Escola d'Enginyeria de Telecomunicació i Aeroespacial de Castelldefels

UNIVERSITAT POLITÈCNICA DE CATALUNYA

TREBALL FI DE CARRERA

TÍTOL DEL TFC: Implementació d'un radio-enllaç de llarg abast per a femto-satèl·lits en òrbita molt baixa

TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

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DATA: 05 de Novembre de 2013

Título: Implementación de un sistema de radio-enlace de largo alcance para femto-satélites en órbitas muy bajas.
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Fecha: 29 de Octubre de 2013

Resumen

Este Trabajo Final de Carrera (TFC) estudia algunas implementaciones reales de radio-enlaces de largo alcance para un femto-satélite (masa inferior a 100 gramos) que estará en una órbita terrestre baja en 250 km y que durará unas pocas semanas de vuelo.

Este satélite (El **WikiSat**) no lleva paneles solares y se alimenta de una batería. Por ello, el sistema de comunicaciones debe estar optimizado, ser eficiente, pesar muy poco y tener margen de potencia. Este satélite fue diseñado por estudiantes. El diseño original del WikiSat no cumple con algunos de los requerimientos por lo que se propone usar dispositivos comercialmente disponibles de la tienda o COTS que formen un sistema completo de radioenlace o implementación como son el transceptor **nRF24L01**, el amplificador **PA2423L**, el módulo **9XTend**, el modulador de vídeo **10MW**, el amplificador **PA5359A** o el módulo **NTX2**. Estos componentes utilizan tecnologías que permiten una alta integración, un buen rendimiento energético y de transmisión.

El punto clave en el diseño será alimentar el módulo de radio directamente de la batería sin ninguna rectificación de voltaje usando una arquitectura distribuida para evitar desperdiciar energía en la transformación. La implementación final será parte de la siguiente versión del **WikiSat**. Algunos requerimientos son impuestos adicionalmente por el diseño del satélite que han realizado otros. El autor deberá analizar su viabilidad y proponer mejoras.

Palabras clave:

Radio-enlace, Femto-satélite, Órbitas muy bajas, Bajo coste

Title: Implementation of a long range radio-link system for femtosatellites in very Low Earth Orbit.
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Date: October, 29th 2013

Overview

This Final Bachelor Work (TFC) studies some real implementations of long range radio-link systems for a femtosatellite (mass lower than 100 grams) in very Low Earth Orbit in 250 km and few weeks of flight.

The satellite (The WikiSat) has not solar panels and is supplied by a battery. For this reason, the communication system should be optimized to be efficient, light with enough power margins. This satellite was designed by students that do not meet some requirements. The author evaluates some implementations based on Commercial off-the-shelf (COTS) devices. Some of them are a whole communications system and some are a group of components like the **nRF24L01** transceiver, the **PA2423L** power amplifier, the **9XTend** radio module, the **10MW** video modulator, the **PA5359A** power amplifier or the **NTX2** radio module. Those devices are based on technologies that allow a high level of integration, a good electrical power and radiation performance.

The key point in the design will to supply the radio module directly from the battery without any voltage rectification with a distributed schema to avoid energy waste in the transformation. The best implementation will be part of the future **WikiSat** version. Some requirements are imposed in addition by the satellite design performed by others.

Keywords:

Radio-link, Femtosatellite, Low Earth Orbit, Low Cost

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Acknowledgements

First of all, I want to thank the completion of this TFC to my advisor, Joshua Tristancho, for giving me the opportunity to be part of his research team and introducing me to a world as interesting as it is the aerospace topic. Also thank all the time (which hasn't been little) addressed me during this semester in order to make the TFC, as well as its understanding, the great interest he has shown, patience and good working environment.

I also want to make special mention of my parents, Victoriano and Josefa, and my eldest brother, Victor, who in times of extreme stress have been able to understand me, support me and endure me; but, above all, they were able to give me the necessary encouragement at each moment and they haven't stopped believing at me. As well thank all the effort they have made over the years so that I could get me the career.

Furthermore, I want to thank my partner, Cristian, for his patience, his support and his confidence in my ability.

Finally, thank you to any potential reader of this TFC your time and interest in it, which I wish and hope find it useful.

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ACRONYMS, ABBREVIATIONS AND DEFINITIONS

APRS	Automatic Position/Packet Reporting System
AV	Audio/Video
C-Band	The IEEE C-band (4 GHz to 8 GHz)
COM	Communication port
COTS	Commercial-off-the-shelf components
FHSS	Frequency-Hopping Spread Spectrum
FSK	Frequency Shift Keying modulation
FSPL	Free Space Path Lost (See LFS)
FM	Frequency Modulation
GFSK	Gaussian Frequency Shift Keying modulation
HDC	High Definition Camera
HGA	High Gain Antenna
IDeTIC	Institute to the Technological Development and the Innovation in the Communications
IMU	Inertial Measurement Unit
LCC	Leadless Chip Carrier technology
LEO	Low Earth Orbit
LFS	Loss in Free Space
LiPoly	Lithium polymer rechargeable battery
LNA	Low Noise Amplifier
MCU	Multipurpose Computer Unit
MEMS	Micro-Electro Mechanical System
NMEA	National Marine Electronics Association
NTSC	National Television System Committee
OIP3	Output Intercept Point at 3 dB
P1dB	Input power at 1 dB
PAL	Phase Alternating Line
PCB	Printed Circuit Board
PLF	Polarization Loss Factor
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RF	Radiofrequency
ROE	Razón de Onda Estacionaria (Like SWR)
RPSMA	Reverse Polarity SMA connector (See annex 6.8)
SECAM	Sequential Color with Memory
SMA	SubMiniature version A connector (See annex 6.8)
SMD	Surface Mounted Device
SSTV	Slow Scan TeleVision
SWR	Standing Wave Ratio
TFC	Trabajo Final de Carrera (Final Bachelor Work)
TH	Through-hole technology
UART	Universal Asynchronous Receiver Transmitter
UAV	Unmanned Aerial Vehicle
UPC	Polytechnic University of Catalonia
VSWR	Voltage Standing Wave Ratio

INTRODUCTION

The relevance of a satellite

The term “satellite” gives name to two types of astronomic objects of very different characteristics:

1. **Natural satellite**: is a celestial body that it is qualify as opaque, being that only it can to shine to reflect the light that arrive it from the Sun. These satellites have the particularity of turn around other celestial body.
2. **Artificial satellite**: is an object of human fabrication that traces orbits around of a planet or other celestial body as a natural satellite does. It has a finality like from terrestrial ground to the space observation with equipment series that permits to gather and relay information. There exist various types of artificial satellites, which are classified by its functionality, its missions (or areas), its applications and according to its mass or orbit.

The missions for whom satellites are built are:

- Military and civilian terrestrial observation
- Communications
- Research
- Navigation
- Meteorology

In addition, satellites are classified in function of the mass in accordance with a general accepted criterion as presented in Figure 1. The **WikiSat** falls inside the category of femto-satellites.

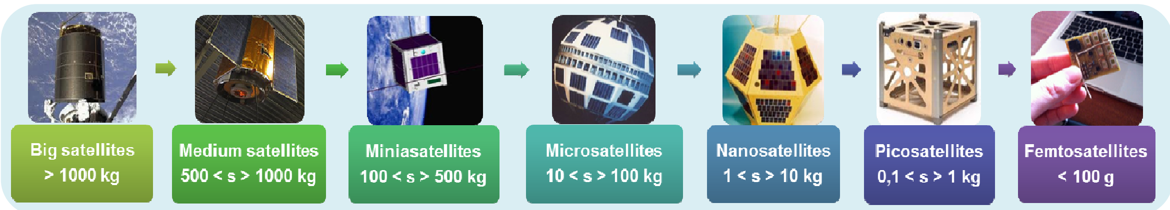

Figure 1 – Satellite classification as a function of mass

Finally, the orbit of the artificial satellites varies in many parameters. Satellite orbits vary greatly depending on its purpose and are classified in a number of ways. I have chosen some:

- Low Earth Orbit
- Mid Earth Orbit
- High Earth Orbit
- Geosynchronous Orbit
- Polar Orbit
- Molniya Orbit

The Sputnik I was the first artificial satellite launched by the Soviet Union on 4th October, 1957. Since then, thousands of artificial satellites have been put in orbit, originated in more of 50 countries and with only 10 countries with launch capability. More than 6,000 artificial satellites orbit around the Earth, while only 2,000 of them continue working. The remainders are orbiting the Earth as space debris[1].

To put an artificial satellite around the Earth is necessary a drive mechanism that provides enough powerful that permits launch objects of considerable mass and it acquire the requested speed (in this case, with a minimum of 7.2 km/sec). This mechanism is the rocket, which in the practice is necessary build as the combination of two or more rockets for to be enough the necessary kinetic energy for enter in orbit. In general, a rocket has a very short time of performance, approximately of five to ten minutes, and after of this time it burns out fully. The satellite (with the necessary speed) is unfastened from the rocket and starts to travel by the space at the mercy of its own inertia, of the same way that Moon orbits around the Earth without the necessity to be driven by anything.

Satellites are usually semi-independent computer-controlled systems. Satellite subsystems attend many tasks, such as power generation, thermal control, telemetry, attitude control and orbit control. The **WikiSat** has all this functions integrated in a single board.

1 http://celestrak.com/NORAD/elements/master.asp

Objectives and work done by the student

The **WikiSat** is supplied by a battery, it has not solar panels thus the communication system should be optimized to be efficient, light with enough power margins, etc. The key point is to supply the radio module directly from the battery without any voltage rectification with a distributed schema to avoid energy waste in the power transformation. This satellite was designed by students and sometimes it does not meet all the requirements.

Since the previous work done by the student Enric Fernandez related to the **WikiSat** communications system does not meet the high demanding requirements, my main objective is to study few real implementations in different ranges to become an expert in this issue and keeping in mind that I am not a telecommunications engineer. It is not enough to know the datasheet specifications for a given component. These component specifications are often degraded or limited when this component is placed inside a real implementation, i. e. many power amplifiers have a power limit in the input and a bandwidth limitation. There are many efficient transceivers but the bandwidth is too wide for this amplifier. Separated, are very good components but when they work together, the amplifier cannot give the best performance because the noise in the lateral bands. Real implementations are proposed by others inside the *WikiSat team* and I will analyze each proposal, considering advantages and drawbacks for each case, i.e. a low frequency requires less power, achieves a better range but the bandwidth is lower.

I will focus not only on components and their performances but the overall performance of the communication system where these components are involved. Some solutions are the addition of selected components and some solutions are a whole radio-link module. The results will be collected from solutions that were tested in near space. Those solutions that have not experimental information, I will try to test in real conditions in order to complete list of specifications. I will define parameters and indicators to compare between each other in similar working conditions.

I will evaluate some implementations based on Commercial off-the-shelf (COTS) devices. Some of them are a whole communications system and some are a group of components like the **nRF24L01** transceiver, the **PA2423L** power amplifier, the **9XTend** radio module, the **10MW** video modulator, the **PA5359A** power amplifier or the **NTX2** radio module. There are others radiofrequency (RF) solutions that, even they are efficient and good performance, they are heavy and useless for this satellite mass category. The proposed devices are based on technologies that allow a high level of integration, a good electrical power and radiation performance.

At the end, I will give some conclusions and recommendations for the future WikiSat communications system based on the experience not only in datasheets.

Distribution of this work

This work is distributed in five chapters detailed as follows:

First chapter is an introduction to the State of the Art of femtosatellites, the *WikiSat Space Program* and finally a state of the art of technologies that are involved in this work.

Second chapter has an extract of requirements that are related with the telecommunications system. These requirements are the reference to evaluate if a implementation are better than other.

Third chapter presents four real implementations proposed inside the WikiSat team that are based on available components in the market (COTS) for the femtosatellite communications system.

Fourth chapter presents several specifications: contains a series of budgets, calculations of the minimum performances for the communication system in every case and comparing the three other implementations with the current *WikiSat* design.

Fifth chapter has the conclusions of all work, the future work and the environmental impact.

Finally, there is the bibliography and the annexes with datasheets and other relevant issues.

CHAPTER 1. STATE OF THE ART

This chapter is an introduction to the State of the Art of femtosatellites, the *WikiSat Space Program* and finally a state of the art of technologies that are involved in this work.

1.1 Origin of this satellite

The origin and reason of the development of the satellite finds it in a contest of universal level known as *N-Prize*, born at 2008. It consists in a challenge to launch an impossibly small satellite into orbit on a ludicrously small budget, for a pitifully small cash prize. The *N-Prize Challenge* is intended to encourage creativity, originality and inventiveness in the face of severe odds and impossible financial restrictions for continue having access to the space through a much cheaper form. The participation is aimed at amateurs, enthusiasts, would-be boffins, foolhardy optimists and individuals or organizations connected with aerospace and other relevant industries.

The challenge raises by the *N-Prize* is to put into orbit around the Earth a satellite with a mass of between 9.99 and 19.99 grams, and to prove that it has completed at least 9 orbits. The most important, nevertheless, is that the budget of the launch (including the vehicle of launch, all the equipment of non-reusable hardware of launch required and the propellant) should be minor than 1,200€.
To opt for the prizes, the win team should complete the challenge before of 19:19:09 (GMT) on September 19th, 2013. The prize for the win team was 12,000€. None team won the prize.

1.2 Femtosatellites

The satellite, called *WikiSat*, the one that will include the radio-link system should have ales than 20 grams mass due to the restrictive rules of the *N-Prize* contest, thus it enter in the femtosatellite category, since according to international classification of satellites depend it of the mass, ‘femtosatellite’ is that one that it have a maximum mass of 100 grams.

Femtosatellites are tiny satellites that contains of all functions of a conventional satellite. It should be able to realize the same mission assignments that are realized by the commercial satellites of navigation, communication and observation of the Earth. The principal advantages that femtosatellites present with regard to the other satellites are that the seconds have at least 100 times more mass, they are more expensive and voluminous, besides that they require a development time of order of years because the use of certificate components for the space flights and environmental testing that are much expensive.

Technology of femtosatellite is relatively new, since only a pair of years ago that it has started its development by several organizations around the world. It is intended to be used at applications and missions where required big speed of actuation, for example to realize observations in a zone dejected for a recent disaster.

In Spain we can find this type of developments through a group of investigators belonging to the Polytechnic University of Catalonia that, as a whole with investigators of Institute to the Technological Development and the Innovation in the Communications (IDeTIC) of *Palmas de Gran Canaria University*, they have already achieved to prove this system of launch of low cost to put in orbit femtosatellites.

1.2.1 Examples of Femtosatellites

There are no femtosatellites in orbit but few universities have developed some prototypes. From the *Investigación y Ciencia* magazine, we can see four of these prototypes presented in Figure 2.

- *PCBSat*, not shown, designed by **Barnhart** [9] in 2007
- *PocketQub,* see figure 2a, designed by **Twiggs**, a cube standard
- *RyeFemSat*, see figure 2b, designed by **Kumar** [4] in 2008
- *KickSat,* see figure 2c, designed by **Zac Manchester** [5] in 2010
- *WikiSat,* see figure 2d, designed by **Joshua Tristancho** [8] in 2010

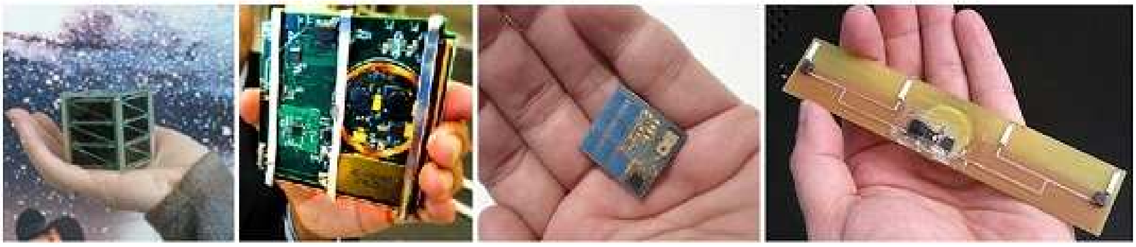

Figure 2 – Some examples of femtosatellite designs. Source: Investigación y Ciencia

1.2.2 WikiSat description

The satellite where we want to implement our radio-link is the so called WikiSat. It is a Satellite-on-a-board that achieves to carry out the challenge of the low cost and low mass. The structure of the satellite is a single PCB whose finality is to hold four arrays of ceramic antenna. This antenna configuration was proposed by **Fernandez-Murcia** in [14]. The PCB board works as a passive thermal control subsystem. The satellite has an Inertial Measurement Unit (IMU) designed originally by **Bardolet** in [15]. Components are connected through an I^2C bus to the Main Control Unit (MCU). The use of same IMU for satellite and launcher trajectory control was proposed by **Tristancho** in [16] who proposes the design of a launcher and the satellite in the same design cycle for a given space mission. This is the meaning of the so called Space Payload Paradigm, to design everything around the payload, including the launcher and the ground station network if required.

