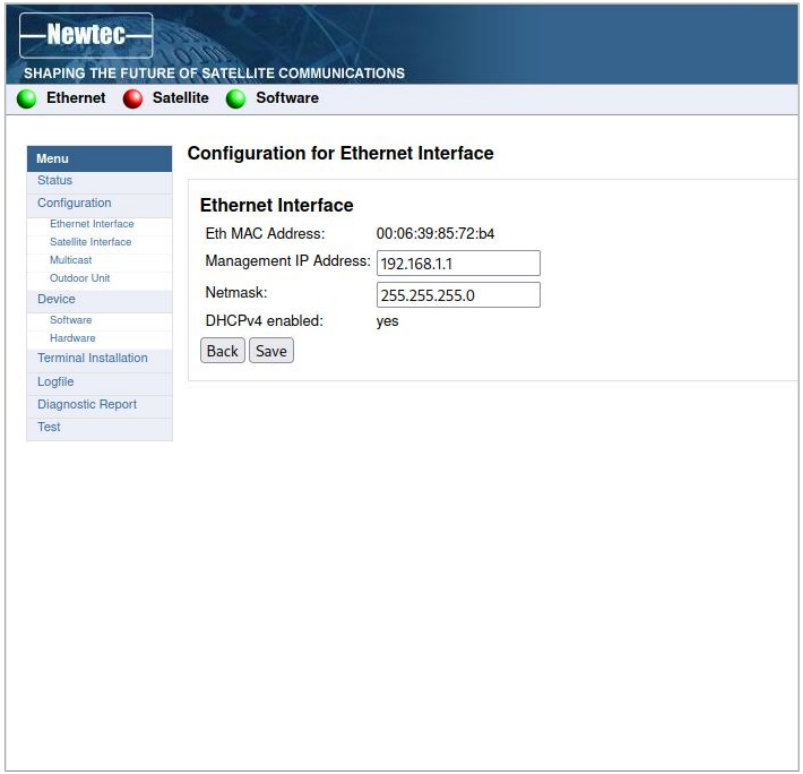
- An **elementary stream** refers to an individual audio, video, or data stream.
- A **program/service** bundles multiple elementary streams that belong together.
- A **transport stream** aggregates multiple services.

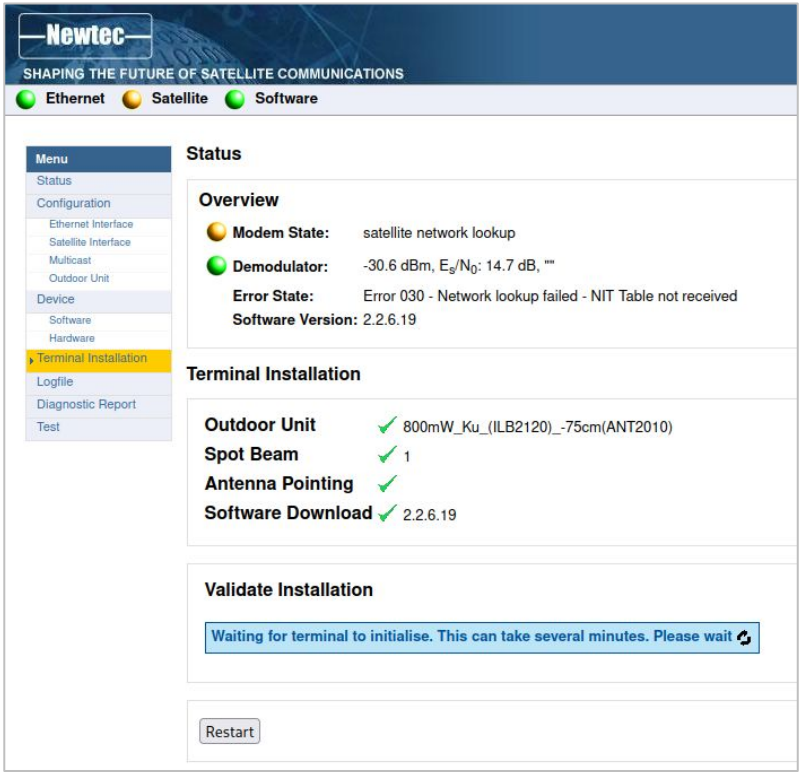
Implementation
Transmitter



- GNU Radio based implementation of only the **forward channel**.

