

Uplink security against airborne adversaries in non-geostationary satellite communications

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Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 31.7.2023

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Title Uplink security against airborne adversaries in non-geostationary satellite communications

Degree programme Master's Programme in Automation and Electrical Engineering

Major Electronic and Digital Systems

Code of major ELEC3060

Supervisor Asst. Prof. Jaan Praks

Advisor M. Sc. (Tech) Tapio Savunen

Date 31.7.2023

Number of pages 22+2

Language English

Abstract

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Keywords For keywords choose, concepts that are, central to your, thesis

Tekijä Markus Säynevirta

Työn nimi Uplink-liikenteen suojaus vihollisen ilma-aluksia vastaan
ei-geostationaarisessa satelliittiviestinnässä

Koulutusohjelma Elektroniikka ja sähkötekniikka

Pääaine Elektroniset ja digitaaliset järjestelmät
(TARKISTA) **Pääaineen koodi** ELEC3060

Työn valvoja Apul. prof. Jaan Praks

Työn ohjaaja DI Tapio Savunen

Päivämäärä 31.7.2023 **Sivumäärä** 22+2 **Kieli** Englanti

Tiivistelmä

Tiivistelmässä on lyhyt selvitys kirjoituksen tärkeimmästä sisällöstä: mitä ja miten on tutkittu, sekä mitä tuloksia on saatu.

Avainsanat Vastus, resistanssi, lämpötila

Preface

I want to thank Professor Pirjo Professori and my instructor Dr Alan Advisor for their good and poor guidance.

Espoo, 31.7.2023

Markus Säynevirta

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Symbols and abbreviations

Symbols

\mathbf{B}	magnetic flux density
c	speed of light in vacuum $\approx 3 \times 10^8$ [m/s]
ω_{D}	Debye frequency
ω_{latt}	average phonon frequency of lattice
\uparrow	electron spin direction up
\downarrow	electron spin direction down

Operators

$\nabla \times \mathbf{A}$	curl of vector in \mathbf{A}
$\frac{d}{dt}$	derivative with respect to variable t
$\frac{\partial}{\partial t}$	partial derivative with respect to variable t
\sum_i	sum over index i
$\mathbf{A} \cdot \mathbf{B}$	dot product of vectors \mathbf{A} and \mathbf{B}

Abbreviations

COMINT	communications intelligence
ELINT	electronic intelligence
EO	earth observation
ES	electromagnetic support
GNSS	global navigation satellite system
ISR	intelligence, surveillance, and reconnaissance
satcom	satellite communication
SIGINT	signals intelligence

1 Introduction

Over the past five decades, satellite systems have emerged as indispensable enablers of the modern way of life within an increasingly technology-driven human society. Innovation in fields such as global navigation satellite systems (GNSS), earth observation (EO), and satellite communication (satcom) has brought us ubiquitous connectivity in every corner of this world, while unlocking previously unimaginable capabilities in position, navigation, and timing (PNT), as well as intelligence, surveillance, and reconnaissance (ISR).

Recently, the satellite communications industry has entered into an era of rapid change. Since the early 2010s, the most prominent new trend have been the large megaconstellations of hundreds to thousands of satellites in low earth orbit (LEO). These have been enabled by the falling cost of space launches and mass-production of satellite hardware based on commercial off-the-shelf (COTS) technology.

However, the current satellite systems lack widely accepted cybersecurity standards. [1] Wildly varying technical solutions and their proprietary nature has raised a set of potential vulnerabilities. Additionally, the wide-area broadcast nature of satellite transmissions poses its own challenges. Attacks on terrestrial communications infrastructure are typically more localised due to the inherent limitations imposed by the laws of radio propagation. In contrast, satellite systems do not benefit from the same physics-driven protection, rendering them vulnerable to adversarial groups from abroad or even across an entire continent.

