ECHOES FROM THE PAST

Alexandru Budianu

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THE COMMUNICATION LAYER

OF A

NANOSATELLITE SWARM

by

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Părinților și bunicilor mei

Summary

The Orbiting Low Frequency Antennas for Radio Astronomy ([OLFAR](#)) project is aimed at developing a low-frequency radio telescope to observe the cosmic radiation in the 0.3–30-MHz domain. This frequency band is one of the last unexplored regions of radio astronomy, and studying it will reveal details about the so-called Dark Ages of the Universe, exoplanets, and other celestial bodies and phenomena. Building a telescope to capture these ultra-long electromagnetic ([EM](#)) waves requires overcoming a few obstacles. The high level of terrestrial radio-frequency interference ([RFI](#)) drives the requirement of a space-based instrument deployed in a remote location (such as a lunar orbit). Furthermore, the size of the required aperture (10–1,000 m) makes a monolithic implementation very difficult. Hence, [OLFAR](#) will consist of a swarm of 50 or more nanosatellites that will sense the [EM](#) waves of interest, distribute the data within the swarm, process it, and send the end results to a base station ([BS](#)) on Earth.

The scientific goal of the mission as well as the implementation details (the lunar orbit, the large number of spacecraft, the distributed processing, and the cubesat platform) will impose stringent restrictions on the communication layer of the [OLFAR](#) swarm. Both inter-satellite as well as swarm-to-Earth communication will have to deal with high data rates (in the order of Mbps) and will have to cover large distances (100 km and 400,000 km, respectively).

The objective of this research is to determine whether a swarm of nanosatellites can meet the data flow requirements of a high-resolution imaging instrument for low-frequency radio astronomy.

Distributing data within the satellite network involves two main aspects: the topology of the network and the inter-satellite links ([ISLs](#)).

The swarm is a complex system that needs a power-efficient organization for data handling. Existent topologies could not be matched to the [OLFAR](#) scenario. Therefore, an adaptive clustering scheme was designed. The proposed two-layered topology exploits the redundancy of the system (the large number of satellites) to reduce the overall power consumption.

As follow up, the problem of establishing [ISLs](#) between the [OLFAR](#) satellites was addressed. Based on the challenges and requirements (data rate, power and satellite platform) of the [OLFAR](#) project, the communication links were designed. Using a link budget analysis the antenna gain requirement was derived. Based on this figure, a suitable antenna system was designed. It consists of an ensemble of six patch antennas, each one placed on one of the cubesat's facets, and a beam-forming controller. A laboratory setup was used to confirm the eligibility of the solution. The tests also exposed weaknesses such as the limited link margin and polarization properties of real antennas.

Performing the link budget analysis for a single satellite-to-Earth link revealed a potential problem. An [OLFAR](#) satellite equipped with a single patch antenna cannot establish a reliable data connection with a [BS](#) on its own. Thus, the influence that the swarm has on the communication link was assessed. It was concluded that either a cooperative communication scheme or a higher-gain antenna at satellite level will be required in order to transfer data from the swarm to Earth.

Based on the requirements of the telescope and the limitations of the cubesat platform, a downlink antenna array was designed. It consists of two five-by-four two-dimensional patch array with a binomial feeding structure. The radiating elements are placed on the backside of the satellites' solar panels, hence, forming a dual-system for energy harvesting and data downlink. A partial prototype consisting of a one-by-four antenna array and the microstrip binomial feeding network was built and tested. The measurement results match outcome of the simulations and endorse the potential of the proposed solutions. Nonetheless, some directions for further optimization and research have been identified.

Overall, this thesis demonstrates the feasibility of the communication layer of the [OLFAR](#) swarm. The next step is to integrate all the designed systems into one platform and test it in an orbital deployment scenario.

Samenvatting

Het *Orbiting Low Frequency Antennas for Radio Astronomy* [OLFAR](#) project heeft als doel een laagfrequente radiotelescoop te ontwikkelen om kosmische straling in het bereik van ongeveer 0.3 tot 30 MHz te bemeuten. Deze frequentieband is een van de laatste onontgonnen frequentiegebieden in de radioastronomie. Het bestuderen hiervan zal kennis opleveren over de zogeheten *Dark Ages* van het universum, exoplaneten, en andere hemellichamen en verschijnselen. Om een telescoop te bouwen die deze ultralange elektromagnetische [EM](#) golven kan opvangen, moeten een aantal hindernissen worden genomen. De grote hoeveelheid radiofrequente interferentie [RFI](#) rondom de aarde zorgt ervoor dat de telescoop op een afgelegen locatie in de ruimte geplaatst moet worden (bijvoorbeeld in een baan om de maan). Daarnaast zorgt de benodigde grootte van de telescoop (diameters tussen 10 en 1000 m) ervoor dat een monolithische implementatie praktisch onmogelijk is. Daarom zal [OLFAR](#) bestaan uit een zwerm van 50 of meer nanosatellieten die de bewuste [EM](#)-golven zullen bemonsteren, de data binnen de zwerm zullen verspreiden en verwerken, en de eindresultaten vervolgens naar een basisstation [BS](#) op aarde zullen sturen.

Zowel het wetenschappelijke doel van de missie als de specificaties van de implementatie (de baan om de maan, het grote aantal satellieten, het gedistribueerd verwerken en het te gebruiken *cubesat*-platform) stellen strenge eisen aan de communicatielaag van de [OLFAR](#) zwerm. De communicatie, zowel tussen de satellieten als van de zwerm naar de aarde, moet kunnen omgaan met hoge datasnelheden (ordegrootte Mbps) en grote afstanden kunnen overbruggen (respectievelijk 100 km en 400.000 km). Het doel van dit onderzoek is te bepalen of een zwerm nanosatellieten aan de datadoorvoereisen van een hoge-

resolutie meetinstrument voor laagfrequente radioastronomie kan vol-
doen.

Het verspreiden van data binnen het satellietnetwerk omvat twee as-
pecten: de topologie van het netwerk en de inter-satellietverbindingen
ISL's. De zwerm is een complex systeem dat een energie-efficiënte
manier van dataverwerking nodig heeft. Bestaande topologieën zijn
niet toepasbaar op het OLFAR-scenario. Daarom is een adaptief clus-
teringconcept ontworpen. De voorgestelde tweelaags topologie maakt
gebruik van de redundantie binnen het systeem (het grote aantal satel-
lieten) om het totale energieverbruik te verminderen.

Daarnaast is het probleem van het maken van ISL's tussen OLFAR-
satellieten aangepakt. De communicatieverbindingen zijn ontworpen
op basis van de uitdagingen en eisen (datasnelheid, energie en satel-
lietplatform) van het OLFAR-project. Via een analyse van het *link bud-
get* is de benodigde antenneversterking bepaald. Op basis van deze
waarde is een antennesysteem ontworpen. Dit bestaat uit een com-
binatie van zes *patch* antennes, die ieder op een zijde van de *cube-
sat* zijn geplaatst, en een bundelvormer die signalen van drie *patch*
antennes combineert. De haalbaarheid van deze oplossing is beves-
tigd door laboratoriumtests. Deze tests lieten ook zwakke punten zien,
zoals de beperkte linkmarge van de radioverbinding en de polarisatie-
eigenschappen van echte antennes.

Het doorrekenen van het *link budget* voor één enkele verbinding
tussen een satelliet en de aarde bracht een mogelijk probleem aan het
licht. Een OLFAR-satelliet uitgerust met slechts één *patch* antenne is
niet in staat in zijn eentje een betrouwbare dataverbinding te maken
met een BS. Daarom is vervolgens de invloed van de zwerm op de
communicatieverbinding beoordeeld. Hieruit werd geconcludeerd dat
er of een samenwerkend communicatiemodel of een hogere antennev-
ersterking op satellietniveau nodig is om de data van de zwerm naar
de aarde te versturen.

Uitgaande van de eisen van de satelliet en de beperkingen van het
cubesat-platform is een *downlink* antenne-*array* ontworpen. Deze bestaat
uit twee vijf-bij-vier tweedimensionale *patch arrays* met een binomi-
ale voedingsstructuur. De stralende elementen zijn geplaatst op de
achterzijde van de zonnepanelen van de satelliet, die zodoende een
tweevoudig systeem voor energieopwekking en *dowlink* dataverbind-
ing vormen. Een prototype bestaande uit een één-bij-vier antenne-*array*

en het microstrip binomiale voedingsnetwerk is gebouwd en getest. De meetresultaten komen overeen met de uitkomsten van simulaties en onderschrijven de haalbaarheid van de voorgestelde oplossingen. Niettemin zijn er enkele richtingen voor verdere optimalisatie en onderzoek aangegeven.

Alles bij elkaar toont dit proefschrift de haalbaarheid van de communicatielaag van de [OLFAR](#)-zwerm aan. De volgende stap is om alle ontworpen systemen te integreren in één platform en dat te testen in de ruimte.

Rezumat

Proiectul *Orbiting Low Frequency Antennas for Radio Astronomy* ([OLFAR](#)) își propune să construiască un radio telescop de frecvențe joase pentru a observa radiațiile cosmice cu frecvențe cuprinse între 0.3 și 30 de MHz. Această bandă de frecvențe este una dintre ultimele arii neexplorate ale radio astronomiei, iar studiul ei va dezvălui aspecte ale așa-numitei Epoci Întunecate a Universului, ale exo-planetelor, și ale altor fenomene și corpuri cerești. Construirea unui radiotelescop capabil să observe undele electromagnetice ultra-lungi necesită depășirea câtorva obstacole. Nivelul ridicat de interferențe de radiofrecvență de origine terestră antrenează nevoia unei misiuni spațiale desfașurată într-o locație îndepărtată (de exemplu în jurul Lunii). În plus, dimensiunea aperturii necesare (10–1,000 m) face ca o implementare de tip monolit să fie foarte dificilă. Prin urmare, [OLFAR](#) va fi compus dintr-o mulțime de 50 sau mai mulți nanosateliti care vor observa undele electromagnetice de interes, vor distribui informația adunată celorlalți sateliți, vor procesa datele și vor trimite rezultatele către o stație de bază situată pe Pământ.

Atât obiectivul științific al misiunii, cât și detaliile de implementare (orbita lunară, numărul mare de sateliți, algoritmi de procesare distribuită și platforma de tip *cubesat* pentru sateliți) vor impune cerințe stricte asupra nivelului de comunicație al rețelei [OLFAR](#). Atât comunicațiile dintre sateliți cât și comunicația [OLFAR](#)-stația-mamă vor trebui să acomodeze viteze mari de transfer (de ordinul Mbps), și vor trebui să se desfășoare pe distanțe foarte mari (100 km și, respectiv, 400,000 km).

Scopul acestui studiu este să se arate dacă rețeaua de nanosateliti satisface cerințele referitoare la transferul de date necesar unui instrument de mare rezoluție pentru radioastronomie de frecvențe joase.

Transferul de date în rețeaua de sateliți are la bază două aspecte: topologia rețelei și legăturile de date satelit-satelit. Rețeaua de sateliți este un sistem complex care necesită o organizare eficientă din punct de vedere a consumului de energie a administrării datelor. Topologiile de rețea existente nu pot fi aplicate și în cazul sistemului [OLFAR](#). Așadar, un algoritm adaptiv de divizare a rețelei a fost conceput. Rezultatul a fost o topologie pe două nivele care profită de redundanța sistemului (numărul mare de sateliți) pentru a reduce energia consumată pentru transferul de date.

Ulterior, problema realizării comunicațiilor între sateliții [OLFAR](#) a fost abordată. Pornind de la provocările și necesitățile (viteza de transfer, energia necesară și platforma pentru implementare) proiectului [OLFAR](#), legăturile de date au fost proiectate. Folosind o analiză de tip buget de legătură, a fost calculat câștigul necesar antenelor de transmisie și recepție. Un sistem de antene corespunzător a fost proiectat folosind acest rezultat. Sistemul este alcătuit din șase antene de tip *patch*, câte una plasată pe fiecare față a satelitului de tip *cubesat*, și un *controller* pentru *beamforming*. Un experiment de laborator a fost efectuat pentru a confirma validitatea soluției. Experimentul a subliniat și câteva slăbiciuni cum ar fi marja de eroare foarte mică și polarizarea practic realizabilă a antenelor.

Analiza bugetului legăturii dintre un singur satelit și Pământ a scos la iveală o potențială problemă. Un satelit [OLFAR](#) echipat cu o singură antenă de tip *patch* nu poate stabili, de unul singur, o conexiune de date sigură cu o stație de bază. Prin urmare, a fost analizat efectul pe care grupul de sateliți îl are asupra legăturii de date. S-a ajuns la concluzia că pentru a transfera date de la grupul de sateliți către Pământ va fi necesară o schemă de comunicație cooperativă sau de antene de câștig mare la nivelul sateliților.

Sistemul de antene pentru legătura de tip *downlink* a fost proiectat pornind de la necesitățile radiotelescopului și limitările platformei de tip *cubesat*. Sistemul de antene este alcătuit din două matrici de antene de dimensiune 5×4 alimentate de structuri binomiale. Elementele celor două matrici sunt plasate pe partea din spate a panourilor solare proprii sateliților, formând astfel un sistem cu funcționalitate dublă—obținerea de energie și transmitere de date. Un prototip parțial, format dintr-un șir de patru antene și structura binomială de alimentare, a fost construit și testat. Rezultatele măsurărilor au corespuns rezul-

tatelor simulărilor și au confirmat potențialul soluției propuse. Cu toate acestea, au fost identificate și câteva direcții de cercetare pentru îmbunătățirea sistemului.

În general, acest studiu demonstrează fezabilitatea nivelului de comunicație al rețelei [OLFAR](#). Următorul pas constă în integrarea tuturor sistemelor proiectate într-un singur satelit și testarea întregului ansamblu în orbită.

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Chapter 1

Introduction

The human curiosity has always been challenged by questions about the Universe and all there is within it. This led to the emergence of the first of the natural sciences—astronomy. Even antiquity people have been interested in identifying celestial objects such as stars, galaxies and planets, and in studying their behavior. Although initially the drive was mainly mythological and religious, with the passage of time, the knowledge and understanding of certain phenomena expanded, and the interest of astronomy shifted to providing an accurate model of the macro-cosmos.

The advancements in certain fields of mathematics, for example geometry and physics, had a catalytic effect on the development of astronomy and helped humankind into perceiving “the bigger picture”. However, it was not until the nineteenth century that modern astronomy¹ was established. The development of specialized instruments, such as high-resolution optical telescopes, as well as the usage of complex mathematical and physical tools, such as photography and spectroscopy, pushed the astronomical knowledge onto an exponential growing curve. Groundbreaking discoveries were made and, with them, a paradigm shift took place. For example, it was proven that the Sun contains chemical elements also found on Earth [1], and that the Solar System is part of a galaxy containing more than a billion stars. Later on, Edwin Hubble identified other galaxies and demonstrated the accelerated expansion of the Universe [2]. Every discovery that was made contributed to the building of a very detailed and tangible

¹ It is considered that modern astronomy started with the use of observation techniques such as photography and spectroscopy.

model of the Universe. Nevertheless, in a very research-oriented fashion, it also raised other questions. This led to the emergence of several branches of astronomy that focus on different aspects of the Universe. Added to this, two directions started to be distinguished in the science community: the theoretical and the observational trends.

One of the branches of astronomy that unfolded was cosmology, strongly connected to the publishing of Einstein's general theory of relativity and to the advancements in quantum physics. Cosmology focuses on fundamental questions about the transformation of the Universe, about its birth, history and future, and about its ultimate fate. Major observational discoveries [2], [3] in the twentieth century favored the establishment of a model for the evolution of the Universe—The Big Bang theory—that was and still is accepted by the majority of the science community to best fit reality. The model has continuously been updated as science progressed—particle physics had a major contribution—and experimental researchers revealed new features. The knowledge about this encountered a rapid growth during the past few decades due to the development of new instruments that observe the various types of radiation emitted by celestial bodies (ultra-violet, infrared, X-ray, etcetera.).

As mentioned previously, apart from the theoretical modeling aspect of astronomy, an observational trend was developed and individualized as a standalone branch. It attracted the interest of many scientists. It concentrates on recording and analyzing the electromagnetic (EM) radiation of all types emitted by stars, planets, comets and other objects in the Universe. Until the middle of the twentieth century all the observations were done in the visible light domain using optical telescopes. At present, this technique is still widely spread and very successful, and a lot of instruments are currently under development [4], [5]. Nonetheless, in 1931, Karl Jansky detected radio waves that originate within the Milky Way [6]. Thus, Jansky's discovery pointed out that celestial bodies also emit EM waves invisible to the human eye. This opened new windows of cosmic exploration. Radio astronomy was born from the curiosity of observing the Universe in other EM domains than visible light. It provided new insights over already known celestial bodies and phenomena, and also revealed new ones. Figure 1.1 contains several images of the sky observed in different domains. It can be seen that EM waves of different frequencies

(X-ray, infrared, microwave) reveal plenty of celestial details that are invisible to the human eye. Furthermore, each EM domain shows off distinctive features from the others.

Figure 1.1: Maps of the celestial sky for different types of EM radiation. ©1998 Robert Nemiroff (MTU) & Jerry Bonnell (USRA)

Cosmologists have benefited greatly from the advancements in radio astronomy as these enhanced the understanding of the Big Bang theory. The accidental discovery of the cosmic microwave background (CMB)² in 1964 came as a validating test for the expansionist model of the Universe [7]. Radio astronomers continued observing the sky in almost all the EM spectrum to find out more about the evolution of the Universe. For example, gamma-ray observations facilitated the identification of supernovae and thus, of the extinction process of stars.

Based on the accelerated expansion model [8] and the hydrogen emission model [9], and using high-performance radio telescopes, scientists could look back in time and determine the transformations the Universe has undergone from its birth and until now. By going towards the lower end of EM spectrum, radio astronomers recreated images of the Universe at a very early stage, as young as 400 million

² The CMB, also known as the after-glow pattern, is the oldest light in the Universe. It was emitted approximately 380,000 years after the Big Bang.

years³ after the Big Bang. When trying to look even further back in time, the scientists had to observe the very low end of the EM spectrum (below 30 MHz)⁴. A few practical limitations were encountered. First of all, the EM radiation of interest is blocked or severely hampered by the ionosphere [10] and as a result, cannot be observed from Earth. Secondly, the size of the required instrument for observation made it impossible to build it in a monolithic fashion. The sensitivity of a radio telescope is directly proportional to the wavelength of the EM radiation of interest and inversely proportional to the diameter of the available aperture. Therefore, since the low-frequency waves have a large corresponding wavelength (above 10 m), a very large aperture will be required to make observations in the very-low frequency domain.

Recent advancements in the field of space exploration—the emergence of cubesats as reliable spacecraft [11]—and the ongoing miniaturization of technology opened the path for new types of applications. It shifted limitations, and it made the radio astronomers community reconsider the idea of exploring the Dark Ages of Astronomy⁵. The question raised was whether technology had reached the maturity level to build the required instrument. If so, what would it reveal?

Multiple studies were conducted on this and confirmed the technological readiness [12], [13]. A monolithic implementation of the required radio telescope is still not possible. To overcome this limitation, projects such as Distributed Aperture Array for Radio Astronomy In Space (DARIS) [12] and Orbiting Low Frequency Antennas for Radio Astronomy OLFAR [14] proposed a distributed approach.

In the rest of this chapter, the general aspects of the Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR) project are presented. At first the main science case⁶—exploring the Dark Ages—and the associated physical model are introduced. In the subchapters that will follow, the focus will be on the required instrument for radio astronomy, the previous attempts, the current approach and its challenges.

³ According to the standard model of cosmology, the Universe is 13.7 billion years old.

⁴ In the following sections, the link between the low-frequency EM waves and the incipient Universe will be explained.

⁵ The Dark Ages of Astronomy is the period in the history of the Universe that started after the emission of the first photons and ended with the formation of the first stars.

⁶ There is evidence that some planets (e.g. Jupiter) emit EM radiation in the very low-frequency domain [15]. Therefore, exploring the 0–30 MHz domain will also uncover information about exo-planets or other unknown celestial bodies and phenomena.

In the final part of the chapter, the research question and goals are stated.

1.1 SCIENCE CASE

The Dark Ages of radio astronomy is one of the last uncovered areas from the history of Universe. It corresponds to the interval of time starting at the end of the epoch of recombination [16], approximately 380,000 years after the Big Bang, and ending with the formation of the first stars, also known as the start of the epoch of reionization [17], approximately 400 billion years after the Big Bang.

During this period, the Universe transitioned from a dense opaque state without organization to a state where neutral hydrogen established filaments that would act as fuel for the formation of the stars. It started to be transparent as EM waves were emitted as a result of some quantum mechanisms. Thus, during the Dark Ages, the Universe was becoming “visible” for astronomers. For a better understanding of the science case, the following subsections will focus on the cosmological model of the Universe.

1.1.1 *History of the Universe*

Currently, the Big Bang theory is considered to be the standard model for the birth and evolution of the Universe [8]. It states that initially all matter and energy was concentrated in a single very hot point. This singularity started expanding, cooled down, and allowed the formation of the first sub-atomic particles. Under the influence of dark matter⁷ these particles grouped and formed the first atoms of neutral Hydrogen. Gravity pushed these atoms into forming stars and galaxies, and later on heavier elements. The Universe, as it is known today, is the result of 13.8 billion years of a still ongoing expansion.

In Figure 1.2, multiple stages of the history of the Universe can be distinguished. Looking at the evolution from both theoretical and observational perspective, two eras can be distinguished.

⁷ The initial expansion of the Universe and the formation of the neutral Hydrogen have yet to be confirmed by observational proof.

1. The nonobservable Universe: this is the era of the very early Universe when all matter was contained in a small region of space, and it was so dense that photons could not escape from it. This period dates from the initial expansion to the emission of the first light, also known as the after-glow [8]. Theoretical physicists have established a model for the chain of events that took part within this interval, but it is still a source of speculations since the model lacks observational proof. The imminent discovery of gravitational waves might change this in the near future [18].
2. The observable Universe: this period started with the first light and it is still continuing. It is characterized by the formation of the chemical elements, the formation of stars and galaxies, planets, the Solar System, and so on. Observational proof of the events that took place in this time interval could be prelevated thanks to the continuous emission of EM waves as elementary particles changed energy states. Thus, optical astronomy and radio astronomy could reconstruct the past of the Universe. Although an image of the Dark Ages is yet to be reconstructed, this is due to the technological limitations rather than the theoretical model. Therefore, this period of time is included in the “visible” era.

One of the key aspects of the cosmological model is the continuous expansion.

1.1.2 *The accelerated expansion*

In 1929, Edwin Hubble measured the redshift of a few distant galaxies and their relative distance. When analyzing the data, he noticed that the redshift of the galaxies increases linearly as a function of their distance. He figured that the only explanation for this is that the Universe is expanding and the incoming light waves suffer from Doppler shift. Figure 1.3 illustrates the concept of receding galaxies and redshift. This discovery came to support the Big Bang model.

Beginning
of the
Universe

Figure 1.2: The history of the Universe. During the Inflation, the Universe expands at an accelerated pace. After light and matter separate, light starts traveling freely and the CMB is formed. Under the pressure of dark matter (white), the quantum seeds of the Universe group together and form and cosmic web of structures, eventually forming stars and galaxies. ©ESA

Figure 1.3: The redshift of receding galaxies.

According to the Doppler law, the relation between the frequency of the observed waves and the frequency of the emitted waves is given by the following equation:

$$f = \left(1 + \frac{\Delta v}{c}\right) f_0, \quad (1.1)$$

where f is the observed frequency, Δv is the relative speed between the source and the receptor (negative if moving away from each other), c is the propagation speed of the EM waves in free-space, and f_0 is the frequency of the emitted wave.

Based on the observations and (1.1), a mathematical model was established for the expansion and it is most often described using the following equation:

$$v = H_0 \cdot D, \quad (1.2)$$

where v is the recessional velocity (the velocity with which the galaxy is moving away from the observed point—Earth), H_0 denotes Hubble’s constant (67.80 ± 0.77 (km/s)/Mpc^{8,9}) and D is the distance to the galaxy. (1.2) is only valid for galaxies observed in deep space, farther than 10 Mpc from Earth.

From (1.2), it can be seen that the farther away a galaxy is from the point of observation, the faster it moves away. This leads to the conclusion that the expansion of the Universe is an accelerated expansion. As a result, EM waves emitted by objects in distant galaxies suffer from a Doppler shift while traveling towards Earth. Hence, light originating from extragalactic stars moves towards the red end of the visible spectrum—are red-shifted.

Using this expansion model, astronomers can translate the spectrum of a distant source into distance and age, thus, are able to build a chronology.

1.1.3 *The Hydrogen Line*

Exploring the Dark Ages is a matter of observing and analyzing the EM radiation that originates in this stage of the history of the Universe. Since this period precedes the formation of the first stars, it is not visible light that needs to be observed but waves that are associated with the formation of the first atoms.

The mechanism of the emission of this EM radiation is illustrated in Figure 1.4. Under the pressure of dark matter and the influence of gravity, spinning protons and electrons grouped and formed the first hydrogen atoms with no electrical charge [8]. The ground state of neutral hydrogen consists of a spherically symmetrical electron cloud bound to one proton. Both of the particles have magnetic dipole moments also known as spins. Depending on the alignment of the spins the atoms could be found in two different energy states: the higher energy state is characterized by parallel spin (identical spin of the electron and proton), while in the lower energy state the particles have antiparallel spins. The astronomical context consisting of hydrogen filaments and clouds favored the transition from the higher energy state

8 1 Mpc (megaparsec) = 3.0857×10^{22} m.