Implementation
Transmitter





Implementation
Transmitter

```
# $ tcpdump -Ani modem
00:05:47.833082 IP 127.0.0.1.49152 > 127.0.0.1.49152: UDP, length 14
E..*..@.@.<.................Hello, World!.
00:05:48.044327 IP 127.0.0.1.49152 > 127.0.0.1.49152: UDP, length 14
E..*..@.@.<.................Hello, World!.
00:05:48.255568 IP 127.0.0.1.49152 > 127.0.0.1.49152: UDP, length 14
E..*..@.@.<.................Hello, World!.
```

✓ Our transmitter implementation allows us to **inject arbitrary IP packets** into the modem's network stack.

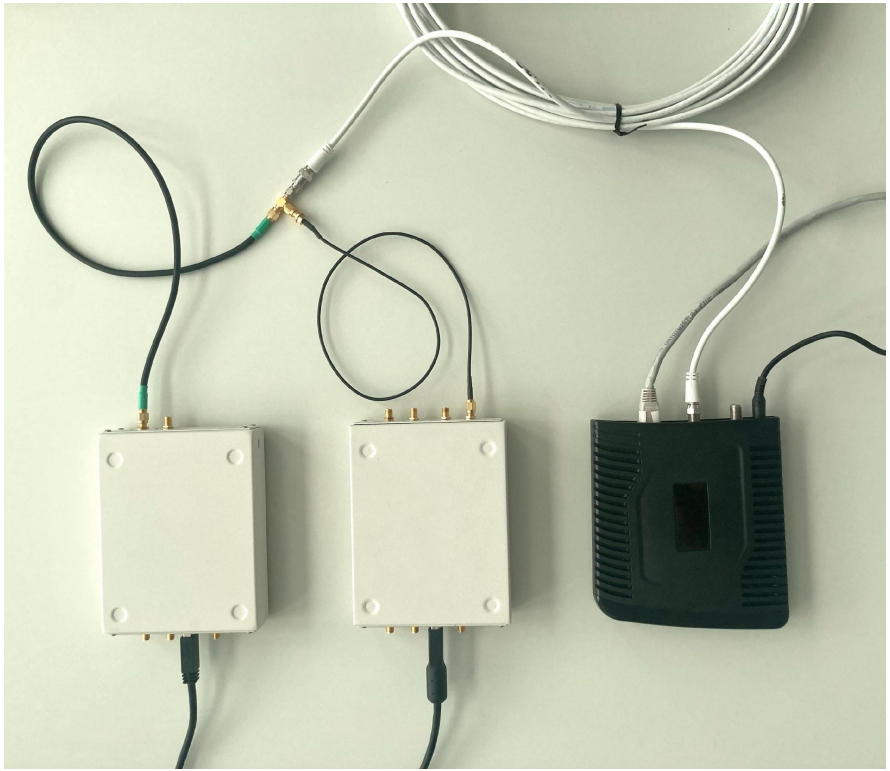
Attack
Modem Reset

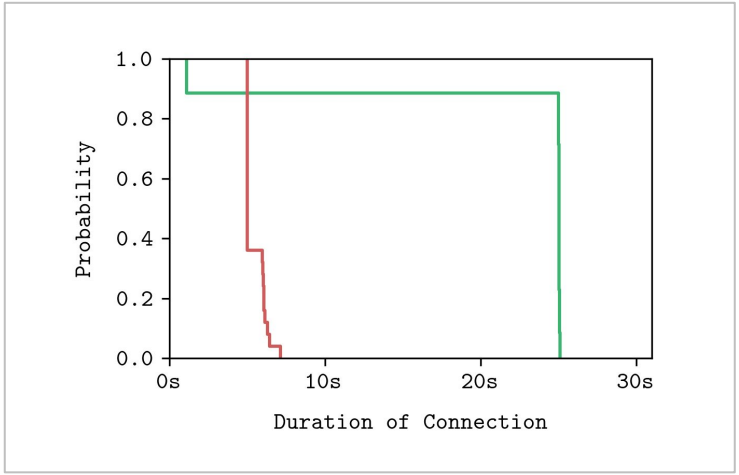
- We emit a **jamming signal** consisting of random noise at the same frequency as the forward channel.
- We establish a jamming-to-signal ratio of **J/S = 1**, as our objective is to only interfere with the signal rather than overpower it.

✓ Because the modem is no longer able to receive the configuration packets, the **modem restarts the channel initialization process**.

✓ By keeping the jamming signal on, the modem is **not able to reinitialize to the forward channel**.