This was demonstrated in [2] where the feasibility of eavesdropping downlink satellite traffic was proven practically with widely available and relatively inexpensive satellite television equipment. Still, the issues are not only limited to the air interface of these commercial systems. Another third-party vulnerability assessment [3] uncovered serious design flaws in the implementation of satellite user terminal firmware, such as backdoors, hardcoded credentials, weak encryption algorithms as well as undocumented and insecure protocols.

One way to examine these empirical findings is through the paradigm of "security through obscurity", a practice with long-running history in the commercial satellite industry. Practically, this model relies on the complexity of the system and limiting of publicly available information on its implementation in securing their systems against potential attacks. [1] The validity of this approach has been long debated within research and industry circles [4] with recent consensus being that security of a system should never rely exclusively on obscurity. [5,6]

Within the field of wireless communication, one key driver for this development have been the proliferation of inexpensive signals processing equipment, such as open source and open hardware software-defined radios (SDR). These devices have brought interacting with satellite systems from the of nation states to even individual enthusiast-level actors.

Aside from commercial markets, governmental organisations, such as civilian public safety authorities and defence ministries, have expressed great interest in these emerging commercial satellite communication solutions. When comparing the user segments, the latter two tend to pay greater attention on the security aspects of the

communications solutions they utilise, which has in turn raised questions regarding the conformity of these systems.

Satellites have proven an invaluable resource in the modern operational environment. Recent adversarial actions against commercial and governmental satellite systems and infrastructure have raised questions on their vulnerability to a range of potential attack vectors. These range from everything from cyberattacks to the physical destruction of individual satellites or their supporting ground infrastructure. Recent examples include incidents like the cyberattack against the KA-SAT satellite network in February 2022, cable cut in one of the optical cables connecting the the SvalSat ground station to mainland Norway. Similarly, hostile actions, like the Chinese high-altitude balloons flying in North American airspace in early 2023, have highlighted the threat of aerial signals intelligence platforms.

Hardening these commercial satellite systems against a growing number of these increasingly cyber-capable adversaries is a prerequisite for their adoption in the mission critical user base, be they civilian or military in nature. Here, robust understanding on the nature of the evolving threat landscape is a key starting point for design of cybersecurity measures.

M

Thus far, the existing research literature has been focused on the security aspects of the long operational geostationary broadband and non-geostationary narrowband systems. These have been mostly examined from the viewpoint of downlink communication between the satellite and different earth stations with the opposite direction seeing relatively little research effort. In terms of signals intelligence platforms, the more capital-intensive space or airborne platforms have received comparatively less attention and research efforts, with a greater emphasis placed on the study of ground-based ones.

Considering this prior history and the recent rapid growth, it is important to better understand the security aspects of this emerging technology. This thesis will start by delving into the methods of eavesdropping a satellite network. General security architecture of the new LEO broadband services will be discussed in relation to this attack vector. Security of these emerging systems will be explored through a threat model comprising of a Walker-type LEO megaconstellation, fixed very small aperture terminals (VSAT) and airborne eavesdroppers. Overall, the topic will be discussed from the context of the public safety and defence user groups.

The thesis is structured as follows. Section 2 will describe the key characteristics of the examined platforms, in essence LEO megaconstellations and the different aerial platforms. The overall theoretical background is completed by the examination of the discipline of signals intelligence as well as a threat model comprising passive and active eavesdropping, jamming as well as signal geolocation. Section 3 goes over the relevant research material and methods, which is in turn reflected against the previously described threat model in section 4. The results of the simulation are outlined in section 5 and discussed in section 6. Conclusions from the work are described in section 7.

2 Background

2.1 LEO megaconstellations

2.1.1 History and recent developments

During the last five years the satellite communications industry has entered into an era of change. The most prominent new trend is the large megaconstellations with hundreds to thousands of satellites in low earth orbit (LEO). These systems have been enabled by the falling costs in space launches and the mass-production of satellite hardware based on COTS technology. [7]

While unlikely to widely replace terrestrial solutions, satellite systems have the potential to serve as a complimentary coverage and capacity solution for both commercial and public safety users. These systems could play a part in the ongoing broadband transition of the existing critical communications networks. Public safety users have more stringent requirements for their communication services when compared to the best effort service provided to normal commercial users.