9 Observed using the European Space Agency’s Planck mission and published on the 21st of March 2013 [19].

to the lower energy state, while the difference of energy was released in the form of a photon.

Figure 1.4: The hydrogen emission mechanism.

Taking into consideration the Planck relation from quantum mechanics:

$$\Delta E = h\nu = \frac{hc}{\lambda}, \quad (1.3)$$

and that the energy difference ΔE between the two states is $5.87433 \mu\text{eV}$, the frequency ν of the emitted wave and the free-space wavelength λ can be calculated to be 1420.40575 MHz and 21.10611 cm , respectively [9]. In (1.3), h denotes Planck's constant¹⁰.

¹⁰ $h = 6.62606957(29) \times 10^{-34} \text{ J} \cdot \text{s}.$

1.2 LOW-FREQUENCY RADIO ASTRONOMY

Understanding phenomena that took place during the Dark Ages of astronomy requires identifying and observing the 21-cm EM waves that were generated in that era. Due to the distance in time and the accelerated expansion of the Universe, this radiation is Doppler-shifted and reaches the vicinity of Earth with very low frequencies.

To better understand the frequency domain, the following numerical example is considered. Let it be assumed that the first light that was emitted (the after-glow pattern) was mainly red with a frequency f_0 of 400 THz. This light traveled in time and space and was observed at the end of the twentieth century with peaks around the frequency f of 160 GHz [20]. Added to this, let it be considered that, exactly after the first light, an atom of neutral hydrogen was formed in a parallel spin state and switched immediately to the lower energy state. Therefore, an EM wave with a frequency f'_0 of 1420 MHz was released. If observed at the same moment as the initial light, this wave suffers from the same Doppler effect and is observed with a frequency f' . From (1.1) it can written:

$$\frac{f}{f_0} = \frac{f'}{f'_0}, \quad (1.4)$$

and the observed frequency can be deduced:

$$f' = \frac{f}{f_0} f'_0 \approx \frac{160 \text{ GHz}}{400 \text{ THz}} \cdot 1420 \text{ MHz} \approx 568 \text{ kHz}, \quad (1.5)$$

In astronomy, the shift in frequency or wavelength, respectively, is expressed in terms of redshift which can be calculated as:

$$z = \frac{f_{\text{emit}} - f_{\text{obs}}}{f_{\text{obs}}} = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}}, \quad (1.6)$$

where f_{emit} and λ_{emit} are the frequency and the wavelength, respectively, of the emitted wave, and f_{obs} and λ_{obs} are the same parameters corresponding to the observed radiation. Therefore, the same scenario described in (1.5) is characterized by a redshift of 2499¹¹.

¹¹ The numbers in the considered scenario do not fit reality entirely. The calculated redshift is used to indicate that the observed EM waves originate very close to the birth of the Universe.

From the numerical example above, it can be concluded that, due to the Universe's expansion, the radiation emitted during the Dark Ages has been shifted to the very low-frequency domain. The time span for observations extends over a large period of time (a few hundred million years) so that, depending on the moment of the emission, these EM waves suffer from different frequency shifts. As a consequence, it is important for radio astronomers and the science case described previously to observe the complete frequency range below 200 MHz [21].

Furthermore, exploring these very low-frequency domains will contribute to the understanding of the Universe not only from the cosmological point of view. The study of very low-frequency EM waves of cosmic origin will also help astronomers to identify exo-planets and possibly, other objects and phenomena that are yet to be known [22].

1.2.1 *A low-frequency radio telescope*

The potential of exploring these new scientific drivers enhanced the development of radio telescopes all across the world. Large dish radio telescopes (e.g. the Arecibo Observatory) and arrays (e.g. Low Frequency Array, LOFAR [23], and Very Large Array, VLA [24]) have been built to observe radiation with frequencies as low as 30 MHz.

One of the last unexplored domains is the 0.3–30-MHz range, and currently, consistent efforts are made for building radio telescopes that would cover this frequency range. However, building an instrument for this scenario comes with a few challenges regarding size, location, and costs.

The radio telescope functionality

A radio telescope functions similar to an optical telescope, gathering data on celestial sources in the radio part of the EM spectrum. It consists of a directional antenna, usually a large dish antenna, that can point towards a very narrow region of the sky. Incident waves on the antenna excite electrical signals which are filtered and processed, and then translated into an image of the sky.

As the frequency of the EM waves of interest gets lower, the wavelength increases and thus, the size of the required aperture. Radio interferometry is used to overcome the size limitations and increase res-

olution of the instruments. For example, by superposing signal waves from two different radio telescopes, an aperture whose size is equivalent to the antenna spacing between the two instruments can be created.

Challenges

Exploring the 0.3–30-MHz frequency range is a difficult task and has to overcome a few limitations.

The wavelength of the radiation of interest ranges from 10 meters to 1 kilometer, being inversely proportional to the frequency. These ultra-long waves can only be observed with apertures which have sizes comparable to their wavelength. Implementing this in a monolithic fashion is impossible. Figure 1.5 shows a comparison between some of the largest dish antennas on Earth. Currently, the Arecibo Observatory benefits from the largest antenna in the world, having a diameter of almost 300 meters. However, the size makes the antenna unsteerable and thus, limits its scientific capabilities.

Figure 1.5: Comparison between the largest dish antennas in the world.

Furthermore, since the bandwidth spans more than six octaves, it is very difficult to build an instrument that will be tuned for all frequencies. Building an array with a large number of elements and varying spacing between the elements could overcome these problems. This solution was adopted by the Ukrainian T-shaped Radio telescope, second modification (UTR-2) which comprises an array of 2,040 antennas spread over an area of 1,800 meters by 900 meters. The multitude of baselines that can be established confer this radio telescope an opera-

tional band from 8 MHz up to 40 MHz [25]. However, meteorological conditions and ionospheric properties hinder the performance of the UTR-2 at very low frequencies.

Hence, the ionosphere's influence is another challenge for exploring the Dark Ages. The ionosphere is, in fact, opaque for ultra-long EM waves with frequencies lower than 15 MHz. Added to this, the influence of scintillation becomes significant below 30 MHz. In Figure 1.6, it can be seen to what extent the atmosphere permits the EM radiation to pass through. Sketches of a few instruments for astronomical and radio astronomical observations are also illustrated. It can be noticed that, as propagation through the atmosphere becomes an issue, space-based solutions are employed.

Figure 1.6: Atmosphere's opacity as a function of frequency.

A space-based instrument is also required to bypass the influence of man-made radio-frequency interference (RFI) [26], which, otherwise, would make it difficult to distinguish the EM radiation of interest.

1.2.2 Low-frequency radio telescope attempts

Until a few years ago, space was a very difficult domain to approach and placing any kind of instrument above Earth's surface required lots of resources. This, aside of the limitations previously stated, made the exploration of the Dark Ages of astronomy to be somewhat impractical.

The technological advancements eased the access to space and made the idea of space-based apertures for very low frequencies realizable.

Because of the relevant scientific drivers, several initiatives to perform space-based ultra-long-wavelength radio astronomy have been developed or are under development [13]. Projects such as Dark Ages Radio Explorer (DARE) [27] or Lunar Radio eXperiment (LRX) [28] are planning to launch spacecraft carrying long wire antennas capable to detect EM waves with frequencies as low as tens of MHz. In order to be able to go lower in frequency, it is needed to overcome the aperture size challenge. Earth-based radio telescopes (Low Frequency Array (LOFAR) [23] and Very Large Array (VLA) [24]) use interferometric arrays as a solution to this problem. By distributing the observation task to a large number of small antennas, it is possible to synthesize very large apertures.

The evolution and ongoing miniaturization of technology led to the emergence of cheap and small satellite platforms such as the cube-sats [11], and it enhanced the possibility of building space-based interferometric arrays for uncovering the Dark Ages.

The distributed approach

In the DARIS project [12], a study about the possibility of doing low-frequency observations with multiple small satellites was conducted. A scenario with eight slave spacecraft and a central spacecraft was proposed, in which the nodes will do the sensing part while the mother-ship will have additional processing and communication tasks. One of the conclusions of the study was that technology has reached a level where this type of scenario is realistic and can be implemented with commercial off-the-shelf (COTS) components. However, having a central spacecraft increases the risk of failure of the system.

By employing a fully distributed system, without specialized master or slave nodes, the single point of failure is removed. The trade-off is that the complexity of the individual nodes will increase, as well as the complexity of the entire system.

1.3 THE OLFAR PROJECT

The [OLFAR](#) project is aimed at developing a large-aperture radio telescope in space to explore celestial radio waves in the very-low-frequency range of 0.3–30 MHz by using a fully distributed system. The radio telescope proposed for [OLFAR](#) consists in an aperture synthesis interferometric array implemented with a swarm of 50 or more nanosatellites, in which each satellite carries one element of the array [\[29\]](#). Figure [1.7](#) shows how interferometry can be performed within the [OLFAR](#) swarm.

Figure 1.7: The [OLFAR](#) satellite swarm. The double arrows illustrate some of the interferometric baselines that can be formed.

The swarm will be deployed in a suitable orbit that provides the radio quietness required for the scientific observations. Location possibilities include orbits around the Moon, the Sun-Earth L₄ or L₅, and Sun-Earth L₂ Lagrangian points¹², as well as Earth leading or trailing solar orbits [\[29\]](#). Although the satellites will be confined into a

¹² A Lagrangian point is an orbital deployment where a small object such as a satellite can maintain its orbital configuration solely due to the gravitational pull of two large celestial bodies (the Sun and the Earth, or the Earth and the Moon).

cloud of 100 km in diameter, the spatial distribution of the swarm will change, allowing baselines of different lengths and orientations to be established. Furthermore, the orbiting will permit the instrument to perform observation over the entire 4π -steradian field of view.

The satellite swarm concept consists in a system made up of simple (almost disposable) autonomous units, which perform small tasks that contribute to the completion of a common system goal [30]. This way, a swarm shows considerable robustness through redundancy, as well as scalability and self-organization capabilities [31]. However, a satellite swarm also imposes considerable engineering challenges that must be addressed in order to exploit the advantages of the concept [32].

Designing the OLFAR satellites requires similar steps as any mainstream space mission. It is a matter of integrating multiple subsystems (processing unit, propulsion, attitude determination and control, and communication units) into a miniaturized satellite platform (e.g. a cubesat). Furthermore, the swarm implementation adds complexity to the individual nodes [33].

The low-frequency telescope functionality also imposes stringent requirements for the data processing and transfer. Imaging the Universe in the ultra-long-wavelength domain requires computationally expensive signal processing algorithms, and very precise ranging and synchronization between the observing nodes [34]. Added to this, the communication layer of the swarm needs to support the transfer of large amounts of data between the satellites, and from the swarm to a base station (BS) on Earth, all at the cost of very limited power [32].

1.4 RESEARCH QUESTION

This thesis will focus on the communication layer of the OLFAR swarm, and will investigate the possibility of transferring the required data within the satellite swarm and from the satellite cloud to Earth. This research will start by analyzing the overall system, the requirements that are associated with the low-frequency imaging task, and the data architecture and topology. This will be followed by the study and design of individual subsystems for inter-satellite and downlink communication. The entire study concentrates on investigating whether a swarm of small satellites can meet the data flow requirements of a low-frequency radio telescope.

The goal of this research is achieved by solving the following engineering challenges.

- designing a communication layer for distributed high-resolution imaging of the Universe in the low-frequency domain;
- optimizing the power consumption for communication tasks at swarm level;
- finding an adequate topology for distributing the observation data within the swarm;
- establishing a reliable inter-satellite link (ISL) between the OLFAR satellites;
- downloading the preprocessed data from the remote location of the OLFAR swarm;
- integrating a downlink antenna system into other subsystems of the OLFAR satellites;
- fitting all these subsystems into a cubesat platform.

1.5 THESIS STATEMENT AND CONTRIBUTION

This research contributes to the area of communication systems for nanosatellite swarms. Specifically, it introduces new concepts and innovative systems for the fields of data distribution, inter-satellite communication and satellite-to-Earth links. An adaptive two-layer hierarchical topology is designed and fitted to the specifics of the OLFAR project. The topology uses the system's redundancy (large number of spacecraft) in order to reduce the power consumption for spreading information in the satellite swarm. Moreover, a general ISL design concept is presented. A data link between any two OLFAR nodes is established by employing a conformal antenna configuration and a beamforming controller. This study also proposes a couple of novel approaches for satellite cooperative communication, and an integrated hardware solution for transmitting data from the OLFAR satellites to a BS on Earth.

1.6 OUTLINE OF THE THESIS

After the introduction, this thesis will continue with the system analysis of the [OLFAR](#) project and the derivation of the data distribution requirements in Chapter 2. In Chapter 3, the data distribution within the [OLFAR](#) swarm and the possibility of using clustering to minimize the communication power consumption are investigated. The design challenges of an [ISL](#) for cubesats, as well as a proposed solution, are presented in Chapter 4. The next two chapters will focus on the downlink communication. Two different approaches for transferring data from the [OLFAR](#) satellites to Earth will be discussed. In Chapter 5, a couple of swarm strategies for data downlink are described. Chapter 6 presents a hardware solution for the downlink problem and includes the design of a dual solar panel-downlink antenna system. The thesis ends with conclusions and recommendations in Chapter 7.

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Chapter 2

System analysis

The [OLFAR](#) project is aimed at developing a radio telescope in space for the 0.3–30-MHz domain by employing swarm of 50 or more nanosatellites. Having identical structures, the spacecraft will exhibit an emergent behavior as a result of only local interactions between entities, thus, acting similar to an insect swarm. The satellites will be deployed in a remote location and will be used to sense and sample the cosmic signals, process the information by means of distributed correlation, and send the processed data to a [BS](#) on Earth.

Several aspects give [OLFAR](#) an unique approach and distinguish the project from previous studies such as [DARIS](#) [1], Formation-flying sub-Ionospheric Radio astronomy Science and Technology ([FIRST](#)) [2] and Spaced-Based Ultra-Long Wavelength Radio Observatory ([SURO](#)) [3]. Unlike these previous projects, the system proposed by [OLFAR](#) is completely distributed and does not use any complex mothership for data processing or relaying. [OLFAR](#) comprises a satellite swarm consisting of a large number of identical spacecraft that will have to fulfill three main tasks—radio observation, distributed data processing, and down-linking. Although different satellites might be assigned different functionalities at certain moments, no difference will be made from the hardware perspective. This increases the robustness and reliability [4] of the swarm and will also enhance the processing of the radio astronomy data.

Another key aspect of the [OLFAR](#) project is its engineering mindset. Previous work [5] has proven the feasibility of a low-frequency radio telescope, and thus, the focus shifted towards the implementation.

In this chapter, the implementation details of the [OLFAR](#) swarm will be discussed and the requirements and challenges for the communica-

tion layer will be extracted. At first, the possible orbital deployments for the satellites will be analyzed, and then **OLFAR**'s main tasks in the lunar orbit scenario will be described. Further on, a functional architecture for a nanosatellite for science is presented, and the data flow is explained. Finally, a cubesat platform is considered for the implementation of **OLFAR**, and a set of requirements and limitations is outlined.

2.1 SWARM DEPLOYMENT

Performing the radio astronomy task using a small satellite cloud raises a lot of challenges, both at the swarm level and for the individual spacecraft. A very important role in designing the system is played by the deployment location of the **OLFAR** swarm. In Chapter 1, the necessity for placing the **OLFAR** instrument far away from the influence of terrestrial **RFI** was explained.

Multiple possible locations have been proposed for **OLFAR** [6]. These include Sun-Earth L₄ or L₅ and Sun-Earth L₂ Lagrangian points, Earth-Moon L₂, as well as a lunar orbit. Some of the possible deployment locations are illustrated in Figure 2.1.

Figure 2.1: Possible deployment locations for the swarm of satellites.

Placing the swarm in the Sun-Earth L₄ or L₅ points would reduce the influence of man-made **RFI** and also has the advantage of stability. Due to the gravitational pull of the Sun and the Earth, satellites could stay in orbit without the need for any propulsion. The drawback of these locations is their remoteness. The distance between these points

and the Earth is approximately 1 astronomical unit (AU)¹. Hence, the amount of propellant required to reach these points makes it very costly to place multiple spacecraft there. Furthermore, maintaining a radio connection with the spacecraft would be very difficult. Sending data to and from L4 or L5 would require a great amount of energy.

The Sun-Earth L2 or Earth-Moon L2 are other stable location that could be suitable for OLFAR. Nonetheless, the free-space attenuation of low-frequency EM waves originating from Earth is not sufficient to facilitate radio astronomical observations.

Measurements of the level of interference and noise were conducted by the Explorer 36 (RAE-A) in 1970 and Explorer 49 (RAE-B) in 1973 [7]. In Figure 2.2, the raised noise floor for low frequencies can be identified. The top frame is a computer-generated dynamic spectrum. The other plots display RFI intensity versus time at variations at frequencies where terrestrial noise levels are often observed. It can be seen that the measured values drop significantly when the spacecraft is behind the Moon—the time interval between the “Immersion” and “Emersion” markers.

Figure 2.2 also shows that, when the RAE-B spacecraft was on the far side of the Moon, the measured level of RFI was considerably lower. Thus, it was concluded that the Moon acts as a shield for interference and creates a radio-silent zone.

It is only a step forward to think that the radio-quiet zone can be exploited by OLFAR for low-frequency radio astronomy. Due to the very low level of man-made noise, it should be possible to distinguish the highly attenuated EM waves that originated in the Dark Ages of astronomy. Therefore, a lunar orbit has also been proposed for the OLFAR satellite swarm, and although it is difficult to reach and maintain, it is highly desirable from the scientific point of view.

In this research, a lunar orbit has been considered for the satellite swarm and the challenges and requirements were drawn accordingly. Nevertheless, opting for one of the other deployment locations would not change the working process of OLFAR fundamentally, and thus, it will neither alter the results substantially.

¹ 1 AU = 149,597,871 km.

Figure 2.2: Example of a lunar occultation of the Earth as observed by the RAE-B. ©European Southern Observatory • Provided by the NASA Astrophysics Data System

2.2 THE OLFAR SATELLITE SWARM IN A LUNAR ORBIT

Table 2.1 summarizes the strong points and weaknesses of a lunar orbit for the OLFAR satellite swarm.

The shielding that the Moon provides makes the lunar orbit an ideal candidate for the deployment of the OLFAR swarm. However, it also makes it impossible to establish direct links with the satellites when on the far side of the Moon. Furthermore, in order to preserve the radio silence, recommendations are that no wireless links should be established by spacecraft that are in the Moon's cone of shadow [8].

Another drawback of the lunar orbit is the instability. Because of the nonuniformity [9] of the Moon's gravitational field, maintaining an orbit around it requires the use of propulsion [10]. In the case of a satellite swarm, spacecraft will tend to drift from the original relative position. The distribution of the entire system will change in time. Furthermore, in a lunar orbit, satellites will tend to drift faster than in

Table 2.1: Advantages and disadvantages of a lunar orbit for the OLFAR system.

Advantages	Disadvantages
Performing observations on the far side will protect them against terrestrial RFI.	On the far side the swarm will have no contact with the BS.
The lunar orbit is the closest to Earth deployment location considered.	It is difficult to maintain the orbit due to nonuniform lunar gravitational field.
Orbital drifts enhance the imaging process.	The continuously changing topology affects the data distribution capabilities within the swarm. Instability of the orbit imposes short integration times, and thus, degrades the observation process.

any of the above-mentioned Lagrangian points. This imposes shorter integration times for the correlation process. This will result either in a lower telescope sensitivity or in harsher requirements for the data distribution and processing.

The dynamics of the satellite swarm can represent an advantage for the low-frequency telescope functionality as various baselines can be established at different moments in time. Varying the distance between satellites helps covering the full frequency range while changing orientations of the baselines is required to construct an all-sky type of image.

Although it is very challenging, the lunar orbit provides significant benefits for the OLFAR project. Added to the radio-silent region and the possibility of establishing many baselines, the proximity to Earth represents a great asset. It is easier to access than the Lagrangian points L4 and L5, and therefore, less costly to launch the spacecraft. The proximity to Earth also will make data downloading and uploading less challenging. The distance to the Moon is on average only 0.00257 AU (384,000 km). Since the free-space path loss is proportional to the square of the distance, the attenuation of data signals will be almost six orders of magnitude lower than in the L4 or L5 scenarios. Thus, the power requirements will be greatly reduced. Nonetheless, in

the worst case scenario—lunar apogee²—the **OLFAR** swarm will have to transmit data over a distance almost as large as 405,400 km.³

It is also important to consider the fact that several successful missions have already flown on lunar orbits [7], [11]. It does not represent uncharted territory. Data about the orbits and the gravitational field of the Moon exist and can be used to enhance the robustness of the **OLFAR** mission.

In order to comply with the advantages and the constraints of a lunar orbit, the satellite swarm will exhibit a temporal separation of the tasks. In Figure 2.3, a possible **OLFAR** orbit and the corresponding stages are illustrated.

Figure 2.3: **OLFAR** satellite swarm.

One orbital period can be divided into three (optionally four) stages, each one corresponding to one of the previously mentioned duties.

1. Observation: while on the far side of the Moon, the satellites will use large dipole antennas (field probes) to sense and sample the cosmic background radiation. Within this period, the amount of electronics used will be kept to a minimum, and no communication duties will be performed.

² Apogee is the point in an elliptical Moon orbit that is farthest away from Earth.

³ The distance swarm-to-Earth also depends on the height of the orbit.

2. Data distribution and processing: after the useful signals have been preprocessed (filtered and sampled), the data will be distributed among the members of the swarm. Once the data is shared, it will be processed by means of distributed correlation.
3. Data downlink: the results of the distributed processing will be sent to a BS when the swarm will face Earth. In this way, the power necessary for the downlink will be minimum.

The fourth optional stage represented in Figure 2.3 could be used to complete the data distribution and processing task or for energy harvesting. If not needed, the system will be in idle mode to preserve its resources. The time that the swarm will spend on each of the tasks depends on the orbital deployment as well on the characteristic of the orbit. In [12], the scenario for a 3,000-km circular lunar orbit has been analyzed. The results, comprising the maximum time span of the corresponding stages and the required power figures for each of the three main tasks, are summarized in Table 2.2. It has been considered that the system takes the same amount of time for scientific recording as for sending the processed data to the BS. The time intervals can be tuned to better match the scientific goals of the project. Changing the duration of each task will alter the power and data rate requirements, yet it will not have a major impact on the design of the associated subsystems. Hence, the validity of the work presented in the following chapters will not be affected.

Table 2.2: Estimated power consumption during the satellite phases in a 3,000-km altitude circular lunar science orbit.

Satellite mode	Power consumption [W]	Worst-case (duration) [hr]
Observation	10	0.97
Data distribution and processing	13.8	5.9
Data downlink	4	0.97

2.3 THE NANOSATELLITE PLATFORM

Implementing a low-frequency radio telescope to cover the complete 0.3–30-MHz frequency band will require a large number of individual antennas to form baselines of different lengths. Moreover, to cover the complete sky and get a 360° image of the Universe, these antennas will need to change position and orientation in time in order to achieve a complete UVW mapping [13].

Performing this mission could be feasible using large satellites with dedicated hardware for ultra-long-wavelength radio astronomy. The costs associated with mainstream missions are, however, very high, and an implementation using 50 or more of this type of spacecraft make this impossible.

For the implementation, [OLFAR](#) plans to use a spacecraft swarm. A swarm is not a formation but more an aggregation of entities that exhibit a collective behavior to achieve a common goal. It is characterized by redundancy, robustness, lack of a hierarchy, and self-organization. For such a system to function as intended, its elements have to be very simple and easily replaceable. The intelligence and reliability of the swarm are collective and not individual [14].

For the [OLFAR](#) project, the requirement is to have a large number of satellites with a very simple structure. The nanosatellite is a recently emerged type of artificial satellite that is meant for performing very simple missions such as telemetry, data-relaying or remote Earth sensing [15], [16]. With a “wet mass” of up to ten kilograms, a nanosat structure can fit a very limited amount of hardware [17]. The low launching costs make the nanosatellite platform suitable for a spacecraft swarm, and these types of designs have already been proposed [18].

2.3.1 *The nanosatellite architecture*

The nanosatellites that are going to be launched in the [OLFAR](#) project should have a very simple architecture. The satellites will have to use most of their resources to fulfill the main observation task, the low-frequency radio astronomy, while the secondary maintenance and support operations should use a minimum of their capabilities.

In [19], an architecture for the [OLFAR](#) nanosats has been proposed. In Figure 2.4, a summarized version is presented. It can be seen that

the satellite only fulfills a limited number of tasks. At the core of the spacecraft there are the electrical power system (EPS) and the onboard processing unit (OPU). The two units provide the required resources (energy and processing power).

Figure 2.4: Architecture of a nanosatellite for radio astronomy.

The OPU manages and controls all the subsystems of the satellite and handles the data processing, while the EPS provides power to the bus and the astronomical payload of an OLFAR satellite.

The propulsion block will be used to transfer the satellites from their initial deployment location to the orbit of interest. Added to this, propulsion can also be used to change the orbital characteristics in order to avoid collisions or fill the observation plane [1]. The attitude determination and control system (ADCS) is necessary for performing the radio interferometry. Controlling the attitude of the OLFAR satellites will also be beneficial to the efficiency of the energy harvesting process and the data downlink process. A storage unit will be used if the processing or the downloading of the data cannot be fulfilled within the associated orbital interval.