The use of this kind of payload will reduce the space access and will increase the periodicity of small launches. A large number of satellites can be sent in the same event, i.e. swarms of these satellites can record the same phenomena from different points of view; distributing the work load when they are coordinated. But all of this is not feasible if all the subsystems are integrated in a so low mass budget and for this reason, some technologies such as Micro-

Electro-Mechanical Systems (MEMS) and Surface Mounted Technology (SMT) is required. In addition, regarding communications, the antenna should fit inside this small budget as well.

From elemental physics [10] the antenna size depends on the working frequency. The Free Space Path Lost decreases in a logarithmic way there by, the transmit power increases with a power of four of the frequency. The frequency used in the original *WikiSat* design was 2.4 GHz, extensively used for applications of ground short distance. This frequency was used in Low Earth Orbit, see [11, 12, 13] but in the case of the *WikiSat*, a power amplifier and a high gain antenna will be required for download communication system. The wave length is about few centimeters and few watts are required for a LEO range. The antenna establishes the limit of the size of the satellite, while the transmit power and the mission schedule establishes the electrical power capacity.

This satellite has a mass less than 20 grams as stated by the *N-Prize* rules. The satellite will control all the parts of the mission: the rocket, the ignition of every stage, the trajectory, the injection and finally the mission itself. That way, repeated components are avoided. The satellite will send all the harvested information through a downlink, mainly HD pictures from a location of the Earth programmed before the launch. The satellite was designed to work as a constellation or swarms. The launcher is designed to inject four or six femtosatellite at the time and launcher can be repeated every few hours in order to reduce the revisiting time.

The launcher provides an initial altitude and later the orbital commanded by the satellite. This rocket is called *WikiLauncher* and is an autonomous vehicle with a configuration of *Rockoon*, a combination of a balloon and a rocket. Starting from a high altitude balloon, first stage reaches the apogee of 250 km whereas the second stage accelerates until the orbital speed of 7.2 km/s. This launch takes about 4 hours since the mission is established, for this reason this platform is suitable for Space Responsive missions. The satellite is dedicated to a single mission (like a disaster) and is only send when the epicenter coordinates is known. Current approach is somehow based on surveillance satellites that are wasting an orbit until the catastrophe happens. This kind of satellites, due to the very low Earth orbit stays for one week then reenters in the atmosphere and burned, letting the orbit free.

1.3 WikiSat Team

The team formed by investigators of UPC and IDeTIC is called *WikiSat* (where femtosatellite catches the name) and pretends to develop and launch femtosatellites of low cost for fast display. The system of launch was developed by the UPC, while the IDeTIC, for your part, has developed the subsystems of telecommunication used by the satellite and ground station, as well as the modeling of the diverse antennas used. These systems permit recover the re-usable elements of the launcher besides to permit the reception and monitoring of its parameters during the flight. The project is directed by Professor **Joshua**

Tristancho, of *Engineering of Telecommunication and Aerospace of Castelldefels School* (EETAC) of UPC. By the part of the IDeTIC, the leadership corresponds to the Dr. **Rafael Pérez Jiménez**, Director of IDeTIC, and expert at advanced communications.

Thus, *WikiSat* represents an official team of the *N-Prize* contest. The *WikiSat* Space Program pretends to implement a low-cost femtosatellite that fits the *N-Prize* rules.

The team stated that the cost[2] of a Disaster Management mission is about 30,000€ suitable for poor countries, small enterprises and science applications. The satellite is designed in a free PCB tool called Eagle PCB[3] where the client will include their surface mounted payload only; they do not have to worry about others issues like power supply, switching or download because satellite does. The mission can be designed by any amateur people thanks to a free open source tool[4] called *Moon2.0*. Quality design will not depend on the cost of the designing tools.

1.4 Micro-Electro Mechanical Systems - MEMS technology

The main improvement for femtosatellites is using Micro-Electromechanical Systems (MEMS) that is a technology that is defined [3] as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of micro-fabrication, and these are available in the domestic market. These components should be validated for space use. Many of them can be used in hard conditions like our femtosatellite is going to resist. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements and controlled by integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move. These components should be validated for space use. Many of them can be used in hard conditions like our femtosatellite is going to resist[5] in the nearspace environment.

The functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, and the most notable (and perhaps most interesting) elements are the microsensors and microactuators, which are categorized as “transducers” (i.e., devices that convert energy from one form to another).

The performance of MEMS devices are exceptional, and their method of production leverages the same batch fabrication techniques used in the

[2] http://code.google.com/p/moon-20/wiki/LowCost_Space_Access
[3] http://www.cadsoftusa.com/eagle-pcb-design-software/
[4] http://code.google.com/p/moon-20/downloads/list
[5] https://www.mems-exchange.org/MEMS/what-is.html

integrated circuit industry, meaning a low per device production costs. Consequently, it is possible achieve stellar device performance at a low cost.

The MEMS technologies have a quality called "heterogeneous integration", meaning that it can be merged with microelectronics, photonics, nanotechnology, and more others. This quality is important because the real potential of MEMS starts to become fulfilled when it can all be merged onto a common silicon substrate along with integrated circuits (i.e., microelectronics).

While electronics are fabricated using integrated circuit (IC) process sequences, the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

There are numerous possible applications for MEMS and Nanotechnology[6]. A few applications of current interest are:

1.3.1 *Biotechnology*

For example[7], the Polymerase Chain Reaction (PCR) microsystems for DNA amplification and identification, enzyme linked immunosorbent assay (ELISA), capillary electrophoresis, electroporation, micromachined Scanning Tunneling Microscopes (STMs), biochips for detection of hazardous chemical and biological agents, and microsystems for high-throughput drug screening and selection.

1.3.2 *Communications*

The main beneficiary from the advent of RF-MEMS technology[8] is high frequency circuits. If they are made using MEMS and Nanotechnology, the electrical components (such as inductors and tunable capacitors) can be improved significantly compared to their integrated counterparts. With the integration of such components, we achieve reduce the total circuit area, power consumption and cost, while the performance of communication circuits will be improved. Of the other hand, the mechanical switch is a key component with huge potential in various RF and microwave circuits. The demonstrated samples of mechanical switches have quality factors much higher than anything previously available. Another successful application of RF-MEMS is in resonators as mechanical filters for communication circuits.

1.3.3 *Inertial Sensing*

MEMS technology has made it possible to integrate the accelerometer and electronics onto a single silicon chip at a cost of only a few dollars[9]. These MEMS accelerometers are much smaller, more functional, lighter, more reliable, and are produced for a fraction of the cost of the conventional macroscale accelerometer elements. More recently, MEMS gyroscopes (i.e., rate sensors)

[6] https://www.mems-exchange.org/MEMS/applications.html
[7] https://www.mems-exchange.org/MEMS/applications.html#Biotechnology
[8] https://www.mems-exchange.org/MEMS/applications.html#Communications
[9] https://www.mems-exchange.org/MEMS/applications.html#Inertial%20Sensing

have been developed for both automobile and consumer electronics applications. MEMS inertial sensors are now being used in every car sold as well as notable customer electronic handhelds such as *Apple iPhones* and the *Nintendo Wii*.

1.3.4 *Medicine*

There are a wide variety of applications for MEMS in medicine[10]. The first and by far the most successful application of MEMS in medicine (at least in terms of number of devices and market size) are MEMS pressure sensors, which have been in use for several decades. The market for these pressure sensors is extremely diverse and highly fragmented, with a few high-volume markets and many lower volume ones.

1.5 Printed Circuit Board – PCB technology

A Printed Circuit Board or PCB is a flat plastic or fiberglass board on which interconnected circuits and components are laminated or etched. This is an old technology that is well known and available in many countries. Chips and other electronic components are mounted on the board. Very often, computers consist of one or more printed circuit boards, usually called cards or adapters[11] and interconnected by wires and connectors.

Printed Circuit Board (PCB) technology is a today very well expanded technology. It is feasible to design with open tools the whole satellite and for less than 300€ manufacturer will build and assemble your design in only few days. Other approaches like the CubeSat standrard require a structure that holds few boards and a complicated wiring system that introduces extra complexity. Each system is placed in a different board. These designs are board oriented since WikiSat approach is component oriented everything placed in a single board.

The advantages of PCB technology[12] are:

- Its use makes the design and implementation very accessible.
- PCB manufacturing process is more simple and cheaper than silicon technology (materials and equipment).
- Smaller and lighter.
- Less sensitive to noise.
- Increased compatibility electromagnetic.
- Greater mechanical strength.
- Rapid prototyping.
- Can be manufactured in series.
- Total integration of electronic components and fluidics on the same PCB.
- Monolithic devices that manipulate, analyze and control fluids.
- Applications biological, chemical, medical.

[10] https://www.mems-exchange.org/MEMS/applications.html#Medicine
[11] http://www.thefreedictionary.com/printed+circuit+board
[12] http://iecon02.us.es/ASIGN/SEA/MEMS3_PROC3_PCBMEMS.pdf

Some alternatives for PCBs technologies[13] include wire wrap and point-to-point construction. In order to build a PCBs, initially it must be designed and laid out then it becomes cheaper, faster to make and potentially more reliable when high-volume production are taken into account; then production and soldering of PCBs can be automated. Many electronics industry of PCB design, assembly, and quality control required are set by standards that are published by the IPC organization[14].

An example of PCB used in one of the *WikiSat* missions (specifically at the Launch05, a mission carried out in Zaragoza[15], July 09th, 2011, that was designed as a *Tracked recovered mission* with PVC launching ramp in bad weather conditions) Launch05 is seen in the Figure 3:

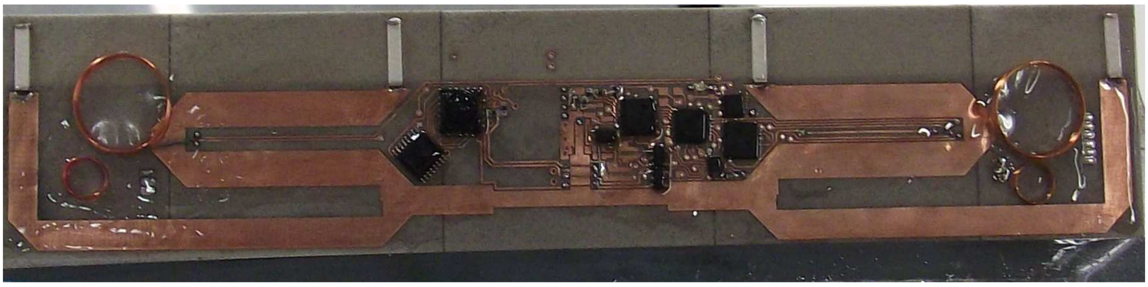

Figure 3 – PCB used for the Launch05 and a WikiSat v4.0 prototype. Source: Joshua Tristancho

1.6 Surface Mounted Device - SMD technology

Surface Mount Device (SMD) technology is another improvement in terms of weight saving, size reduction, high shock resistant and robustness compared to other technologies like through-hole used very often in the CubeSat approach. They are components soldered to a PCB board through a paste. Because they are easy to assemble during the re-flow, we are interested in the use of these devices for the femtosatellite development.

Many electronic components are available in this format: High Definition Camera (HDC), Multipurpose Computer Unit (MCU), Inertial Measurement Unit (IMU), etc.

The Leadless Chip Carrier (LCC) is another version compatible with SMT technology without soldering. Connections are made by any four edges. Chip carriers may have either J-shaped metal leads for connections by solder or by a socket, or may be lead-less with metal pads for connections. Also it is known as “Flat-pack” If the leads extend beyond the package. Figure 3 have two examples of this technology: an *u-blox* GPS[16] and a *TOSHIBA* camera[17]. The future WikiSat will include these two LCC components that were not included in

13 http://download.intel.com/design/chipsets/applnots/29817901.pdf
14 http://www.ipc.org/ContentPage.aspx?pageid=IPCs-Name
15 http://code.google.com/p/moon-20/wiki/WikiBalloon_
16 http://www.u-blox.com/en/gps-modules/pvt-modules/neo-6-family.html
17 http://kreature.org/ee/avr32/tcm8230/tcm8230.jpg

the previous satellite version. This technology permits to include the client component inside the design cycle when the satellite application is to test a new MEMS system or LCC component in the nearspace.

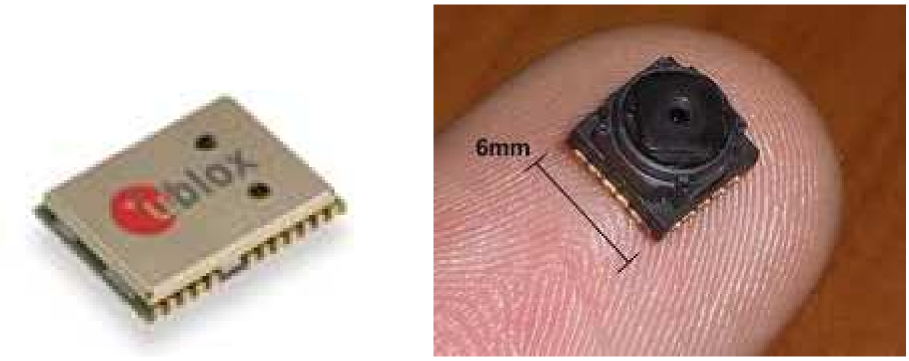

Figure 4 - LCC devices: u-blox NEO6M GPS (a) Source: u-blox and TOSHIBA TCM8230 camera (b) Source: TOSHIBA

Some manufacturers assemble their Commercial-off-the-shelf (COTS) solutions in the LCC format that is compatible with SMD technology as we saw before but in such a way that it can be integrated in the PCB board of the satellite as another SMD component does. We will use this fact to propose some solutions to the communications system and overcome this challenge.

CHAPTER 2. SYSTEM REQUIREMENTS

This chapter has the list of minimum requirements that are necessary for the correct operation of the antenna. The requirements are classified as: system requirements, high level requirements and low level requirements. These requirements were extracted from **Lara Navarro** requirements list in [11].

2.1 System requirements

There are two system requirements:

- SR01 The communications system shall fit inside the femtosatellite.
- SR02 The communications system shall have a mass smaller enough to fit the satellite in the category of femtosatellite.

2.2 High level requirements

There are two high level requirements:

- HLR01 The communications system shall transmit and receive the tracking and payload information.
- HLR02 The communications system shall be simple and based on COTS.

2.3 Low level requirements

There are nine low level requirement for the first high level requirement and three low level requirement for the second high level requirement:

- LLR010 The communications system shall transmit the payload information to a ground station.
- LLR011 The communications system shall broadcast the tracking information to any ground station or other femtosatellite.
- LLR012 The communications system shall receive new commands from the control centre.
- LLR013 The communications system shall be inoperative during the inactive phases of the orbit.
- LLR014 The communications system shall work in a range of 500 km.
- LLR015 The communications system shall have a signal-to-noise ratio of at least 3 dB.
- LLR016 The communications system shall have a band-with of at least 9,600 bps.
- LLR017 The communications system shall be able to illuminate an area of 200 km.

- LLR018 The communications system shall be electrically supplied by the same voltage as the femtosatellite.
- LLR020 The communications system shall use Commercial-off-the-shelf components.
- LLR021 The communications system shall not require in flight adjustments.
- LLR022 The communications system shall not require maintenance during the storage phase.

CHAPTER 3. CASES OF STUDY

This chapter describes four implementations as the candidate for the femtosatellite communications system, based on Commercial-off-the-Shelf components. These four transceiver cases of study include the original one, the *Nordic* **nRF24L01P** and the *Digi* **9XTend** that was the baseline in my work:

- CASE 1. The *Nordic* **nRF24L01P** implementation.
- CASE 2. The *FPV* **10MW** implementation.
- CASE 3. The *Digi* **9XTend** implementation.
- CASE 4. The *Radiometrix* **NTX2** implementation.

The last three cases will be compared with the original *WikiSat* PCB based design marked as CASE 1. The communications system *Nordic* **nRF24L01P** was optimized for a less than 20 grams budget but other configurations are feasible and is want to check if can be optimize still more inside the femtosatellite category of 100 grams mass budget. Afterwards to present the four cases, are realized a comparison between the same for to determinate which one is the best adapted and presents more performance features and advantages.

3.1 Description of the proposed implementations

3.1.1 Nordic nRF24L01P and SiGe PA2423L

The original *WikiSat* communications module [7] is based on a *Nordic* **nRF24L01P** transceiver[18] [6.4] and a *SiGe* PA2423L [6.5] power amplifier[19] mounted in the satellite PCB board. The result is a high level of integration and good energy efficiency, extending the battery life and maintaining the 500 km required range. It has some problems with the noise in the lateral bands due to its large bandwidth. Nowadays, this system never has been proven in space environment but in nearspace.