So far the furthest strides in the new telecom constellations have been made by four companies: SpaceX with its Starlink, OneWeb, Telesat and Amazon with its Project Kuiper. SpaceX and Amazon are U.S. companies and Telesat is Canadian, while OneWeb is controlled by its investors from India, the U.K., France and Japan. In addition to them, multiple other actors from around the world have expressed interest in similar projects. These include for example the EU's Secure Connectivity Initiative and the Chinese Guo Wang constellation.

All four projects furthest in development have significant funding behind their concepts and have secured the necessary regulatory approvals for the initial deployments of their systems. As of May 2023, OneWeb has finished its first generation constellation of 648 satellites while SpaceX was still rolling out its much larger first generation constellation of 4408 satellites. Technologically, these constellations are characterised by their employment of dedicated and vendor-specific technologies in their implementation. For example, all four previously mentioned constellations are currently operating or planning to operate on dedicated Ku and Ka-band frequencies. Also, their user equipment is vendor-specific in nature, be they more traditional parabolic or modern flat-panel phased array technology-based very small aperture terminals (VSAT).

Two US companies, Lynk and AST SpaceMobile, are also planning on beaming broadband service from orbit directly to smartphone sized handsets on 5G frequencies. The latter services are less demonstrated and will need significant R&D investment before becoming a viable option, while the prior are already reaching commercial operability in limited geographic regions.

2.1.2 Key technical characteristics

The main elements of a LEO satellite constellation were characterised into distinct space, ground and user segments in [8], which are visualised in figure ?? . Space segment comprises the satellite constellation flying in orbit. Constellation optimiza-

tion is typically the primary design problem in LEO-based satellite networks as the parameters, such as orbital altitude, density of satellites, the number and inclination of orbital planes and the phasing between them, affect directly the feasibility of user applications.

The user segment is the most case-specific of the three segments to optimise. End user applications range from communication to sensing and navigation with their optimization criteria often contradicting each other. Here [8] raises the example of bandwidth and carrier frequency, where higher numbers are generally desired for example in high-throughput communication applications the opposite are better suited for achieving suitable link budgets for example when navigation satellite systems for challenging urban terrain or indoor use.

The LEO altitude leads to significantly lower latency and the large number of satellites allows for relatively high overall data throughput when compared with the earlier satellite systems but still significantly lower when compared to terrestrial systems. While NGSO constellations are nothing new, the emerging operators are promising to offer magnitudes better broadband service when compared to the earlier services offered by e.g. SES O3b and Iridium while providing the services also at a price point that is competitive with other forms of connectivity [1].

The services are built around vendor-specific user terminals working as WiFi routers that relay the communications on dedicated Ka and Ku-band frequencies to the satellite constellation.

2.1.3 Example system architectures (OneWeb / Starlink)

The space segment of the OneWeb system comprises a megaconstellation of 648 LEO satellites distributed into 12 polar orbital planes of 49 evenly spaced satellites, as well as a number of in-orbit spares. Operational satellites fly in an inclined polar orbit with an altitude of 1200 km. Each satellite transmits and receives user terminal (UT) traffic via its 16 fixed Ku-band beams, each of which covers a geographic area with dimensions of 1600 km in longitude and 65 km in latitude. Gateway traffic is forwarded to the satellite network portals (SNP) via two identical steerable Ka-band spot beams with a significantly more focused circular coverage pattern. [9, 10]

Earth Stations of the OneWeb system can be broadly divided into three categories: tracking, telemetry and control (TT&C) sites, gateways and user terminals (UTs). In the following, we will focus on the two latter ones, as they are integral to describing the end-to-end configuration of the OneWeb network. [10]