2.3.2 The data flow architecture

The rest of the subsystems of the nanosatellite architecture make up the information path. These subsystems are responsible for performing the data collection, distributed data processing tasks, and downlink. Figure 2.5 is a zoomed-in version of the nanosatellite architecture with the emphasis on the data flow.

Figure 2.5: Data flow architecture of the OLFAR nanosatellites.

Unlike the EPS and the OPU that are critical for existence and functionality of every satellite, the blocks in Figure 2.5 are important for achieving the radio telescope goal.

In [4], a Markov-chain analysis is performed to extract the reliability of the OLFAR satellites as well as the OLFAR swarm. It was concluded that, with the use of hardware already flown in space, a single swarm satellite can perform its tasks error-free for more than 7 years. This gives the OLFAR swarm sufficient time to fulfill the radio observation goal and complete its scientific mission described in Chapter 1. Moreover, when used in a swarm the error-free functioning time of the entire system increases to 11 years.

Considering the architecture illustrated in Figure 2.4, the importance of the communication layer in realizing a distributed radio telescope can be noticed. The data distribution within the swarm and from the

swarm to Earth is strongly connected to the signal acquisition and processing. Thus, for a better understanding and to extract the requirements of the communication subsystems, the individual and collective signal processing will be briefly explained in the following subsection.

2.3.3 Requirements of the distributed correlation

The [OLFAR](#) satellite swarm will use a distributed frequency correlator FX architecture to realize the low-frequency map of the sky [20]. For space-based interferometry, the distributed frequency correlator is seen as the optimal solution [21]. For the radio astronomical imaging process, the satellites will observe the low-frequency radiation by using long dipoles, and then cross-correlate and integrate the received signals [20].

To cover the complete 0.3–30-MHz band, the swarm will divide it into smaller bands and will process an instantaneous bandwidth Δf_i of 1 MHz. The [OLFAR](#) system consists of a 3D imaging array. Satellites will be spread in a spacecraft cloud and will sense incoming low-frequency radiation from every direction possible. In order to achieve sufficient spatial resolution, the satellite cloud will have a diameter of up to 100 km [22]. Unlike radio telescope arrays on Earth, not all the formed baselines in [OLFAR](#) will be coplanar. Therefore, if a Cartesian reference system is considered, each member of the swarm will simultaneously have to observe three field components (X, Y and Z).

For each of these components, satellites will acquire a signal, Nyquist sample it at 60 MHz, quantize it, and mitigate the [RFI](#). After these steps, a filter bank is used to select the frequency band for processing. The data rate for the observed astronomical data D_{obs} can be calculated as

$$D_{\text{obs}} = 2\Delta f_i N_{\text{comp}} N_{\text{bit}} \quad [\text{bps/satellite}], \quad (2.1)$$

where Δf_i is the instantaneous bandwidth, N_{comp} is the number of field components, and N_{bit} represents the number of bits per sample [20].

At the level of the individual satellite, the acquired astronomical signal will have to undergo several processing steps as shown in Figure 2.6.

If in (2.1) a 1-MHz instantaneous bandwidth is considered, and that after the [RFI](#) mitigation 1 bit per sample will be used for further processing, the observed data rate D_{obs} for each satellite will be 6 Mbps.

Figure 2.6: **OLFAR** nanosatellites level signal processing. The poly-phase filter bank (PFB) blocks are used to separate incoming signals into subbands that can be processed.

The observed astronomical data will be processed at swarm level in a distributed manner. The analyzed band of 1 MHz will be divided into a number of subbands equal to the number of satellites N_{sat} . Thus, each satellite will calculate crossproducts for its assigned frequency band and integrate them over a period of duration τ . The width of each subband is

$$\Delta f_{\text{sb}} = \frac{\Delta f_i}{N_{\text{sat}}}. \quad (2.2)$$

For the distributed processing it is necessary that every satellite acquires its corresponding dataset from all its peers and sends its observed data to all the other members of the swarm. Hence, the amount of data an **OLFAR** node has to be able to send and receive is

$$D_{\text{ISL}} = 2\Delta f_{\text{sb}} (N_{\text{sat}} - 1) N_{\text{comp}} N_{\text{bit}} \quad [\text{bps}]. \quad (2.3)$$

Once the data is received, the satellites divide their subbands into smaller frequency bins of 1 kHz each and calculate the correlation elements on each bin. The correlation element is given by

$$\hat{\mathbf{r}}_{ij} = \frac{1}{\tau} \int_0^{\tau} \mathbf{s}_i \mathbf{s}_j^{\dagger} dt, \quad (2.4)$$

where τ is the integration period, $\mathbf{s}_i$ and $\mathbf{s}_j$ are the signal sets corresponding to satellites i and j , respectively, and † is the Hermitian transpose operator [23]. The signal set $\mathbf{s}$ is given by

$$\mathbf{s} = \begin{bmatrix} s_X(t) \\ s_Y(t) \\ s_Z(t) \end{bmatrix}, \quad (2.5)$$

where $s_X(t)$, $s_Y(t)$ and $s_Z(t)$ are the signals that correspond to the three Cartesian field components.

After the processing, due to the integration step, the amount of data will be significantly reduced. The total amount of processed data available at swarm level will have to be sent to a BS on Earth. The required data rate for the downlink [21] can be calculated as

$$D_{\text{down}} = \frac{2N_{\text{sat}}N_{\text{comp}}^2(\Delta f_i/1 \text{ kHz})N_{\text{bit}}}{\tau} \quad [\text{bps/satellite}]. \quad (2.6)$$

If the values in the first part of Table 2.3 are used in (2.1), (2.3) and (2.6), the data rates for observation, ISL and downlink can be calculated to be as shown in the second part of the same table. The integration time τ of 1 second is imposed by the choice of a lunar orbit [24]. A more stable orbit would allow longer integration times, and hence, smaller data rates.

2.4 THE CUBESAT IMPLEMENTATION

The data rates for inter-satellite communication and downlink calculated in Section 2.3.3 are not very uncommon for satellite scenarios. However, OLFAR intends to achieve its goal by employing a swarm of nanosatellites. The limited available space and power in these small

Table 2.3: Distributed processing parameters of the [OLFAR](#) system.

Parameter	Symbol	Value [Unit]
Instantaneous bandwidth	Δf_i	1 MHz
Number of satellites	N_{sat}	50
Number of field components	N_{comp}	3
Number of bits per sample	N_{bit}	1 bit
Integration time	τ	1 second
Observed data rate	D_{obs}	6 Mbps/satellite
Inter-satellite data rate	D_{ISL}	5.88 Mbps
Downlink data rate	D_{down}	900 kbps/satellite

spacecraft make it difficult to transfer large amounts of data between the satellites and from the swarm to Earth.

The implementation of [OLFAR](#) will be based on the cubesat platform [17]. The project plans to launch three-unit (3U) cubesats similar to Delfi-C3 [25] or DelfiNext [26]. These types of spacecraft have been developed by the academic community to gain access to space, and, after many successful launches [15], it was concluded that cubesats can replace mainstream missions with simple tasks.

The 3U cubesat platform consists of a rectangular cuboid structure of 10 cm $\times$ 10 cm $\times$ 30 cm. Within this volume, all the hardware components associated to the blocks in Figure 2.4 have to be accommodated. This leaves very little room available for batteries or propulsion. Furthermore, the area on the exterior of the satellite can be used to host a small number of solar cells and has to be shared with other components (antennas and sensors). Thus, 3U cubesats have a power budget of only few Watts [25].

Deployable structures can be added to the cubesat platform. However, these are also subject to some constraints. This category of spacecraft uses standardized orbital deployers such as the poly-picoSatellite orbital deployer (P-POD) [27] or ISIPOD [28]. In Figure 2.7a, the dimensions of an [OLFAR](#) cubesat are sketched. Figure 2.7b shows an example of a 3U cubesat (Triton-1 [29]) and its ISIPOD orbital deployer.

The [OLFAR](#) satellite will have to meet the size requirements of the aforementioned space hardware.

(a) Cubesat platform

(b) Triton and the ISIPOD

Figure 2.7: The cubesat platform (a) and an example of a 3U cubesat (Triton-1) and its ISIPOD orbital deployer (b).

Table 2.4: ISL and downlink requirements for the OLFAR swarm.

Parameter	Value
Inter-satellite data rate D_{ISL}	5.88 Mbps
Maximum distance satellite-to-satellite	100 km
Downlink data rate D_{down}	900 kbps/satellite
Maximum distance swarm-to-Earth ^a	402,400 km

^a Maximum distance for the downlink communication assuming a 3,000-km altitude circular lunar orbit.

2.5 CONCLUSIONS

After stating the requirements for the communication layer—the link parameters (data rate, distance) for the ISL and for the swarm-to-Earth communication—and the limitations imposed by the satellite platform, this study continues with the design of two links. For each of the two components, data distribution within and data transfer from the OLFAR swarm, the logical layer is analyzed, and a communication strategy is proposed. Subsequently the design of the physical layer and the antenna configurations for the two subsystems are presented.

Table 2.4 summarizes the distance and data rate requirements for both the ISL and downlink communication for the OLFAR satellites.

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Chapter 3

Data distribution topology

As already described in Chapters 1 and 2, the [OLFAR](#) project will consist of more than 50 very small satellites, that will gather data individually and process it in a collective manner, ensuring the functionality of a low-frequency radio telescope. On the whole, the system will act as a large wireless sensor network, with a few peculiar requirements such as sparsity, sustained high data rates (around 6 Mbps/satellite) and changing topology [1].

Hence, distributing the collected astronomical data within the network of satellites is a very challenging task. This step is mandatory for the collective processing of the scientific data, and requires the design of a communication layer both at logical and physical levels. Thus, in order to fulfill the data distribution task, a logical topology as well as the associated inter-satellite links have to be established.

This chapter focuses on the first of the two problems and proposes an adaptive topology for the [OLFAR](#) swarm. Initially, the challenges of the communication layer are analyzed in Section 3.1. In Section 3.2, the possibility of using nonhierarchical (gossiping and broadcasting) and hierarchical (clustering) topologies for data distribution is investigated, and different approaches are compared from the power-efficiency point of view. In Section 3.3, the eligibility for the [OLFAR](#) scenario of several existent clustering schemes is analyzed. Section 3.4 consists of the design of an adaptive clustering scheme for a satellite swarm. Its performance is evaluated in Section 3.5, and conclusions are drawn in Section 3.6.

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3.1 DATA DISTRIBUTION CHALLENGES

The satellite swarm will consist of simple spacecraft, but as a whole it will act as a very complex structure. The low-frequency radio telescope functionality requires the nodes to form very long baselines. Therefore, within the [OLFAR](#) cloud, the distance between two nanosatellites can be from a few meters up to 100 km. If the size of the topographical distribution of the satellite swarm and the available resources are taken into consideration, as well as the number of nodes, it can be stated that, unlike most sensor networks, the swarm is very sparse. This type of network imposes a high reliability on the communication links since alternative routing paths are rarely available.

In Chapter 2, the acquisition and processing of the signals from the astronomical sources have been briefly discussed, and the data rates for the acquired astronomical data and for the [ISL](#) have been evaluated to be in the order of megabits per second. From (2.1) and (2.3), it resulted that after the [RFI](#) mitigation, each [OLFAR](#) node will have had collected 6 Mbps of scientific data, out of which 5.88 Mbps will have to be distributed later on to all the other members of the swarm. If these data rates and the time intervals for each operational stage of the swarm (listed in Table 2.2) are taken into account, it can be predicted that the satellites will transfer their data almost continuously. Store-and-transmit solutions such as delaying the data communication until the satellites are in the proximity of each other have not been considered for [OLFAR](#) to avoid increasing the hardware complexity of the spacecraft. The cubesat platform limits the data storage capabilities of the swarm.

Furthermore, the use of cubesats will introduce several constraints that most sensor networks encounter. One of the most important limitations of the satellite platform is the available power. Several factors (such as the available surface on the satellite, the residual volume in the orbital deployer and the solar eclipse time) bound the power budget. In Chapter 6, a discussion on the available power of the [OLFAR](#) satellites will be presented. For now the fact that the data distribution topology should be power-efficient has to be taken into account.

Another important aspect to consider is the mobility of the nodes. The swarm will consist of simple spacecraft deployed into unstable orbits. Hence, the [OLFAR](#) nodes will drift away from the ideal trajectory

and will move relative to each other [2]. The topographical spread of the satellites will be time-variant, and thus, the data distribution topology will have to continuously adapt to the changes.

All these requirements make the communication task very challenging to fulfill. The system will have to use most of its resources to achieve the low-frequency radio telescope goal and should not be overloaded with secondary operations. An efficient communication topology is required to reduce the data distribution efforts within the satellite swarm.

3.2 HIERARCHICAL AND NONHIERARCHICAL TOPOLOGIES

3.2.1 *Gossiping and Broadcasting*

The most straightforward way to solve the communication layer problem would be to employ a full-mesh topology for the network. For the distributed imaging to be performed, it is necessary that satellites share part of their collected data with all the other members of the swarm, as discussed in Section 2.3.3. In the *OLFAR* cloud, each satellite will have to transmit D_{ISL} and be able to receive the same amount of data. In the full-mesh scenario, every node will have to establish $N_{\text{sat}} - 1$ data links, each link with a throughput of $2 \times D_{\text{ISL}} / (N_{\text{sat}} - 1)$. Each *OLFAR* satellite will have to divide its observed data into N_{sat} subbands and send every subband to its corresponding processing node. At the same time each node will receive its corresponding data from all the other peers in the network.

The advantage of this topology is that the data rate of each link is fairly low. Nonetheless, the high resource demands make this type of network inappropriate for the *OLFAR* swarm. It would be difficult for each nanosatellite to establish $N_{\text{sat}} - 1$ links. Even if the communication links do not have to be simultaneous, the maximum diameter of the satellite cloud is a significant drawback. Furthermore, the distributed imaging process can be compromised by the failure of any of the links. The full-mesh topology is certainly not feasible for a large network distributed over a vast area in space, because the necessary power will tend to increase exponentially with the number of nodes and the distances between them.

For sensor networks, other nonhierarchical solutions such as gossiping or broadcasting are often used to deal with the limited resources or with the large number of nodes, respectively.

The Gossip protocol [3] has been proven to be successful in some ad-hoc networks that implement distributed algorithms. The protocol has been inspired by social networks and uses local interactions (communication with the closest node) to distribute information over the network. It is a good solution for sensor networks with inconvenient structures, but is not suitable for a satellite swarm with high data rate requirements. In Figure 3.1, it can be seen how using only local interactions causes data to aggregate and increases the data rate requirement from one node to the other. Although it cannot guarantee the correct functioning of the swarm as a radio telescope, gossiping remains a good solution for the initialization of the system—network discovery.

Figure 3.1: Data aggregation using the Gossip protocol in a WSN.

Broadcasting is another potential solution for distributing the data all over the network. The main advantage of broadcasting is that it does not require physical point-to-point links between satellites in the swarm [4]. As illustrated in Figure 3.2 in an OLFAR broadcast scenario each satellite will send its entire data set to all the other swarm members by radiating it in an omnidirectional fashion. It is then up to each node to extract the data it requires for the processing.

Figure 3.2: Information distribution in the satellite network using broadcast.

The major drawback of a broadcasting network is its power efficiency. Since a node will transmit in every direction possible, it will radiate power in the complete 4π -sr sphere. Since the [OLFAR](#) swarm will be sparse, a lot of energy will be wasted. Furthermore, the maximum distance to be covered will be 100 km and even the best positioned satellite (in the center of the cloud) will still have to reach nodes as far as half of the maximum distance.

An estimation of the required power budget and a discussion over the power efficiency of both broadcasting and full-mesh scenarios will be presented in the following sections.

3.2.2 Clustering

A hierarchical approach (clustering) can be used for the swarm to enhance the data distribution task. For most large-scale mobile ad-hoc networks ([MANETs](#)), dividing the nodes into clusters is essential to guarantee basic levels of system performance, such as throughput or

delay. This provides additional benefits that could be exploited also in the case of the [OLFAR](#) swarm.

A cluster structure eases spatial reuse of resources and can increase the system's capacity. Same frequencies or codes can be deployed in disjoint clusters. Added to this, routing is more facile to do in a hierarchical approach. Cluster heads or gateways can form a backbone for the system, simplifying the data distribution task. Nonetheless, one of the most important advantages of clustering is that it makes the network more stable and smaller from the members' point of view. Local changes in one domain will not cause disturbances in the entire system [5].

There are also drawbacks in using clustering for a satellite swarm. Assigning a backbone or relay role to some satellites will use most of their resources for communication duties and a higher latency might be experienced because of the multi-hop communication links.

The goal is to reduce the complexity of the communication task and minimize the energy consumed for transmitting and receiving information. In this way, the system's resources will be used more efficiently to achieve the science objective, namely, exploring the Universe in the low-frequency band.

In order to see which type of topology suits the [OLFAR](#) cloud the most, the performances of a broadcast scheme and of a simple geometrical clustering scheme were analyzed in terms of power efficiency and their limitations.

3.2.3 *Model*

To compare the power efficiency of clustering and broadcasting, the scenario of a sensor network with 50 nodes was considered. The positions of the nodes were chosen randomly. A full-mesh topology and a clustered topology were fitted to the system and then the total required power for communication was calculated. The required power figure is the sum of power required for transmitting the data to all members of the network and the power required for receiving and processing the data.

The following assumptions have been made:

1. The network terminals are uniformly distributed on an L by L square surface. The considered scenario was two-dimensional as adding a third dimension would not enhance or contribute significantly to the results. Spreading the nodes over a three-dimensional domain would resemble more the actual implementation (a satellite cloud) but will also add unnecessary complexity to the calculations.
2. Each sensor uses power P for receiving and processing one unit of data in one unit of time.
3. Each sensor has a minimum transmission power that corresponds to a transmission distance $d_{\min}$. If the distance d_{ij} between the sending sensor i and receiving sensor j is smaller than $d_{\min}$, power P is consumed for transmitting one unit of data in one unit of time. Otherwise, the consumed power for transmitting one unit of data increases quadratically, by the following rule:

$$P_{\text{TX}} = \begin{cases} P, & d_{ij} \leq d_{\min}, \\ (d_{ij}/d_{\min})^2 P, & d_{ij} > d_{\min}, \end{cases} \quad (3.1)$$

The minimum transmission distance is equivalent to the minimum transmission energy for one unit of data. It is a parameter that was derived from the fact that the circuitry required for releasing information in its wireless form requires certain resources to achieve its static functioning point. The minimum distance corresponds, in fact, to the power unit P . This can be verified by replacing d_{ij} with $d_{\min}$ in (3.1).

4. In the broadcasting scenario, each node transmits its data set by radiating it using isotropic antennas. The level of the radiated power is equal to the necessary power to reach the farthest node in the network. As a result, the antenna gain associated for each terminal in the network is 0 dBi.
5. Clustering is done according to the following rules:
 - a) Clusters are attained by dividing the initial surface into four equal squares. This is illustrated in Figure 3.3. As the clus-

ters are formed considering a geometric criterion, the number of nodes may vary from cluster to cluster.

- b) For each cluster, the node closest to the center of gravity $\mathbf{r}_{G_k}$ of the cluster is elected as the cluster head, where:

$$\mathbf{r}_{G_k} = \frac{1}{N_k} \sum_{i=1}^{N_k} \mathbf{r}_i. \quad (3.2)$$

Figure 3.3: Clustering example. The area over which the sensor network is spread was divided into four equal subareas, each one corresponding to a different cluster. The master nodes are represented by larger “satellite” shapes, whereas the slaves are represented by the smaller ones.

$\mathbf{r}$ is the position vector in a Cartesian reference system, index k denotes a particular cluster, N_k is the number of nodes in cluster k , and $\mathbf{r}_i$ corresponds to node i in cluster k .

- c) A node that is not a cluster head is considered to be a slave node. All slave nodes send and receive data only to and from their corresponding cluster head. In other words, each cluster employs a star topology.
 - d) Each cluster head exchanges data with all slaves in its cluster and with all the other cluster heads. The cluster heads form a full-mesh network.
6. A full-mesh topology for data distribution was also considered. In this scenario, each sensor transmits and receives data from all the other sensors.
 7. For the clustering and the full-mesh cases', it was considered that the network terminals establish directional links. Each node is equipped with an antenna system capable of providing 5 dBi of gain for either transmitting or receiving information. Therefore, each directional link benefits from a total gain of 10 dBi (transmit + receive). The 5 dBi figure will be further explained in Chapter 4 when the link budget of a satellite-to-satellite connection will be discussed.

3.2.4 Results

Considering all the assumptions, the total required power for communication tasks for all the cases—full-mesh, broadcasting and clustered network—was calculated. The calculations were performed for 100 random network configurations and the results are the average of all the realizations.

In Figure 3.4, the ratio between the broadcasting and clustering is plotted as a function of $d_{\min}$, as well as the ratio between the full-mesh and the clustering implementation. In Figure 3.4a, the ratio is higher than one for small values of $d_{\min}$ ($< L/5$). Hence, a clustered approach is more power-efficient than a broadcasting scenario if the default cov-

erage¹ of the nodes is significantly smaller than the area covered by the network. Furthermore, if both Figure 3.4a and Figure 3.4b are taken into account, it can be concluded that a full-mesh is the most power-efficient due to the very low data rates. Nonetheless, the hardware challenges and the lack of robustness make a full-mesh undesirable.

As previously mentioned, there is a direct connection between $d_{\min}$ and the minimum transmission power. It is assumed that the OLFAR swarm scenario corresponds to the very small values of $d_{\min}$, since the power resource of cubesats is very scarce.

For the scenario described above, the average power consumed by different types of nodes—master² for clustered network, and peer node for the full-mesh case and the broadcasting scenario—was also calculated. In Figure 3.5, the values are plotted on a logarithmic scale, as a function of $d_{\min}$. Clustering a network will make most of the members consume less power for communication, at the cost of overloading the relay nodes. There is a trade-off, yet for low values of $d_{\min}$, the advantage is clearly in favor of clustering.

The average power consumed by a slave node is very low compared to a peer node or a master node. Thus, in a clustered network the slaves could save their resources for fulfilling other tasks than data distribution. Master nodes, on the other hand, will tend to consume their energy mostly for communication duty. For that reason, the contribution of master nodes to the observation task will be very limited.

Despite using a basic clustering scheme, the results show that dividing a network into multiple clusters increases its efficiency.

Clustering is a step forward in achieving a functional distributed radio telescope in space. By dividing the OLFAR swarm into small groups of satellites, and electing certain gateway satellites to route the astronomical data, energy resources of the system will be used more efficiently. This hierarchical approach, though an effective tool for the communication layer, comes with one major drawback. Some of the satellites that will act as group leaders, will not be able to actively participate in the scientific task of the swarm. However, as long as

¹ The default coverage of a node is the the area comprised within the circle centered in the node's position and of radius $d_{\min}$.

² The average power consumption of the slave nodes is very low compared to the one of the master nodes, therefore, it is not plotted.

(a) Broadcasting-to-clustering power ratio

(b) Full-mesh-to-clustering power ratio

Figure 3.4: Power efficiency of different communication topologies as a function of $d_{\min}$.

this trade-off only impacts the redundancy of the system, the improvements are incontestable.

Figure 3.5: Power requirements: average node power consumption.

3.3 CLUSTERING THE OLFAR SWARM

Many clustering schemes proposed in the literature are suitable for dynamic WSNs. Most of them have the same objective, and that is to optimize the resource usage of the network. Nevertheless, for achieving this goal, different criteria are used. Dominant-Set-based [5] protocols are aimed at reducing the routing cost by finding a Dominant Set³ in the network. Other clustering schemes [5] try to provide stable cluster architectures so that re-clustering situations are avoided. In this way, the maintenance cost of the network is minimized. Mobility-aware clustering [6] tries to group nodes by their dynamics, as movement is usually the main cause for changes in the topology. Other used algorithms try to maximize the life time of mobile devices in a network

³ A Dominant Set is a set of nodes to which all other nodes in the network are adjacent (can connect via a single hop).

or to balance the power consumption amongst all the nodes. Added to these, combined metrics can also be employed to attain a desired clustering scheme.

When dealing with a swarm of satellites, it is difficult to find a clustering algorithm that matches all the requirements: power efficiency, mobility and high data rates. However, there are a few algorithms that are partially fit for the OLFAR project, and, out of these, worth mentioning are Ryu's algorithm for power-efficient clustering, the global k -means algorithm, the Algorithm for Cluster Establishment ([ACE](#)) for uniform cluster formation, the so-called ASH algorithm for highly dynamic networks, and Mobility-aware Clustering ([MOBIC](#)) for networks that exhibit group mobility behavior.

In his paper [7], Ryu proposes two distributed heuristic clustering schemes that minimize the required transmission power in two-tiered [MANETs](#). Figure 3.6 illustrates how clusters are established.

Figure 3.6: Example of Ryu's clustering algorithm.