Attack
Modem Reset

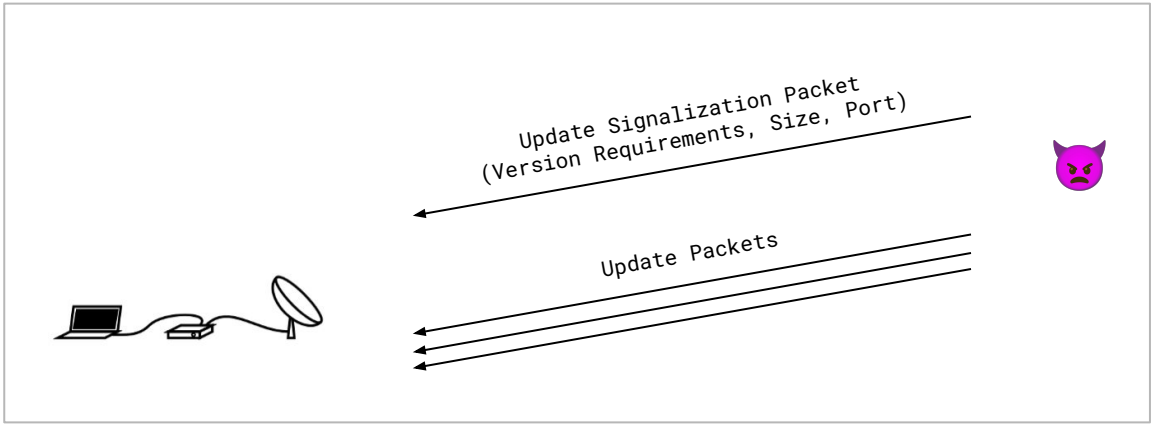




- Under **jamming** a deterioration in connection duration is noticeable.
- Under **normal conditions** the modem anticipates return channel configurations after 25 seconds.

Attack
Malicious Firmware Update

- To not risk rendering the modem inoperable, we transmit an **update with an invalid checksum**.
- The signalization packet and the firmware update are **neither authenticated nor encrypted**.



Attack
Malicious Firmware Update

```
Jan 1 00:00:38 S3P user.info swdownload[396]: All data received
Jan 1 00:00:38 S3P user.info swdownload[396]: All packets received
Jan 1 00:00:38 S3P user.info swdownload[396]: SW download finished
Jan 1 00:00:38 S3P user.err  swdownload[396]: CRC on the header was not correct!
Jan 1 00:00:38 S3P user.err  swdownload[396]: - Calculated=1972200246, expected=0n
Jan 1 00:00:38 S3P user.info swdownload[396]: CRC not correct!
```

- ✓ The modem confirms the **successful firmware reception**.
- ✓ Allows an attacker to **overwrite the firmware**.