Going deeper into the gateway-side architecture, the infrastructure can be further split into three components, which are network data centres (NDC), points-of-presence (PoP) and satellite network portals (SNP). NDCs host the authentication, authorization, policy and UT databases and are deployed in key global locations. PoPs connect the OneWeb network to the Internet and are deployed at key Internet peering points. Finally, SNPs maintain the connectivity to the LEO space segment composed of the OneWeb satellite constellation. They are situated in remote locations around the globe with room for large antenna arrays of 7 to 30 full motion antennas (on average 16) equipped with a 3.5 m Ka-band dish. [9]

On the user terminal side, a similar architectural breakdown can be made – the terminal consists of a satellite antenna, receiver and a customer network exchange (CNX) router. The latter connects the terminal to the end-user devices such as laptops or smartphones. [9] RF transmissions received by the satellite antenna are demodulated and converted to a digital data stream by the receiver hardware of the terminal.

As OneWeb is a LEO satellite system, UTs need to track the movements of the orbiting satellites in real-time and handover between them as they move in and out of view in order to maintain constant connectivity. This can be achieved either with traditional steerable dish or more modern phased array antenna designs. With the prior, two apertures may need to be employed for uninterrupted connectivity, as retrace speed of a single aperture is the inherent limiting factor for hand-over time between satellites. On the other hand, phased array antennas require only a single aperture as their electronic switching can be considered almost instantaneous. [10]

Continuing with the distinguishing qualities of the OneWeb system, maybe the most significant is the nature of its air interface coverage pattern, also known as the cell layout. In the OneWeb satellite RAN, the cells are inherently varying and mobile, while on the contrary they are practically geographically static and pre-defined in a terrestrial network of fixed eNBs. Consequently, the movement of the UTs (for example equipment mounted on an aircraft or a high-speed train) is relatively slow when compared to the relative velocities of the satellites in orbit. This means that UT handovers happen mostly due to the orbital movement of the satellites rather than the movement of the UT relative to the surface of the earth, which is the dominating cause of UE handovers in terrestrial systems. [11]

In addition to their moving nature, satellite cells are significantly larger in their coverage area when compared to their terrestrial counterparts. This has multiple consequences for [11]

OneWeb satellite system makes use of a bent pipe architecture for both its forward and return links. In the forward direction, each Ku-band user terminal downlink maps onto a predetermined Ka-band gateway uplink and vice-versa in the return direction. [7, 10]

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2.2 Aerial Platforms

2.2.1 Technical capabilities

2.2.2 Key trade-offs

2.3 Signals intelligence

Signals intelligence (SIGINT) is intelligence gathering through the exploitation of communication systems and noncommunications emitters. Based on the nature

of the target system, the discipline of SIGINT can be further subdivided into the sub-disciplines of communications intelligence (COMINT) and electronic intelligence (ELINT). [12] [JP 1-02, JP 2-0 (2013), JP 3-85]

Considering satellite communication systems, the two disciplines of signals intelligence provide a wide range of tools for intelligence gathering at different levels of abstraction. On the most resource-intense end, we have the interception and extraction of user traffic, the defined scope of COMINT. However, less sophisticated methods, such as signal detection and fingerprinting, direction finding (DF) and radiopositioning may still yield valuable insights into the nature of the utilized systems, the user organisations, use patterns. As no

Interception of user traffic in satellite networks falls under the discipline COMINT. On based on methods such as time of

EOB (WIP / J03-85)