Ryu's algorithms assume that the network has only two types of nodes: masters (cluster heads) and slaves (members). A slave node

can be connected only to one master, and links between slaves are not allowed. Master nodes are selected in advance, and each master node establishes a cluster based on its connection to the slaves. The clustering process starts with a paging phase in which every master pages the slave nodes with the maximum allowed power. A slave that receives this messages replies with an acknowledgment to the master corresponding to the strongest signal. First, the nodes that receive only one paging signal are allocated with communication channels, and afterward, other slaves are allocated channels in the decreasing order of their received power level. By giving priority to slaves that receive only one paging signal and employing power control, this scheme can achieve nearly optimum performance. However Ryu's algorithm uses pre-defined masters and has no method for mobility scenarios.

The global k -means algorithm [8] describes a deterministic global optimization method that minimizes the clustering error (sum of the squared distances between nodes and cluster centers). The algorithm is a fast iterative one that solves the clustering problem with M clusters by solving all intermediate problems with $1, 2, \dots, M - 1$ clusters. The basic idea is that an optimal solution for the M clusters problem can be obtained using a series of local searches with the k -means algorithm. At each local search, $M - 1$ cluster centers have their initial optimal position according to the $M - 1$ clusters problem. In [8], the method is proposed for a pattern recognition scenario but it can be extended for the networking case.

Both ACE [9] and ASH [10] are emergent cluster formation algorithms. In their approaches, there is no use of central control or visibility over all the network. In addition, all the nodes communicate with only a limited number of immediate neighbors. In ACE, the objective to create highly uniform clusters is achieved using two processes. The first controls the spawning of new clusters by having nodes elected as leaders, and the second controls how clusters migrate dynamically to reduce overlap. For instance, a node can decide by itself to become a cluster head. It will broadcast a "Recruit" message to its neighbors that will become the followers of the new cluster. Migration of a cluster is controlled by the leader. Each cluster head will poll its followers to determine the best candidate for the leader of the cluster. Once the best candidate is determined, it will be promoted as the new leader. Thus, the position of the cluster will appear to migrate in the direction

of the new cluster head. While some of the former followers of the old cluster-head will no longer be part of the cluster, some new nodes near the new cluster head will become the new followers of the cluster [9].

Based also on emergent behavior, ASH [10] tackles the problem of node grouping in networks that exhibit high mobility. Node movement usually introduces a lot of problems in a wireless network, such as routing failure, information loss, and others. The mechanism described in [10] handles mobility in large-scale networks by employing a diffusion process that tends to equalize the pressure in the created groups. It creates domains whose centers of gravity move around slowly, providing a quasi-static overlay.

The **MOBIC** clustering scheme [6] takes mobility into consideration for cluster formation, and, especially, for leader election. It uses the premise that cluster head election is a local process and should only be determined by the neighbors and itself. The algorithm calculates the variance of a node's speed relative to its neighbors, and increases its probability of becoming a master based on that. This is suitable for **MANETs** in which groups of nodes tend to move with similar speeds and directions. However, if the nodes' moving patterns are uncorrelated and there is no group mobility behavior, **MOBIC** will not show good performance. The network terminals will exhibit similar values for the leader metric and hence, re-clustering will be frequent and will degrade the network's performance.

3.4 A DYNAMIC CLUSTERING SCHEME

All the algorithms described above have good results in terms of efficiency for different scenarios. Yet, applying them on a complex system, such as the **OLFAR** satellite swarm, will cause the system to overload and fail. For instance, Ryu's algorithm and the global k -means algorithm optimize the power consumption for a static network. The presence of mobile terminals will cause the cluster structure to be rebuilt when events take place, and thus, the performance will be degraded. Mobility-aware schemes generate either large numbers of clusters or multi-hop topologies. For **WSNs** that exhibit high data rates, it is best to avoid these scenarios as much as possible, because of their need for data aggregation.

This study proposes an algorithm that combines the aforementioned advantages, fitting to the necessities of a satellite swarm. It starts with electing the cluster heads and creating their corresponding clusters, depending on the distribution of nodes. Afterward, it uses two procedures for node migration and for leader election that keep the system stable and minimize the risk of reclustering. All the decision-making is done using power metrics, so that, in the permanent regime, the network tends to evolve to minimum power consumption.

3.4.1 Assumptions

The following assumptions were made when designing the clustering scheme:

1. The clustering process starts after the initialization of the swarm. During the initialization phase, the satellites exchange a limited amount of information with each other via broadcasting and gossiping. This phase serves for synchronization and localization. Hence, after this phase every node is aware of the spatial distribution of the swarm.
2. The initialization is done very fast compared to the mobility of the nodes. Therefore, for the initial cluster formation the network can be assumed to be static.
3. All the nodes of the swarm will start with an undefined role and will become either a master or a slave during clustering.
4. Every cluster has a star topology. Master nodes are connected in a full-mesh. A slave node can only be connected to one master.
5. A slave node can migrate to another cluster. A master node cannot migrate, unless it changes its role to a slave.
6. For the transmission power P_{TX} , the same assumption as in Section 3.2.3 is used:

$$P_{\text{TX}} = \begin{cases} P, & d_{ij} \leq d_{\min}, \\ (d_{ij}/d_{\min})^2 P, & d_{ij} > d_{\min}, \end{cases} \quad (3.3)$$

where d_{ij} is the distance between sensor i and sensor j .

7. Receiving and processing power is ignored. After simulating the scenario described in Section 3.2.3, it was concluded that receiving and processing power is a negligible quantity when comparing it to the transmission power.
8. Each master can have up to N_{ch} slaves by default. If the number of slaves is larger than N_{ch} , the master will suffer a power penalty. This will be detailed in the following subsections.

3.4.2 Initial cluster formation

In order to choose the nodes that are most suited for the leader role, the influence that a node has on all the other nodes of the network is quantized into a density parameter which is defined as

$$\rho_i = \sum_{\substack{j=1 \\ j \neq i}}^N P_{ij}^{-1}, \quad (3.4)$$

where node i is an unconnected node, and P_{ij} is the power required for transmitting one unit of data from node i to node j in one unit of time, if node j is unconnected, or infinite otherwise. Using this value, the clusters are formed as described in the flowchart in Figure 3.7. The main idea of the initial cluster formation is that the closer the nodes are the less power they need to communicate. Hence, if a small area of the network exhibits a high density of nodes, then a cluster will be formed in that area and terminals will connect to the node that offers the best overall power efficiency. The process will continue iteratively with the remainder of the nodes until one of the stop criteria is met—all the nodes are connected to a cluster head or the maximum number of clusters is achieved.

The steps of the cluster formation algorithm are as follows:

1. Calculate node densities.
2. The node with the highest density is elected as the cluster head.
3. The cluster head pages all its neighbors in a radius d_{min} . Nodes that do not belong to any cluster respond with an acknowledgment signal and join the newly formed cluster. If the number of

Figure 3.7: Initial cluster formation. (N_{ACK} is the number of acknowledgment messages that an elected cluster head receives after paging, N_K is the number of formed clusters, and M is the desired number of clusters)

acknowledgments N_{ACK} is larger than the number of channels N_{ch} , the cluster head chooses only the closest N_{ch} nodes as his followers.

4. The process is repeated until an *a priori* chosen number M of clusters is created or all the nodes are connected.

3.4.3 Slave migration

In order to maintain the cluster structure and to keep the power consumption to a minimum, a slave migration procedure is defined. The migration mechanism will be controlled entirely by the cluster heads and will work as follows:

1. Each master node will calculate the cost parameter C_{ij} for all the slaves in the network, where C_{ij} approximates the necessary power for node i to be part of cluster j .
2. Nodes that do not belong to any cluster are attributed a default cost value.
3. If for a slave node i , member of cluster j , the following condition is true:

$$\frac{C_{ik}}{C_{ij}} \leq \theta_{mig}, \quad (3.5)$$

then node i cancels its membership to cluster j , and joins cluster k . θ_{mig} is a migration parameter and is equal to one in the ideal case. In order to avoid node migrating back and forth between two clusters, as a result of their random movement, the migration constant can be set lower than one. This way, a node joins a different cluster only if it finds a much better one in terms of cost.

As already mentioned, the cost function of a slave will approximate the required power for a slave node to be part of a certain cluster. Initially, the cost C_{ij} was defined as being the necessary power for a node i to communicate with another hypothetical node positioned in the center of gravity of cluster j .

$$C_{ij} = \begin{cases} 1, & d_{ij} \leq d_{\min}, \\ (d_{ij}/d_{\min})^2, & d_{ij} > d_{\min}, \end{cases} \quad (3.6)$$

where d_{ij} is the distance between node i and the center of gravity of cluster j . The coordinates for the centers of gravity are calculated according to (3.2).

Calculating the cost relative to the center of gravity instead of relating to the position of the master node makes the system more stable. The movement or re-election of the cluster head has less influence on the behavior of the slave nodes. The migration process will be controlled by the entire cluster.

The cost function described by (3.6) is valid only if the number of slaves in a cluster is less than the number of channels a master can allocate. In most of the clustering algorithms, it is not allowed to have more slaves than the number of channels. Yet, this cannot be the case for the algorithm proposed for [OLFAR](#), as it cannot afford to lose data from any satellite.

According to the Shannon-Hartley theorem:

$$C = B \log_2 (1 + SNR), \quad (3.7)$$

where C is the communication channel's maximum capacity in bits/s, B is the bandwidth in Hz, and SNR is the signal-to-noise ratio.

If the communication between every two nodes is considered ideal, the following assumptions can be made. Let C_n be the channel capacity for accommodating n users, requiring SNR_n . And let SNR_{n+m} be the required signal-to-noise ratio ([SNR](#)) to achieve a channel capacity C_{n+m} , thus satisfying the requirements of an additional m users. In both of the cases, it is assumed that the available bandwidth B as well as the noise power are the same.

Since all users are supposed to have the same requirements, it can be written that:

$$\frac{C_n}{C_{n+m}} = \frac{n}{n+m}. \quad (3.8)$$

Using (3.7) and 3.8 a relation between SNR_n and SNR_{n+m} can be deduced. This describes, in fact, the amount of additional power needed for a cluster to host $n + m$ slaves when it is designated for n slaves.

$$SNR_{n+m} = (1 + SNR_n)^{(1+m/n)} - 1. \quad (3.9)$$

As a result, in case a cluster will have more than N_{ch} nodes, the necessary power will increase exponentially.

Based on (3.9), using a Taylor series approximation, and assuming $SNR_n \gg 1$ and m considerably smaller than n , a new cost function is defined:

$$C_{ij}^* = \theta_{\text{cost}}(N_j - N_{\text{ch}})C_{ij}, \quad (3.10)$$

for when the number of slaves in a cluster is larger than the number of allocated channels. In (3.10), θ_{cost} is a parameter depending on SNR_n , N_j is the number of nodes in cluster j (including the potential node i), and C_{ij} is the cost calculated according to (3.6).

3.4.4 Cluster head re-election

Similar to the slave migration process, a mechanism for changing the leader of a certain cluster is defined. As the nodes move, a master can turn up to be inefficient as a cluster head, so that another member of the cluster should take its role. The master node should always be the node closest to the center of the group, moving in similar direction and at a similar speed as its members. In Figure 3.8, a flowchart of the entire process of a master node is shown.

The re-election process is a local activity, in which all the members of a certain domain are involved. Let there be a cluster j with master node i . Let $\mathbf{r}_G$ be the position vector of the center of gravity of the cluster.

With these definitions, the decision to attribute the role of the leader to a new node is made based on the following condition:

$$\frac{\|\mathbf{r}_i - \mathbf{r}_G\|}{\|\mathbf{r}_j - \mathbf{r}_G\|} \leq \theta_{\text{CH}}, \quad (3.11)$$

where i denotes the slave node that candidates for a leader position, and j is the actual master node. θ_{CH} is a parameter that has the same role as θ_{mig} defined in the previous section.

Figure 3.8: Master node task.

3.5 SIMULATIONS

The algorithm was simulated using a Netlogo [11] environment and Matlab. The test scenario consisted of a network of 100 nodes uniformly distributed on a square plane. The number of clusters was selected to be 6, and for every cluster 16 channels were allocated without any penalty. The number of nodes was set to be 100 instead of 50 (as in Section 3.2.3) to better visualize the cluster formation in the graphical interface of the Netlogo package. The pair (number of clusters, number of channels) was selected so all the nodes can be assigned to a cluster without any power penalty. From the 100 nodes, six nodes will be elected as cluster heads. That leaves 96 available channels for 94 slave nodes.

For all the nodes, a minimum transmission range of $L/4$ was chosen, where L has the same meaning as in Section 3.2.3. The default cost value for unconnected nodes was set to four. According to this value, it is possible for unconnected terminals to join a cluster only when the distance to the center of gravity is less than $2d_{\min}$.

The movement pattern was chosen to be a random walk pattern: each node was given a speed of $L/200$ per time step and could change its movement direction at every simulation step with a probability of 0.1. Finally, the parameters θ_{cost} , θ_{mig} , and θ_{CH} were set to 2, 0.6 and 0.6, respectively.

The results of the numerical simulations are statistics which are the mean values of 1,000 random configurations of the network. As performance metrics, the total consumed power for transmission and the average cluster size is used. The consumed power for receiving and processing is ignored as it is very low compared to the transmitting power [12]. The total consumed power consists of the power required for all the existing links in the considered network: slave-master, master-slave, and master-master links.

The dynamic clustering scheme is compared with three other implementations—a broadcasting network, a full-mesh topology and a geometric clustering scheme similar to the one employed in Section 3.2.2 in terms of total required power. The geometric scheme used in this section forms six clusters by dividing the available area into six sectors. The sectors are attained by intersecting the deployment area with the following lines:

$$\begin{aligned}
L_1 : y &= 0, \\
L_2 : y &= x\sqrt{3}, \\
L_3 : y &= -x\sqrt{3}.
\end{aligned} \tag{3.12}$$

The other aspects of the geometrical clustering scheme are identical to the ones described in Section 3.2.3.

In Figure 3.9, three power ratios are plotted—the ratio between the power needed for a broadcasting scenario and the power needed when the proposed clustering scheme is applied, the power needed for a full-mesh topology divided by the power needed by the dynamic clustering scheme, and the ratio between the total required power when a geometric clustering is applied and the power required when the proposed scheme is employed, respectively. After the initial cluster formation, all the markers exhibit raised values due to the fact that the dynamic clustering scheme will not instantly achieve 100% coverage of the network. In time, all the nodes become cluster members and the values tend to stabilize. As anticipated in Section 3.2.4, the clustered network is more power-efficient than the broadcasting solution, but less efficient than a full-mesh topology. Furthermore, the total power requirement for the dynamic clustering scheme is slightly higher than the power required for the basic geometric clustering scenario. Nevertheless, the adaptive scheme handles mobility better and provides stable clusters.

The stability with respect to mobility is an important advantage of the algorithm. The node migration process prevents the need for reclustering, and thus, it saves the resources that a complete network reorganization would require. Furthermore, if the cluster head re-election procedure and the cost function associated with slave nodes are taken into account, it can be concluded that a change in the leadership of a domain will not have an immediate impact on the membership of the nodes. The cost associated with every slave node of the cluster in discussion will actually tend to drop.

The cumulative number of transitions for both dynamic clustering and geometric clustering, respectively, are plotted in Figure 3.10. Node mobility will generate node transitions from one cluster to the other, and role transitions from master to slave and vice-versa. Changes in the node distribution will not generate global reclustering, but will

Figure 3.9: Power Ratios: transmission power needed for a broadcasting topology, a full-mesh scenario and a geometric clustering scheme divided by the transmission power necessary when applying the dynamic clustering scheme.

have a major impact in the roles of the swarm members. For the dynamic scheme, the initial cluster structure will not be very stable, as a large number of nodes will tend to join the newly formed clusters. This results in a high number of master-slave and slave-master transitions. After a transient phase, cluster head re-election will occur less often. Yet the number of slave migrations will increase.

Due to its static character, the geometric clustering will exhibit slave and master transitions at much higher rates than the proposed clustering algorithm. Master changes will happen more than twice as often in the static implementation than in the dynamic clustering. This process is equivalent to a local reclustering and will have a significant effect on the functioning of the network.

Figure 3.10: Cumulative number of transitions.

Figure 3.11 illustrates the power requirements for different types of network nodes. As anticipated, the power requirements for master nodes will prevent them from having other tasks than communication. The main drawback of the algorithm is common for most of the clustering schemes. The power requirements for the master node will prevent cluster heads from carrying any other tasks.

When configuring the simulation scenario, the values of the parameters (distance, transmission range, speed) were set to mimic a realistic behavior of a swarm of nanosatellites. These values can be tuned for a better match with a potential physical implementation of the [OLFAR](#) project. Although the presented results are connected to initial assumptions, the tuning will not have a significant impact on the measured trends. As long as the network properties will not differ substantially (low-power nodes, slowly varying topology), the conclusions regarding power efficiency of the topologies and power requirements for the all types of nodes will be the same.

Figure 3.11: Power Requirements: maximum transmission power for master nodes (clustering approaches, dynamic and geometric) and peer nodes (broadcasting and full-mesh).

3.6 CONCLUSIONS AND FUTURE WORK

In this chapter, an adaptive topology that matches the demands of the OLFAR satellite swarm was presented. By employing power cost functions and a node migration mechanism, the proposed algorithm creates a two-layer hierarchical structure that improves the data distribution in the system. Power consumption for communication will mainly be concentrated in only a few satellites, leaving the other members of the swarm with enough resources to fulfill the low-frequency observation task.

Although the presented mechanisms were designed for a particular application, they can be used for most WSNs with similar characteris-

tics. By simply tuning the parameters, the scheme may be a solution for many distributed systems that exhibit mobility.

Further optimization can be performed on the clustering scheme. The overall power efficiency or the power requirements for the masters and slaves can be improved by defining more accurate cost functions or changing the decision criteria.

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Chapter 4

Inter-satellite links

With the logical aspect of the data distribution task within the [OLFAR](#) swarm established, the design of the physical layer of the communication is conducted. In Chapters [1](#) and [2](#), the importance of the data distribution task for achieving the scientific goal of the project has been discussed, and its challenges have been stated. In Figure [4.1](#), the main components of the data distribution are illustrated. The previous chapter focused on the topology aspects of the information sharing within the satellite swarm—the first of the [ISL](#) components.

Figure 4.1: Inter-satellite link components in each nano-satellite.

The physical implementation of the [ISL](#) is a fundamental building block for communication data within the [OLFAR](#) swarm and it is critical for the success of the entire project. One of the research questions outlined in Chapter [1](#) was whether or not it is possible to establish a

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reliable data connection between two of the [OLFAR](#) satellites, and its answer determines the success of the low-frequency radio telescope mission. To emphasize the importance of a data connection between two members of the swarm, let the following aspects be considered:

- The swarm behavior is a result of local interactions between swarm members. Thus, the satellite swarm concept is only valid if there is information exchange between the satellites.
- A distributed system can be established as long as the comprising entities communicate messages to each other to coordinate their actions and achieve a greater goal.
- The low-frequency radio telescope goal requires the formation of very long baselines. Thus, two satellites forming a baseline need to share localization and synchronization information by means of an [ISL](#).

Thus, data links within the swarm are a key aspect of the [OLFAR](#) project. They are important for both fulfilling the scientific goal as well as ensuring the autonomy of the system. Satellites will use radio-frequency ([RF](#)) links to share the observation data alongside timing, positioning and other meta information [1], [2].

In this chapter, the problem of establishing [ISLs](#) between the [OLFAR](#) satellites is addressed and a complete design proposal for the links to be used in the [OLFAR](#) project is showcased. The rest of chapter is organized as follows. In Section 4.1, the challenges and requirements for setting up [ISLs](#) between cubesats are stated. The baseband signal processing is analyzed in Section 4.2 and the link budget in Section 4.3. The link budget analysis is done to derive the gain requirement for the antenna system, and, based on it, a suitable antenna system is designed. The antenna system considerations are presented in Section 4.4 and an analytical model of the proposed antenna system is done in Section 4.5. This is followed by the implementation and testing of a laboratory setup in Section 4.6. Concluding remarks are presented in Section 4.7.

4.1 CHALLENGES FOR THE INTER-SATELLITE LINK

Up to now, establishing direct data transfer between cubesats has not often been attempted as high payload costs make it unattractive. Creating a network between satellites requires extra transceivers, which add to the weight and power consumption of the flying units [3]. High-throughput optical [4] and RF ISLs have been proposed in literature for transferring information between satellites. What is more, some active low and medium Earth orbit satellite systems use RF links to ensure a good quality of service and global coverage. For example, in the Iridium constellation [5],[6], the satellites use RF transceivers in the 22.55–23.55-GHz band to route traffic via the intra-plane and inter-plane neighboring satellites. Nevertheless, existing solutions are not applicable to the case of a communication link between cubesats. Size and power limitations, coupled with requirements imposed by the swarm’s functionality, mandate use of an application-specific communication system.

Therefore, in designing the ISLs for a swarm of cubesats, both cubesat-specific and swarm-specific requirements have to be taken into consideration.

In Chapter 2, it was specified that the OLFAR satellites will be 3U cubesats with a volume of $10\text{ cm} \times 10\text{ cm} \times 30\text{ cm}$ and a maximum mass of 4 kg [7]. This limits the available power for communication and processing to several Watts.

Another important aspect to consider is the variable attitude that cubesats have towards each other. Figure 4.2 illustrates how the relative attitude of two satellite changes over four time instants. The OLFAR array consists in a constellation of (slowly) free-drifting satellites, with baselines as long as 100 km [2]. This configuration is suitable for OLFAR’s scientific purposes, but, because of the free drift, the relative orientation of the satellites with respect to each other changes continuously, even in the presence of attitude control. This means that the ISLs can have any direction with respect to the satellite body.

As for the swarm-specific requirements, the functionality of the system sets the bounds for the data rate and length of the links. These link parameters have been thoroughly discussed in Section 2.3.3. Figure 4.3a summarizes these requirements for the scenario in which no adaptive topology is employed for the swarm. In Chapter 3, it has been

Figure 4.2: Variation of the direction of the inter-satellite link for four time instants (t_1 , t_2 , t_3 and t_4).

shown that the overall power efficiency of the swarm can be improved by the use of a dynamic clustering scheme. Using an hierarchical topology for the **OLFAR** cloud will create a backbone network of satellites that will handle most of the data traffic. Thus, the requirements for the **ISLs** will change and differ between the types of satellites (master or slaves). Using the same simulation environment (Netlogo [8]) and a similar scenario as in Section 3.5¹, the link parameters for a clustered **OLFAR** network were determined. Figure 4.3b illustrates the requirements for the two (three) types of formed **ISLs**—master-to-master and master-to-slave (slave-to-master).

Figure 4.3: Link parameters for the **ISL**.

¹ This simulation scenario considered a 50-satellite swarm divided into seven clusters as opposed to the 100 satellites swarm scenario considered in Chapter 3.

As expected, the communication burden shifts from the swarm to the master satellites that will route big parts of the astronomical data and other types of information. In the proposed clustered scenario, seven satellites will act as master nodes, leaving 43 of the swarm members to handle the astronomical observation task. Simulations performed in Section 3.5 showed that each cluster will have between six and eight slaves. Furthermore, due to clustering the maximum distance between two communicating nodes is slightly reduced from 100 km to 90 km. The maximum data rate D_{clust} going in and out of each satellite group can be calculated as

$$D_{\text{clust}} = N_{\text{max}} \cdot D_{\text{ISL}} = 47.04 \text{ Mbps}, \quad (4.1)$$

where N_{max} is the maximum number of nodes in a cluster, and D_{ISL} is the ISL data rate extracted from Table 2.3. Hence, a master node will have to be able to transfer data to other masters in the network at speeds of approximately 47.04 Mbps over distances of up to 90 km.

The total throughput for each OLFAR cluster will be $2 \cdot D_{\text{clust}}$ since the same amount of data has to be transmitted and received. Because of the high figure for D_{clust} , a time separation of the data transmission and reception tasks is assumed. Later on the possibility of establishing full-duplex ISLs will be discussed.

Based on the latter data rate requirements and the limits imposed by the cubesat standard, the work is continued with the design of the physical layer of the ISLs, consisting of the baseband signal processing and the antenna system.

4.2 CODING, MODULATION AND MULTIPLE ACCESS

Transferring data between the OLFAR cubesats requires a simple and power-efficient baseband signal processing scheme. The communication channel of in-space transmission is mainly characterized by free-space path loss and thermal noise of the electronics, presumed to be additive white Gaussian noise (AWGN). Radiation noise has a very low influence [9], and fading is practically nonexistent. A satellite cloud is a very-low-density sensor network spread in a reflection-free environment. Added to this, the lack of atmosphere translates into no atmospheric fading.

The fundamental blocks for the digital communication scheme of OLFAR's inter-satellite communications are shown in Figure 4.4.

Figure 4.4: Fundamental blocks of a digital communication scheme.

The proposed configuration consists of 3/4 low-density parity-check (LDPC) coding, offset quadrature phase-shift keying (OQPSK) modulation with raised-cosine pulse shaping with a roll-off factor of 0.2 [10] and a frequency division multiple access (FDMA) scheme [2]. 3/4 LDPC coding provides considerable coding gain without restrictive latencies, while OQPSK with raised-cosine pulse shaping gives the mentioned balance between bandwidth and power [10]. The maxim data rate (including coding) corresponding to a cluster head can be calculated as

$$D_{\text{clust coded}} = D_{\text{clust}} \cdot n/k \approx 63 \text{ Mbps}, \quad (4.2)$$

where n/k is the inverse of the coding rate.