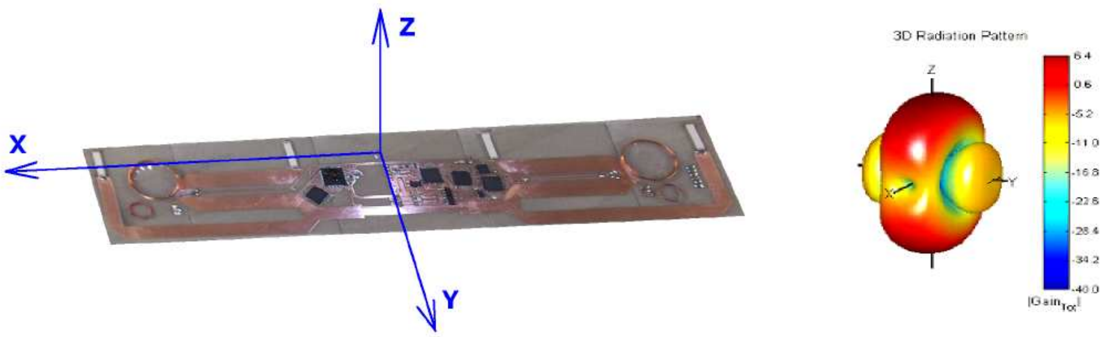

Figure 5 – Femtosatellite axes (a) and radiation pattern (b). Source: Enric Fernandez

[18] http://www.*Nordic*semi.com/eng/Products/2.4GHz-RF/nRF24L01

[19] http://www.datasheetcatalog.org/datasheet/sige/PA2423L-EV.pdf

Figure 5(a) shows a prototype where those components are in the PCB board of 141x34 mm. The antenna is based on four ceramic antennas generating a theoretical diagram pattern like the figure 5(b). The working frequency is the 2.4 GHz that has problems with the clouds and rain but plenty of bandwidth (250 kbps) for image applications, not only telemetry.

3.1.2 FPV 10MW and Ku PA 5359 implementation

The Slow Scan Television[20] (SSTV) [6.1] is a picture transmission method used mainly by amateur radio operators, to transmit and receive static pictures via radio. Broadcast television requires 6 MHz wide channels, because it transmits 25 or 30 picture frames per second like happens in the NTSC, PAL or SECAM color systems. SSTV usually takes up to a maximum of 3 kHz of bandwidth. It takes from about eight seconds to a couple of minutes, depending on the mode used to transmit one image frame.

Figure 6 – FPV 10MW implementation (Source: Argent) with Power Amplifier. Source: Kuhne-electronic

Figure 6 shows a commercial available implementation by *Argent Data Systems*[21]. This implementation, proposed by our ham colleague **Carlos Flores**[22], consists of an *Argent* SSTV camera[23], a *FPV* **10MW** 5.8 GHz AV transceiver[24] [6.2] and a *Ku* PA 5359 power amplifier[25] [6.3].

The overall module is about 322 grams a bit far from a femtosatellite mass budget but it is a good baseline for future developments in terms of low-cost real-time satellite camera applications thanks to its large data rate of 21 Mbps. The C-Band power amplifier box can be replaced for a lighter one, integrating the SSTV camera, transceiver and the heavy LiPoly battery pack inside the Power amplifier. Everything can fit in 1/2u *Cubesat*.

The wide bandwidth of this implementation (3.5 MHz) is a waste because the use of a SSTV that only requires 3 kHz. An interesting application in this working frequency is the so called *Guifi.net* that is a free, neutral and open telecommunications network. It is built through a peer to peer agreement where everyone can join the network by providing his connection, and therefore, extending the network and gaining connectivity to all. A satellite like this could improve a local network for few minutes; it means that, during a disaster, the satellite will provide some communications capabilities when passing. This time

20 Slow-scan television (SSTV) is a picture transmission method used mainly by amateur radio operators
21 https://www.*Argent*data.com/catalog/product_info.php?products_id=150
22 http://www.ure.es/foro/11-nuevas-tecnologias/204581.html
23 https://www.*Argent*data.com/catalog/product_info.php?cPath=33&products_id=150
24 http://www.fpvhobby.com/transmitter/21-2-55-volt-500mw-24ghz-video-transmitter.html
25 http://www.kuhne-electronic.de/en/products/power-amplifiers/ku-pa-5359-a.html

is about 8 minutes every day as **Raquel Gonzalez** computed in [6] page 45 from her TFC.

3.1.3 Digi 9Xtend implementation

This implementation is based on a *Digi* **9XTend** module[26] [6.6] showed in figure 7 and was the baseline of this work. The proposed module only requires an UHF antenna in the frequency of 902 MHz that is more suitable for Low Earth Orbit communications than the *WikiSat* proposal of 2.4 GHz and bandwidth of 100 kHz as recommended by the FCC[27] Part 15.247. The data rate is in the limit of the requirements 9,600 bps in highest transmit power. This is enough to download pictures but not video. This module was not tested in nearspace and for this reason I have done a realistic experiment with two of these modules as I will explain in the next chapter.

Figure 7 – *Digi* 9Xtend implementation. Source: *Digi*

The connection between this module and the satellite is done by an UART bus direct to the *Arduino MCU* computer. To have profit of the maximum power, supply requires 5 volts; hence, battery energy efficiency is not maximized. Two serial batteries are required which means an increase of battery mass and a reduction of the battery usage. This module is not suitable for a femtosatellite application but can be included in some Unmanned Aerial Vehicles (UAV). This module will be used by the ICARUS research group in the EETAC University.

3.1.4 Radiometrix NTX2 implementation

This implementation is based on a *Radiometrix* **NTX2** transmitter[28] [6.7] and is available in through-hole technology. This module was tested in near-space several times by the *WikiSat team*; from the near-space launch 6 and on[29], this module was inside the APRS[30] localizer as well.

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26 https://www.sparkfun.com/products/9411
27 **FCC Part 15.247** http://www.semtech.com/images/datasheet/fcc_digital_modulation_systems_semtech.pdf
28 http://www.*Radiometrix*.com/files/additional/ntx2nrx2.pdf
29 http://code.google.com/p/moon-20/wiki/WikiBalloon_Launch06
30 http://aprs.fi/

Figure 8 – Radiometrix NTX2 implementation. Source: Radiometrix

Figure 8 shows an example of transceiver. A lambda/4 wire antenna could be connected to the PIN 2 easily as detailed in the wiring drawing in page 94 from the annexes. That way it reduces the overall weight and complexity. The working frequency is 434 MHz and the bandwidth is 5 kHz. The data rate is 10 kbps thatis in the limit of the requirements and a huge range as we will see later.

This implementation has been proven for more than 500 km in many near-space ballooning expeditions[31] around the world and amateur satellites like *CubeSats*. The *WikiSat* team tested this module In the Gran Canaria Space port launch 15. See http://code.google.com/p/moon-20/wiki/WikiBalloon_Launch15

3.2 Comparison of the implementations

This section is a summary of performances for every implementation, and is represented in Table 1. Each one is compared with the original **nRF24L01P** implementation. Some requirements are not fully accomplished. Parameters do not fits the requirements are marked in red as summarized in the row failed requirements.

At the following table is observed that, having with a reference the **nRF24L01P**, two of the implementations don't carry out all minimum requirements specified at the chapter 2, in spite of count on improvement. Only in the case of the **NTX2** is carried out all requirements.

In this way, at the case 2 (corresponding to **10MW**), is observed that don't carry out some of the requirements previously mentioned in the chapter 2 that following:

1. *SR01 The communications system shall fit inside the femtosatellite.* The communication system doesn't fit into satellite, being that the maximum size of the PCB board of the original *WikiSat* satellite corresponds to 141x34 mm (department 3.1.1), since the *10MW* has a dimensions of 158x59x19 mm. The components should be fit inside the original PCB board.
2. *SR02 The communications system shall have a mass smaller enough to fit the satellite in the category of femtosatellite.*

[31] http://ukhas.org.uk/guides:linkingarduinotontx2

The **10MW** don't fit in the category of femtosatellite, being that its mass is of 500 grams.

3. *LLR018 The communications system shall be electrically supplied by the same voltage as the femtosatellite.*
   This system of communications don't feed of the same voltage that the femtosatellite.

Table 1 – Performance comparison

	CASE 1	CASE 2	CASE 3	CASE 4
Designation	WikiSat	SSTV	9XTend	NTX2
Manufacturer	Nordic	Argent	Digi	Radiometrix
Transceiver model	nRF24L01P	10MW	9Xtend	NTX2
Maximum range	500 km	2,500 km	3,800 km	1,800 km
Original battery life	6.6 hours	**8 minutes**[32]	**1 hour**	33.9 hours
Space validated	No	Yes	No	Yes
Failed requirements	LLR015 3dB margin	SR01 Fit inside satellite SR02 Mass < 100 grams LLR018 Same voltage	SR01 Fit inside satellite LLR018 Same voltage	All requirements are accomplished
Frequency	2.4 GHz	5.8 GHz	902 MHz	434 MHz
Bandwidth	700 kHz	3.5 MHz	100 kHz	5 kHz
Data rate	250 kbps	21 Mbps	9600 bps	10 kbps
Modulation	GFSK	QPSK/64-QAM	FHSS	FM
Impedance	50 Ω	50 Ω	50 Ω	50 Ω
Purpose	Peer-to-peer	Video streaming	Peer-to-peer	Broadcast
Transmit power	63 mW	**9 W**	500 mW	25 mW
TX antenna	18 dBm	39.5 dBm	27 dBm	14 dBm
Current (TX mode)	92 mA	4.5 A	600 mA	18 mA
Supply voltage	3.3 V	**12 V**	**5.0 V**	3.3 V
Power Amplifier	PA2423L	Ku PA 5359	Internal	Internal
Transceiver mass	0.3 grams	322 grams	15 grams	7 grams
Satellite mass	20 grams	**500 grams**	30 grams	25 grams
Bill of materials[33]	51.95€	717.34€	187.52€	64.92€
Module size	33x15x1 mm	**158x59x19 mm**	**61x37x5 mm**	43x15x8 mm

It should be remarked that the life of the battery is very short. As we saw before, a minimum of 8 minutes is required for realize a communication. Therefore, although all requirements are accomplished, this implementation cannot count as a valid option, being that with the battery completely loaded only permits to realize one communication, what results insufficient at any type of mission. Besides, this is the case where the price of the materials increases of more significant form.

[32] A battery pack will be required in this implementation

[33] Bill of materials does not include manufacturing cost, customs, courier, calibration costs, taxes, etc.

As an improvement we found that the Case 2 is enough a maximum range of 2,500 km respect to the 500 km of the **nRF24L01P**. Moreover, it has the advantage that is validated for its use at the space.

At the Case 3, corresponding to the **9XTend**, is observed that doesn’t carry out with the requirements of:

1. *SR01 The communications system shall fit inside the femtosatellite.*
   Equal that the previous case, the system of communications has a superior dimensions respect to the maximum specificity by the PCB board.
2. *LLR018 The communications system shall be electrically supplied by the same voltage as the femtosatellite.*
   In spite of works with an average voltage of 3.3 V, the voltage that is needed for to obtain the maximum power is of 5 V, thus doesn’t carry out the requirement of to feed to the same voltage that the femtosatellite.

On the one hand, as occurs at the Case 2, the time of life of the battery is insufficient for realize communications, being that 1 hour we permit to realize 7 communications totally, and for this type of missions, where the satellite is in orbit about 3 days, results limited. It is possible sends it, but isn’t advisable. Cost is very high if we compare with the Case 1 and 4.

On the other hand, it has as advantage that its distance of maximum range is of 3,800 km, while that the **nRF24L01P** is limited to 500 km.

Finally, at the case of **NTX2**, it carries out all the minimum necessary requirements for the correct working of the radio-link. The dimensions are a bit larger but area is smaller, replacing the original *WikiSat* antenna of 141x34 mm by the new of 43x15 mm and the antenna that is a wire of few centimeters. Furthermore, the maximum range that reaches is bigger than the original **nRF24L01P**, and the same occurs with the autonomous of the battery, that is of 33.9 hours respect to the 6.6 hours of the Case 1.

Nevertheless, the **nRF24L01P** still weight less: 20 grams in front of these 25 grams that weights the **NTX2** as we will present in the next chapter.

CHAPTER 4. SPECIFICATIONS

In this chapter main radio-link issues are presented. The original design of the *WikiSat* **nRF24L01P** antenna was proposed by **Fernandez-Murcia** in [14] but without margin.
Also is presented de cost budget of the four antennas, the required energy for the four cases and, finally, it is explained the manipulation of one of them.

4.1 Link budget

In order to know the communications parameters as was proposed by **Fernandez-Murcia** in [14], it is necessary an accurate power link budget for the communication where the minimum link distance is fixed at 500 km. The budget is initially set as a download link from the satellite to the ground station. Initially, we have proposed to use the **9XTend** transceiver[34] but since the expectations are not meet, other transceivers such as the SSTV **10MW** transceiver[35] or the **NTX2** transceiver[36] are considered. See annexes for datasheets. We propose to start from the original *WikiSat* communication system based on the *Nordic* **nRF24L01P** transceiver[37] at 2.4 GHz System-on-Chip working at 250 kbps bandwidth, 0 dBm TX power and GFSK modulation.

The link budget is based in the equation 4.1 where extra components like amplifiers (in both sides of the radio link) are necessary to increase the range. It is mandatory to begin with the computation of how many G_{extra} extra gain (dB) will be necessary at a distance of 500 km. Having:

$$P_{rx} = P_{tx} + G_{tx} - e_{tx} - LFS - PLF + G_{rx} - e_{rx} \tag{4.1}$$

Equation 4.1 can be easily transformed in order to estimate the extra gain necessary as shown in Equation 4.2.

$$G_{extra} = P_{tx} + G_{tx} - e_{tx} - LFS - PLF + G_{rx} - e_{rx} - P_{rx,\min} \tag{4.2}$$

For the transmission, a power amplifier (PA) with an adequate trade-off of gain-consumption, easy to implement (not too much components) and the better OIP_3 and P1dB as possible are the main specifications considered. The selected power amplifier is the PA2423L from *SiGe* manufacturer.

From point of view of reception, the noise figure and gain are critical; hence the selected component is a Low Noise Amplifier (LNA), the ADL5521 from Analog Devices, by its low noise figure, and is located as close to the antenna as possible.

[34] http://www.*Digi*.com/pdf/ds_xtendmodule.pdf
[35] http://www.*Argent*data.com/files/SSTVCam.pdf
[36] http://www.*Radiometrix*.com/files/additional/ntx2nrx2.pdf
[37] http://www.*Nordic*semi.com/eng/Products/2.4GHz-RF/nRF24L01

As a matter of summary, the figure 9 shows the schema of femtosatellite communication as well as the link budget calculations with the original *WikiSat* communications module [14]:

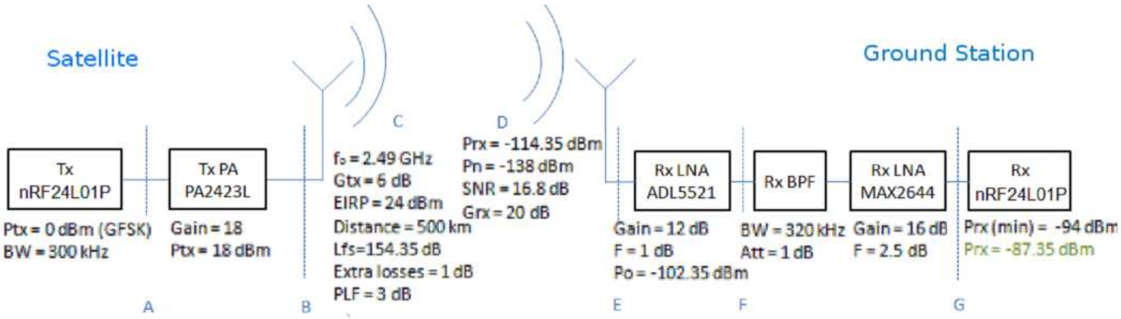

Figure 9 – Femtosatellite diagram block and link budget for the original nRF24L01P configuration. Source: Enric Fernandez

This compute is achieved for a separation of 500 km. Due to the different polarization of the antennas (one linear and the other circular), a polarization loss factor (PLF) of 3 dB has been considered. This is critical because the polarization may change the satellite movement or produce any other undesired effect. A circular polarization (20 dB of gain) *Yagi* antenna is selected for reception and is considered a 6 dB antenna (the gain expected for the array) for transmission. Finally, 0.5 dB losses due efficiencies have been considered at each side of the link. Also we have considered the same values for the G_{tx} antenna and ground segment. All these values are fixed factors that not change at the schema and the design of system communication. For the precise case of **nRF24L01P**, the operating frequency (f_0) selected is 2.4 GHz.

Note that for the Loss in Free Space (LFS) or FSPL (Free Space Path Lost) is not the same for all the cases because it depends on the frequency that each implementation requires. For the others losses are taken the same values as Case 1 from the original schema of *WikiSat*.