Electromagnetic support (ES) and SIGINT. ES is closely related to, but separate from, SIGINT. The distinction between an asset performing an ES mission or an intelligence mission is determined by who tasks or controls the collection assets, what they are tasked to provide, and for what purpose they are tasked. The distinction between ES and SIGINT is delineated by purpose, scope, and context. Operational commanders task ES assets to search for, intercept, identify, and locate or localize sources of intentional or unintentional radiated EM energy. In contrast, the Director, National Security Agency (NSA)/Chief, Central Security Service, or an operational commander delegated SIGINT operational tasking authority, task SIGINT assets. The purpose of ES is immediate threat recognition, support to planning, and conduct of future operations and other tactical actions such as threat avoidance, targeting, and homing. ES is intended to respond to an immediate operational requirement. ES and SIGINT operations often share the same or similar assets and resources and may be tasked to simultaneously collect information that meets both requirements. That is not to say that data collected for intelligence cannot meet immediate operational requirements. Information collected for ES purposes is normally also processed by the appropriate parts of the intelligence community (IC) for further exploitation after the operational commander's ES requirements are met. As such, it can be said that information collected from the EMS has "two lives." The first is as ES, unprocessed information used by operational forces to develop and maintain SA for an operationally defined period of time. The second is as SIGINT, retained and processed under appropriate intelligence authorities in response to specified intelligence requirements.

2.3.1 Signal detection

2.3.2 Direction finding and radiopositioning

Geolocating fixed VSAT terminals implemented as phased arrays, different direction finding techniques can be assessed for their suitability based on several factors. Some of the modern techniques include:

Angle of Arrival (AoA): AoA techniques can be suitable for geolocating VSAT terminals. By measuring the angles from which the signals arrive at the aircraft's

direction finding array, the azimuth and elevation of the terminals can be estimated. AoA techniques like beamforming, MUSIC, or ESPRIT can be effective in estimating the angles of arrival, especially if the phased array terminals have discernible sidelobes or beam characteristics.

Time Difference of Arrival (TDOA): TDOA relies on measuring the time delays between signals received at multiple spatially separated sensors.

Frequency Difference of Arrival (FDOA): FDOA relies on measuring the frequency differences of signals arriving at different sensors or antennas. FDOA techniques may provide useful information if the signals have specific frequency characteristics or modulation patterns that can be exploited.

Beamforming: Since phased array VSATs employ beamforming, the listeners direction finding array can analyze the received signals' phase and amplitude information to estimate the direction of arrival.

Additionally, multiple techniques can be combined into a hybrid approach if the complexity and capabilities of the direction finding array permit. For example, combining AoA and beamforming techniques can enhance the accuracy and robustness of geolocation estimates, especially if the phased array terminals exhibit unique radiation patterns or have challenging sidelobe characteristics.

2.3.3 Eavesdropping and traffic analysis

Fundamentally, secure communications rely on two core objectives being fulfilled. The intended receiver should be able to recover the original message without errors, while nobody else should be able to acquire any of the contained information. As is customary in cryptography, the transmitter is often referred to as Alice, the receiver as Bob and the eavesdropper as Eve. [13]

This core principle of secure communications was formalised by Shannon [14] in his 1949 paper through the notion of perfect secrecy achieved through a one-time pad. Shannon's secrecy system assumes that both the intended recipient and the eavesdropper acquire the encoded codeword without any degradation, i.e. the communication channel is error-free. This theoretical assumption applies very rarely to real world systems, where some noise is almost always present. [13]

Wyner [15] expanded on Shannon's original system by exploring the role of noise in the context of secure communications through the channel model called *degraded wiretap channel* (DWTC). The model assumes a situation where the sender (Alice) attempts to communicate with the legitimate recipient (Bob) over a noisy channel. Simultaneously an eavesdropper (Eve) observes a degraded version of the signal received by the legitimate recipient. [16]

Wyner's wiretap channel introduced many mathematical tools for modelling information-theoretic security without the added complexity of fully general channel models. One of these important concepts is the secrecy capacity of the channel, which describes the greatest amount of information that can be confidentially communicated between the legitimate transmitter and receiver from the information-theoretic secrecy perspective. [13]

Csiszár and Körner [17] developed a more general approach that they termed the

broadcast model with confidential messages.