With this communication scheme, the 63 Mbps data rate requirement for a cluster head imposes a bandwidth requirement of about 33 MHz for the antenna system as calculated from (4.3).

$$BW_{\text{clust}} = D_{\text{clust coded}} \cdot R/B \approx 33 \text{ MHz}, \quad (4.3)$$

R/B is the spectral efficiency of the considered modulation scheme. Further details will be given in Section 4.2.2.

In the following subsections, further details over the baseband signal processing will be discussed.

4.2.1 Multiple access

As mentioned, the satellites will have to deal with intense traffic of tens of Mbps and will use an FDMA scheme to share the bandwidth resource. Since the satellites are identical and can migrate between clusters, they will have to be able to transmit and receive data in all

the allocated frequency bands. Thus, if only the master links are considered, the total bandwidth of the system can be calculated as:

$$B_{\text{clust}} = N_{\text{clust}} \cdot B_{\text{cluster head}} = 231 \text{ MHz}, \quad (4.4)$$

where N_{clust} is the number of clusters, and $B_{\text{cluster head}}$ is the bandwidth for each master-to-master link (33 MHz). The channel separation is considered perfect so that no guard bands are necessary [11]. In the following sections, it will be shown that the bandwidth is an important design constraint for the antenna system. Hence, it is considered that the inter-cluster (master-master links) and intra-cluster (master-slave and slave-master links) data distribution tasks are time-separated in order to limit the bandwidth requirement.

The bandwidth parameter will play an important role in the data distribution activity. A trade-off between available frequency bands and time is critical for the fulfillment of the tasks.

4.2.2 Digital modulation

The simplicity of the propagation channel leads to the use of a basic modulation scheme, linear or exponential, rather than opting for adaptive modulation and coding. On one hand, the digital modulation for an ISL has to be power-efficient. On the other hand, the high data rates requirement imposes effective use of the bandwidth resource. In Figure 4.5, multiple modulation techniques of different types (amplitude, frequency and phase) and different orders are analyzed in terms of spectral efficiency and power efficiency. The values in the graph are calculated for a bit error rate (BER) of 10^{-5} [11].

A quaternary constellation offers a good compromise between required signal-to-noise ratio per bit and the spectrum usage. QPSK is preferred over quadrature phase-shift keying (QPSK) modulation. Due to lower amplitude fluctuations, QPSK enables the use of more efficient power amplifiers [12].

4.2.3 Channel coding

To provide robustness against noise and decrease transmission power, an LDPC coding block is added to the scheme. Sparse matrix codes

Figure 4.5: Spectral efficiency versus required signal-to-noise ratio per bit for several modulation formats and BER of 10^{-5} .

are a good option for low-power ISLs as they provide a good compromise between latency, extra information and gain. What is more, their excellent properties have been proven for AWGN channels [13].

The performance of the LDPC codes was evaluated by means of Matlab simulations. In Figure 4.6, simulated BER curves for coded OQPSK with different rate LDPC codes are plotted. A 3/4 rate code with a length of 64,800 was chosen as it provides almost 8 dB of gain while increasing the necessary channel rate by 33%.

To summarize, the baseband signal processing in the transmitter for the ISL will consist of an LDPC coding block, followed by an OQPSK modulator and a code division multiple access (CDMA) block. The proposed scheme is characterized by a required E_b/N_0 of 2.1 dB (for a BER of 10^{-5}) and a spectral efficiency of 1.9 bits/s/Hz which is practically achievable. The necessary channel rate will increase by a factor of 1.33, meaning that satellites will have to transmit a maximum of 63 Mbps.

The communication channel for any of the ISLs is mainly characterized by free-space path loss and thermal noise. As a result, the baseband signal processing aims mainly for a sensible balance between

Figure 4.6: Simulated BER for OQPSK without and with LDPC coding with a code length of 64,800 and different coding rates. The dashed line represents the theoretical BER curve for uncoded OQPSK modulation.

spectral and power efficiency. The choices for the coding, modulation and multiple access blocks can be modified if the practical limitations of the systems (e.g. power budget or platform size) impose a different balance in the frequency-time-power trade-off.

4.3 LINK BUDGET

The digital communication scheme plays an important role in the antenna system design as well. After calculating the parameters of the baseband signal processing, E_b/N_0 and spectral efficiency, the link budget of the communication is calculated and the gain requirement of the antenna system is extracted. The calculations are done using the following assumptions :

1. The link margin is assumed to be 2 dB. The link budget is a worst-case scenario calculation. The 90 km distance is, in fact,

the maximum distance an ISL will have to cover. In most of the cases, the link length will be shorter, allowing a wider margin.

2. The central frequency f_c is set to 2.45 GHz, as radio waves in this band can be received with small antennas suitable for cubesats and have good propagation properties. The frequency band for OLFAR's ISL has not been fixed yet, but is a fundamental consideration for the antenna system design in terms of antenna size and link performance. As will be discussed in Section 4.4.4, the antenna implementation proposal changes with the selected frequency band, but it must be above roughly 2 GHz due to the size limitations. In order to consider a (preliminary) band, it is assumed that the 2.45 GHz industrial-scientific-medical (ISM) band is used for OLFAR's ISL. This band provides a suitable balance between antenna size, beamwidth and gain (as it will be shown in Section 4.4.4). Furthermore, the availability of COTS components for this frequency band facilitates the laboratory testing of the ISL and keeps the implementation costs low.
3. A total power of 4 W is available for communication in each satellite. Even though a complete power budget for OLFAR has not been developed yet, an assumption that 4 W are available for transmission of inter-satellite radio signals in a cluster head seems sensible considering that three-unit cubesats can extract more than 25 W from their solar panels [14].
4. The noise parameters of the system are calculated based on the assumption that satellites will experience an ambient temperature of 353 K (80 °C) [15]. Heat flow and dissipation in space are neglected [16]. The antenna noise temperature is mostly given by the background noise radiation it picks up. For the considered scenario, this will mainly be cosmic microwave background radiation [17] (at about 3 K at 2.45 GHz), with some contributions from the Sun, the Moon and the Earth. An antenna noise temperature of approximately 10 K is considered in order to account for these celestial noise contributions. Using these values, the noise figure NF and the effective source noise temperature are calculated to be 4.6 dB and 44.3 K, respectively [10].

5. The Doppler shift caused by the relative movement of the satellites is neglected. In case of a 3,000-km lunar orbit, the [OLFAR](#) baselines change at rates in the order of m/s. For short baselines (less than 10 km) the relative speed between the satellites is less than 3 m/s, while for very long baselines (up to 100 km) the relative speed is lower than 30 m/s [[18](#)]. From (1.1) it follows that the Doppler shift is less than $10^{-7}f_c$.

The link budget analysis is done as in Figure 4.7. Based on the required bandwidth and the noise parameters, the noise floor (N) at the input of the low-noise amplifier ([LNA](#)) is calculated. To this value the signal-to-noise ratio (SNR) and the noise figure (NF) are added, and the received power P_R is obtained. Finally, in order to derive the total required antenna system gain (transmit and receive), the losses, the link margin (LM), and the received power are subtracted from the available transmission power P_T . The values are summarized in Table 4.1.

Figure 4.7: Link budget analysis.

In conclusion, for establishing [ISLs](#) between cubesats, it is mandatory to design an antenna system that can provide 5 dBi (10 dBi if both, the transmitter and the receiver, are considered) of gain in any direction. This value acts as a starting point for the next section.

Table 4.1: Link budget parameters for the proposed system.

Parameter		Proposed value
Center frequency	f_c	2.45 GHz
Bandwidth	B	33 MHz
Link distance	d	90 km
Transmitter power	P_T	4 W
Transmitter losses	L_T	1 dB
Friis path loss	L	139.3 dB
Receiver losses	L_R	1 dB
Link margin	LM	2 dB
Signal-to-noise ratio	SNR	4.9 dB
Receiver noise figure	NF	4.6 dB
Noise floor	N	-107.1 dBm
Antenna system gain	G_T, G_R	≈ 5 dBi

4.4 ANTENNA SYSTEM DESIGN

The antenna system for inter-satellite communications in swarms of cubesats must consider several aspects integrally. In order to be able to cover different directions for the ISL, multiple antennas must be used. An antenna system control scheme is also necessary to ensure the system's efficient operation. Additionally, the individual antenna characteristics and implementation should also be studied, since they have a considerable influence in the ISL performance.

4.4.1 Narrowband and farfield assumptions

For the antenna system design, the relevant radio link characteristics are the channel properties and the validity of the narrowband and far field assumptions. Narrowband, farfield links allow convenient simplifications in their analysis and design, specially for beamforming systems [19].

The channel for OLFAR's ISL is considered to be free-space, so that only for AWGN and free-space losses are taken into account, and no fading is assumed.

For the narrowband assumption, the link bandwidth is compared to the carrier frequency. As it was mentioned in Section 4.2, the radio link between cluster heads has a bandwidth $B_{\text{cluster head}}$ of 33 MHz. For a carrier frequency f_c of 2.45 GHz, this gives

$$\frac{B_{\text{cluster head}}}{f_c} = 0.013, \quad (4.5)$$

which is a good indication that each cluster-head link can be considered narrowband [20]. Nevertheless, the OLFAR swarm involves several cluster heads and many observation satellites, so the overall bandwidth required for inter-satellite communications is much larger. This imposes a restrictive requirement on the bandwidth of the ISL antennas, as will be discussed in Section 4.4.4.

For the far field assumption, the formal evaluation [11] is developed. For a wavelength λ of 12.24 cm and a largest antenna dimension L_{max} of 3 cm (which is proposed in Section 4.4.4), the Fraunhofer distance D_F is

$$D_F = \frac{2 L_{\text{max}}^2}{\lambda} = 1.47 \text{ cm}. \quad (4.6)$$

Then, the minimum link distance r_{min} of 10 m is clearly larger than D_F , L_{max} and λ , which are the requirements for the far field assumption.

4.4.2 Antenna system configuration

Since the ISL must work for any link direction, the ISL antennas should cover the whole 4π -sr (solid angle) range. However, because the satellite surface area is considerably limited, the number of antennas used for the ISL is kept as low as possible.

Therefore, a configuration of six individual antennas placed on the different faces of each cubesat is proposed. Assuming that the swarm's minimum baseline is considerably larger than the satellite dimensions, the ISL transmitter can be considered as a point source by the receiver.

Therefore, the exact location of the antennas on each face is not relevant for the link performance and can be conveniently selected for coexistence with other devices. Figure 4.8 shows the proposed configuration for the antenna system in a three-unit cubesat, namely one antenna per face in arbitrarily selected locations.

Figure 4.8: Proposed antenna configuration for a three-unit cubesat.

In this configuration, each individual antenna must cover a ‘square’ area of $2\pi/3$ -sr (see Figure 4.9a). However, antenna beams usually have circular (or elliptical) cross-sections. Then, the required area should be roughly covered by a beam with a circular cross-section and a width of $\pi/2$ (90°) (see Figure 4.9b). The remaining area that is not covered by the beam can be compensated if the individual antennas have a higher beamwidth, or with an adequate antenna system control (as proposed in the next section).

Figure 4.9: (a) ‘Square’ area coverage required from each individual antenna and (b) its approximation with a circular cross-section beam.

For the 2.45 GHz band, an antenna system gain of 5 dBi for any link direction must be provided, so each individual antenna must have a gain of at least 5 dBi over the mentioned beamwidth of 90°. This requirement for the individual antenna radiation pattern is shown in Figure 4.10.

Figure 4.10: Requirement for the individual antenna radiation pattern (for all ϕ).

For an antenna with a circular cross-section beam, the relation between its directivity D and its 3-dB (half-power) beamwidth $\Theta_{3\text{dB}}$ can be approximated as

$$D \approx \frac{16 \eta_b}{\Theta_{3\text{dB}}^2}, \quad (4.7)$$

where η_b is the ratio of power that flows within the 3-dB beamwidth. If the antenna radiation pattern has low side lobes, a gain of 5 dBi is quite feasible for $\Theta_{3\text{dB}} = \pi/2$ [21].

4.4.3 Antenna system control

A *smart antenna* approach [11] is proposed for the antenna system control strategy. This is implemented by multiplying the complex base-band signal delivered to (or received from) each antenna by a given weight. This weight can be a binary value, given by a *selection* scheme, or a complex number that conveniently affects the amplitude and phase of the transmitted (or received) signals, for a *combining* scheme. Moreover, ranging and direction-of-arrival (DOA) estimation techniques can be employed in the receiver to determine the location of the transmitter.

A beamforming algorithm that maximizes the antenna system directivity for any link direction (θ, ϕ) is proposed for the calculation of the weights. For a given direction, at most three individual antennas (marked by X , Y and Z) will have the most relevant contributions, namely the ones that ‘face’ the other satellite. Then, the proposed global coordinate system is centered in the corner of the satellite that is common to the faces that hold these antennas. Figure 4.11a shows the definition of this global coordinate system.

Figure 4.11: Proposed (a) global coordinate system and (b) individual antenna coordinate system.

Furthermore, for each individual antenna i (i can be X , Y or Z) the following assumptions are made:

- the link direction referred to its local coordinate system is (θ_i, ϕ_i) , as shown in Figure 4.11b;
- the directivity for this direction is $D_i(\theta_i, \phi_i)$;
- a sensible approximation of its radiation pattern is known;
- the distance from the antenna system coordinates' origin is d_i .

Then, the complex weight for each antenna can be calculated as

$$w_i = \sqrt{c_i} e^{j\beta_i}, \quad (4.8)$$

where

$$c_i = \frac{D_i(\theta_i, \phi_i)}{\sum_{j \in \{X, Y, Z\}} D_j(\theta_j, \phi_j)} \quad (4.9)$$

ensures that the power is distributed optimally, and

$$\beta_i = k d_i \sin \theta_i \quad (4.10)$$

is the necessary phase change so that, for a wavenumber k , the electric fields (E fields) from the different individual antennas add up in phase. The antennas are assumed to have a real radiation pattern. For complex patterns additional phase corrections have to be made.

With this complex weight calculation algorithm, the E fields from the three participating antennas are properly scaled and added up in phase, giving an increase of up to 4.8 dB² in the antenna system gain compared to a selection scheme.

4.4.4 Antenna characteristics

The characteristics of the individual antennas are critical for the performance of the antenna system. Even though a specific antenna design is not proposed here, a set of characteristics that it must exhibit are discussed. These characteristics include bandwidth, radiation pattern, polarization, impedance and (radiation) efficiency.

1. **Bandwidth**—the frequency band for inter-satellite communications includes several cluster-head and observation channels, as well as their corresponding guard bands. Depending on the selected antenna type, it may not be possible to cover the complete ISL band with one antenna. As a result, a frequency reuse strategy might be necessary. A minimum bandwidth of 150 MHz provides a sensible balance between antenna feasibility and capacity, especially if microstrip (patch) antennas are used.
2. **Radiation pattern**—different radiation patterns can be used for the individual antennas, as long as they comply with the requirement from Figure 4.10. However, if the proposed beamforming algorithm is used as the antenna system control scheme, a 3-dB increase can be obtained at $\pm 45^\circ$ in the individual antennas' radiation pattern. Then, an antenna with a maximum gain of 5 dBi and a *half-power* beamwidth of 90° still provides a (minimal) useful solution.

² The 4.8 dB corresponds to the case when all three antennas (X,Y and Z) contribute equally.

3. **Polarization**—in a free-drifting cubesat constellation the ISLs can take any direction. Likewise there can also be any orientation between the transmitting and receiving antennas. Therefore, circular polarization is required for the ISL antennas.

However, since the individual antennas on each satellite have different spatial orientations, an additional phase compensation (with respect to a selected reference antenna) is required in order to perform beamforming for circular polarization. For a given link direction, the phase compensation δ_{cp} is equal to the angle between the direction of the E field radiated by antenna i and the direction of the E field radiated by the reference antenna. For a practical implementation, it can be shown that the value of δ_{cp} depends on—and can be derived from—the locations of the different individual antennas and the link direction.

4. **Impedance and efficiency**—the impedance and efficiency characteristics are proposed in order to ensure the minimum required antenna system gain. Failure in meeting these requirements will cause losses due to reflections and ohmic effect, hence, adding to the L_T and L_R parameters. With convenient 50- Ω antennas (or using appropriate matching networks), the voltage standing wave ratio (VSWR) can be minimized. Also, following (4.7), antennas with the required gain and beamwidth are feasible if their radiation efficiency is above 80%.

4.4.5 Antenna implementation

For the 2.45 GHz band, patch antennas are considered since they can achieve the previously mentioned characteristics with a very practical form factor. The required length ℓ of a standard ceramic patch antenna [20] with a relative dielectric constant ϵ_r of 5 and a resonance frequency f_c of 2.45 GHz is

$$\ell = \frac{c}{2 f_c \sqrt{\epsilon_r}} = 2.7 \text{ cm}. \quad (4.11)$$

That means that a simple square patch can properly fit in the available area described in Chapter 2.

For higher frequencies, the available area must be exploited as much as possible so that the link budget from Section 4.2 remains valid. The

5 dBi gain requirement obtained for 2.45 GHz actually implies a necessary effective area A_{eff} of

$$A_{\text{eff}} = \frac{\lambda^2}{4\pi} G_R = 37.67 \text{ cm}^2 \quad (4.12)$$

which is independent of frequency [11]. Therefore, this is the requirement that antennas must fulfill for any frequency band. If the frequency increases, higher gain is required to achieve the same effective area. From (4.7), the value of η_b must be higher for a higher gain (given the required beamwidth of 90°), which means more demanding requirements on the antenna radiation pattern.

For higher frequencies a planar phased array can be accommodated by the same area. An array would have a narrower beamwidth and higher gain, and would also be able to steer its beam over the $\pm 45^\circ$ range at the expense of increased complexity and radio hardware. For an array of N_{elem} elements, the required element gain over the proposed 90° range is

$$G_{\text{elem}} = \frac{1}{N_{\text{elem}}} \frac{4\pi}{\lambda^2} A_{\text{eff}} = \frac{G_R}{N_{\text{elem}}} \quad (4.13)$$

which is a feasible requirement. Figure 4.12 illustrates the implementation possibilities with a single patch antenna and a planar array.

4.4.6 Transceiver architecture

The performance of the different possible control schemes and the channel allocation flexibility are significantly influenced by the transceiver architecture. Regarding this, the antenna system control implementation and the RF transceiver structure are the main factors that affect the performance of the ISL.

First, the weight multiplication proposed for the control scheme can be implemented as an analog RF or a digital baseband control block. These architecture possibilities are shown in Figure 4.13. For example, a selection scheme can be efficiently implemented with analog RF control, which in this case would be performed by switches. For a combining scheme, like the proposed beamforming algorithm, analog RF control would consist of phase shifters and variable gain amplifiers,

Figure 4.12: Individual antenna implementation with (a) a single patch antenna and (b) a 2×2 planar array.

while digital baseband control would use an application specific integrated circuit (ASIC) or a field programmable gate array (FPGA).

While analog RF control is less flexible and precise, it requires considerably fewer components since only one RF transceiver is necessary. On the other hand, digital baseband control is far more flexible and precise, but requires more radio hardware. If the RF transceiver integration can be such that the additional transceivers do not impose a significant volume load, and the power requirements of the extra transceivers fall within the power budget, digital baseband control is clearly the preferred option for the ISL transceiver.

Finally, the antenna system controller must perform the weight calculation for the implemented control scheme. Its functional components are shown in Figure 4.14. With digital baseband control, the controller takes the sampled complex baseband signals from each antenna, estimates their received power and phase, performs DOA and range estimation to determine the location of the transmitter, and calculates the weights that correspond to the identified link direction. This process should be repeated at a rate that is proportional to the relative rotation speed between the transmitter and the receiver, which can be estimated using link tracking algorithms.

Figure 4.13: Transceiver architecture with (a) analog RF and (b) digital base-band control.

4.5 ANALYTICAL MODEL OF THE ANTENNA SYSTEM

A simulation of the ISL for the proposed antenna system was implemented using Matlab. The antenna system's performance was evaluated using an analytical model of the ISL, which involves the E fields present in the link, the radiation patterns of the individual antennas and the system control scheme. With this model, the antenna system's radiation pattern can be obtained for any link direction, and thus the performance (in terms of gain) of the proposed beamforming algorithm can be evaluated for any direction of the ISL. The Matlab model is presented in the following section.

Figure 4.14: Antenna system controller functional components.

4.5.1 Analytical model

The analytical model developed for the ISL consists of five functional parts:

- an individual antenna radiation pattern model, used to simulate the gain and E field of each individual antenna for a given link direction;
- a 3D satellite model, used to represent the individual antenna locations and orientation;
- an antenna system controller, used to implement the weight calculation algorithm;
- a field/signal calculator, used to obtain the resulting transmitted field and the combined received signal of the antenna system;
- a channel simulator, used to model the effects of the propagation channel.

These are organized in the structure shown in Figure 4.15.

With this architecture, the individual antenna model, the antenna configuration and the control scheme can be changed independently,

Figure 4.15: Analytical model structure.

making the ISL model flexible enough to evaluate the antenna system performance, considering different combinations of characteristics.

The model uses farfield and narrowband approximations, and neglects coupling since the interaction between E fields is relatively low. Three-dimensional complex-valued vectors are used to represent the E fields, which simplifies the simulation of circular polarization. The global and individual antenna coordinate systems presented in Figure 4.11 are also considered in the model, in order to be consistent with the presented proposal.

4.5.2 Settings

A Matlab simulation scenario was developed. The following considerations were made:

1. **Individual antennas**—a basic individual antenna radiation pattern with 5 dBi gain and 90° half-power beamwidth, described by $\cos^2(\theta)$ and shown in Figure 4.16 was used. This radiation pattern provides the minimum gain and bandwidth requirements for the individual antennas, as mentioned in Section 4.4.
2. **Satellite model**—a three-unit cubesat model with antennas on three faces (corresponding to X, Y and Z) placed in arbitrary positions was used.

Figure 4.16: Modeled individual antenna radiation pattern (for all ϕ).

3. **Channel model**—since noise and propagation loss hardly affect the antenna control scheme under the mentioned assumptions, the channel model includes only the orientation difference between the transmitting and receiving satellites, implemented using Tait-Bryan rotations [22].

4.5.3 Results

The resulting antenna system radiation patterns for an arbitrarily selected link direction (θ_d, ϕ_d) of $(58.1^\circ, 38.3^\circ)$ using the proposed beamforming algorithm and an antenna selection scheme are shown in Figure 4.17. The three-dimensional radiation patterns are illustrated in Figure 4.18. The antenna system controller shows the expected performance, since the proposed beamforming algorithm provides a gain increase (of about 3 dB for this particular angle) for the proposed direction of transmission compared to the selection scheme.

Additionally, the gain of the proposed antenna system was obtained for different link directions, in order to show that the beamforming algorithms ensures maximal antenna system gain for all link directions, even using individual antennas with the minimum gain and beamwidth requirements. The results are shown in Figure 4.19, along with the results for a selection scheme. The control schemes work symmetrically for $\phi = 0^\circ$, $\phi = 90^\circ$ and $\theta = 90^\circ$, and therefore, Figure 4.19 shows only one of these cases.

The analytical model shows that the proposed antenna system fulfills the 5 dBi gain requirement for any direction of transmission. The conformal beamforming exhibits up to 3 dB more gain than the antenna selection scheme for values of θ_d around 45° .

Figure 4.17: Antenna system radiation pattern for $(\theta_d, \phi_d) = (58.1^\circ, 38.3^\circ)$, both using antenna selection and conformal beamforming.

4.6 EXPERIMENTAL SETUP AND RESULTS

A set of experiments was carried out to further validate the antenna system proposal. An evaluation platform was developed to emulate a simplified 2-D version of the proposed antenna configuration in a cubesat, and to perform the proposed control scheme.

4.6.1 Evaluation platform

The evaluation platform architecture consists of two identical integrated direct-conversion in-phase/quadrature (IQ) modulators with patch antennas for the transmitter, and two identical direct-conversion integrated IQ demodulators, two low-noise amplifiers and two patch antennas for the receiver. Figure 4.20 shows the evaluation platform architecture. COTS components were used for the realization of the evaluation platform. The Texas Instruments TRF372017 and TRF371135 were used for the IQ modulators and demodulators, respectively. Two Maxim MAX2644 circuits were used for the LNAs, and 2.4-GHz circularly polarized patch antennas from Taoglas were used for the platform's antennas.

Figure 4.18: Antenna system 3D radiation pattern for $(\theta_d, \phi_d) = (58.1^\circ, 38.3^\circ)$ using (a) a selection scheme and (b) the proposed beamforming algorithm.

The platform configuration includes two satellite ‘simulators’, separated by 80 cm^3 , each with two aluminum ‘faces’ of $10 \text{ cm} \times 10 \text{ cm}$ that act as ground planes for the patch antennas that are placed on their center. This works as a representation of antennas X and Y from Figure 4.11. The satellite ‘simulators’ can be rotated over their own axes to simulate a difference in orientation between the transmitter and the receiver, which in this case corresponds to a variation in ϕ . Figure 4.21 shows the dimensions and configuration of the evaluation platform.

The baseband input signal used for the experiments was a sinusoid of 1 V peak-to-peak amplitude at 50 kHz, which was applied to both the in-phase (I) and quadrature (Q) inputs of one transmitter. The evaluation of the control scheme was performed in the receiver, post-processing the measured IQ signals obtained from each antenna (X and Y). However, instead of the ‘blind’ beamforming weighting from the proposed algorithm, a maximal-ratio combining (MRC) [11] diversity technique was employed, since it converges to the beamforming behavior in the analytical model but shows a considerable performance increase in practical situations.