Attack
Remote Admin Shell

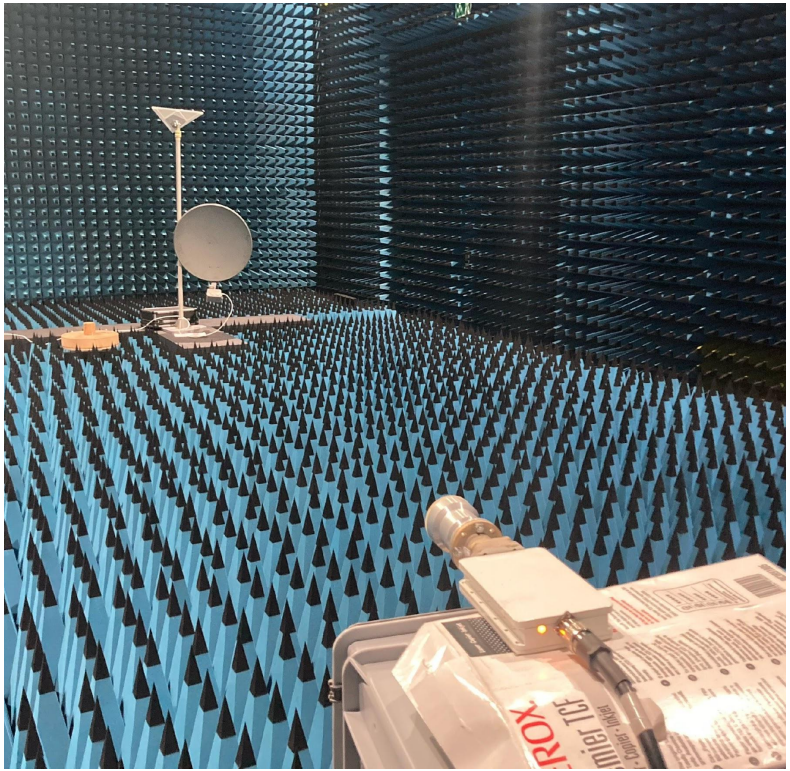
- We inject a signal that contains our **exploit of the RCE vulnerability**.

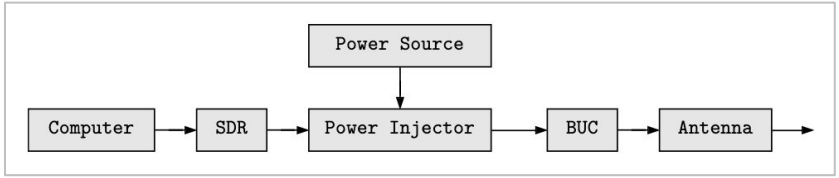


✓ We were able to execute commands with visibly verifiable results, for example by **turning on an LED**.

✓ We were able to open a **reverse shell to a host in the LAN**.