2.4 Threat model

2.4.1 Passive and active eavesdropping

Space uplink Ground downlink

The eavesdropper can act both passively and actively. In the prior case

Regarding these two vectors, the research community has been thus far more focused on securing downlink communications from satellites to user terminals and gateways. Here, eavesdroppers have been assumed to be ground based, as space or airborne RF monitoring equipment has been seen as relatively limited in its performance compared to the terrestrial counterparts.

2.4.2 Jamming

2.4.3 Active eavesdropping

2.4.4 Signal geolocation

2.5 Link budgets

2.6 Channel models

3 Research material and methods

3.1 Analysis toolchain

3.1.1 Aerospace Toolbox

3.1.2 Modelling of the HAPS

3.1.3 Modelling of the satellite constellation

3.1.4 Channel model

4 Threat scenarios in relation

Tässä osassa kuvataan käytetty tutkimusaineisto ja tutkimuksen metodologiset valinnat, sekä kerrotaan tutkimuksen toteutustapa ja käytetyt menetelmät.

5 Results

5.0.1 Passive eavesdropping

5.0.2 Active eavesdropping

5.0.3 Jamming

5.0.4 Radiolocation

Tässä osassa esitetään tulokset ja vastataan tutkielman alussa esitettyihin tutkimuskysymyksiin. Tieteellisen kirjoitelman arvo mitataan tässä osassa esitettyjen tulosten perusteella.

Tutkimustuloksien merkitystä on aina syytä arvioida ja tarkastella kriittisesti. Joskus tarkastelu voi olla tässä osassa, mutta se voidaan myös jättää viimeiseen osaan, jolloin viimeisen osan nimeksi tulee »Tarkastelu». Tutkimustulosten merkitystä voi arvioida myös »Johtopäätökset»-otsikon alla viimeisessä osassa.

Tässä osassa on syytä myös arvioida tutkimustulosten luotettavuutta. Jos tutkimustulosten merkitystä arvioidaan »Tarkastelu»-osassa, voi luotettavuuden arviointi olla myös siellä.

6 Discussion

7 Conclusion

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A Esimerkki liitteestä

Liitteet eivät ole opinnäytteen kannalta välttämättömiä ja opinnäytteen tekijän on kirjoittamaan ryhtyessään hyvä ajatella pärjäävänsä ilman liitteitä. Kokemattomat kirjoittajat, jotka ovat huolissaan tekstiosan pituudesta, paisuttavat turhan helposti liitteitä pitääkseen tekstiosan pituuden annetuissa rajoissa. Tällä tavalla ei synny hyvää opinnäytettä.

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Liitteeseen voi laittaa esimerkiksi listauksia. Alla on listausesimerkki tämän liitteen luomisesta.

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\clearpage
\appendix
\addcontentsline{toc}{section}{Liite A}
\section*{Liite A}
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Kaavojen numerointi muodostaa liitteissä oman kokonaisuutensa:

$$d \wedge A = F, \tag{A1}$$

$$d \wedge F = 0. \tag{A2}$$

B Toinen esimerkki liitteestä

Liitteissä voi myös olla kuvia, jotka eivät sovi leipätekstin joukkoon: Liitteiden taulukoiden numerointi on kuvien ja kaavojen kaltainen: Kaavojen numerointi

Table B1: Taulukon kuvateksti.

9.00–9.55	Käytettävyytestauksen tiedotustilaisuus (osanottajat ovat saaneet sähköpostitse valmistautumistehtävät, joten tiedotustilaisuus voidaan pitää lyhyenä).
9.55–10.00	Testausalueelle siirtyminen

muodostaa liitteissä oman kokonaisuutensa:

$$T_{ik} = -pg_{ik} + wu_i u_k + \tau_{ik}, \tag{B1}$$

$$n_i = nu_i + v_i. \tag{B2}$$