³ Considering a maximum dimension of the antenna of 10 cm (size of the metallic plate) in (4.6), it follows that the Fraunhofer distance is 16.33 cm, considerably smaller than the distance between the two ‘simulators’.

Figure 4.19: Simulated antenna system gain for different link directions (for $\theta = \theta_d = 90^\circ$).

Figure 4.20: Evaluation platform architecture.

The individual antennas used in the evaluation platform show a radiation pattern that is very similar to the one used in the analytical model.

The experiments were performed in an anechoic room provided by the Netherlads Institute of Radio Astronomy (ASTRON), located in Dwingeloo, the Netherlands. A photograph of the evaluation platform is presented in Figure 4.22.

Figure 4.21: Evaluation platform dimensions and configuration.

4.6.2 Results

The same evaluation of the antenna system gain for different directions of reception carried out with the analytical model (and shown in Figure 4.19) was performed in the evaluation platform. The obtained results are shown in Figure 4.23. The losses of the system were not measured, so the platform was used to evaluate the performance in terms of directivity. The measured and simulated values were normalized by the maximum values for comparison purposes.

The experimental results roughly match the modeling done in Section 4.5. By using the proposed antenna system controller, the system achieves a higher gain than by using individual antennas for the ISLs. The influence of the beamforming scheme is less important for link directions that are almost perpendicular to the cubesat's 'faces'. The antenna that does not face the transmitter hardly makes any contribution to the gain. However, the contribution of beamforming becomes noticeable for values of ϕ_d around 45° . In this case, the fields radiated by the two antennas add up in-phase and, as a result, the system performs better than if the antenna selection scheme would be used.

Figure 4.22: Evaluation platform in the anechoic room.

If Figures 4.19 and 4.23 are compared, it can be noticed that there are gaps between the experimental results and the proposed model. The imperfections of the testing environment (presence of multipath, etcetera) result in gain characteristics for the real antennas fairly different from the ideal one. Because of the multipath propagation, antenna X and antenna Y are capable of receiving or transmitting even when they are facing away from the link direction. As a result, the measured characteristic of the antenna X exhibits elevated values for ϕ_d approaching 90° , while antenna Y's characteristic has elevated values for ϕ_d approaching 0° . This does not have a significant impact on the antenna selection scheme. The antenna that faces the transmitter (receiver) has the higher gain, and therefore, it is the only antenna taken into consideration. However, for the proposed beamforming both antennas are considered and multipath propagation results in errors for gain and phase estimation. Thus, in the experimental setup the beamforming does not exhibit the same flat behavior as in the analytical model.

Figure 4.23: Simulated and measured antenna system gain (normalized by the maximum value) for different link directions (for $\theta = \theta_d = 90^\circ$). The discrete values correspond to the measurement results, and the curves correspond to the simulation results, respectively.

4.7 CONCLUSIONS AND FUTURE WORK

In this chapter, the design of the communication layer to be used for ISLs in swarm of cubesats has been presented. With the requirements and limitations for the master-to-master ISL derived in Chapters 2 and 3, the design of the physical layer is carried out. After selecting the components for the digital communication scheme, a link budget analysis was performed. 5 dBi was derived to be the lower limit for the gain of the antenna system. Correspondingly, an antenna system design has been proposed and verified by analytical performance calculations, and demonstrated by an experimental prototype. A system that combines a power-efficient communication scheme with a simple antenna configuration (one patch antenna per ‘face’ of the cubesat), and an adequate beamforming technique was implemented, and tested in a laboratory environment. The results fit the theoretical model and confirmed that high data rate ISLs can be established between the OLFAR cubesats.

When trying to overcome the ISL challenge of the OLFAR project, the approach was to solve the weakest aspect of the physical layer of the data distribution within the swarm. Hence, the initial calculations and the follow-up design was meant to solve the problem of communicating data between the two farthest cluster heads. Nevertheless, the same solution can be applied for any other ISL in the OLFAR cloud.

Several aspects should be thoroughly analyzed before declaring the design ready to launch. In Sections 4.3 and 4.4, a number of assumptions were made regarding available power, link properties and antenna characteristics. Although these assumptions are confirmed by previous work and practical implementations, the fact that the considered link margin LM is only 2 dB restricts the error margin for any possible mismatch or losses of the components.

As shown, establishing an ISL between two OLFAR cubesats requires that multiple components (antennas, antenna system controller, transceivers, baseband processing and power system) are in tune. The complexity of the system increases the chance of additional losses, and, therefore, the probability of failure of the link. Some of the important loss factors are the LNAs, the antennas (polarization, impedance), the dynamics of the satellite and of the swarm.

For example, in the link budget calculation a power figure of 4 W was used. The transmitter losses L_T were considered to be 1 dB, which covers mainly the radiation efficiency of the antenna. Hence, the 4 W figure represents the power delivered to the antenna. The efficiency of the transceiver has to be taken into account as well. Transceivers integrate power amplifiers (PAs) and LNAs that use a certain amount of power to operate. The power efficiency of an RF PA is below 80%, while for an LNA it is even lower than that [23]. This will cause a few extra dBs of loss due to the RF front end. Hence, the actual power that will need to be delivered to the ISL block will have to be higher.

The individual antennas are another important aspect of the ISL, and meeting the criteria listed in Section 4.4.4 is critical for the data distribution. To cope with the platform limitations a patch antenna was chosen for implementation, and this fits the cubesat platform well. The bandwidth of this type of antenna can be around 8–10%. Considering that 2.45 GHz was selected as the central frequency, the bandwidth requirement for a single link can be easily met. Nevertheless, if multiple simultaneous links are needed—master nodes should form a full-mesh

network—the bandwidth will become an issue, as well as the validity of the previously made narrowband assumption.

What is more, polarization of the antennas will also affect the link budget. There are multiple solutions for radiating a circular polarized wave using patch antennas (asymmetric feeding, double feeding, asymmetric geometry) [20]. Nonetheless, perfect circular polarization will not be achieved in practical implementations. The typical value for the axial ratio (AR) of circularly polarized patch antennas exceeds 1–2 dB, and, thus, this may drop the link margin LM parameter below 0 dB. Hence, for certain directions a link cannot be establish.

The dynamics of the satellites will also have to be taken into account. Translation and rotation of the OLFAR cubesats can cause synchronization loops not to lock, and result in loss of connectivity. The list of influence factors for the ISLs can be extended. However, it is important to conclude that further improvements have to be made for the link margin.

There are multiple parameters that can be tuned to improve the link parameters—power, time, data rate, attitude, and bandwidth. The link margin can be raised by increasing the power allocated for the ISL task. The observation parameters can be changed to loosen the link budget. The observation period can be shortened or the integration time can be made longer to reduce the data rate. However, this will influence the characteristics of the low-frequency radio telescope, and will have an impact on the entire mission. Attitude control can be used to compensate for the faulty AR of the antennas, and propulsion can be used to compress the swarm and make inter-satellite distances shorter.

To summarize, the problem of distributing data within the OLFAR swarm is multidimensional optimization problem. Ultimately, it resumes to a trade-off between the resources of the whole system.

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Chapter 5

Swarm-to-Earth communication strategy

Having established a topology for the satellite network in Chapter 3 and [ISLs](#) in Chapter 4, the observed data can be distributed within the [OLFAR](#) cloud. The astronomical data will flow in between slave nodes via backbone communication links established by the master nodes. Following this step, the satellite swarm performs the distributed processing of the data. In Figure 2.3, the time separation of the swarm's functionalities is illustrated. [OLFAR](#) satellites perform different tasks depending on their placement on the orbit. The distributed data processing routine (which includes the data distribution part) is immediately followed by the data downlink. The main reasons for this are closely related to the scientific goal of the project and the cubesat implementation.

After the distributed processing the satellites will end up with matrices of correlation coefficients. This information is not relevant for the general public and still has to be analyzed by radio astronomers. They will connect the numbers to certain celestial objects and phenomena, and will fulfill the end goal of the project. Hence, the processed data has to be sent from the [OLFAR](#) swarm to a [BS](#) on Earth. Furthermore, the cubesat implementation limits the space available for hardware within the satellite platform. In order to avoid the use of bulky storage units, it is highly desirable that the data observed and processed within one orbit is sent within the same orbital period. Otherwise, data accumulation might result in the failure of the entire system.

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Transferring the processed data from swarm level to a BS on Earth requires establishing a communication link between the OLFAR satellites and a receiving station on ground. In Chapter 4, the difficulty of transferring data wirelessly over a large distance (up to 100 km) using the limited power of a cubesat was emphasized. A satellite-to-Earth link has somewhat different challenges from the ISL discussed in Chapter 4. The gain of the receiving antenna in the case of the first link can be substantially higher than the planar antennas used for the ISL. Large parabolic antennas or even ground telescope arrays can be used as a BS providing gain of several tens of dBi. Moreover, the large number of satellites can be exploited to improve the transmitter parameters. On the other hand, the satellite-to-Earth link will have to cover distances several orders of magnitude larger than the ISLs.

In this chapter, the work on the communication layer of the project is continued, and the design of the swarm-to-Earth communication link is presented. The rest of the chapter is organized as follows. In Section 5.2, an analysis of the link parameters is conducted and the link budget for a single satellite communication is realized. Some solutions for establishing a single satellite downlink are outlined in Section 5.3. In Section 5.4, the effect of the swarm on the communication link is discussed. Concluding remarks are made in Section 5.5.

5.1 DOWNLINK REQUIREMENTS

As stated in Chapter 2, for realizing the low-frequency radio telescope, the OLFAR satellites will sample cosmic noise, spread the data within the swarm and then process it by means of distributed correlation. After the processing step has ended, every node will need to transmit the resulting data to a BS on Earth. Using (2.6) the required data rate for the downlink communication is calculated to be around 900 kbps/satellite¹.

Such data rates are not unusual for satellite downlinks. However, the peculiar implementation details of the OLFAR swarm make it difficult to comply with the requirement.

¹ The data rate corresponds to an implementation using 50 satellites, and 1-bit processing for an instantaneous bandwidth of 1 MHz, for each of the three Cartesian field components.

One of the major obstacles to overcome is the link distance. In Chapter 1, it was mentioned that the [OLFAR](#) swarm will be placed on a lunar orbit. This offers protection from the man-made [RFI](#) while placing the swarm relatively close to Earth. Even so, in a worst-case scenario (lunar apogee), the distance to Earth will be around 405,000 km. In Figure 5.1, the lunar orbit is depicted.

Figure 5.1: Apogee and perigee of the Moon's orbit.

An important aspect to consider is the limited available power in a nano-satellite. Deployable solar panels will be able to provide around 30 watts of power [1], that will have to be shared by all of the subsystems shown in Figure 2.4 (processing unit, propulsion, attitude determination and control, and communication block). By making the same considerations as in Chapter 4, it is expected that only several watts of power will be available for the data downlink.

The outer surface of a cubesat will not only serve for the solar cells, but will also have to accommodate downlink antennas, [ISL](#) antennas and sun sensors [2]. In Chapter 4, it has been shown that the [ISLs](#) will require that a patch antenna is placed on each facet of the cubesat, thus limiting the area for the downlink antennas even more. Most probably, a separate antenna system will be required for the data downlink since the link parameters (data rate and distance) are very different from the [ISL](#). Nevertheless, patch antennas are suitable also for the downlink. They provide a reasonable gain (up to 9 dBi),

while being lightweight, conformal and efficient. Moreover, they have wide receiving/transmitting angles, and do not require any deployment mechanism. Added to this, the fractional bandwidth of patch antennas (around 10% even for very thin substrates) makes them suitable for supporting frequency-separated communication channels [3]. In literature, inflatable parabolic reflector antennas have also been proposed for cubesats platforms in order to achieve better directivity [4]. The increased complexity and reduced viability of such a system make it unattractive for a satellite swarm.

When designing the downlink antenna system, the stability of the cubesat will play an important role. The maximum antenna gain will be achieved when the transmitting antenna (cubesat) and the receiving antenna (base station on Earth) are aligned and facing each other. A change in the orientation of the satellite will have an impact on the total gain of the system and on the communication link. Let the following scenario be considered: a cubesat that uses only one planar antenna for the downlink, placed on one of the facets. The antenna is assumed to have a $\cos^2$ radiation pattern, resulting in a 90° half power beamwidth, similar to the antenna considered in Section 4.5.1. The cross section of the radiation pattern is shown in Figure 4.16. The cubesat has no internal stabilization, and rotates freely around the three axes (roll, yaw and pitch), as shown in Figure 5.2.

In Figure 5.3, the variation in time of the transmission gain is illustrated. The results were attained after simulating the following scenario. A cubesat with a single patch antenna placed on the top facet was considered. The satellite has no internal stabilization and rotates freely along the three rotation axes (as shown in Figure 5.2). An initial rotation of the cubesat framework of ($\alpha = 0.312$ rad, $\beta = 2.379$ rad, $\gamma = 3.436$ rad) and angular speeds of ($\omega_\alpha = 0.0057$ rad/s, $\omega_\beta = 0.0063$ rad/s, $\omega_\gamma = -0.0127$ rad/s). The values for the rotation angles and angular speeds were randomly generated. They do not match the real case. However, this does not have any impact as the purpose of the simulation was to point out that the transmission gain depends strongly on the orientation of the spacecraft. The stability of the satellite is very important for the quality of the communication link. In a single satellite scenario, it is important to stabilize the spacecraft so that it will exhibit a high transmission gain throughout its whole life-

Figure 5.2: Cubesat with patch antenna on the top facet and 3D radiation pattern attached. Rotation axes and angular speeds—measured counterclockwise. (α, ω_α) , (β, ω_β) and (γ, ω_γ) correspond to roll, pitch and yaw, respectively.

cycle. In the case of a swarm of cubesats, the gain variations can be compensated by the large number of transmitting antennas.

Figure 5.3: Normalized linear transmission gain as a function of time.

Table 5.1: Link budget analysis for the worst-case scenario of swarm-to-Earth communication.

Parameter	Symbol	Value [Unit]
Carrier frequency	f_c	2.4 GHz
Transmission power	P_{TX}	4 W
Transmitter/receiver losses	L_{TX}, L_{RX}	1 dB
Transmitting antenna gain	G_{TX}	5 dBi
Path loss	PL	212 dB
Link margin	LM	5 dB
Receiving antenna gain	G_{RX}	60 dBi
System noise temperature	T_{sys}	140 K
Antenna noise temperature	T_{ant}	40 K
Data rate	D_{down}	900 kbps
Coded data rate	$D_{down \text{ coded}}$	1200 kbps
Bandwidth	BW	630 kHz
Noise floor	N	-118.1 dBm
Signal-to-noise ratio	SNR	0 dB

After the requirements and challenges have been stated, the link budget of a single satellite scenario is conducted.

5.2 LINK BUDGET

Establishing communication links between the satellites in the swarm and the BS is important for the entire downlink process. Thus, by assessing the quality of these links, a downlink strategy can be applied to the swarm in order to maintain a reliable communication. In Table 5.1, the parameters of a typical cubesat-to-base station link are summarized.

The following assumptions have been made:

1. The carrier frequency f_c has been chosen to be 2.4 GHz. The 13 cm band is a license-free band that can be used for satellite communications [5]. The dimensions of the radiating patch element for this frequency band match the requirements imposed by the cubesat standard [6]. $\lambda/4$ -spaced arrays of such elements

can be placed on the cubesats facets or deployable solar panels to improve the link quality. Furthermore, satellite communication hardware in this frequency band has already been built and tested in space [7]. The availability of COTS components is an advantage for the cost of testing, prototyping and final implementation of the OLFAR satellites.

2. The transmission power P_{TX} is set to 4 watts. The same amount of power that is used for ISLs in Chapter 4 is used for the downlink communication. In this manner, by switching from one communication task to the other, the load remains constant.
3. The atmospheric losses are neglected because the atmosphere has little influence on EM waves with frequencies higher than 1 GHz.
4. PL is the free-space path loss calculated for the worst case scenario (maximum distance between the swarm and base station—lunar apogee). It corresponds to a link distance of 402,000 km.
5. The link margin LM covers for other unaccounted losses (polarization, impedance mismatches). The LM figure for the downlink communication is higher than the value considered for the ISL in Chapter 4 in order to allow attenuation caused by rain fading or other external factors [8]. The attenuation caused by rain fading strongly depends on the amount of precipitation, and can be in the order of a few dBs for links in the 2.4-GHz band [9].
6. The bandwidth BW has to fit the required data rate D_{down} while using an appropriate modulation technique and guard intervals. The digital communication scheme proposed for the downlink is similar to the one described in Section 4.2. The transmitted data rate will increase by a factor of 1.33 due to the coding block, and an E_b/N_0 of 2.1 dB (SNR of 4.9 dB) will be required to achieve a BER of 10^{-5} .
7. The transmitting and receiving antennas are perfectly aligned. For radio interferometry it is required that the OLFAR satellites are aware of their position and orientation, and the distribution of the swarm. Relative positioning is determined by employing

a joint ranging and synchronization algorithm [10], and pulsar-referenced navigation will be used for absolute localization [11].

8. G_{TX} is the gain of the antenna of the satellite. 5 dBi is a typical achievable gain for a planar (patch) antenna as shown in Chapter 4. Since the transmitting and receiving antennas are perfectly aligned, linearly polarized patches can be used. Nevertheless, if the satellite can spin around the boresight direction, then a circularly polarized antenna must be used to account for the rotation of the spacecraft.
9. G_{RX} represents the gain of the antenna of the base station. Since both the available gain and power at the satellite level are very limited, it is mandatory to compensate for these values with a high receiving gain. A very large dish antenna or a radio telescope can be used to achieve this. The antenna noise temperature T_{ant} has been extracted from [9].

5.3 NON-COOPERATIVE DOWNLINK COMMUNICATION

The link budget calculation results in a very low value for the SNR even if the antennas are perfectly aligned. Hence, given the requirements it is impossible to establish a reliable link between a nanosatellite orbiting the Moon and a BS on Earth. Analyzing the values in Table 5.1 it can be seen that there is little room for improvement. The link margin can be reduced for gaining a few dBs for the SNR figure, but the risk of a communication drop increases and this cannot be afforded. A lower link margin means that even slight changes in the weather conditions can cause a link failure.

Other tunable link parameters include the transmission power P_{TX} , the transmitting antenna gain G_{TX} , and the receiving antenna gain G_{RX} , and the data rate D_{down} . Raising the SNR figure to 4.9 dB would mean increasing P_{TX} more than three times. Considering the cubesat platform limitations discussed in Chapter 2, it can be concluded that this solution is not feasible. Furthermore, using higher gain antennas for the BS is not an option since the considered gain is already very close to the maximum achievable in practice. Using an improved antenna system—such as a planar array—at the level of the satellite is a possible solution, and it will be discussed in Chapter 6.

A reliable connection could also be established if the data rate requirement is decreased by a factor of 3.1. If the amount of processed data would be reduced from 900 kbps to 290 kbps, then a BER of 10^{-5} would be practically achievable. Dropping the D_{down} rate is only possible by lowering either the observed data rate or the observation time, both resulting in a longer mission time for OLFAR. This will require a more robust design of the individual satellites, and will increase the overall costs of the project.

The OLFAR satellite swarm will consist of many satellites, and, thus, the downlink problem is not a single-satellite issue, but more of a collective problem. Nonetheless, the large number of spacecraft can represent an advantage as multiple satellites can work together for establishing a reliable downlink communication.

In the following section, a couple of cooperative communication strategies will be described.

5.4 THE COOPERATIVE COMMUNICATION SCHEME

The swarm-to-Earth link has to consider data and power availability within the swarm. If multiple satellites will have to work together for the downlink, it is necessary that OLFAR satellites share the results of the correlation process. Therefore, before using a cooperative communication scheme the results of the processing task have to be distributed in the satellite network. Thus, an extra data distribution step is required. For the next sections it is assumed the processed information is available in every node of the swarm. Added to this, the use of multiple satellites for the downlink implies that the overall power consumption per unit of sent data will increase. Nonetheless, the goal of this chapter is to establish a reliable data connection between the OLFAR swarm and the BS, rather than reducing the power consumption.

Uploading data to the OLFAR satellites is less challenging. Since the swarm will act as an autonomous system [12], it will not be remotely controlled. The uplink will be used only for transferring housekeeping information, and the required data rate will be a few orders of magnitude lower than the downlink, thus, making the SNR for the uplink a few tens of dB higher. Moreover, the transmission power available at ground level is less of an issue.

As previously stated, the **OLFAR** swarm consists of 50 or more nano-satellites. Thus, it consists of 50 or more downlink antennas grouped together in a 100 km diameter cloud. This can be exploited to improve the quality of the link to the **BS** by employing an adequate communication strategy.

Multiple scenarios can be thought of. The most straightforward solution would be to implement a selection scheme. In this approach, the satellite that will exhibit the best alignment with the receiving antenna will be selected as the gateway of the swarm to the **BS**. In this way, it is ensured that the link with the best **SNR** will be chosen for data downlinking. This scheme is not really feasible for the **OLFAR** swarm. In Section 5.2, a maximum **SNR** for an **OLFAR** satellite-to-Earth link of 0 dB has been calculated. As a result, even with perfect alignment between the transmitting and the receiving antennas, a reliable data connection from a single satellite to the **BS** is not feasible.

Hence, in order to facilitate a data connection between the satellite network and Earth, the link budget has to be improved. The previous section focused on the individual satellites and outlined a few solutions for ensuring a reliable data connection between the **OLFAR** swarm and a **BS** on Earth. A different approach is to improve the link budget at swarm level by using the cooperation between multiple nodes. In the following paragraphs, the focus is on the swarm approach for data downlink. Two cooperation scenarios are proposed: an **MRC** strategy or an antenna array strategy.

The first scenario is illustrated in Figure 5.4. The **MRC** approach takes advantage of multiple transmit antennas available in the **OLFAR** cloud. Diversity schemes are often used to minimize the effect of fading [13] which is not really the case with **OLFAR**. Nonetheless, transmit diversity can be employed to exploit the spacecraft dynamics.

As stated before, the **OLFAR** satellites will be characterized by translation and rotation movements. The radio telescope functionality of the swarm imposes some restrictions over the motion of the satellites. In order to perform accurate low-frequency imaging, the distribution of the satellites should not change significantly over the integration period. Therefore, the translation and rotation movements of the **OLFAR** satellites will be rather slow. The rotation of the satellites will cause a variation of the transmit antenna gain as shown in Figure 5.3. If this behavior is included into the channel models, an effect similar to fading

Figure 5.4: [MRC](#) scheme implemented with a swarm of satellites.

ing will be attained. The characteristics of the communication channel hardly change during one symbol time. Thus, the fading can be assumed to be slow. Furthermore, due to the small required channel bandwidth and the absence of any frequency-selective effect, the fading can also be considered flat. The “flat fading” effect added to the fact that satellites will tend to drift and rotate independently from each other suggests the use of an [MRC](#)-like solution. [MRC](#) diversity combining is optimum for independent channels with [AWGN](#) [13].

Even though [MRC](#) combining is mostly used for receive diversity, a similar approach can be thought of to exploit the antenna diversity of the [OLFAR](#) swarm. For example, since the data rate and, hence, the required bandwidth are low, the satellites can transmit their data simultaneously by separating the communication channels in frequency. At the reception, all the incoming signals are demodulated and brought to baseband. A weighted sum is then performed on the baseband signals, increasing the overall [SNR](#) and minimizing the probability of error.

In a perfect MRC diversity combining scheme, the resulting SNR of the communication is equal to the sum of SNRs.

At a first glance, using transmit diversity could improve the SNR such that the downlink connection with the BS could be established. Several aspects of OLFAR, such as swarm distribution and mobility, have to be taken into consideration. For a diversity combining scheme to function properly, symbol synchronization is required. The OLFAR satellites require high-accuracy synchronization for performing the distributed correlation process [14], so transmitting at the same time is not an issue. However, this does not guarantee that after the demodulation step the symbol streams are synchronized. The link distance will be different for each satellite in the swarm, and, hence, the propagation delay that each signal exhibits will be different. With the satellites being spread in a cloud with a diameter of 100 km, each link distance will depend on the actual position of the satellite². The maximum path difference between two satellite-to-Earth links is 100 km. The corresponding difference in time delay $\Delta\tau$ between the two received signals can be calculated as

$$\Delta\tau = \frac{\Delta d_{\text{Earth}}}{c} = \frac{\Delta d_{\text{Earth}}}{\lambda_{\text{RF}}} T_{\text{RF}} \approx 0.33 \cdot 10^{-3} \text{ s}, \quad (5.1)$$

where d_{Earth} is the distance to Earth, Δd_{Earth} is the difference in path length, λ_{RF} is the wavelength of the the radiated wave, T_{RF} is the period of the carrier signal, and c is the speed of light in vacuum³.

Taking into account the data rate and the modulation scheme described in Section 5.2, the symbol time T_{symbol} can be calculated as

$$T_{\text{symbol}} = \frac{1}{\text{symbol rate}} = \frac{1}{600 \cdot 10^3} \approx 0.17 \cdot 10^{-5} \text{ s}, \quad (5.2)$$

From (5.1) and (5.2), it can be noticed that the maximum difference in path delay is significantly larger than the symbol time, and has to be accounted for if diversity should be used.