From equation 4.2, we proceed to compute the extra gain for every implementation that we propose: the **10MW** implementation, the *WikiSat* v4.1 implementation, the **9XTend** implementation and the **NTX2** implementation, beginning with the original design **nRF24L01P**:

CASE 1. nRF24L01P

The original **nRF24L01P** implementation has $P_{tx} = 18\,dBm$, $LFS_{2.4GHz} = 154.35\,dB$, the G_{extra} is computed in equation (4.3).

$$P_{tx} + G_{tx} - e_{tx} - LFS - PLF + G_{rx} - e_{rx} - P_{rx,\min} = 0\,dBm \tag{4.3}$$

In this case, there is no extra gain, so the maximum range is $d_{Gtx=0dB} = 500\,km$.

CASE 2. 10MW

The *FPV* **10MW** implementation for the *Argent* SSTV camera has $P_{tx} = 39.5\,dBm$, $LFS_{5.8GHz} = 64.06\,dB$,

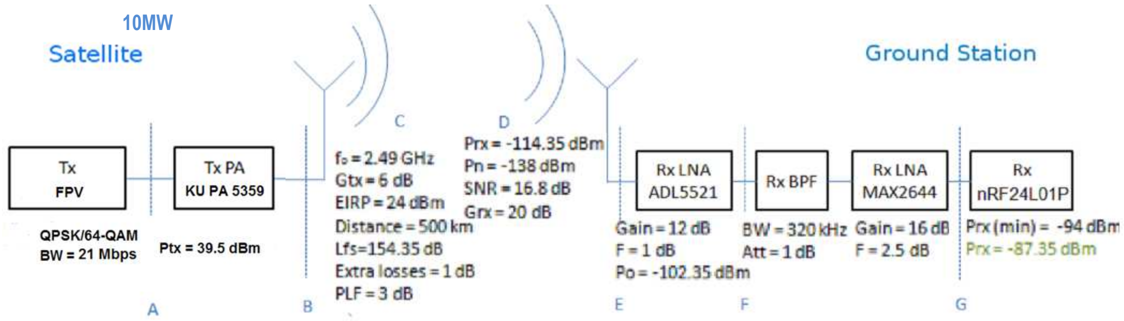

Figure 10 – Femtosatellite diagram block and link budget for the 10MW configuration. Adapted from: Enric Fernandez

In the second case, the G_{extra} is computed in equation (4.4).

$$P_{tx} + G_{tx} - e_{tx} - LFS - PLF + G_{rx} - e_{rx} - P_{rx,\min} = 111.79\,dB \tag{4.4}$$

This extra gain allow us to achieve a maximum range of $d_{Gtx=0dB} = 2{,}500\,km$.

CASE 3. 9XTend

The *Digi* **9XTend** implementation has $P_{tx} = 27\,dBm$, $LFS_{902MHz} = 55.98\,dB$,

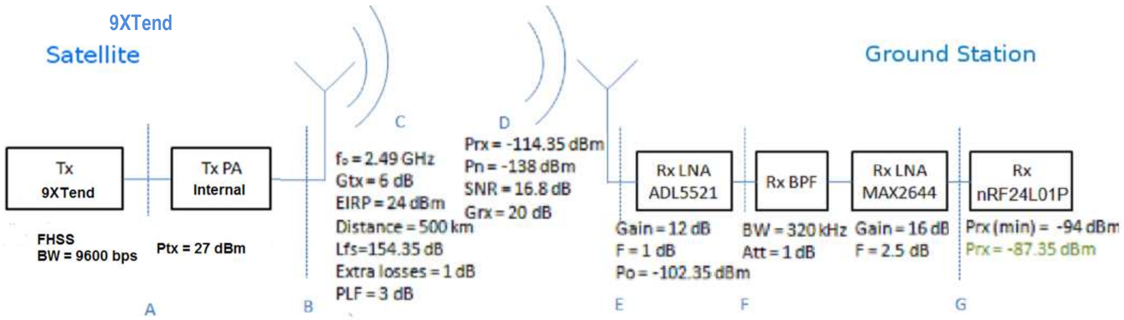

Figure 11 – Femtosatellite diagram block and link budget for the 9XTend configuration. Adapted from: Enric Fernandez

In the third case, the G_{extra} is computed in equation (4.5).

$$P_{tx} + G_{tx} - e_{tx} - LFS - PLF + G_{rx} - e_{rx} - P_{rx,\min} = 107.37\,dB \tag{4.5}$$

This extra gain allow us to achieve a maximum range of $d_{Gtx=0dB} = 3{,}800\,km$.

CASE 4. NTX2

The *Radiometrix* **NTX2** implementation has $P_{tx} = 14\,dBm$, $LFS_{434MHz} = 52.80\,dB$,

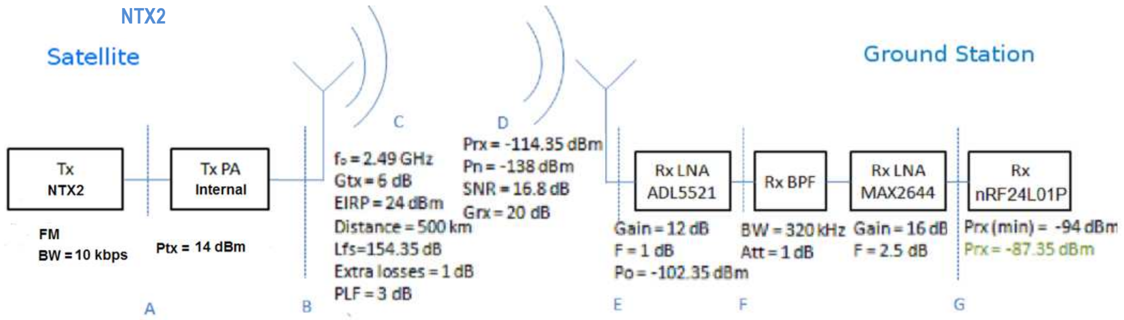

Figure 12 – Femtosatellite diagram block and link budget for the NTX2 configuration. Adapted from: Enric Fernandez

In the last case, the G_{extra} is computed in equation (4.6):

$$P_{tx} + G_{tx} - e_{tx} - LFS - PLF + G_{rx} - e_{rx} - P_{rx,\min} = 97.55\,dB \tag{4.6}$$

This extra gain allow us to achieve a maximum range of $d_{Gtx=0dB} = 1{,}800\,km$.

The LFS_{500km} is obtained using the next equation (4.7):

$$LFS = \left(\frac{4\pi f d}{c}\right)^2 \tag{4.7}$$

Where, supposing that maximum range is $d = 500km$, knowing that speed of light in a vacuum is $c = 3\times10^8\,m/s$, and setting the frequency of each case, we obtain the different values of LFS.

Once we have calculated the value of the extra gain for each case, for to obtain the value of the maximum ranges, we have used the equation (4.8):

$$Range = 10^{\frac{LFS_{\max} - 147.5}{20} - \log f - 3}\ km \tag{4.8}$$

Where, if it is added the value of LFS_{500km} with the value of the G_{extra} calculated, is obtained the value of the $LFS_{\max}$. This is the maximum value of LFS that each case can reach and that is obtained when the femtosatellite arrives to the maximum range, in which the extra gain will be $G_{extra} = G_{tx} = 0dB$.

4.2 Energy budget

The electrical power source is a battery, not a solar panel and the power budget has an important limitation. The satellite will have a distributed voltage regulation strategy, figure 13(a), because it has a single source, the battery and each SMD component will have a voltage regulator inside. Instead, the payload will have a centralized strategy, figure 13(b), because each voltage level is supplied from a single voltage regulator, feeding to any payload SMD component in the payload area.

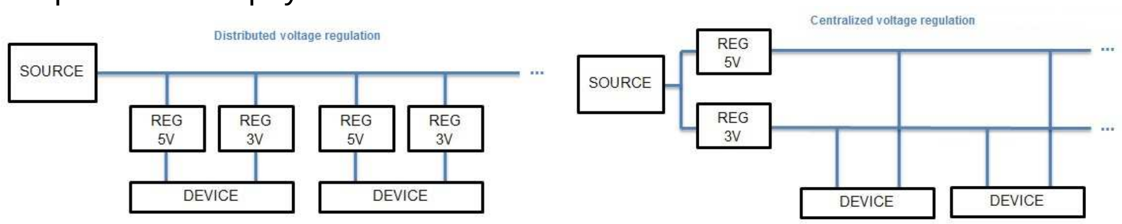

Figure 13 – Voltage regulation diagram blocks: distributed strategy (a) and centralized strategy (b).

The diagram block for a distributed strategy in figure 13(a) shows how this schema achieves the best battery usage while the centralized strategy in figure 13(b) has a weak point that is the regulator.

4.2.1 *Power budget*

For the power budget, there are two working modes: Standby and Active. The active mode is the most consuming state that the satellite has when downlink is established and satellite is pointing towards the required station through the Magnetorquers. These magnetorquers can generate a magnetic field in order to have an attitude control to point the high gain antenna towards the ground station or to follow an interesting point for the payload.

The available power should be used only when necessary. **Navarro** in [11] has calculated the total time of the mission when the satellite could stays in active mode. During a total of nine days of mission, there are about 382 minutes of a total of about 13,000 minutes of downlink. Only 3 percent of the mission time, the femtosatellite will have an important battery leak. The total mission consumption is about 520 mAh and the total available is 610 mAh. The average consumption per hour is 2.4 mA/h. Each case is studied following and they were summarized in table 2.

CASE 1. For the case of the **nRF24L01P**, the power consumption is 92 mA. The battery can afford a peak of power is 12 A. The maximum continuous operation of this module is 6 hours, 37 minutes and 48 seconds.

CASE 2. For the case of the **10MW**, the power consumption is 4.5 A. The original battery can afford a peak of power is 12 A. The maximum continuous operation of this module is 8 minutes and 8 seconds. Obviously, a battery pack is required in this case.

CASE 3. For the case of the **9Xtend** module, the power consumption is 600 mA. The battery can afford a peak of power is 12 A. The maximum continuous operation of this module is 1 hour and 1 minute.

CASE 4. For the case of **NTX2** module, the power consumption is 18 mA. The battery should feed this power is 12 A. The maximum continuous operation of this module is 33 hours, 53 minutes and 24 seconds.

4.2.2 Power source

For this kind of missions, due to the short mission time, it is strongly recommended to use batteries instead of solar panels. As reported by **Navarro** in [11], the 34 percent of the mass budget is for the battery that represents 6.6 grams compared to the tracking subsystem that is the 36 percent of the mass budget in 7.0 grams. In the early designs, i.e. *WikiSat* v3 a coin battery was selected having a better consumption to mass ration that the current LiPoly batteries. The main problem that a coin battery has got is not the fact that it is no rechargeable but it has a very low drain power, about 50 mAh, while the total consumption is 610 mAh. LiPoly batteries have maximum power in the order of 12 Ah for a short time.

Different values for each case are summarized in table 2:

Table 2 – Link-budget summary (Four cases)

	Freq.	P_{tx}	LFS	G_{extra}	Range	Power	Live
CASE 1.nRF24L01P	2.4 GHz	18.0 dBm	154.35 dB	0.00 dB	500 km	92 mA	6:37:48
CASE 2. 10MW	5.8 GHz	39.5 dBm	64.06 dB	111.79 dB	2,500 km	4,500 mA	0:08:08
CASE 3. 9XTend	902 MHz	27.0 dBm	55.98 dB	107.37 dB	3,800 km	600 mA	1:01:00
CASE 4. NTX2	434 MHz	14.0 dBm	52.80 dB	97.55 dB	1,800 km	18 mA	33:53:14

In table 2, transmit power has been converted[38] in dBm units using the following equation (4.9) where 1 watt is 30 dBm.

$$P_{(dBm)} = 10 \cdot \log_{10}\left(1000 \cdot P_{(W)}\right) = 10 \cdot \log_{10}\left(P_{(W)}\right) + 30 \tag{4.9}$$

As well as the power consumption or continuous live time, marked in red the parameters that do not fit any requirement. Available power is 610 mA from the main battery and the minimum operational live time is set at a minimum of 6 hours of continuous recording as calculated **Navarro** in [11].

It is observed the required values of each case (recover of their respective datasheets), as well as: frequency, power P_{tx}, the LFS and the required power. On the other hand, if is fixed the maximum distance at 500 km (bringing with reference always the **nRF24L01P**, whose distance of maximum range is 500 km), is obtained the extra gain G_{extra} that is seen at the table 2. It should be noted that the **nRF24L01P** has an extra gain of 0 dB, being that cannot reach a major distance. At the range we observe the maximum real distances to which arrives each one of the implementations. For these distances, the $G_{extra} = 0dB$. Also it is shown the useful life for a continued use, and coming determinates for the calculations shown on the 4.2.1 section based of the power that requires each case.

Typical extra gain in communications is $G_{Typical} = 6dB$ but some amateur satellites are even more. Requirement LLR015 stated this margin at $G_{Typical} = 3dB$. The original **nRF24L01P** communication system was designed

[38] http://www.rapidtables.com/convert/power/Watt_to_dBm.htm

with no margin which means that in practice, the range is in fact less than 500 km. The proposed cases have extra margin instead, which means that the range will be more than 500 km as showed in table 2.

4.3 Bill of materials

Table 3 presents the bill of materials of the original **nRF24L01P** implementation and the new components such as the transceivers and power amplifiers for each option or implementation presented in the chapter 3.

Table 3 – Mass and cost budget (Four cases)

		Provider	Model	Case	Size mm	Cost
MCU computer		Atmel	ATmega1682	1,2,3,4	4	3.07€
Accelerometer		ST	LIS331HH	1,2,3,4	3	3.64€
Rate gyroscope		Invensense	ITG-3200	1,2,3,4	4	25.39€
HD Camera		TOSHIBA	TCM8239MD	1,3,4	6	9.95€
SSTV Camera		*Argent*	SSTVCA	2	36	60.00€
Serializer		TI	SN74HC165PW	1,3,4	4	0.27€
IO expander		TI	TCA6408A	1,2,3,4	4	1.86€
Voltage regulator		TI	TPS719XXXX	1,2,3,4	3	1.36€
Transceiver	**2.4 GHz**	Nordic	nRF24L01P	1	4	3.78€
	5.8 GHz	FPV	10MW	2	158	21.75€
	902 MHz	Digi	9XTend OEM RF	3	61	141.52€
	434 MHz	Radiometrix	NTX2	4	43	19.38€
Power Amplifier	**2.4 GHz**	SiGe	PA 2423L	1	3	2.63€
	5.8 GHz	KU	PA 5359	2	158	600.00€
	902 MHz	Digi	Internal	3	61	-
	434 MHz	Radiometrix	Internal	4	43	-

In the table 3 we can see the cost budget for each case, furthermore of the size, provider and model of each material. For the transceiver, the cheapest is the **nRF24L01P** implementation, and the next cheaper is the **NTX2**. For its part, the most expensive is the **9XTend** implementation.

If we notice at the power amplifier, it is repeated that the cheapest is the **nRF24L01P** implementation. In this case, we have not information about the cost of *Digi* and *Radiometrix* power amplifier, but the cost of **10MW** implementation is known.

4.4 Digi 9Xtend test

There is experimental information about all the implementations in nearspace except for the *Digi* **9XTend**. For this reason I proceeded to make a test with the **9XTend** module which consisted of to realize a realistic radio-link between two **9XTend** modules. The reason of choose it, is determined by that we have of two modules for realize the transmission and reception of data. Nevertheless, at the beginning we haven't got the necessary components to create the radio-link: the antenna of the transmitter module, and the FTDI converter from UART for the receptor module to USB for the PC (That emulates the ground station). So, is explained the manufacturing, certification and validation of the antenna and, finally, the test of radio-link.

4.4.1 *Antenna manufacturing*

We tried to find a 902 MHz antenna with a Reverse Polarity SubMiniature version A (RPSMA) connector but it was not possible in our location. The alternative option was to manufacture our own lambda/4 monopole antenna from a SMA adapter and a wire. See figure 14.

The working frequency is around 902 MHz so the wire length is computed by the equation (4.10) in $l_{902MHz} = 83.2\,mm$.

$$l_{902MHz} = \frac{c}{4f} = \frac{3 \cdot 10^8}{4 \cdot 902 \cdot 10^6} = 83.2\,mm \qquad (4.10)$$

Figure 14 shows the process. The nut (1) and the Rubber (2) are assembled with the needle (3) and the wire, removing the varnish layer (4) with a light before solder (5). The female needle should not be filled with tin to do not damage the radio male needle connector. The rubber is placed (6) and sealed with extra wire length (7). The nut is a SMA plug connector, the needle inside, see last annex.