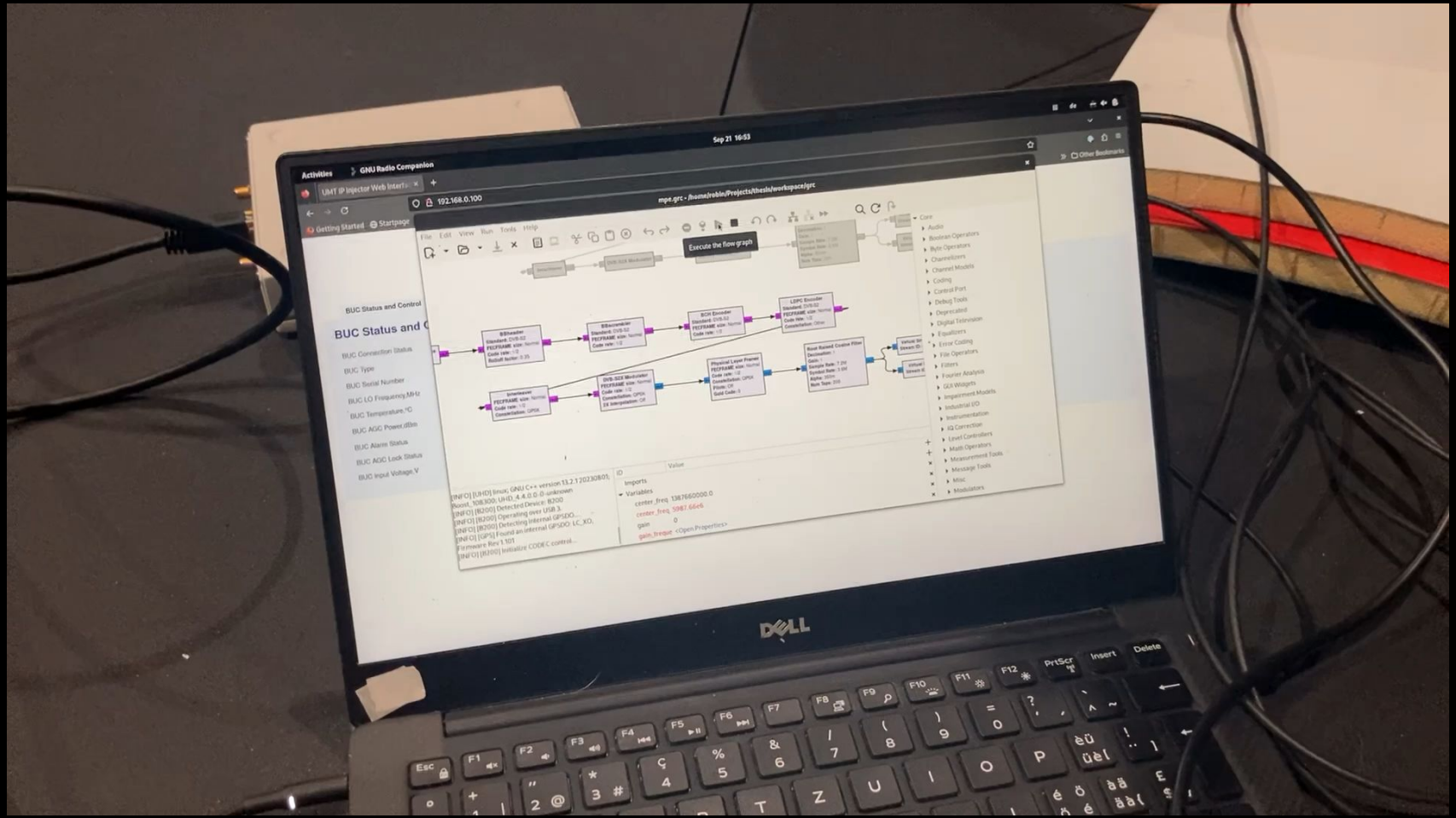
Evaluation
Hardware Setup





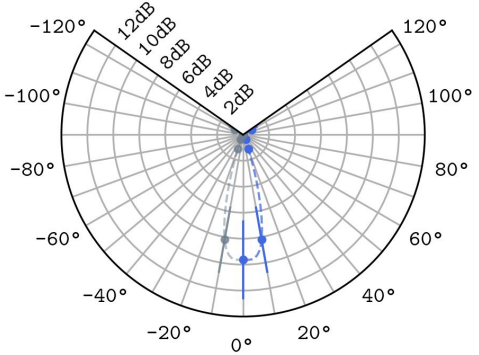
- Software-defined Radio:
  Ettus Research USRP B200
- Power Injector:
  UMT-TV BUC-Ku002-10.6 v2.0
- Block Upconverter:
  UMT-TV DC Injector IDCI with IP Ctrl
- Antenna:
  UMT-TV Offset Feed