The continuous spacecraft motion is another important factor that has to be taken into account. Satellite drift causes the propagation delays to be also time variant. In [15], it has been shown that the relative

² The orbital movement is ignored as it is described by deterministic laws and, thus, phase corrections can be made accordingly.

³ $c = 2.99 \times 10^8 \text{ m/s}$.

speed between **OLFAR** nodes can be up to 30 m/s. The maximum difference in time delay $\Delta\tau_{ij}$ will change at a rate that can be approximated to be

$$\frac{\partial\tau_{ij}}{\partial t} = \frac{v_{ij}}{c} \leq 10^{-7}, \quad (5.3)$$

where v_{ij} is the relative speed between satellite i and satellite j , and t denotes time.

Furthermore, the rotation of the satellites also impacts the variation of the signal path length as shown in Figure 5.5.

Figure 5.5: Change in satellite-to-Earth link distance due to rotation of spacecraft.

Since the size of the cubesats is comparable to λ_{RF} , any slight deviation ϕ from the boresight direction of the downlink antenna will result in a path length difference Δd_{Earth} that can be approximated as

$$\Delta d_{\text{Earth}} \cong \frac{L_{\text{sat}}}{2} (1 - \cos \phi), \quad (5.4)$$

where L_{sat} is the length of the cubesat⁴. Using (5.1), the introduced time delay can be calculated as

$$\Delta\tau = \frac{\Delta d_{\text{Earth}}}{c} \approx \frac{L_{\text{sat}}}{2c}(1 - \cos\phi). \quad (5.5)$$

The time delay can also be expressed as a phase delay of the RF signal:

$$\Delta\theta_{\text{RF}} = \frac{2\pi\Delta d_{\text{Earth}}}{\lambda_{\text{RF}}}, \quad (5.6)$$

or of the baseband signal:

$$\Delta\theta_{\text{symbol}} = \frac{\Delta\theta_{\text{RF}}T_{\text{RF}}}{T_{\text{symbol}}}. \quad (5.7)$$

Implementing a transmit diversity scheme in a mobile network, such as the OLFAR swarm, has to overcome the symbol synchronization challenge. As suggested by the results attained in (5.1) and (5.3), improving the SNR figure by means of diversity combining is not possible without taking into account the delays caused by spacecraft distribution and satellite motion.

In [16], multiple solutions—open loop and closed loop—for transmit diversity in networks with mobile terminals have been outlined. Open loop schemes are versatile solutions suitable for systems where a feedback link between the receiver and transmitter is not available. They employ a predetermined form of diversity such as space-time coding [17], irrespective of the channel characteristics, to combat fading. The closed loop implementations make use of channel knowledge in order to maximize the received power. Pilot sequences are transmitted from the BS to the mobile station to estimate the propagation channel properties. The estimates are then used for optimum combining at either the receiver or the transmitter. Closed loop solutions have the advantage of being adaptable, but they require that a bidirectional link is established between the BS and mobile terminals.

The large number of transmit antennas in the OLFAR swarm as well as the rather slowly-varying communication channel suggest that a

⁴ The antenna is placed on the smaller facet of the cubesat.

closed loop approach can also be employed to achieve symbol synchronization and combine the multiple received replicas of the information-bearing signal. In Section 5.3, it has been shown that, by reducing the data rate, a reliable downlink can be established between an OLFAR node and a BS on Earth. Therefore, it is safe to assume that a very low data rate feedback communication link can be settled between the two parties as well. This link can be used to determine the different propagation delays the OLFAR satellites exhibit in the downlink communication. Furthermore, estimated satellite velocity information as part of the node synchronization process [18] can also be transmitted and taken into account at the receiver level. As a result, this data can be used to synchronize the N_{sat} symbol streams and perform MRC diversity combining to improve the SNR figure.

Attitude determination information could also be included in the feedback to correct for the rotation of the satellites. Nevertheless, (5.5) proved the limited effect of the random orientation of the cubesat. The delay induced by the rotation of the spacecraft is a lot smaller than the symbol time. What is more, the larger ϕ and, thus, higher the time delay, the less transmitting gain the link will exhibit. Therefore, taking into account the MRC scheme, it can be stated that the signals received via these links will not contribute significantly to the overall SNR figure.

In the proposed scenario for the OLFAR swarm—closed loop transmit diversity with MRC combining—the resulting SNR can be calculated as

$$SNR = \sum_{k=1}^{N_{\text{sat}}} SNR_k \cos^2 \Delta\theta_{\text{symbol},k}, \quad (5.8)$$

where SNR_k corresponds to the communication channel established by satellite k , and $\Delta\theta_{\text{symbol},k}$ corresponds to the delay caused by the satellite's rotation movement calculated as in (5.7).

From the link budget analysis conducted in Section 5.2, it can be seen that the only satellite-dependent variable in the calculation for SNR_k is the gain of the transmitting antenna. Therefore, it can be written as

$$SNR_k \cong SNR_{\text{iso}} G_{\text{TX},k}, \quad (5.9)$$

where $G_{\text{TX},k}$ is the linear transmitting antenna gain corresponding to satellite k , and SNR_{iso} is the SNR that would be achieved if an isotropic

antenna was employed at satellite level. In the calculation for the individual SNR figures, an average satellite-to-Earth distance is considered, and no variation of the receiving antenna gain is assumed. Therefore, (5.9) is an approximation.

Taking into account the antenna considerations from Section 5.1, it can be noticed that the gain depends only on the inclination angle ϕ_k . This can be expressed as follows

$$G_{\text{TX},k} = g(\phi_k) = \begin{cases} G \cos^2 \phi_k, & 0 \leq \phi_k \leq \frac{\pi}{2}, \\ 0, & \frac{\pi}{2} < \phi_k \leq \pi, \end{cases} \quad (5.10)$$

where G is the maximum linear gain of the antenna, and $g(\cdot)$ is the gain function. ϕ_k is measured from the z -axis.

Using (5.4), (5.6), (5.7), (5.8), (5.9), and (5.10), the resulting SNR figure can be expressed as

$$\text{SNR} \cong \text{SNR}_{\text{iso}} G \sum_{k=1}^{N_{\text{sat}}} g(\phi_k) \cos^2 \left(\frac{\pi L_{\text{sat}}(1 - \cos \phi_k)}{c T_{\text{symbol}}} \right). \quad (5.11)$$

Furthermore, using the same model as illustrated in Figure 5.2 and assuming the z -axis to be the boresight direction, the inclination angle can be expressed as a function of two rotation angles, α_k and β_k , the corresponding angular speeds and time. Since the z -axis is the boresight direction, the rotation around this axis has no influence on the inclination angle.

Using a Cartesian-to-spherical transformation, the inclination angles can be written as

$$\phi_k = \arccos \left(\frac{z_k}{\sqrt{x_k^2 + y_k^2 + z_k^2}} \right), \quad (5.12)$$

and

$$\begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} = \mathbf{R}_x(\alpha_k + \omega_{\alpha,k} t) \mathbf{R}_y(\beta_k + \omega_{\beta,k} t) \begin{bmatrix} 0 \\ 0 \\ L_{\text{sat}}/2 \end{bmatrix}. \quad (5.13)$$

$\begin{bmatrix} 0 & 0 & L_{\text{sat}}/2 \end{bmatrix}^\top$ is the position vector of the satellite's top facet relative to its center—the initial boresight direction—whereas $\begin{bmatrix} x_k & y_k & z_k \end{bmatrix}^\top$

corresponds to the boresight direction after rotation. $\mathbf{R}_x(\alpha)$ and $\mathbf{R}_y(\beta)$ are the rotation matrices corresponding to the rotations around the x and y axis as functions of the rotation angles α and β , respectively, given by

$$\mathbf{R}_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{bmatrix} \quad (5.14)$$

and

$$\mathbf{R}_y(\beta) = \begin{bmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{bmatrix}. \quad (5.15)$$

Using (5.12), (5.13), (5.14), and (5.15), it results in

$$\phi_k = \arccos(\cos(\alpha_k + \omega_{\alpha,k}t) \cos(\beta_k + \omega_{\beta,k}t)). \quad (5.16)$$

By inserting the result of (5.16) in (5.11), the resulting SNR figure can be expressed as a function of rotation angles α_k and β_k , rotation speeds $\omega_{\alpha,k}$ and $\omega_{\beta,k}$, and time t .

For $T_{\text{symbol}} \gg L_{\text{sat}}/c$ the “symbol phase delay” tends to zero, and the resulting SNR can be approximated to be

$$\text{SNR} \cong \text{SNR}_{\text{iso}} G \sum_{k=1}^{N_{\text{sat}}} g(\arccos(\cos(\alpha_k + \omega_{\alpha,k}t) \cos(\beta_k + \omega_{\beta,k}t))). \quad (5.17)$$

In order to evaluate the performance of the diversity approach, the following Matlab simulation scenario was considered: 50 cubesats were randomly spread in a sphere of 50 km radius using a uniform distribution. The sphere was placed at a distance equal to the lunar apogee from the receiving point. Each satellite has only one patch antenna placed on one of its facets. Every satellite starts in a randomly oriented position relative to the base station. This orientation is given by the three rotation angles, α , β and γ , that are uniformly distributed between 0 and 2π . Each satellite exhibits rotations over all three axes

(pitch, yaw and roll), and all the rotations speeds are uniformly distributed in the interval $[-0.01 \pi/\text{s}, 0.01 \pi/\text{s}]$.

In Figure 5.6, the instantaneously achieved SNR values for three different scenarios, selection of the best link scheme, diversity scheme with symbol synchronization, diversity scheme without symbol synchronization, are plotted. It can be seen that if the received symbol streams are synchronized—the time delays caused by the difference in the propagation paths are corrected—the MRC scheme improves the SNR figure on average by roughly 7 dB as compared to a selection scheme—selection of the best link. The simulations also show that the random phase caused by the satellite rotation has very little impact on the performance of the cooperative communication scheme. The resulting SNR curve for the “no rotation phase correction” scenario would perfectly overlap the “Diversity - ideal” curve, and, so it was not plotted. However, using no channel estimation at all degrades the SNR considerably. Since the satellites are spread in a very large cloud, transmitted signals will reach the BS with different delays. If there is no symbol synchronization, some signals will cancel each other resulting in unacceptable level of SNR as shown in the “Diversity - no correction” plot.

Since the OLFAR satellites rotate rather slowly, the feedback link can be used to periodically estimate the total delay each received signal exhibits—due to both translation and rotation. By means of phase shifters, the different propagation delays are corrected and the signals add up in phase at the reception point. This approach is also known as Transmit Adaptive Array (TXAA) and has been proposed in [19] for increasing the SNR in third generation (3G) CDMA systems. Assuming that the phase shifters are ideal and the channel estimation is done without errors, the resulting SNR figure can be calculated as follows

$$SNR = \left(\sum_{k=1}^{N_{\text{sat}}} \sqrt{SNR_k} \right)^2. \quad (5.18)$$

Using (5.9), (5.10) and (5.16), (5.18) can be rewritten as

$$SNR \cong SNR_{\text{iso}} G \left(\sum_{k=1}^{N_{\text{sat}}} \sqrt{g(\phi_k)} \right)^2. \quad (5.19)$$

Figure 5.6: Simulated SNR for a selection diversity scheme and a MRC scheme as a function of time. The “Selection” plot is the SNR achieved when the selection of the best link scheme is employed. The “Diversity - ideal” plot corresponds to the scenario where the diversity scheme is used and the received symbol streams are synchronized. The “Diversity - no correction” plot corresponds to a diversity implementation without any phase correction of the received symbol streams.

If (5.17) and (5.19) are compared, it can be noticed that the TXAA solution provides a better SNR than the diversity approach.

The improvement of the link quality is displayed in Figure 5.7. The results were attained after simulating the previously described scenario. Although the array scheme exhibits better performance than the MRC scheme, this comes at the cost of increased complexity of the spacecraft. Additional RF phase shifters are required. Furthermore, the array implementation is very sensitive to the rotation of the satellites and the channel characterization errors. The “Array - rotation phase” plot shows that slight mismatches in the estimated propagation delays may cause received signals to cancel each other, resulting in a significant degradation of the overall SNR. In order to avoid disrupting the downlink communication, the array approach will require accurate channel estimation and phase shifting.

Figure 5.7: Simulated SNR of the selection scheme and SNR of the array strategy as a function of time. The “Array - ideal” corresponds to the scenario in which the difference in propagation paths and random rotation of satellites is taken into account. In the “Array - rotation phase” scenario, the random phase corresponding to the satellites rotation is not corrected. The “Selection” plot has the same meaning as in Figure 5.6.

Nevertheless, it is important to notice that, in the ideal scenarios, the resulting SNR maintains high values for most of the simulation period. Thus, with good estimation of the channel parameters, the two approaches allow the swarm to establish a connection with the BS and to transmit the processed data almost continuously.

5.5 CONCLUSIONS

The link budget analysis conducted in Section 5.2 proved that it is difficult to establish a reliable link between a nanosatellite (cubesat) that orbits the Moon and a base station placed on the ground. Nonetheless, the further from Earth these miniaturized spacecraft will have to go, the lower the probability of a successful communication, and, hence, of a successful mission will be. Such remote missions will have to exploit the advantage of the large number of nanosatellites to fulfill all the tasks (sensing but also communicating).

In case of the **OLFAR** swarm, sending the processed data to Earth will have to be the result of a collective effort. An **MRC** scheme will improve the global **SNR** and make it possible to establish a reliable link between the swarm and the base station. It has the advantage that it requires no extra hardware (phase shifters) at the swarm level, but will shift the complexity to the receivers at ground level.

The results presented in Figure 5.6 and 5.7 also suggest that the satellites can establish a data connection with a **BS** on Earth without attitude stabilization. In a large swarm, at every moment, a few antennas will point towards the base station making it possible to establish a data link. Nonetheless, the power consumption for the downlink will increase due to the use of multiple satellites for transmitting the same data set, and the additional distribution step. In the cooperative communication schemes, the power used for the data downlink can grow by a factor of up to 50 (17 dB) if all the satellites contribute to this task. Nevertheless, in most cases, three to five **OLFAR** nodes will have a significant contribution to the communication.

Further work needs to be done on enhancing some of the link's parameters. Improving the gain of the transmitting antenna can be a solution for achieving a better **SNR** without any additional inter-satellite traffic. The design of a suitable antenna system that uses the large area of the backside of the solar panels and their steering properties will be presented in the next chapter.

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Chapter 6

Downlink antenna system

As shown in the previous chapter, transmitting the processed data from the [OLFAR](#) swarm to the [BS](#) on Earth is a resource-consuming process. Nevertheless, it is critical for achieving the end goal of the project. The remote deployment, the distance to Earth, and the limited capabilities of the cubesat platform are some of the obstacles to overcome in order to establish and maintain a data connection from the [OLFAR](#) swarm to Earth.

In Chapter [5](#), it has been shown that a single [OLFAR](#) satellite cannot send information to the [BS](#) using a single patch antenna. Even if the spacecraft is stabilized and the transmitting and receiving antennas are perfectly aligned, the resulting [SNR](#) is insufficient for data transfer. The approach was to limit the use of additional hardware as much as possible. Thus, by using an antenna diversity analogy, a cooperative communication scheme was considered to marginally improve the [SNR](#) figure. The results were promising, but they came at the cost of introducing an extra in-swarm data distribution step. Based on the outcome of Chapter [3](#) and Chapter [4](#), it can be estimated that distributing the processed astronomical data between the satellites will require a significant amount of time and power.

The satellite-to-Earth link budget analysis conducted in Section [5.2](#) does not allow significant improvements. Few of the parameters can be changed in order to achieve a better [SNR](#). The link margin LM can be lowered or the transmission power P_{TX} can be slightly increased. Nonetheless, the enhancement would only be a few dBs. Significant

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progress can be made at the transmitting antenna level by using a larger aperture or a reflector [1]. In [2], it has been shown that the power budget of the OLFAR spacecraft can only be provided by using additional energy harvesting structures—deployable solar panels. Therefore, space available on these structures can be used to accommodate a higher-gain downlink antenna system such as a patch array.

In this chapter, the downlink antenna systems is addressed, and a design proposal for a combined solution for energy conversion and data transmission is presented. The chapter starts with a summary of the design of the EPS and the solar panels. Then, based on the resulted spatial constraints, the construction and integration of a suitable downlink patch array on the backside of the panels is performed. The rest of the chapter is organized as follows. In Section 6.1, an overview of the EPS and its associated solar arrays is presented. Section 6.2 outlines the theoretical design considerations of the patch array. A laboratory prototype (of a partial antenna array and a microstrip feeding network) is described in Section 6.3. Conclusions are drawn in Section 6.4.

6.1 ELECTRICAL POWER SYSTEM

The EPS¹ is the backbone of the satellite and the energy supply for most of the satellite's components (processor, reaction wheels, ISL, and astronomical payload). This section summarizes the work done by Matthijs J. Klein on the EPS and serves as a support for the design of the downlink antenna system.

The power demands of the OLFAR nanosatellites and the design constraints imposed by the cubesat platform, as well as the mission goal, were discussed in Chapter 2. The required power figures for each of the three main tasks—observation, distributed processing and downlink—for a 3,000-km circular lunar orbit scenario were outlined in Table 2.2. When building a suitable satellite EPS for the OLFAR scenario all of these have to be taken into account.

In order to ensure the economical viability of the swarm, the EPS is required to make use of COTS components and to be series-producible at low cost. The EPS of an OLFAR satellite will consist of an array of

¹ The complete design proposal of OLFAR's EPS has been presented in [2].

photovoltaic cells, maximum power point trackers (MPPTs) and a bank of batteries.

The panel uses crystalline silicon photovoltaic cells and is optimized for a 3,000-km altitude circular lunar orbit. The required panel surface area follows from the panel output power requirement at the satellite's end of life (EOL), the orbit, and the photovoltaic cell and cover sheet technology used. In order to achieve this surface area, the panel consists of five panel segments and a yoke. Two panels are symmetrically deployed by each OLFAR satellite as shown in Figure 6.1a. A layout resulting from the allocated stowing volume is presented in Figure 6.1b. This is caused by OLFAR's adoption of the 3U cubesat form factor and the ISIPOD [3]. The length of the panel is constrained by the presence of OLFAR's observation antennas [4].

A highly integrated panel design is achieved using printed circuit board (PCB) as panel substrate. PCBs are laminates of patterned copper sheets onto dielectric sheets. Typically, a Flame Retardant 4 (FR-4) dielectric is used due to its cost efficiency. They are mass-producible with high precision and have been used for nanosatellite solar panel substrates in other satellite missions as well [5]. Their composition allows for the integration of planar antennas and integration of conducting traces for antenna signals and electrical interconnections of photovoltaic cells, while providing the necessary mechanical stiffness. The front and back side layers of the PCB are allocated to the photovoltaic cell array and the antenna, respectively. The thickness available for both panel functions is mutually dependent, and is restricted to 1.5 mm by the available stowing volume. The EPS utilizes two copper layers of the 1-mm thick PCB, and leaves 0.7 mm of the substrate thickness available for the downlink antenna.

Male and female pairs of right-angle MMCX RF connectors are used as the hinge between two panel segments, allowing for folding of the panel and providing a common ground for all segments [2]. At least two hinges are required for structural stiffness.

6.2 DOWNLINK COMMUNICATION ANTENNA ARRAY

With the benefits and limitations of the considered EPS taken into account, the design of an antenna system for establishing the communication link with the BS on Earth is performed. Since the resources (area,

(a) OLFAR nanosatellite showing front and back side of the solar panels and part of the astronomical antennas.

(b) Front view of one solar panel.

Figure 6.1: Deployable solar panels of the OLFAR nanosatellite.

thickness, and materials) are clearly stated by the previous design, the goal is to build an antenna system and optimize its RF properties such as directivity, side-lobe level, and beamwidth.

Also, in this case, the cubesat platform is a very important limiting factor. The low power available to establish a link with a ground

BS imposes the need of a high-gain system. Furthermore, the use of a standardized deployer bounds not only the available space but also the type of structure to be used. Each solar panel is a modular structure made out of five subpanels so that it can be folded to fit into the ISI-POD [3] alongside the cubesat. The subpanels have a length of 34 cm and are 8.2 cm wide. As a result, a single-antenna-per-panel implementation would not use the area efficiently since it could occupy only one fifth of the available surface (at most). The radiating element cannot spread over multiple subpanels because of the space separating them.

A more suitable implementation is to build an array of simple planar antennas and feed them through integrated microstrip lines. Aperture-fed patches make an excellent candidate and can be implemented using the FR-4 substrate.

The next subsections outline the design considerations and simulation results.

6.2.1 Antenna array design

A two-dimensional array of linearly polarized patch antennas has been chosen for implementation. Circular polarization is not required as the aim is to use the system for stabilized spacecraft. To determine the resonance frequency for the radiating elements, the available space on the back side of each subpanel is considered. In Figure 6.2, a sketch of the patch antennas implementation is presented. The following notations have been used:

- W_{panel} is the width of the subpanel;
- L_{panel} is the length of the subpanel;
- W_{patch} is the width of the patches;
- L_{patch} is the length of the patches;
- $h_{\text{substrate}}$ is the thickness of the substrate;
- h_{ground} is the thickness of the ground plane;
- h_{patch} is the thickness of the patches;
- d_{array} is the array spacing, and represents the distance between two adjacent radiating edges;

- *PEC* refers to a perfect electrical conductor, and was the material chosen only for simulations.

Figure 6.2: Sketch of the patch antennas implementation.

As the thickness of the panel should be exploited to the maximum, and the length of the subpanels is considerably larger than their width, the most influential patch parameter is, in this case, the width. The central frequency is chosen so that the width of the antennas fits in the 8.2 cm width of the subpanels, and creates a spacing between the elements of the array that is larger than a quarter of the wavelength and smaller than half of the wavelength. A different spacing would result either in high coupling between the elements of the array or in poor radiation parameters (low directivity and high side lobes). Moreover, the frequency value is also bounded by the dimensions of the ground plane. The lower the frequency, the more prone the patches are to undesired radiation patterns.

Table 6.1: Downlink antenna parameters.

Parameter	Value [Unit]
W_{panel}	8.2 cm
L_{panel}	34 cm
W_{patch}	3.68 cm
L_{patch}	2.88 cm
d_{array}	4.62 cm
h_{patch}	0.01 mm
h_{ground}	0.01 mm
$h_{\text{substrate}}$	0.68 mm
ϵ_r	4.4
f_{down}	2.4 GHz

Hence, to achieve a good array performance, it is important to fulfill the following inequality relations [1]:

$$\lambda/4 \leq d_{\text{array}} \leq \lambda/2. \quad (6.1)$$

Added to this, the design implies the following equality:

$$d_{\text{array}}/2 + W_{\text{patch}} + d_{\text{array}}/2 = W_{\text{panel}}. \quad (6.2)$$

Finally, the width of the patch depends on the relative dielectric permittivity ϵ_r of the substrate and on the resonance frequency f_{down} as follows:

$$W_{\text{patch}} = \frac{c_0}{2f_{\text{down}}} \sqrt{\frac{2}{\epsilon_r + 1}}, \quad (6.3)$$

where c_0 is the speed of light in vacuum [1].

Equations (6.1), (6.2), and (6.3) are used for selecting the resonance frequency f_{down} . Based on this value, the dimensions of the patches are then determined. The values are summarized in Table 6.1.

The central frequency f_{down} of 2.4 GHz corresponds to a wavelength λ of around 13 cm. That means that the size of ground plane is less than a wavelength.

CST Microwave Studio [6] was used to evaluate the performance of the designed patches. The resulting radiation pattern of the individual

antenna is different from the ideal one as it can be seen in Figure 6.3. The direction of the main lobe is not perpendicular on the antenna plane, and higher back radiation is exhibited. A linear scale is used in this case to emphasize the asymmetry that the short ground plane causes.

Figure 6.3: Simulated farfield radiation patterns—linear directivity—of a single antenna for different width of the ground plane.

It is important to mention that the spacing between patches on the subpanels has to fulfill a similar condition as in (6.1). However, the subpanels are a continuous structure and the spacing can be easily adapted.

Having calculated the width and length of each patch antenna, it followed that each subpanel can accommodate an array of up to four

patches. Therefore, on the back of each of the two solar panels, a five-by-four rectangular array of patches was placed, as shown in Figure 6.1a.

The feeding of the antennas plays an important role in the performance of the array. Since the two solar panels are separated by the cubesat structure and the sustaining rods, the distance between them exceeds a wavelength, and thus, in the considered model, the two five-by-four arrays are viewed as two separate systems. For each of the panels, the power is distributed to the antennas using a binomial scheme [1].

6.2.2 Simulations

To evaluate the performance of the proposed downlink array, a CST Microwave Studio [6] model was built and farfield simulations were conducted. The model made use of available material characteristics for the FR-4 substrate. The metallic parts were modeled as perfect electric conductors (PECs) as the influence of their limited conductivity is not significant. The effect of uniform and binomial feeding was evaluated using post-processing macros. Figure 6.4 shows the radiation pattern of the five-by-four array of patches when considering uniform and binomial power distribution in the feed network. It can be observed that in the binomial case the performance in terms of *beamwidth* and *side-lobe level* is better at the cost of a lower *directivity*. In the swarm-to-Earth communication, a higher beamwidth increases the tolerance of the link to antenna alignment errors, and therefore, to spacecraft stabilization.

The selection of the power weighting scheme will also depend on other subsystems of the cubesat. For example, a stabilized cubesat with precise pointing capabilities will use the higher-*directivity* scheme whereas an unstabilized spacecraft would be better off with a scheme that has a larger *beamwidth* and radiates less power outside the main beam.