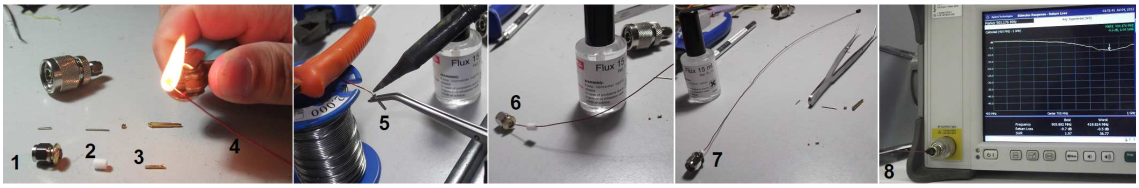

Figure 14 – 902 MHz lambda/4 antenna manufacturing

4.4.2 *Monopole antenna certification (902 MHz SMA)*

The monopole antenna certification process as prototype consists of the antenna calibration and the antenna validation. This antenna is manufactured by me with the collaboration of the *WikiSat team*.

This is the manufacturing procedure for a 902 MHz antenna, 9 dB gain with a Reverse Polarity SubMiniature version A (RPSMA) connector. It is based on a lambda/4 monopole antenna extracted from a SMA adapter and a wire. The working frequency is around 902 MHz so the wire length is computed by the equation (4.10) in $l_{902MHz} = 83.2\,mm$.

The antenna prototype certification process is done using an *Agilent* CSA Spectrum Analyzer model N1996A where the "Stimulus response – Return Loss" mode is selected. For the calibration procedure, first of all, a large range is selected from 400 MHz to 1 GHz as showed in figure 15. A calibration process is done as explained by **Ángel de las Heras** in [17] in section 4.4.1

Equipment calibration (Page 74). The wire is cut slowly until the best response for the working frequency selected with the marker at 901.176 MHz is obtained.

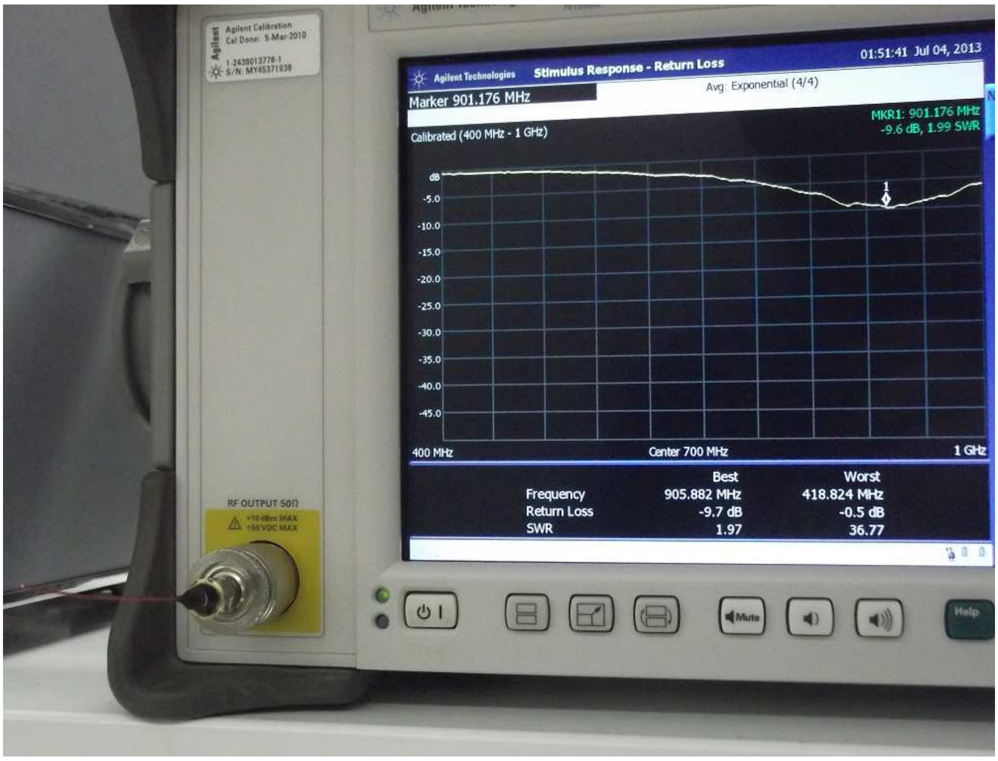

Figure 15 – Antenna A. Best frequency 905.882 MHz with -9.7 dB and SWR 1.97

Figure 16 – Antenna B. Best frequency 904.329 MHz with -9.5 dB and SWR 2.01. Worst frequency 922.91 MHz with -9.0 dB and SWR 2.11

For the validation procedure a narrow range is selected corresponding to the operative range, see previous figure, from 900 MHz to 930 MHz in order to ensure all the working frequencies have a SWR less than 2.11 and a gain of 9.0 dB in the worst case. Standing wave ratio, equation (4.11), is used in telecommunications as the ratio in amplitude of a partial standing wave at a maximum to the amplitude at an adjacent minimum but often it is used the Voltage Standing Wave Ratio (VSWR) in Spanish: *Razón de onda estacionaria* where V_i and V_r are incident (Forward wave) and reflected voltages.

$$ROE = \frac{V_i + V_r}{V_i - V_r} \tag{4.11}$$

The certification procedure was repeated for each antenna (we needed two) but before this, an additional antenna was manufactured in order to validate the model. We cut the wire beyond the adapted frequency in order to demonstrate that we have found the absolute maximum. Some kinds of antennas have many maximums but only one is the absolute maximum. Obviously, a monopole antenna does not have this behavior but we must be sure our antenna behaves like a monopole antenna.

4.4.3 Antenna validation

The antenna validation as a component is done using an *Agilent* CSA Spectrum Analyzer model N1996A where the “Stimulus response – Return Loss” mode is selected. First of all, a large range is selected from 400 MHz to 1 GHz as showed in figure 15. A calibration process is done as explained by **Ángel de las Heras** in [17] in section 4.4.1 Equipment calibration (Page 74). The wire is cut slowly (8) until the antenna is adapted to the working frequency as seen by the marker at 901.176 MHz.

Finally, in order to validate antenna for the **9XTend** module, a narrow range is selected corresponding to the operative transceiver range, see figure 16, from 900 MHz to 930 MHz in order to ensure all the working frequencies have a SWR[39] less than 2.11 and a gain of 9.0 dB in the worst case. Same calibration is required in every test.

4.4.4 Module test

The early test consisted of two modules as depicted in figure 17. Left hand module is connected to an *u-blox* NEO-6M GPS with ceramic antenna that sends the NMEA[40] messages through an UART. The right hand module is connected to an FTDI converter from UART to a virtual serial port (Virtual COM) in the USB of a computer. Each module has a connector for a LiPoly battery (Not shown in the figure) that supplies both, the transceiver and the associated device. The whole system was delivered to another section inside the team, they will be responsible to assemble the system with the final vehicle. There was no time for a near-space test in a balloon. I conclude that this module is not useful for femtosatellite applications but for Unmanned Aerial Vehicles (UAV).

[39] Standing Wave Ratio (SWR)

[40] NMEA National Marine Electronics Assoication data specification used for GPS applications

The work done is not a waste because this module will be included in a real UAV vehicle from the ICARUS research group in the EETAC in the same University.

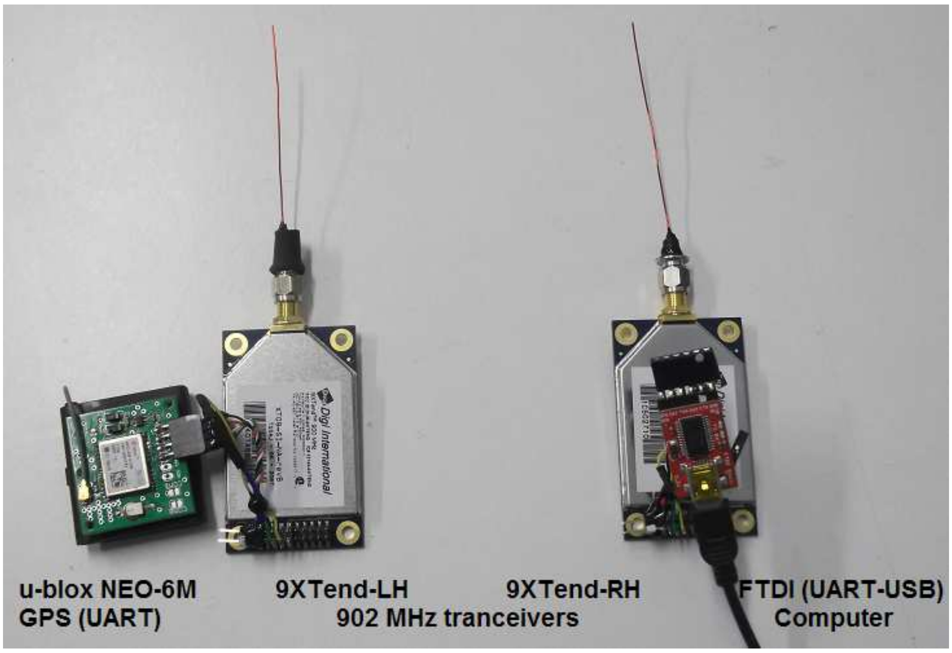

Figure 17 – Early radio-link test. NEO-6M GPS->9XTend (a) and 9XTend->FTDI (b)

CHAPTER 5. CONCLUSIONS

This chapter contains the general conclusions, future work and the environmental impact study.

5.1 General conclusions

- The original communication system of **nRF24L01P** proposed by **Enric Fernández** has not extra gain. Telecommunication applications have a typical extra gain of 3dB; amateur satellites have even more. For these reason, is concluded two things:

    - The same original communication system does not accomplish the minimum extra gain of 3 dB as set by requirements.
    - The typical extra gain is, minimum, of 6 dB for telecommunication applications. The communication system of **nRF24L01P** does not achieve to the minimum typical extra gain $G_{Typical} = 6dB$ for this type of applications.

- Although the new technologies go forward very fastly and, often, there are new actualizations, is very complicated to find the necessary designs (that it accomplish all requirements) for to implement and optimize a femtosatellite with a mass minor than 20 grams.

- A secondary objective was achieved with success when I made an evaluation and test of radio-link implementation between the two *Digi* **9XTend** modules, my baseline implementation. However, we expected that this modules were valid but they performances be a deception, being that don't accomplish several of minimum requirements and they didn't had the necessary complements for achieve the radio-link.
- On the other hand, I demonstrated that the *Digi* **9XTend** module does not accomplish with neither requirements system of fitting inside the satellite nor to have the same voltage. This module is discarded and not suitable for the next **WikiSat** version.

- Inside the WikiSat team, a ham proposed the *FPV* **10MW** implementation. This implementation has been not validated, since it doesn’t accomplish several of the minimum requirements: too large, too heavy and different voltage.

- Other WikiSat team proposal was the module the *Radiometrix* **NTX2** implementation. I demonstrated that it has best performances: a very low mass budget and also a large bandwidth. It has the best battery usage. It accomplishes with all the requirements, expected result due to the WikiSat team already has tested this module in nearspace and also it has been used in other similar missions.

- The main objective of to find and validate a module that permits the improvement and optimization of the communications system better than the **nRF24L01P** femtosatellite was achieved. My recommendation to the *WikiSat team* is to discard the other proposals and use the *Radiometrix* **NTX2** for future **WikiSat** versions.

- In addition I demonstrated that the design and implementation of the communications system of a small satellite like this can be based on Commercial-off-the-shelf solutions, providing a fast development time.

5.2 Future work

This work is a evaluation of three extra communication implementations that are based on COTS. These proposals can be useful or not depending on initial requirements but they can be placed in other kind of vehicles.

The *Digi* **9XTend** module requires a field test and a near-space balloon expedition in order to test the real performances before to be used in femtosatellite applications.

As per *FPV* **10MW** implementation, it has been proven in the amateur field but it can be explores new possibilities such as the *Guifi.net*[41]; a satellite that can provide wireless networking communications for few minutes from the space.

It should be studied the possibility to use the *Radiometrix* **NTX2** on a board of the communication systems of *WikiSat* and to do tests to verify if is better than the original communication module **nRF24L01P**, not only in the balloon.

5.3 Environmental impact

The use of COTS very often includes a recycling procedure designed by the manufacturer. Nowadays, the electronics assemble is built in a massive production approach. Electronic components are lead-free devices, mainly the LCC technology or Leadless Chip Carrier. Electronics are everyday more respectful with the environment avoiding lead-based components.

During the development of this work, all the *WikiSat* members have observed the safety measurements and industrial standards in terms of environmental issues.

[41] http://guifi.net/

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ANEXES

TÍTOL DEL TFC: Implementació d'un radio-enllaç de llarg abast per a femto-satèl·lits en òrbita molt baixa

TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

AUTOR: Sara Izquierdo Jiménez

DIRECTOR: Joshua Tristancho Martínez

DATA: 29 de Octubre de 2013

DATASHEETS

Manufacturer	Model	Source
6.1 *Argent*data	SSTV	http://www.*Argent*data.com/files/SSTVCam.pdf
6.2 FPV	10mW	http://www.fpvhobby.com/transmitter/21-2-55-volt-500mw-24ghz-video-transmitter.html
6.3 Kunhe	PA5359	http://www.kuhne-electronic.de/en/products/power-amplifiers/ku-pa-5359-a.html
6.4 *NORDIC*	nRF24L01	http://www.*Nordic*semi.com/eng/Products/2.4GHz-RF/nRF24L01
6.5 *SiGe*	PA2423L	http://www.datasheetcatalog.org/datasheet/*SiGe*/PA2423L-EV.pdf
6.6 *Digi*	9XTend	https://www.sparkfun.com/products/9411
6.7 *Radiometrix*	NTX2	http://www.*Radiometrix*.com/files/additional/ntx2nrx2.pdf
6.8 SMA connector family		http://i01.i.aliimg.com/photo/v0/256281235/SMA_connector.jpg

6.1 *Argent*data SSTV camera datasheet

http://www.*Argent*data.com/files/SSTVCam.pdf

SSTVCAM

Stand-Alone Slow Scan TV Camera

ARGENT DATA SYSTEMS

SSTVCAM Features

- Send SSTV pictures without a PC
- Decode with PC and Sound Card using free software
- Stores up to 8 frames in permanent memory for later recall
- Manual or automatic timed operation
- Robot 36 & 72, Scottie 1 & 2 modes
- Interface to almost any radio
- Serial character generator for Scottie modes
- Runs on 5 to 15v DC
- Automatic white balance and exposure

Uses

- High-altitude balloons
- Storm Spotting
- Repeater sites
- "Webcam" over voice band radio

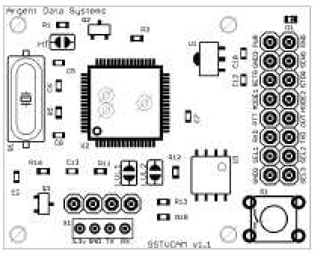
Technical Specifications

- Supply voltage: 5 to 15v DC
- Current draw: 3.5 mA idle, 18 mA transmitting, 75 mA capturing (~15 seconds per frame)
- Dimensions: 1.6"x1.3"x1.4" (40x33x36mm)
- Weight: 20 grams
- Optical specifications: 1/4" CMOS Sensor, 60° FOV, F/2.5

Hookup Information

The SSTVCAM interfaces through a 16-pin, 0.1" pitch header. At a minimum, power, ground, and audio out must be connected.

Pinouts



Pin	Function		
PWR	Power input - 5 to 15 volts DC	GND	Ground
GND3	Ground	SEND	Sends or stores a frame
RETR	Selects memory retrieve mode	STOR	Selects memory store mode
MODE1	Selects SSTV format	MODE2	Selects SSTV format
PTT	Open collector push-to-talk output	OUT	Audio output
RXD	Serial data input (LVTTL) - 3.3v max	TXD	Serial data output (LVTTL)
SEL1	Selects memory slot or timer interval	SEL2	Selects memory slot or timer interval
GND2	Ground	SEL3	Selects memory slot or timer interval

The GND, RX, TX and 3.3v pads above the camera connector are provided for remote connection of the camera module. Cable length should be kept to not more than a few inches.

E-mail: sales@argentdata.com
http://wiki.argentdata.com/index.php/SSTVCAM

Argent Data Systems PO Box 579 Santa Maria, CA 93456

SSTVCAM
Stand-Alone Slow Scan TV Camera

ARGENT DATA SYSTEMS

Jumper Information

Three sets of jumper pads on the main board can be set by shorting the pads with solder.

Jumper	Function
HT	Selects handheld PTT mode
SJ1	Increases audio output level
SJ2	Increases audio output level

Operation

Pushbutton S1 is internally connected to the SEND input.

All of the digital inputs on the SSTVCAM are active low - grounding a pin sets it 'on'. The SSTV format to be used is selected by the MODE1 and MODE2 inputs, as shown.