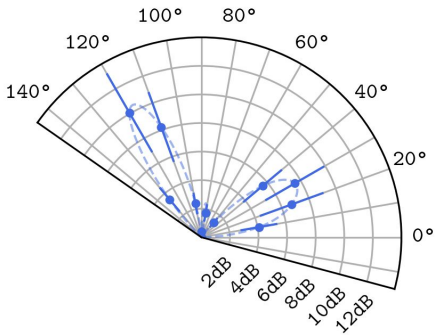
~ $2000


Activities
GNU Radio Companion
Sep 21 16:53
192.168.0.100
mpe.grc - /home/robin/Projects/thesis/workspace/grc
Execute the flow graph
BUC Status and Control
BUC Status and
BUC Connection Status
BUC Type
BUC Serial Number
BUC LO Frequency,MHz
BUC Temperature,°C
BUC AGC Power,dBm
BUC Alarm Status
BUC AGC Lock Status
BUC Input Voltage,V
DELL

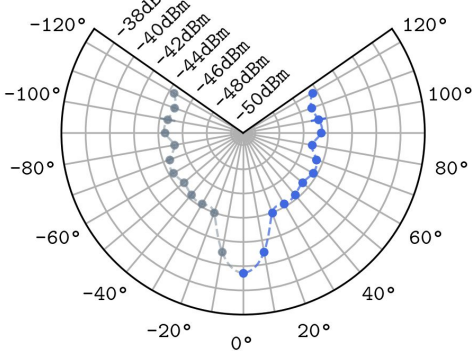
Evaluation
Anechoic Environment (TX Power: 9.5dBm)