The results confirm the possibility of establishing a data connection between an OLFAR satellite and terrestrial BS. A dual-panel implementation can achieve a total transmitting gain of more than 18 dBi (in the boresight direction)². If this value is compared to the G_{TX} in Table 5.1,

² The spacing between the radiating edges of the two antenna arrays—solar panels—is slightly larger than the wavelength. As a result, the twin-panel solution will exhibit

Figure 6.4: Simulated farfield radiation patterns of a single panel array with uniform and binomial weighting.

it represents an improvement of around 13 dB. Thus, the resulting [SNR](#) is sufficient for establishing communication links between the swarm and the [BS](#). Moreover, the high [SNR](#) value also means that the processed data can be downloaded from the [OLFAR](#) cloud at a higher data rate than indicated in Table 2.4.

Another important aspect of the proposed configuration is its gain pattern. The 3-dB beamwidth is about 22° . Hence, slight mismatches in the alignment of the transmitting and receiving antennas will not have a significant influence on the link quality.

an increase of 3 dB in the gain figure only in the boresight direction. The spacing will also cause slight degradation of the side lobe properties.

6.3 ANTENNA ARRAY PROTOTYPE

The simulations performed in the previous section showed that the two-dimensional antenna array is a suitable solution for the downlink communication issue, and also revealed some of its advantages. Therefore, a laboratory prototype was developed in order to study whether or not the solution is practicably achievable.

A few limitations were encountered. Only certain types of FR-4 materials with standardized thicknesses were available in the production facilities. A Nelco®N4000-6 FC substrate with a thickness of 787 μm was chosen, since it was the closest to the 0.7 mm ideal FR-4 substrate considered initially. As a result, slight modifications (in the order of 0.1 mm) were made to the dimensions of the patches. Furthermore, due to cost reasons, it was not possible to build the complete five-by-four array, nor to use a multi-layer structure. The manufactured prototype was limited to one subpanel. It consisted of a one-by-four inset-fed patch array and a binomial microstrip feeding network. Both components were printed on the same PCB sheet. Thus, the fabricated demonstrator is meant to prove the subpanel implementation feasibility of the antenna array and the feeding network on the very small substrate.

In the following subsections, the produced components and measurements results will be presented.

6.3.1 Binomial feeding network

The designed feeding network is presented in Figure 6.6. In order to cope with the space-based implementation of OLFAR, the structure consists only of microstrip components. The use of discrete elements such as resistors would make the structure too thick to be folded. Two levels of unisolated power dividers and impedance tapers [7] were used to achieve the binomial power distribution.

A network analyzer was used to evaluate the scattering parameters (S-parameters) of the built five-port [7]. A scattering coefficient S_{ij} is defined as

$$S_{ij} = \frac{V_i^-}{V_j^+}, \quad (6.4)$$

Figure 6.5: Microstrip layout of the binomial feeding network.

where V_i^- is the amplitude of the reflected wave coming out of port i when an incident wave of amplitude V_j^+ is applied to port j , while all the other ports are terminated with a matched load.

Table 6.2: Microstrip layout parameters.

Impedance			$\lambda/4$ -length	
Notation	Value [Ω]	Width [mm]	Notation	Value [mm]
Z_{50}	50	1.592	L_{50}	17.825
Z_{38}	38.72	2.374	L_{38}	17.497
Z_{17}	17.32	6.860	L_{17}	16.655
Z_{10}	10	13.008	L_{10}	16.262
Z_{20}	20	5.755	L_{20}	16.783
Z_{27}	26.67	3.988	L_{27}	17.069
Z_{80}	80	0.644	L_{80}	18.483
Z_{63}	63.25	1.050	L_{63}	18.149
Z_{36}	36.51	2.588	L_{36}	17.425
Miter band			Value	
M_{20}			0.401	
M_{27}			0.412	
M_{80}			0.648	
Substrate parameters				
Substrate thickness	Relative dielectric permittivity	Relative magnetic permeability	Copper thickness	Conductivity
$H_{\text{substrate}}$ [μm]	ϵ_{r}	μ_{r}	T_{copper} [μm]	ρ [S/m]
787	4	1	17	$5.8 \cdot 10^7$

In Figure 6.7a, the simulated transmission coefficients S_{21} and S_{31} are plotted. Similar plots correspond to S_{51} and S_{41} due to the symmetry of the structure. According to the binomial power distribution, the values for S_{21} and S_{31} at 2.4 GHz should be -9.03 dB and -4.26 dB, respectively. The simulated values are somewhat different due to the losses of the substrate. In Figure 6.7b, the simulated and measured values for the input port reflection coefficient S_{11} are plotted. The two curves exhibit a similar behavior. The differences are probably caused by connector and substrate losses.

Figure 6.6: Prototype of the microstrip binomial feeding network. The unisolated power splitters and the $50\text{-}\Omega$ impedance tapers can be identified.

Measurements of all other S-parameters proved the complexity of the feeding structures. Although local optimization was performed for the microstrip components, imperfect matching between them caused resonances that influenced the transmission coefficients.

6.3.2 Microstrip patch array prototype

A one-by-four microstrip patch array was added to the feeding network to complete the prototype. The complete structure is shown in Figure 6.8. Inset-fed patch radiators were used as an alternative to the proposed aperture-fed patches. The inset-fed patches have similar radiation properties as the aperture fed-patches, and can be printed on a single layer PCB. This solution was preferred in order to simplify the manufacturing process.

After the prototype was finalized, it was tested within the anechoic facilities of Thales Nederland B.V. The simulated and measured farfield pattern are plotted in Figure 6.9. The back radiation of the antenna system mock-up was not of interests since the solar cells were not present on the back side of the prototype.

(a) Simulated transmission parameters

(b) Simulated and measured S_{11}

Figure 6.7: Simulated and measured S-parameters of the microstrip feeding network.

The two patterns are very similar. A minor tilt is present in the measured directivity curve, which is most probably caused by an alignment error. Hence, the measurements back the simulation results and confirm the feasibility of the binomial array concept.

Figure 6.8: Laboratory prototype of the [OLFAR](#) downlink array. It consists of a one-by-four microstrip patch array connected to a binomial feeding network.

6.4 CONCLUSIONS

This chapter continues to address [OLFAR](#)'s data downlink and presents the design consideration of an integrated downlink array in the solar panels of a [3U](#) cubesat. Based on the requirements presented in Chapter 2, and taking the limitations imposed by the design of the [EPS](#) [2] into consideration, a two-dimensional patch array was built. By fitting the antenna systems into the deployable solar panels of the [OLFAR](#) cubesats, each of the swarm members will be capable of establishing a data link with the [BS](#), making it possible to download the processed astronomical data.

After designing the antenna array, simulations were performed to assess the performance of the systems. The results confirmed the eligibility of the solution for solving the data downlink problem. Added to this, the radiation properties of the binomially fed array proved to be very useful to the cubesat scenario. The gain improvement due to the large number of radiating elements and the resulting beamwidth relax the requirement burden for the power system and the [ADCS](#), respec-

Figure 6.9: Simulated and measured farfield radiation pattern (normalized to the maximum value) of the single subpanel array using binomial power weighting.

tively. A higher gain could mean either a lower transmitting power, a higher data rate or a lower bandwidth. The trade-off also depends on the other subsystems of the satellite.

Nonetheless, the building process of the partial array and its associated feeding network, and the measurements led to valuable insights. The directivity of the measured system was very close to the directivity of the theoretical model. Nonetheless, losses due to the substrate and imperfect matching have a significant influence on the gain figure. Furthermore, the selected implementation of the feeding network resulted in a complex structure that was very difficult to optimize. Mi-

nor impedance mismatches (different widths of adjacent microstrip components) generate resonances that can have a destructive effect on the desired performance.

Another important aspect to consider is the directionality of the system. The output port reflections were considerably high as opposed to the input port, both in simulations and measurements. Therefore, the feeding network acts solely as a power splitter and not as power combiner. Such an implementation can then be used only for transmitting the data. As a result, a separate antenna (system) will have to be used for uploading data to the OLFAR swarm. Thus, additional hardware will have to be fitted into the already “crowded” OLFAR satellite

Future work will include the design of a better feeding network, perhaps including different types of power splitters, such as ring couplers or sectorial power dividers [7]. Also, a panel implementation consisting of the five subpanels, solar cells, the two-dimensional patch array, the integrated feeding network and the power and RF connections has to be built and tested before an eventual satellite launch.

In [8], a few algorithms that combine the dual functionality of the design with the swarm concept are described. These algorithms exploit the large number of spacecraft in the OLFAR cloud, and try to conserve the swarm’s energy/power resources by assigning different tasks (energy harvesting, observation, downlink) to different satellites.

Although the designed system is meant to allow each of the OLFAR satellites to establish a communication link with the BS, a scenario that combines the downlink antenna array with the swarm strategy described in Chapter 5 can also be thought of. This will greatly improve the resulting SNR figure. Nonetheless, the narrower available beamwidth will play an important role in the link establishment. Further investigation is required.

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Chapter 7

Conclusions and directions for further research

This chapter outlines the conclusions that can be drawn from the work described in this thesis. Added to this, recommendations for further research are given.

7.1 CONCLUSIONS

This study addresses the communication layer of the [OLFAR](#) project and investigates the feasibility of a distributed low-frequency radio telescope from the telecommunications point of view. In Chapter 2, it was mentioned that [OLFAR](#) is aimed at expanding the knowledge on space-based ultra-long-wavelength radio astronomy provided by the [DARIS](#) study and the [SURO](#) project. While the latter were purely theoretical, studies that investigated the feasibility of building a radio telescope (for exploring the very low frequency domain) with [COTS](#) components, [OLFAR](#) tackles, besides the scientific goal, the engineering challenges and the implementation details of the required instrument.

The process of solving the problem of data distribution within the swarm and from the swarm to the [BS](#) provided the answers to the research questions stated in Chapter 1. Mainly, the research presented in this thesis proved that a swarm of nanosatellites can meet the data flow requirements of a low-frequency radio telescope, thus bringing technology one step closer to mapping the Universe in the ultra-long-wavelength domain.

The outcome of the conducted research also consists of innovative solutions for the data distribution within the [OLFAR](#) swarm and from

the swarm to Earth. The proposed designs cover both the logical and physical components of **OLFAR**'s communication layer.

The proposed scheme for distributing data within the satellite network employs an adaptive topology and physical communication links between the satellites. The developed clustering scheme uses the redundancy of the swarm to its advantage, and is able to reduce the overall power consumption for data distribution by a factor of 2.5. Furthermore, the **ISLs** use an innovative antenna system concept consisting of a six-patch configuration and a beamforming controller that can achieve a gain of 5 dBi regardless of the direction of transmission or reception.

Two approaches have been investigated for solving the data down-link issue. Whether at the logical level or hardware level, the proposed implementations provide a considerable enhancement of the link budget. The cooperative communication strategies, the **MRC** and the array schemes add around 7 dB and 18 dB, respectively, to the **SNR** figure (as compared to the ideally oriented single-satellite scenario) using just one patch antenna per satellite. Another benefit of these schemes is the reliability of the link since the **OLFAR** swarm will be able to maintain a data connection with the **BS** throughout the designated orbital interval. The hardware solution consisting of two five-by-four patch antenna arrays adds 13 dB to the gain figure.

The performed analysis and design work contributed to working solutions for the **OLFAR** system. Nevertheless, it unfolded further challenges and limitations.

One of the most important bottlenecks of the project is the **ISL**. The **ISL** budget calculation in Section 4.3 exposed some weak points of the link. The considered link margin parameter leaves little room for errors. Thus, any additional implementation loss such as faulty matching or slightly elliptical polarization of the antennas will have a fatal effect on some of the links. For example, the antennas used in the laboratory setup had a typical **AR** of 3 dB. That translates into a 3 dB loss for a certain orientation of the antenna. In a swarm scenario, where all the satellites exhibit free drift and rotations, this type of loss will cause some links to be interrupted during certain time intervals. Since the telescope functionality is tightly connected to the scheduling of the tasks, malfunctioning of the **ISLs** will affect the end goal of the project.

Sending the processed data to a BS on Earth has its challenges as well. Nonetheless, unlike the ISL implementation, the burden of this link could be shifted to the receiver on Earth, where the limitations in terms of space, gain and processing power are less strict. Added to this, available space on the deployable solar panels allowed the integration of a large antenna array that improved the transmission gain. Nevertheless, the design and manufacturing process of the prototype exposed some of the practical issues such as the optimization of the feeding network or its directionality. Hence, sending feedback or control information to the swarm may require an additional communication system.

The ISL and swarm-to-Earth link impediments may drive the reevaluation of the timing in OLFAR. Similar tuning will also be required if the OLFAR implementation hypotheses will be changed. In the OLFAR swarm, time is the fundamental resource, whether it is integration time, mission time, orbital period or task duration. Other important parameters such as energy (power) and bandwidth are directly related to the time resource. Energy depends on the harvesting period, while bandwidth is linked to the data rates and, hence, the communication intervals. It is likely that the allocated time for the OLFAR functions—integration and data transmission—will be modified to meet the theoretical and practical limitations. The bandwidth-channel rate relation, added to the implementation boundaries—such as the achievable gain and AR of the antennas, material loss and available space in the nanosatellite platform—will dictate the resource allocation in the OLFAR swarm.

Modifying the initial hypotheses will also alter the above-mentioned performance figures. For example, increasing the number of satellites will influence the data rates of the ISL and data link, as well as the mission time. Thus, different numbers will have to be considered for the link budget calculations, which might result in different values for the ISL gain requirement and the downlink SNR. Nevertheless, the proposed solutions retain their validity.

7.2 DIRECTIONS FOR FURTHER RESEARCH

Throughout the research a number of ideas have been approached but due to time constraints could not be brought to completion. The design proposals comprised by this thesis cover several aspects of the OLFAR

communication layer. Nonetheless, additional work should be done to complete the solutions and bring the project to a ready-to-launch stage. Therefore, in this section some recommendations and directions for further investigation are given. They can be classified according to their corresponding topic.

- *Clustering.* Further work should be done to optimize the dynamic clustering scheme. The cost functions that govern the migration process of slave nodes can be recalculated to better approximate the power costs of each slave node. A realistic orbiting model can be used to estimate the scheme's performance in the deployment scenario, and to test the mobility component. Moreover, the group mobility behavior has to be taken into consideration for cluster formation and, especially, for leader elections. Since the goal of the adaptive scheme is to preserve the clusters and maintain a cluster head on its role for as long as possible, the master node should be elected also according to its ability to follow the cluster's movement tendency. The orbital model has to be employed in the simulations in order to prove the eligibility of this concept and evaluate how often local reconfiguration will take place.

Future developments should also focus on implementing the clustering in a completely distributed manner. Optimization of the adaptive clustering scheme has to take into account some consideration regarding the *ISLs*—bandwidth and power requirements—so that the resulting topology also relaxes the link budget.

- *ISL.* A thorough study of the characteristics of the individual antennas (bandwidth, *AR* and impedance) is fundamental for a better understanding of the *ISL* concept and for identifying other sources of loss. Additionally, a custom design of an integrated *RF-to-bits* transceiver for the antenna system can give insight into its power requirements. It is also necessary to perform a study of the bandwidth required for the *ISL*, which should involve the bandwidth of the individual antennas, the proposed multiple access technique and an eventual frequency reuse plan. If the *ISLs* can no longer be considered narrowband, then the beamforming algorithm must be reevaluated.

Finally, the experiments with the evaluation platform can be performed with higher precision, using an enhanced setup consisting of a better anechoic chamber and a revised evaluation platform. The platform can also be improved with a digital signal processor (DSP) and even a field programmable gate array (FPGA) to provide higher bandwidths. Experiments involving beamforming in the transmitter, real-time operation, and performance evaluation of the proposed coding and modulation schemes can be carried out to provide more insight over the ISL.

Other smaller optimizations and studies can be performed for the proposed ISLs. An optimization of the adaptive clustering algorithm could balance better the bandwidth and power requirements between masters and slaves, relaxing the link budget. Different possibilities for DOA estimation and ranging techniques must also be studied in order to provide reliable and efficient localization capabilities. Moreover, the impact of errors in the estimation of the direction of arrival or the individual antenna radiation pattern have to be analyzed as well.

- *Swarm-to-Earth.* The proposed solutions rely on the existence of a bidirectional feedback link between the satellites and the BS. More consideration has to be given to the realization of this link, and a thorough analysis of the channel estimation process has to be made. The influence that errors in the diversity and array weights calculation has on the overall SNR figure have to be evaluated.

The orbital model should be used to estimate the performance of the proposed algorithms for the swarm-to-Earth link in a realistic deployment scenario. Added to this, more consideration should be given to the availability of hardware for the array implementation and the possibility of integrating it into the OLFAR nanosatellite.

- *Downlink antenna system.* The impact that the spacecraft stability has on the quality of the link has to be addressed. A complete prototype of a solar panel with the downlink aperture-fed patch array has to be built and tested in order to confirm the eligibility of the solution. Thus, the influence of the solar cells on the

radiation properties can be measured. The prototype will also offer more information about the routing of the RF signals, the mechanical properties of the structure, and about the effect that the dual hinges-RF connectors have on the overall performance.

Further optimization has to be performed on the designed feeding network to minimize the unwanted effects. Moreover, a six-port binomial power divider to split the RF power between the subpanels still has to be developed, implemented and tested.

More research is required to finalize the proposed solutions, to optimize the designs, and to proceed to the hardware implementation and integration into the OLFAR nanosatellite platform.

Acronyms

3U	three-unit
3G	third generation
ACE	Algorithm for Cluster Establishment
ADCS	attitude determination and control system
ADC	analog-to-digital converter
AR	axial ratio
AU	astronomical unit
AWGN	additive white Gaussian noise
BER	bit error rate
BS	base station
CDMA	code division multiple access
CMB	cosmic microwave background
COTS	commercial off-the-shelf
DARE	Dark Ages Radio Explorer
DARIS	Distributed Aperture Array for Radio Astronomy In Space
DOA	direction-of-arrival
DSP	digital signal processor

EM	electromagnetic
EOL	end of life
EPS	electrical power system
FDMA	frequency division multiple access
FIRST	Formation-flying sub-Ionospheric Radio astronomy Science and Technology
FPGA	field programmable gate array
FR-4	Flame Retardant 4
ISL	inter-satellite link
ISM	industrial-scientific-medical
LDPC	low-density parity-check
LNA	low-noise amplifier
LOFAR	Low Frequency Array
LPF	low-pass filter
LRX	Lunar Radio eXperiment
MANET	mobile ad-hoc network
MOBIC	Mobility-aware Clustering
MPPT	maximum power point tracker
MRC	maximal-ratio combining
OLFAR	Orbiting Low Frequency Antennas for Radio Astronomy
OPU	onboard processing unit
OQPSK	offset quadrature phase-shift keying
P-POD	poly-picoSatellite orbital deployer
PA	power amplifier

PCB	printed circuit board
PEC	perfect electric conductor
PFB	poly-phase filter bank
QPSK	quadrature phase-shift keying
RF	radio-frequency
RFI	radio-frequency interference
SNR	signal-to-noise ratio
SURO	Spaced-Based Ultra-Long Wavelength Radio Observatory
TXAA	Transmit Adaptive Array
UTR-2	Ukrainian T-shaped Radio telescope, second modification
VLA	Very Large Array
VSWR	voltage standing wave ratio
WSN	wireless sensor network

Acknowledgments

"If you can find a path with no obstacles, it probably doesn't lead anywhere."

Frank A. Clark

The past years have definitely been a journey, and obstacles never ceased to appear. Looking back now, it gives a great feeling of accomplishment, and therefore, I could not agree more with Frank A. Clark. I had ups and downs, and it all helped me develop into the person I am today. Throughout the journey, I had continuous support from lots of people. Perhaps, I will not be able to mention them all, but I would like to extend my gratitude towards all of them.

I would like to specially thank Mark, my supervisor, for giving me the opportunity to pursue the Ph.D. degree and making me part of a great and interesting project. I had a lot to learn from you, and your support helped me to go through the moments of discouragement. By the way: *What happens in Naples, stays in Naples!... and on the internet.*

Dear Arjan, thank you for the numerous discussions and countless pieces of advice, and for making my work better comma by comma. It was not always "fun" to have you correcting my papers, nonetheless, it was very useful. In many ways, you are the big brother TE students need, so I hope you will be back soon.

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My work was not only within the UT. Therefore, I also want to express my gratitude towards my colleagues from the [OLFAR](#) project, Raj, Steven, David and Chris, and towards Gertjan and Ufuk of Thales.

But life in Enschede was not only about work. As I mentioned before, the start was challenging but I had help. My fellow citizen, Matei, was in Enschede already when I arrived, and he helped get accustomed to the campus and the Dutch life style. Furthermore, thanks to him I started meeting other Romanians. During the first days, I met Victor, Laura, Mircea, Elena and, later on, Ioana, Corina, Dan and many more. So homesickness was almost never an issue. When homesickness was an issue, Victor made sure I listen to "*Grigore Leșe - Cântec despre Bucovina*" in order to amplify the feeling.

I met lots of people and shared a lot of good times here. I made friends and never felt alone. A warm thank you goes to my friends, Giorgio and Virginia, Marco, Riccardo, Niloofar and Gerard, thanks to whom no weekend went to waste. Thanks to most of them, I also have an Italian accent in English now, which I really... "like". Giorgio, thanks for teaching me how to snowboard using the "good cop" method! Matteo and Aga, thanks a lot for being there whenever I

needed you! You've always been truly helpful. I don't want to forget my housemates, Ramazan, Ertug, Daniel and Renata, Moh and Ana. Hope I was less of a pain than expected.

Competition was another important aspect of my life in Enschede. Whether it was basketball or football, playing sports helped me to relax and to take my mind away from problems. Although it started out of the passion for the games, playing sports slowly became more about getting better and the love for being a good teammate. It was in the Netherlands that I experience being part of a group of people that shared the same passion and desire for success. Weirdly enough, I think we also liked getting constantly yelled at. Two teams will always have a special meaning for me—Arriba H1 and Soup-A-Stars. Playing basketball for Arriba was great and turned something that I liked into a passion. A special thanks goes to my coach, Bas, and my teammates, Sam, Age, Robert and Beer, with whom I shared memories and bruises on the court, and who showed me how to play the game and how to constantly challenge myself. To all my former teammates, Davey, Rene H, Claudiu, Marco, Redmer, Rens, Jonas, Tim, Rene T, Lammert and many more, it was a “whirlwind”, and I enjoyed it a lot! I also want to thank the Jugglers for welcoming me into their team!

As for Soup-A-Stars, that team was incredible. Actually, it was not a team... it was a dynasty, a self-coached group that went from being the rookies to being the dominant contenders for five straight seasons. To the core group of guys, Emilio, Teo, Adi and Damir, thanks a lot for making this experience possible! You guys are my team on and off the pitch! Obinna, Jorge, Lasse, Joris, Max, Sertan and many more, it was wonderful competing alongside you all. I hope to meet again and to taunt *Dominare!* one last time.

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Federico, you guys are made of pure kindness, fun and “amazing”. I wish you all the best for the future. You are going to be great parents! Samuele and Elena, you’ve had an impact on my life that I could have not even imagined before. Sam, thanks for being the “bad cop” type of professor in everything that you taught me. To be honest, in Winterberg, during the first snowboarding lessons, I kind of wanted to pick up the board and smack you, but I did not and, instead, I continued falling until I succeeded. I learned that, no matter how hard they are, challenges are only going to make me better. I will be forever grateful for your help! *Vi voglio bene!*

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*Alexandru Budianu
Enschede, the Netherlands
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List of publications

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- [1] A. Budianu, A. Meijerink, and M. J. Bantum, "Swarm-to-Earth communication in OLFAR," *Acta Astronautica*, vol. 107, pp. 14–19, Feb. 2015.

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- [2] A. Budianu, T. J. Willink Castro, A. Meijerink, and M. J. Bantum, "Communication schemes for OLFAR's inter-satellite links," in *63rd International Astronautical Congress*, Naples, Italy, Oct. 2012.
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Biography

Alexandru Budianu was born on the 25th of December 1985 in Iași, Romania. In July 2009, he received his degree in the field of Electronic Engineering - Telecommunications from the Technical University “Gheorghe Asachi”, graduating with the highest average in his class. He spent his final semester as an Erasmus student in Gent, Belgium, conducting research within the Telecommunications Lab of the Katholieke Hogeschool Sint-Lieven. There, he worked on his final project on “Public-key Cryptography for Wireless Sensor Networks”. Between September 2007 and December 2009, he also worked as a part-time junior researcher for a small partner company of EcoGlove Ltd. There, he was involved in the “Glove Reprocessing Unit” project. In January 2010, he joined Continental’s Automotive Division as a Function Developer. He was involved in the Electric Power Steering Project developed for Volkswagen AG and PSA Peugeot Citroën Group. His tasks were to design and test computation models and signal processing algorithms. Since November 2010, he worked as a Ph.D. Candidate in the Telecommunication Engineering Group, at the University of Twente. His work was part of the framework of the [OLFA](#) project, and focused on developing the communication layer for swarms of nanosatellites. During his PhD research, he collaborated with ASTRON and Thales Nederland B.V. Currently, he is working in the field of telecommunications R&D. His interests lie in the antenna systems and satellite communication, as well as in astronomy and cosmology.