MODE1	MODE2	Format
Off	Off	Robot 36
On	Off	Robot 72
Off	On	Scottie 2
On	On	Scottie 1

If STOR and RETR are off, pressing button S1 or momentarily grounding the SEND line triggers an immediate transmission in the selected mode. If STOR is on, a frame will be saved to the memory slot selected by SEL1-SEL3. If RETR is on, a previously saved frame will be sent from the selected memory slot. If both STOR and RETR are on, the unit will operate in self-timed mode, sending frames automatically with a delay between each frame specified by SEL1-SEL3, as shown.

SEL1	SEL2	SEL3	Delay
Off	Off	Off	0 seconds
On	Off	Off	10 seconds
Off	On	Off	30 seconds
On	On	Off	60 seconds
Off	Off	On	120 seconds
On	Off	On	300 seconds
Off	On	On	600 seconds
On	On	On	1200 seconds

Character Generator

A 1-line character generator occupies the top of the frame in Scottie mode. By default, this line displays the SSTVCAM version and a frame sequence number. The contents of the line can be changed by sending serial data to the unit through the RXD line at 4800 baud with LVTTL (0 to 3.3v) signal levels. Sending a carriage return or linefeed moves the cursor to the start of the line.

E-mail: sales@argentdata.com
http://wiki.argentdata.com/index.php/SSTVCAM

Argent Data Systems PO Box 579 Santa Maria, CA 93456

6.2 FPV 10 mW AV transmitter datasheet

Provider: FPV
Model: 10MW
Source: http://www.fpvhobby.com/transmitter/21-2-55-volt-500mw-24ghz-video-transmitter.html
Type: Transmitter module
TX power: 10 mW
Frequency: 5.8 GHz
Range: 100 meters
Data: Audio and Video
Current: 70 mA
Voltage: 3.3 V
Size: 20x20x4 mm
Weight: 1.2 grams
Cost: $20.00
Channels: Ch1:5705mhz , Ch2:5685mhz , Ch3:5665mhz , Ch4:5645mhz , Ch5:5885mhz , Ch6:5905 , Ch7:5925mhz , Ch8:5945mhz

6.3 Kuhne PA5359A power amplifier datasheet

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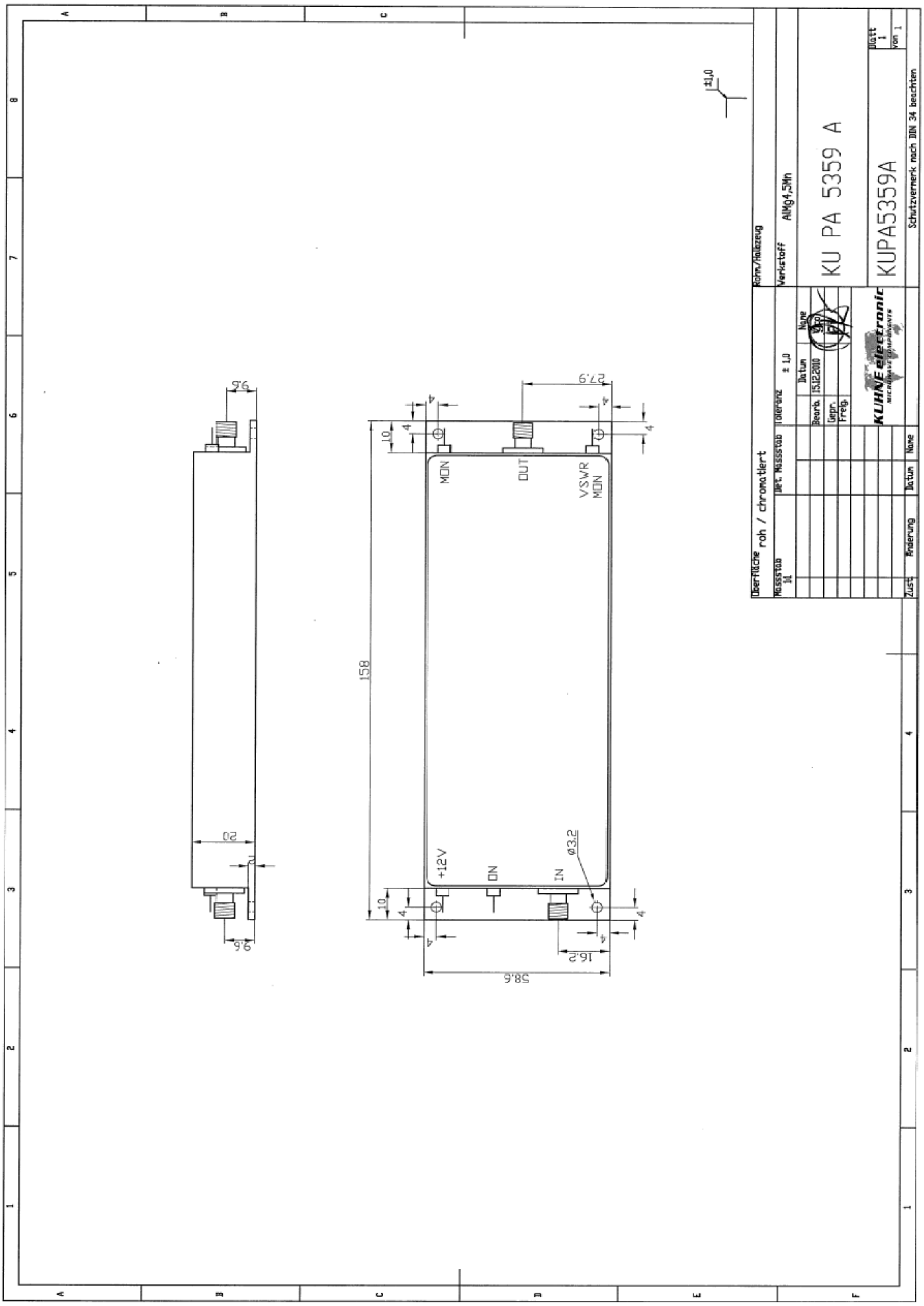

6.4 *NORDIC* nRF24L01 transceiver datasheet

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nRF24L01+

Single Chip 2.4GHz Transceiver

Product Specification v1.0

Key Features

- Worldwide 2.4GHz ISM band operation
- 250kbps, 1Mbps and 2Mbps on air data rates
- Ultra low power operation
- 11.3mA TX at 0dBm output power
- 13.5mA RX at 2Mbps air data rate
- 900nA in power down
- 26µA in standby-I
- On chip voltage regulator
- 1.9 to 3.6V supply range
- Enhanced ShockBurst™
- Automatic packet handling
- Auto packet transaction handling
- 6 data pipe MultiCeiver™
- Drop-in compatibility with nRF24L01
- On-air compatible in 250kbps and 1Mbps with nRF2401A, nRF2402, nRF24E1 and nRF24E2
- Low cost BOM
- ±60ppm 16MHz crystal
- 5V tolerant inputs
- Compact 20-pin 4x4mm QFN package

Applications

- Wireless PC Peripherals
- Mouse, keyboards and remotes
- 3-in-1 desktop bundles
- Advanced Media center remote controls
- VoIP headsets
- Game controllers
- Sports watches and sensors
- RF remote controls for consumer electronics
- Home and commercial automation
- Ultra low power sensor networks
- Active RFID
- Asset tracking systems
- Toys

September 2008

1 Introduction

The nRF24L01+ is a single chip 2.4GHz transceiver with an embedded baseband protocol engine (Enhanced ShockBurst™), suitable for ultra low power wireless applications. The nRF24L01+ is designed for operation in the world wide ISM frequency band at 2.400 - 2.4835GHz.

To design a radio system with the nRF24L01+, you simply need an MCU (microcontroller) and a few external passive components.

You can operate and configure the nRF24L01+ through a Serial Peripheral Interface (SPI). The register map, which is accessible through the SPI, contains all configuration registers in the nRF24L01+ and is accessible in all operation modes of the chip.

The embedded baseband protocol engine (Enhanced ShockBurst™) is based on packet communication and supports various modes from manual operation to advanced autonomous protocol operation. Internal FIFOs ensure a smooth data flow between the radio front end and the system's MCU. Enhanced ShockBurst™ reduces system cost by handling all the high speed link layer operations.

The radio front end uses GFSK modulation. It has user configurable parameters like frequency channel, output power and air data rate. nRF24L01+ supports an air data rate of 250 kbps, 1 Mbps and 2Mbps. The high air data rate combined with two power saving modes make the nRF24L01+ very suitable for ultra low power designs.

nRF24L01+ is drop-in compatible with nRF24L01 and on-air compatible with nRF2401A, nRF2402, nRF24E1 and nRF24E2. Intermodulation and wideband blocking values in nRF24L01+ are much improved in comparison to the nRF24L01 and the addition of internal filtering to nRF24L01+ has improved the margins for meeting RF regulatory standards.

Internal voltage regulators ensure a high Power Supply Rejection Ratio (PSRR) and a wide power supply range.

1.1 Features

Features of the nRF24L01+ include:

- Radio
  - Worldwide 2.4GHz ISM band operation
  - 126 RF channels
  - Common RX and TX interface
  - GFSK modulation
  - 250kbps, 1 and 2Mbps air data rate
  - 1MHz non-overlapping channel spacing at 1Mbps
  - 2MHz non-overlapping channel spacing at 2Mbps
- Transmitter
  - Programmable output power: 0, -6, -12 or -18dBm
  - 11.3mA at 0dBm output power
- Receiver
  - Fast AGC for improved dynamic range
  - Integrated channel filters
  - 13.5mA at 2Mbps
  - -82dBm sensitivity at 2Mbps
  - -85dBm sensitivity at 1Mbps
  - -94dBm sensitivity at 250kbps
- RF Synthesizer
  - Fully integrated synthesizer
  - No external loop filer, VCO varactor diode or resonator
  - Accepts low cost ±60ppm 16MHz crystal
- Enhanced ShockBurst™
  - 1 to 32 bytes dynamic payload length
  - Automatic packet handling
  - Auto packet transaction handling
  - 6 data pipe MultiCeiver™ for 1:6 star networks
- Power Management
  - Integrated voltage regulator
  - 1.9 to 3.6V supply range
  - Idle modes with fast start-up times for advanced power management
  - 26μA Standby-I mode, 900nA power down mode
  - Max 1.5ms start-up from power down mode
  - Max 130us start-up from standby-I mode
- Host Interface
  - 4-pin hardware SPI
  - Max 10Mbps
  - 3 separate 32 bytes TX and RX FIFOs
  - 5V tolerant inputs
- Compact 20-pin 4x4mm QFN package

1.2 Block diagram

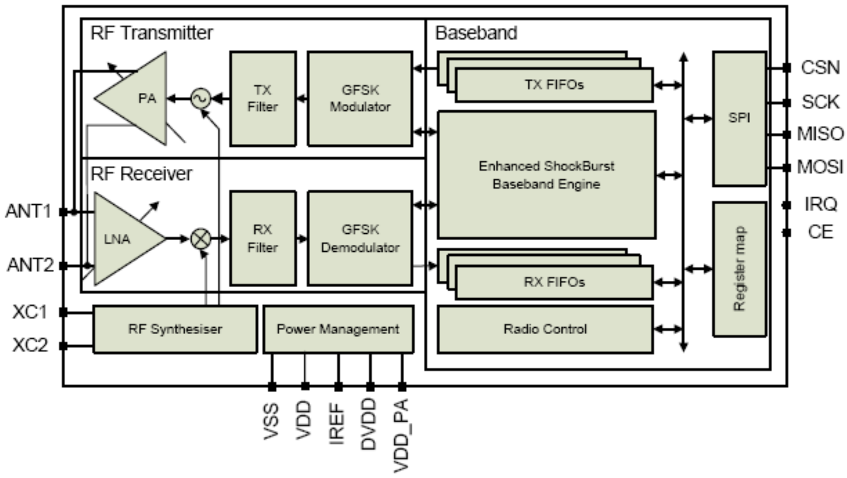


Figure 1. nRF24L01+ block diagram

2 Pin Information

2.1 Pin assignment

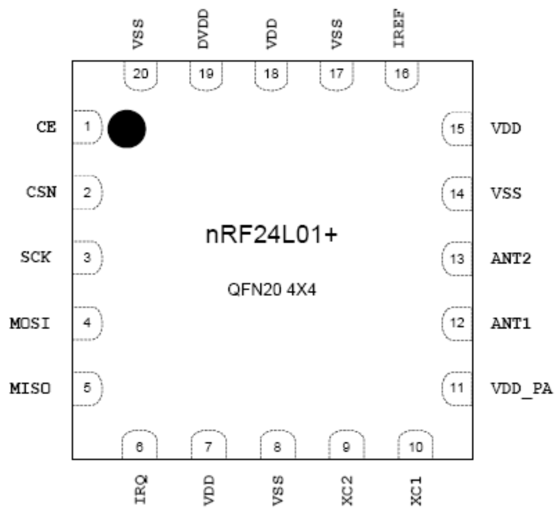


Figure 2. nRF24L01+ pin assignment (top view) for the QFN20 4x4 package

2.2 Pin functions

Pin	Name	Pin function	Description
1	CE	Digital Input	Chip Enable Activates RX or TX mode
2	CSN	Digital Input	SPI Chip Select
3	SCK	Digital Input	SPI Clock
4	MOSI	Digital Input	SPI Slave Data Input
5	MISO	Digital Output	SPI Slave Data Output, with tri-state option
6	IRQ	Digital Output	Maskable interrupt pin. Active low
7	VDD	Power	Power Supply (+1.9V - +3.6V DC)
8	VSS	Power	Ground (0V)
9	XC2	Analog Output	Crystal Pin 2
10	XC1	Analog Input	Crystal Pin 1
11	VDD_PA	Power Output	Power Supply Output (+1.8V) for the internal nRF24L01+ Power Amplifier. Must be connected to **ANT1** and **ANT2** as shown in Figure 32.
12	ANT1	RF	Antenna interface 1
13	ANT2	RF	Antenna interface 2
14	VSS	Power	Ground (0V)
15	VDD	Power	Power Supply (+1.9V - +3.6V DC)
16	IREF	Analog Input	Reference current. Connect a 22kΩ resistor to ground. See Figure 32.
17	VSS	Power	Ground (0V)
18	VDD	Power	Power Supply (+1.9V - +3.6V DC)
19	DVDD	Power Output	Internal digital supply output for de-coupling purposes. See Figure 32.
20	VSS	Power	Ground (0V)

Table 1. nRF24L01+ pin function

NORDIC SEMICONDUCTOR nRF24L01+ Product Specification

3 Absolute maximum ratings

Note: Exceeding one or more of the limiting values may cause permanent damage to nRF24L01+.

Operating conditions	Minimum	Maximum	Units
Supply voltages			
VDD	-0.3	3.6	V
VSS		0	V
Input voltage			
V_I	-0.3	5.25	V
Output voltage			
V_O	VSS to VDD	VSS to VDD	
Total Power Dissipation			
P_D (T_A=85°C)		60	mW
Temperatures			
Operating Temperature	-40	+85	°C
Storage Temperature	-40	+125	°C

Table 2. Absolute maximum ratings

NORDIC SEMICONDUCTOR nRF24L01+ Product Specification

5 Electrical specifications

Conditions: VDD = +3V, VSS = 0V, T_A = - 40ºC to + 85ºC

5.1 Power consumption

Symbol	Parameter (condition)	Notes	Min.	Typ.	Max.	Units
	Idle modes					
I_{VDD_PD}	Supply current in power down			900		nA
I_{VDD_ST1}	Supply current in standby-I mode	a		26		µA
I_{VDD_ST2}	Supply current in standby-II mode			320		µA
I_{VDD_SU}	Average current during 1.5ms crystal oscillator startup			400		µA
	Transmit					
I_{VDD_TX0}	Supply current @ 0dBm output power	b		11.3		mA
I_{VDD_TX6}	Supply current @ -6dBm output power	b		9.0		mA
I_{VDD_TX12}	Supply current @ -12dBm output power	b		7.5		mA
I_{VDD_TX18}	Supply current @ -18dBm output power	b		7.0		mA
I_{VDD_AVG}	Average Supply current @ -6dBm output power, ShockBurst™	c		0.12		mA
I_{VDD_TXS}	Average current during TX settling	d		8.0		mA
	Receive					
I_{VDD_2M}	Supply current 2Mbps			13.5		mA
I_{VDD_1M}	Supply current 1Mbps			13.1		mA
I_{VDD_250}	Supply current 250kbps			12.6		mA
I_{VDD_RXS}	Average current during RX settling	e		8.9		mA

a. This current is for a 12pF crystal. Current when using external clock is dependent on signal swing.
b. Antenna load impedance = 15Ω+j88Ω..
c. Antenna load impedance = 15Ω+j88Ω. Average data rate 10kbps and max. payload length packets.
d. Average current consumption during TX startup (130µs) and when changing mode from RX to TX (130µs).
e. Average current consumption during RX startup (130µs) and when changing mode from TX to RX (130µs).