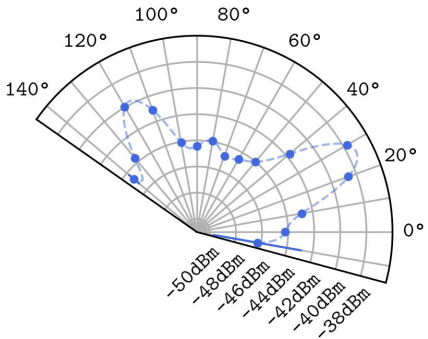
Signal-to-Noise Ratio



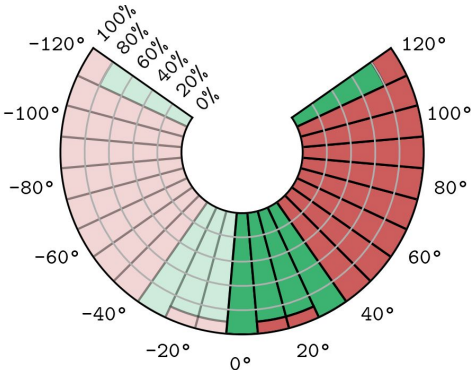


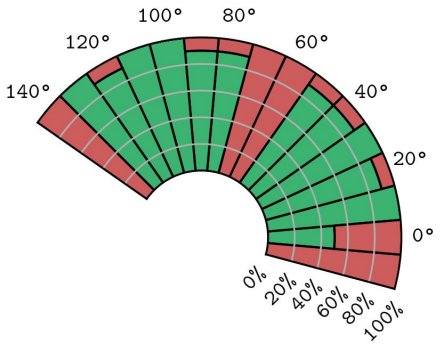
Signal Strength





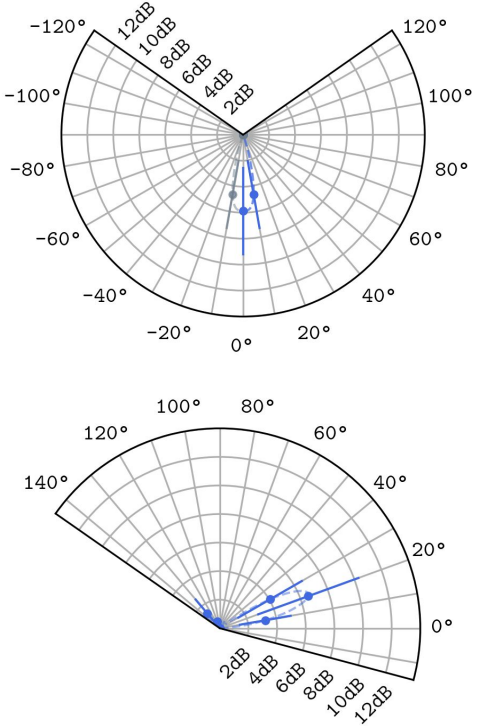
Success Ratio



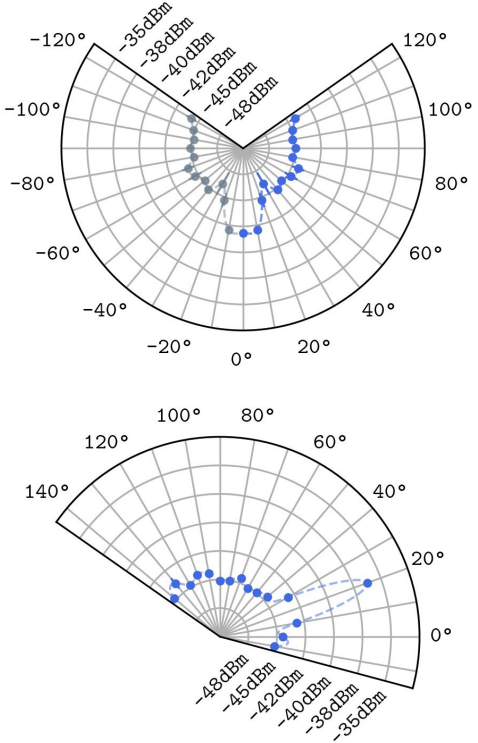


Evaluation
Multipath Environment (TX Power: low)

