Uplink Interception of Very Small Aperture Satellite Terminals from Aerial Platforms

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

Espoo 29.5.2023

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Abstract of the master's thesis

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Title Uplink Interception of Very Small Aperture Satellite Terminals from Aerial Platforms

Degree programme Electronics and electrical engineering

Major Electronics and Digital Systems **Code of major** ELEC3060

Supervisor Asst. Prof. Jaan Praks

Advisor M. Sc. (Tech) Tapio Savunen

Date 29.5.2023 **Number of pages** 17+2 **Language** English

Abstract

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Engineering

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Diplomityön tiivistelmä

Tekijä Markus Säynevirta

Työn nimi LEO-megakonstellaatioiden salakuunteleminen

Koulutusohjelma Elektroniikka ja sähkötekniikka

Pääaine Sopiva pääaine **Pääaineen koodi** ELEC3060

Työn valvoja Apul. prof. Jaan Praks

Työn ohjaaja DI Tapio Savunen

Päivämäärä 29.5.2023 **Sivumäärä** 17+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, 29.5.2023

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 vectorin $\mathbf{A}$
$\frac{\mathrm{d}}{\mathrm{d}t}$	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

AC	alternating current
APLAC	an object-oriented analog circuit simulator and design tool (originally Analysis Program for Linear Active Circuits)
BCS	Bardeen-Cooper-Schrieffer
DC	direct current
TEM	transverse eletromagnetic

1 Introduction (WIP)

During the last decade, 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 have been enabled by the falling costs in space launches and the mass-production of satellite hardware based on COTS technology.

Aside from commercial markets, governmental organisations, such as civilian public safety authorities and defence ministries, are looking into augmenting their existing connectivity infrastructure with commercial satcom services. Among a set of requirements, these organisations place a very stringent standard of security on the communications solutions they utilise.

Prior experimental research into the security of traditional geostationary broadband services has revealed serious security vulnerabilities. Known attack vectors include for example the eavesdropping of network traffic with widely available and relatively inexpensive television equipment. Rapidly growing number of users and limits in launch capacity are exposing bottlenecks in the throughput of LEO satcom networks. In the worst case scenario, this may tempt the new operators to follow the questionable practices of their predecessors in trading information security for gains in network performance.

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. Possible vulnerabilities will be further explored via simulation and field experiments with the OneWeb satellite constellation. Overall, the topic will be discussed from the viewpoint of the public safety and defence user groups.

The thesis seeks to answer what kind of risk space-borne uplink eavesdropping poses to modern very small aperture terminal satellite communications. The eavesdroppers are assumed to be randomly distributed at a set of altitudes according to homogenous binomial point processes. Eavesdroppers are assumed to be passive in nature and to be not colluding with each other, i.e. the received signals are decoded individually.

Knowing the history of the field and the prior vulnerabilities with geostationary satcom networks, the current hypothesis is that there could be information leakage happening in the over-the-air communications of the constellation. It is important to understand whether this is happening and if so, to what extent, as it might be possible to extract sensitive user information from these transmissions.

The core goal of the thesis is to gain better understanding regarding the security of the over-the-air communications with modern LEO satcom constellations.

Areas of interest include the traffic flow security of the constellation and whether transmissions sent over it are possible to be set up in a way that avoids information leakage to adversarial groups. This is of paramount importance for the defence user groups, as the traffic patterns or information in the packet headers could reveal factors such as location, number or identity of an individual or a group of users.

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.

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.

Multiple LEO megaconstellations are currently in the design and deployment phase, of which Starlink, OneWeb, Telesat and Kuiper are farthest in the development and deployment. These constellations are operating on dedicated bands and are likely the most viable near term solution. They are based on vendor-specific vendor-specific user terminals working as WiFi routers that relay the communications on Ka and Ku-band frequencies to the satellite constellation.

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 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 architechtures (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. [1, 2]

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. [2]

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. [1]

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. [1] 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. [2]

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. [3]

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 [3]

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. [2, 4]

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2.2 Aerial Platforms

2.2.1 Technical capabilities

2.2.2 Key trade-offs

2.3 Communications intelligence

Communications intelligence (COMINT) is often used as a synonym of signals intelligence (SIGINT) but it is actually a subfield of that broader area, which also includes electronics intelligence (ELINT). Both of them share a common set of methods.

2.3.1 Signal detection

2.3.2 Direction finding and radiopositioning

2.3.3 Eavesdropping and traffic analysis

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

References

[1] Y. Henri, *The OneWeb Satellite System*. Cham: Springer International Publishing, 2020, pp. 1–10. ISBN 978-3-030-20707-6

[2] WorldVu Satellites Limited, "OneWeb LEO K-band NGSO constellation FCC filing SAT-LOI-20160428-00041," Apr. 2016, accessed: 2022-12-22. [Online]. Available: https://licensing.fcc.gov/cgi-bin/ws.exe/prod/ib/forms/reports/swr031b.hts?q_set=V_SITE_ANTENNA_FREQ.file_numberC/File+Number/%3D/SATLOI2016042800041&prepare=&column=V_SITE_ANTENNA_FREQ.file_numberC/File+Number

[3] M. S. Corson, "Admission control system for satellite-based internet access and transport," Dec. 10 2019, US Patent 10,506,437.

[4] I. del Portillo, B. G. Cameron, and E. F. Crawley, "A technical comparison of three low earth orbit satellite constellation systems to provide global broadband," *Acta Astronautica*, vol. 159, pp. 123–135, 2019. doi: 10.1016/j.actaastro.2019.03.040

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

muodostaa liitteissä oman kokonaisuutensa:

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

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