Table 4. Power consumption

5.2 General RF conditions

Symbol	Parameter (condition)	Notes	Min.	Typ.	Max.	Units
f_{OP}	Operating frequency	a	2400		2525	MHz
PLL_{res}	PLL Programming resolution			1		MHz
f_{XTAL}	Crystal frequency			16		MHz
Δf_{250}	Frequency deviation @ 250kbps			±160		kHz
Δf_{1M}	Frequency deviation @ 1Mbps			±160		kHz
Δf_{2M}	Frequency deviation @ 2Mbps			±320		kHz
R_{GFSK}	Air Data rate	b	250		2000	kbps
$F_{CHANNEL\ 1M}$	Non-overlapping channel spacing @ 250kbps/ 1Mbps	c		1		MHz
$F_{CHANNEL\ 2M}$	Non-overlapping channel spacing @ 2Mbps	c		2		MHz

a. Regulatory standards determine the band range you can use.
b. Data rate in each burst on-air
c. The minimum channel spacing is 1MHz

Table 5. General RF conditions

5.3 Transmitter operation

Symbol	Parameter (condition)	Notes	Min.	Typ.	Max.	Units
P_{RF}	Maximum Output Power	a		0	+4	dBm
P_{RFC}	RF Power Control Range		16	18	20	dB
P_{RFCR}	RF Power Accuracy				±4	dB
P_{BW2}	20dB Bandwidth for Modulated Carrier (2Mbps)			1800	2000	kHz
P_{BW1}	20dB Bandwidth for Modulated Carrier (1Mbps)			900	1000	kHz
P_{BW250}	20dB Bandwidth for Modulated Carrier (250kbps)			700	800	kHz
$P_{RF1.2}$	1st Adjacent Channel Transmit Power 2MHz (2Mbps)				-20	dBc
$P_{RF2.2}$	2nd Adjacent Channel Transmit Power 4MHz (2Mbps)				-50	dBc
$P_{RF1.1}$	1st Adjacent Channel Transmit Power 1MHz (1Mbps)				-20	dBc
$P_{RF2.1}$	2nd Adjacent Channel Transmit Power 2MHz (1Mbps)				-45	dBc
$P_{RF1.250}$	1st Adjacent Channel Transmit Power 1MHz (250kbps)				-30	dBc
$P_{RF2.250}$	2nd Adjacent Channel Transmit Power 2MHz (250kbps)				-45	dBc

a. Antenna load impedance = 15Ω+j88Ω

Table 6. Transmitter operation

11 Application example

nRF24L01+ with single ended matching network crystal, bias resistor, and decoupling capacitors.

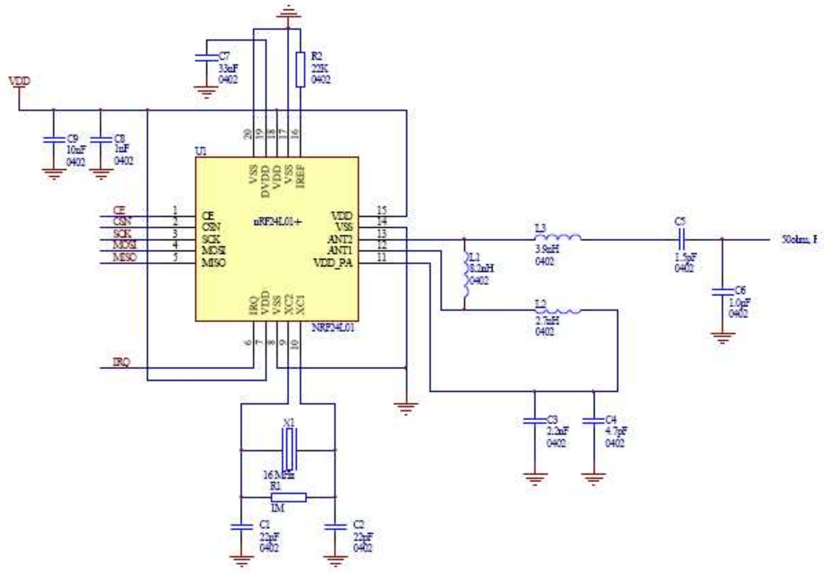


Figure 32. nRF24L01+ schematic for RF layouts with single ended 50Ω RF output

Part	Designator	Footprint	Description
22pF[a]	C1	0402	NPO, +/- 2%
22pF[a]	C2	0402	NPO, +/- 2%
2.2nF	C3	0402	X7R, +/- 10%
4.7pF	C4	0402	NPO, +/- 0.25pF
1.5pF	C5	0402	NPO, +/- 0.1pF
1,0pF	C6	0402	NPO, +/- 0.1pF
33nF	C7	0402	X7R, +/- 10%
1nF	C8	0402	X7R, +/- 10%
10nF	C9	0402	X7R, +/- 10%
8,2nH	L1	0402	chip inductor +/- 5%
2.7nH	L2	0402	chip inductor +/- 5%
3,9nH	L3	0402	chip inductor +/- 5%
Not mounted[b]	R1	0402	
22kΩ	R2	0402	+/-1%
nRF24L01+	U1	QFN20 4x4	
16MHz	X1		+/-60ppm, C_L=12pF

a. C1 and C2 must have values that match the crystals load capacitance, C_L.

b. The nRF24L01+ and nRF24L01 application example and BOM are the same with the exception of R1. R1 can be mounted for backward compatibility with nRF24L01. The use of a 1Mohm resistor externally does not have any impact on crystal performance.

Table 29. Recommended components (BOM) in nRF24L01+ with antenna matching network

11.1 PCB layout examples

Figure 33., Figure 34. and Figure 35. show a PCB layout example for the application schematic in Figure 32..

A double-sided FR-4 board of 1.6mm thickness is used. This PCB has a ground plane on the bottom layer. Additionally, there are ground areas on the component side of the board to ensure sufficient grounding of critical components. A large number of via holes connect the top layer ground areas to the bottom layer ground plane.

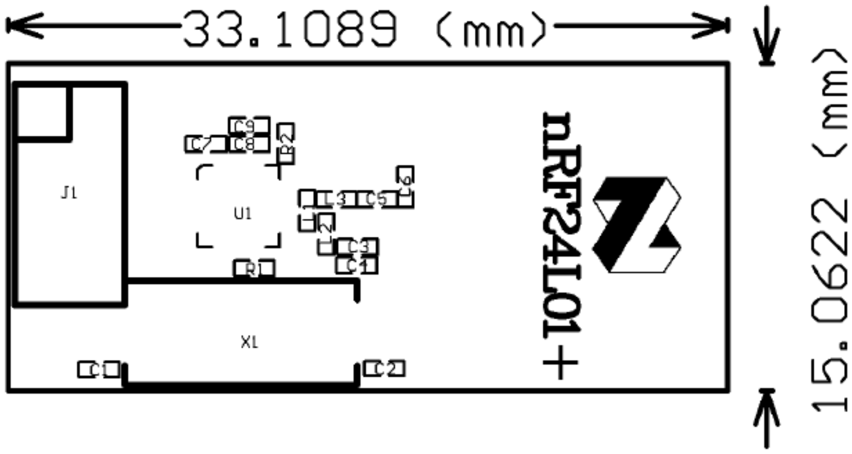


Figure 33. Top overlay (nRF24L01+ RF layout with single ended connection to PCB antenna and 0402 size passive components)

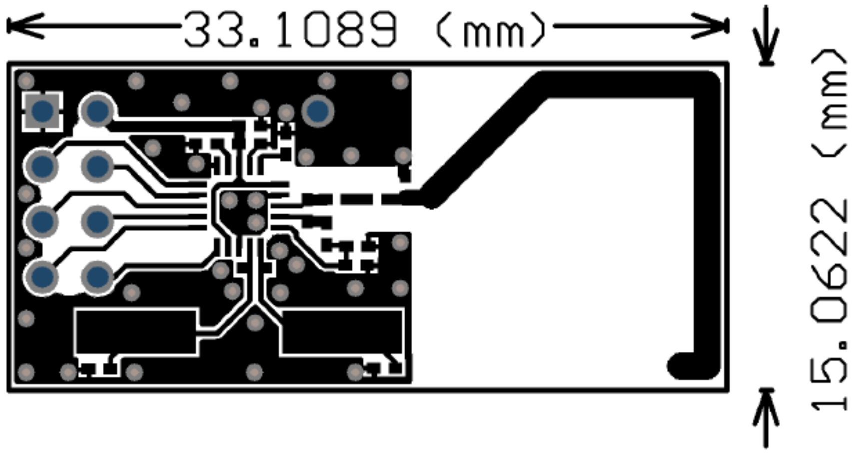


Figure 34. Top layer (nRF24L01+ RF layout with single ended connection to PCB antenna and 0402 size passive components)

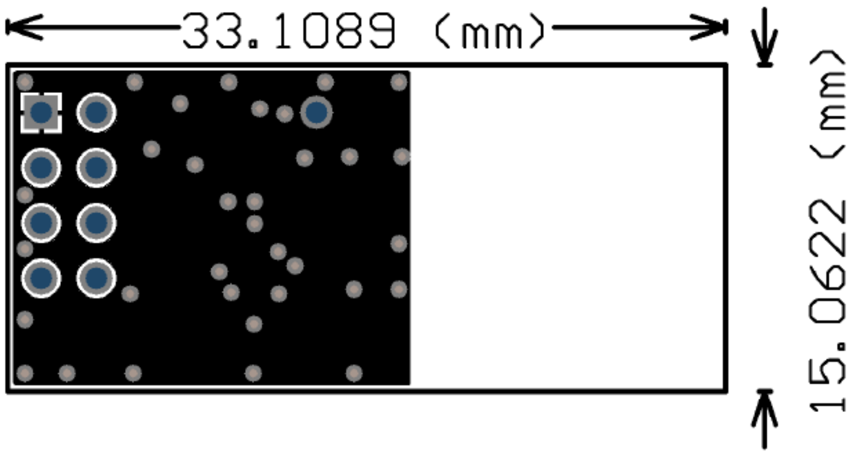


Figure 35. Bottom layer (nRF24L01+ RF layout with single ended connection to PCB antenna and 0402 size passive components

The nest figure (Figure 36., Figure 37. and Figure 38.) is for the SMA output to have a board for direct measurements at a 50Ω SMA connector.

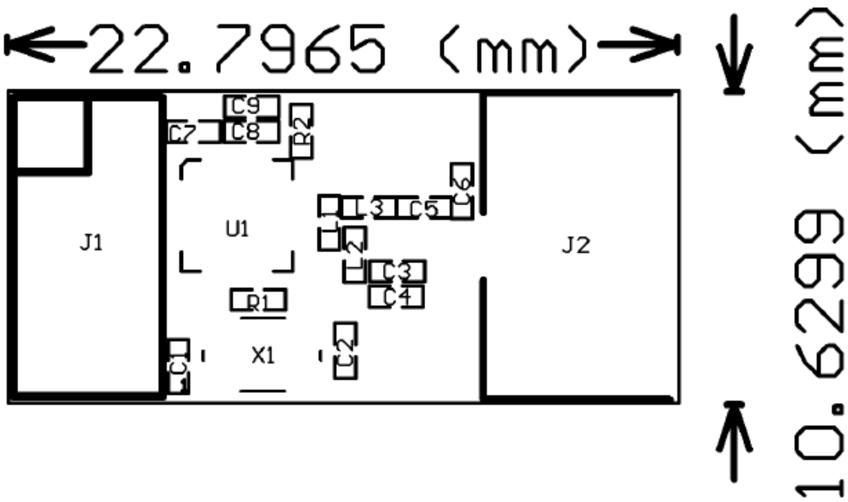
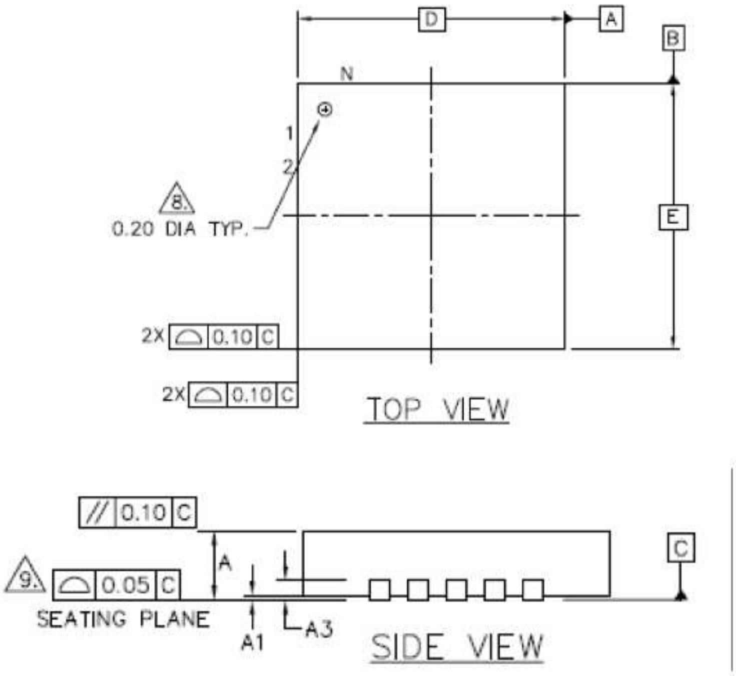
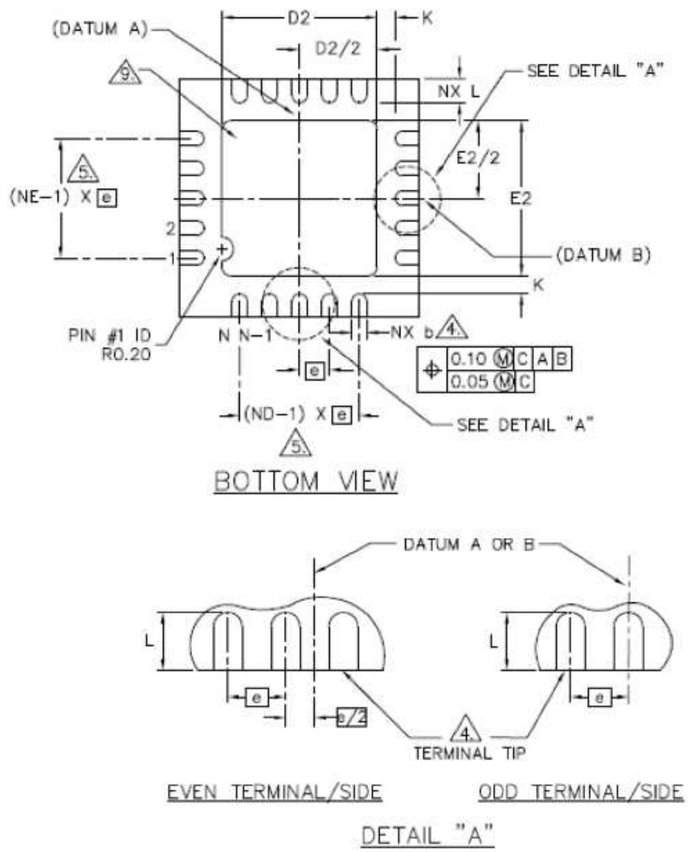


Figure 36. Top Overlay (Module with OFM crystal and SMA connector)

12 Mechanical specifications

nRF24L01+ uses the QFN20 4x4 package, with matt tin plating.