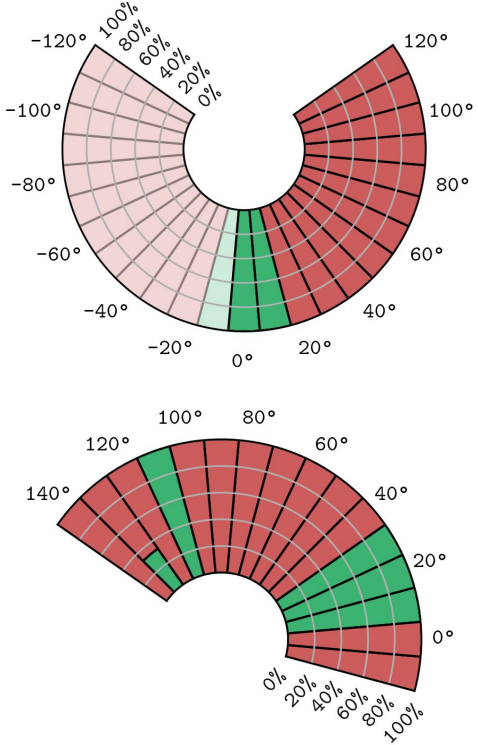
Signal-to-Noise Ratio



Signal Strength

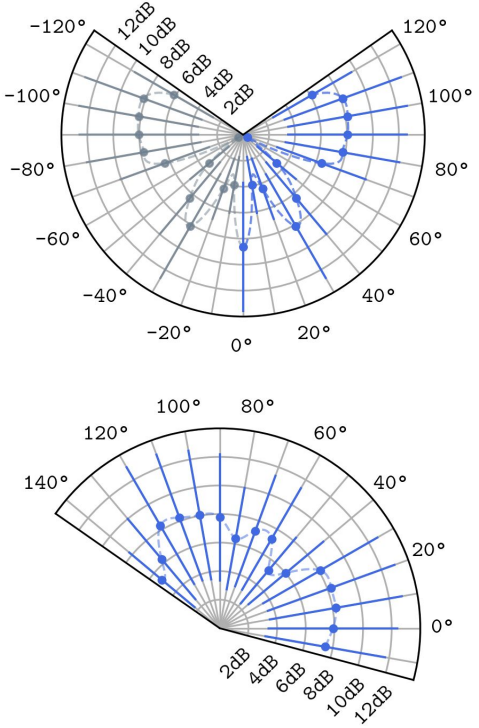


Success Ratio

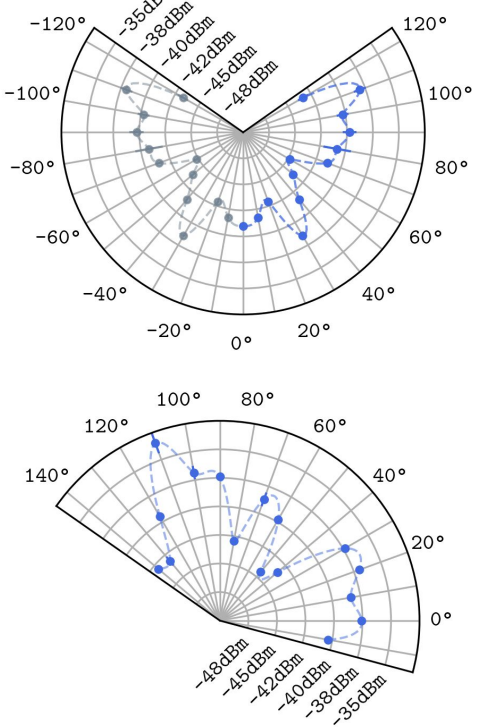


Evaluation
Multipath Environment (TX Power: 9.5dBm)

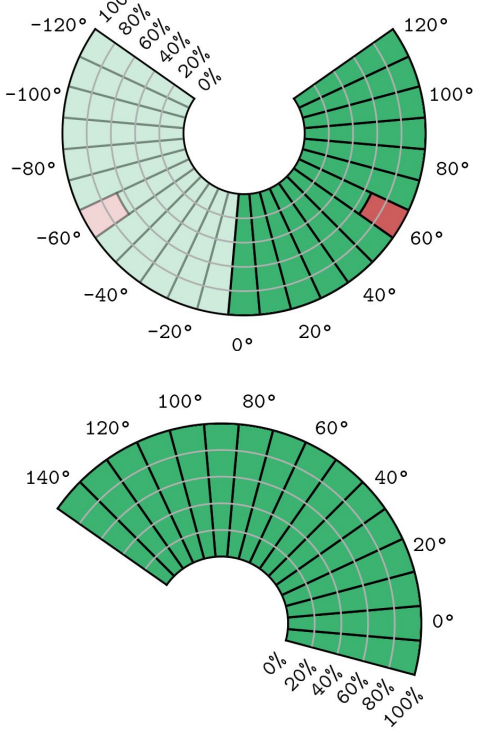
Signal-to-Noise Ratio



Signal Strength



Success Ratio



Real-World Impact

- Attacks demonstrated on the Newtec MDM2200 from iDirect can be launched with a budget of **US $ 2,300**
- Attacks expected to work on other modems of the same vendor that use **Sat3Play**
- We believe that the results of this study can be transferred with only minimal adjustments to devices from other vendors that are based on **DVB-RCS** (e.g. Viasat, Hughes, Advantech and Satlink)
- The market share of such solutions is estimated at around **10-20%** out of millions of deployed VSAT terminals

Possible Mitigations

Physical layer

- Spoofing detection
- Signal fingerprinting

Data link layer

- MAC layer encryption
- Source authentication

Network layer

- IPSec

Conclusion

- VSAT systems are deployed in **critical infrastructures**
- We reversed engineered a VSAT modem and analyzed signal injection attacks, identifying **numerous potential attack vectors** due to a lack of mandatory authentication.
- We introduced an **attacker implementation** that can inject arbitrary IP packets into the Newtec MDM2200.
- We successfully demonstrated three **signal injection attacks**.
- If the transmission power is high enough, signal injection attacks can potentially be carried out **from any angle on earth and hence break the beam**.