Package Type		A	A1	A3	K	D/E	e	D2/E2	L	L1	b
Saw QFN20	**Min.**	0.80	0.00					2.50	0.35		0.18
(4x4 mm)	**Typ.**	0.85	0.02	0.20	0.20	4.0	0.5 BSC	2.60	0.40	0.15	0.25
	Max	0.95	0.05	REF.	min.	BSC[a]		2.70	0.45	max	0.30

a. BSC: Basic Spacing between Centers, ref. JEDEC standard 95, page 4.17-11/A

Figure 39. nRF24L01+ Package Outline

nRF24L01+ Product Specification

14 Glossary of Terms

Term	Description
ACK	Acknowledgement
ACS	Adjacent Channel Selectivity
AGC	Automatic Gain Control
ART	Auto Re-Transmit
CD	Carrier Detect
CE	Chip Enable
CLK	Clock
CRC	Cyclic Redundancy Check
CSN	Chip Select NOT
ESB	Enhanced ShockBurst™
GFSK	Gaussian Frequency Shift Keying
IM	Intermodulation
IRQ	Interrupt Request
ISM	Industrial-Scientific-Medical
LNA	Low Noise Amplifier
LSB	Least Significant Bit
LSByte	Least Significant Byte
Mbps	Megabit per second
MCU	Microcontroller Unit
MISO	Master In Slave Out
MOSI	Master Out Slave In
MSB	Most Significant Bit
MSByte	Most Significant Byte
PCB	Printed Circuit Board
PID	Packet Identity Bits
PLD	Payload
PRX	Primary RX
PTX	Primary TX
PWR_DWN	Power Down
PWR_UP	Power Up
RoHS	Restriction of use of Certain Hazardous Substances
RPD	Received Power Detector
RX	Receive
RX_DR	Receive Data Ready
SPI	Serial Peripheral Interface
TX	Transmit
TX_DS	Transmit Data Sent

Table 32. Glossary

6.5 *SiGe* PA2423L power amplifier datasheet

http://www.datasheetcatalog.org/datasheet/*SiGe*/PA2423L-EV.pdf

SiGe Semiconductor

PA2423L
2.4 GHz Bluetooth Class 1 Power Amplifier IC
Preliminary Information

Applications

- Bluetooth[tm] Class 1
- USB Dongles
- Laptops
- Access Points
- Cordless Piconets

Features

- +22.5dBm at 45% Power Added Efficiency
- Low current 80mA typical @ Pout=+20 dBm
- Temperature stability better than 1dB
- Power-control and Power-down modes
- Single 3.3 V Supply Operation
- Temperature rating: -40C to +85C
- Very small plastic package - 6 lead LPCC (1.6mm x 3.0mm)

Ordering Information

Type	Package	Shipping Method
PA2423L	6 - LPCC	Tape and reel Tubes -samples
PA2423L-EV	Evaluation kit	

Product Description

A monolithic, high-efficiency, silicon-germanium power amplifier IC, the PA2423L is designed for class 1 Bluetooth[tm] 2.4 GHz radio applications. It delivers +22.5 dBm output power with 45% power-added efficiency – making it capable of overcoming insertion losses of up to 2.5 dB between amplifier output and antenna input in class 1 Bluetooth[tm] applications.

The amplifier features:

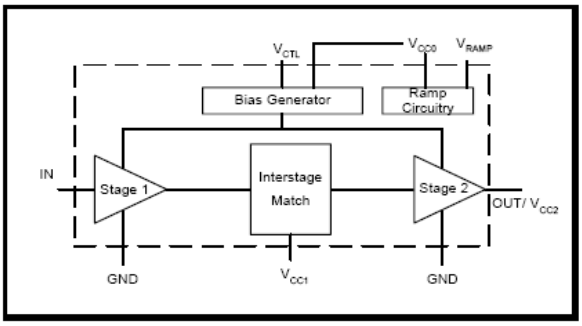
- an analog control input for improving PAE at reduced output power levels;
- a digital control input for controlling power up and power down modes of operation.

An on-chip ramping circuit provides the turn-on/off switching of amplifier output with less than 3dB overshoot, meeting the Bluetooth[tm] specification 1.1.

The PA2423L operates at 3.3V DC. At typical output power level (+22.5 dBm), its current consumption is 125 mA.

The silicon/silicon-germanium structure of the PA2423L – and its exposed-die-pad package, soldered to the system PCB – provide high thermal conductivity and a subsequently low junction temperature. This device is capable of operating at a duty cycle of 100 percent.

Functional Block Diagram

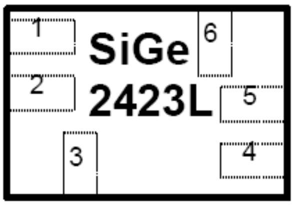


SiGe Semiconductor

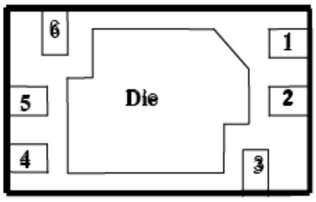
PA2423L
2.4 GHz Bluetooth Class 1 Power Amplifier IC
Preliminary Information

Pin Out Diagram

TOP VIEW



BOTTOM VIEW



Pin Out Description

Pin No.	Name	Description
1	V_{CTL}	Controls the output level of the power amplifier. An analog control signal between 0V and Vcc varies the PA output power between minimum and maximum values
2	V_{RAMP}	Enable/Disable the power amplifier. A digital control signal with Vcc logic high (power up) and 0V logic low (power down) is used to turn the device on and off.
3	IN	Power amplifier RF input, external input matching network with DC blocking is required
4	V_{CCO}	Bias supply voltage
5	V_{CC1}	Stage 1 collector supply voltage, external inter-stage matching network is required
6	OUT/V_{CC2}	PA Output and Stage2 collector supply voltage, external output matching network with DC blocking is required
Die Pad	GND	Heatslug Die Pad is ground

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PA2423L
2.4 GHz Bluetooth Class 1 Power Amplifier IC
Preliminary Information

Absolute Maximum Ratings

Symbol	Parameter	Min.	Max.	Unit
V_{CC}	Supply Voltage	-0.3	+3.6	V
V_{CTL}	Control Voltage	-0.3	V_{CC}	V
V_{RAMP}	Ramping Voltage	-0.3	V_{CC}	V
IN	RF Input Power		+8	dBm
T_A	Operating Temperature Range	-40	+85	°C
T_{STG}	Storage Temperature Range	-40	+150	°C
T_J	Maximum Junction Temperature		+150	°C

Operation in excess of any one of above Absolute Maximum Ratings may result in permanent damage. This device is a high performance RF integrated circuit with ESD rating < 600V and is ESD sensitive. Handling and assembly of this device should be at ESD protected workstations.

DC Electrical Characteristics

Conditions: $V_{CC0} = V_{CC1} = V_{CC2} = V_{RAMP} = 3.3V$, $V_{CTL} = 3.3V$, $P_{IN} = +2dBm$, $T_A = 25°C$, f = 2.45GHz, Input and Output externally matched to 50Ω ,unless otherwise noted.

Symbol	Note	Parameter	Min.	Typ.	Max.	Unit
V_{CC}		Supply Voltage	3	3.3	3.6	V
I_{CC}	1	Supply Current ($I_{CC} = I_{VCC0} + I_{VCC1} + I_{VCC2}$), $V_{CTL} = 3.3V$		125	150	mA
ΔIcc_{temp}	3	Supply Current variation over temperature from $T_A = 25°C$ (-40°C < T_A <+85°C)		25		%
V_{CTL}		PA Output Power Control Voltage Range	0		Vcc	V
I_{CTL}	1	Current sourced by V_{CTL} Pin		200	250	µA
V_{RAMP}	3	Logic High Voltage	2.0			V
	3	Logic Low Voltage			0.8	V
I_{stdby}	1	Leakage Current when $V_{ramp} = 0V$, V_{ctl} = high		0.5	10	µA

SiGe Semiconductor

PA2423L
2.4 GHz Bluetooth Class 1 Power Amplifier IC
Preliminary Information

AC Electrical Characteristics

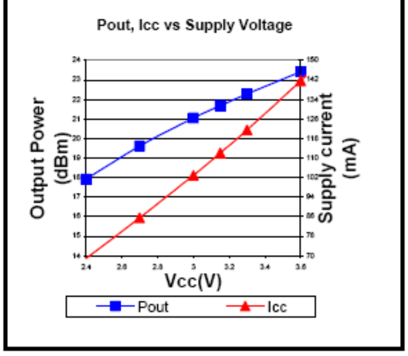
Conditions: $V_{CC0} = V_{CC1} = V_{CC2} = V_{RAMP}$ =3.3V, V_{CTL} = 3.3V, PIN =+2 dBm, T_A =25°C, f =2.45 GHz, Input and Output externally matched to 50Ω, unless otherwise noted.

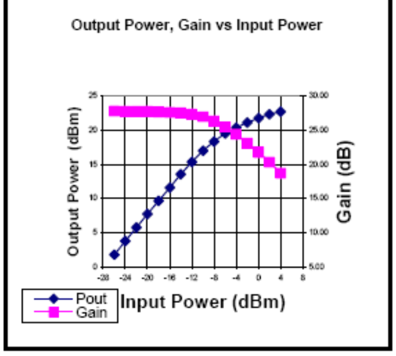
Symbol	Note	Parameter	Min.	Typ.	Max	Unit
f_{L-U}	3	Frequency Range	2400		2500	MHz
P_{out}	1	Output Power @ P_{IN} =+2 dBm, V_{CTL} = 3.3V	20	22.5	23.5	dBm
	1	Output Power @ P_{IN} =+2 dBm, V_{CTL} =0.4V		-20	0	dBm
ΔP_{temp}	3	Output Power variation over temperature (-40°C <T_A <+85°C)		1	2	dB
dP_{OUT}/dV_{CTL}	3	Control Voltage Sensitivity			120	dBm/V
PAE		Power Added Efficiency at +22.5 dBm Output Power		45		%
G_{VAR}	3	Gain Variation over band (2400-2500 MHz)		0.7	1.0	dB
2f, 3f, 4f, 5f	3.4	Harmonics		-40	-35	dBc
IS21 IOFF	2	Isolation in "OFF" State, P_{IN} = +2dBm, V_{RAMP} = 0V	15	20		dB
IS12I	2	Reverse Isolation	32	42		dB
STAB	2	Stability (P_{IN} = +2dBm, Load VSWR = 6:1)	All non-harmonically related outputs less than -50 dBc			

Notes: (1) Guaranteed by production test at T_A =25°C.
(2) Guaranteed by design only
(3) Guaranteed by design and characterization
(4) Harmonic levels are greatly affected by topology of external matching networks.

Typical Performance Characteristics

Test Conditions: SiGe PA2423L-EV: $V_{CC0}=V_{CC1}=V_{CC2}=V_{RAMP}$=3.3V, V_{CTL} = 3.3V, P_{IN} = +2 dBm, T_A = 25°C, f = 2.45GHz, Input and Output externally matched to 50Ω, unless otherwise noted.





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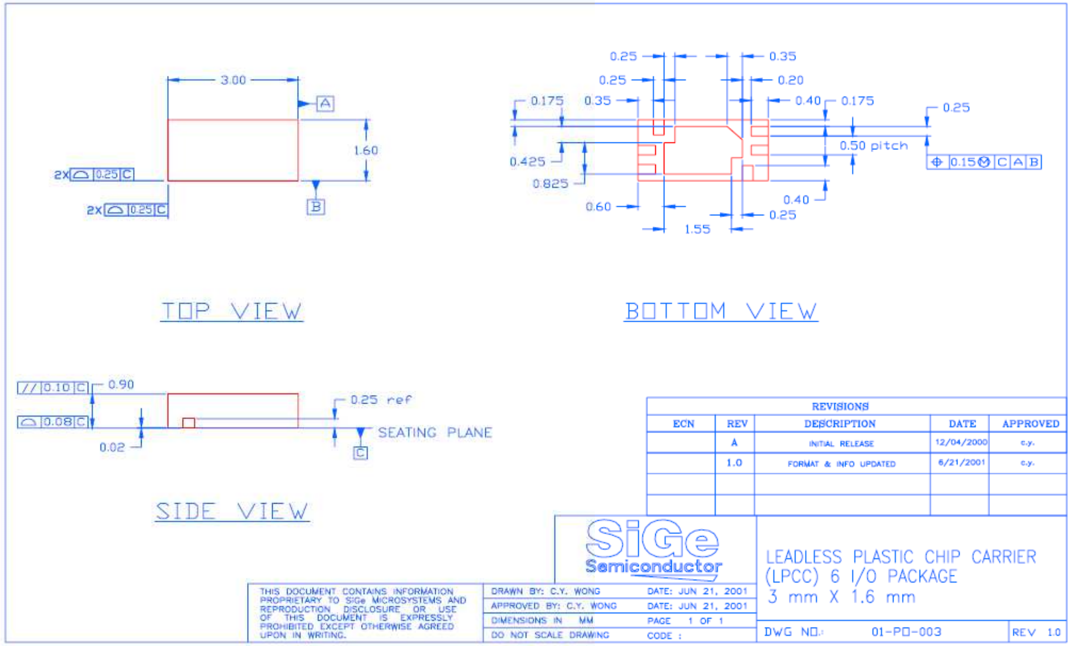
Package Dimensions

The PA2423L is packaged in a 1.6 mm x 3.0 mm 6 lead LPCC package. The underside of the package is an exposed die-pad structure. This allows for direct soldering to the PCB for enhanced thermal conductivity. The package dimensions are shown in the drawing below.



Using V_{CTL}

V_{CTL} is an analog pin that is designed to control the gain of PA2423L. Applying a voltage between 0V and Vcc will adjust the gain between -15dB and 21 dB. Used in combination with a variable drive level to PA2423L, the V_{CTL} function can greatly optimize the PAE of the system at all four Bluetooth™ transmitted power levels.

By applying approximately 1.4V to V_{CTL}, for example, a Class1 radio can be modified to a Class2 radio with the PA2423L consuming only 15mA.

By implementing a resistor DAC, the V_{CTL} pin can interface with Bluetooth™ transceivers offering digital and programmable outputs.

PA2423L
2.4 GHz Bluetooth Class 1 Power Amplifier IC
Preliminary Information

http://www.sige.com

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6.6 *Digi* 9Xtend RF module datasheet

https://www.sparkfun.com/products/9411

XTend® OEM RF Modules

1 Watt/900 MHz OEM RF Modules

Long-range wireless modules enable communication from UART serial data with peer-to-peer, point-to-multipoint, repeater and DigiMesh® networking topologies.

Overview

The XTend OEM RF module provides unprecedented range in a low-cost wireless data solution. The module is easy to use, requires minimal power, provides reliable delivery of critical data between devices, and its small form factor saves valuable board space.

The XTend module utilizes FHSS (Frequency Hopping Spread Spectrum) agility to avoid interference by hopping to a new frequency on every packet transmission or re-transmission. Its transmit power is software adjustable from 1 mW to 1 W—the maximum output power allowable by governments that use 90(MHz as a license-free band. The XTend module is approved for use in the United States, Canada, Australia and other countries (contact Digi for a complete listing).

Innovations stamped in its design enable the XTend module to supply two- to eight-times the range of other modules operating within the unlicensed 900 MHz frequency band. The range gained by OEMs and integrators is due to proprietary technologies embedded into each module, including superior RX (receiver) sensitivity, interference immunity, modulation/demodulation techniques, and others.

No configuration is necessary for out-of-the-box RF communication. The XTend module's default configuration supports a wide range of data system applications. Advanced configurations can be implemented using simple AT or binary commands.

Application Highlight

Features/Benefits

- Indoor/urban range up to 3000 feet
- Outdoor line-of-sight range up to 40 miles (with high gain antenna)
- Outstanding receiver sensitivity (-110 dBm @ 9600 bps)
- Peer-to-peer, point-tomultipoint, repeater, and DigiMesh networking topologies
- Adjustable power output from 1 mW to 1 W; up to 4 W EIRP (with 6 dBi antenna)
- Low power consumption for power-sensitive applications
  - Pin, serial port and cyclic sleep modes available
- Fully interoperable with other Digi Drop-in Networking products, including extenders and XTend-PKG modems
- RPSMA and MMCX antenna options

Features/Specifications

PERFORMANCE

- Indoor/Urban range (w/ 2.1 dB dipole antenna): Up to 3000 feet (900 m)
- Outdoor RF line-of-sight range (w/high gain antenna): Up to 40 miles (64 km)
- Outdoor RF line-of-sight range (w/ 2.1 dB dipole antenna): Up to 14 miles (22 km)
- Transmit power output (software selectable): 1mW - 1W (0 - 30 dBm)
- Interface data rate: 10 - 230,400 bps (including non-standard baud rates)
- Receiver sensitivity: -110 dBm (@9,600 bps throughput data rate), -100 dBm (@115,200 bps)
- Throughput data rate (software selectable): 9,600 or 115,200 bps
- RF data rate: 10,000 bps or 125,000 bps

ENVIRONMENTAL

- Operating temperature: -40º C to 85º C (Industrial)

CERTIFICATIONS

- FCC ID (U.S. Certification Part 15.247):
  - OUR-9XTEND
- IC ID (Canada):
  - 4214A-9XTEND
- Australia

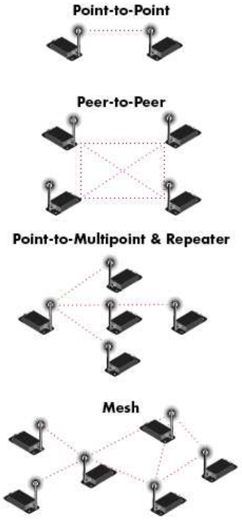
POWER REQUIREMENTS

- Supply voltage: 2.8 – 5.5 VDC
- RX current: 80 mA
- Transmit current: See chart below
- Shutdown pin power-down: < 1 µA
- Pin sleep power down: 147 µA
- Cyclic sleep (idle current): 0.3 – 0.8 mA (16 sec cyclic sleep)

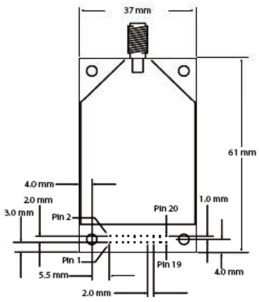
NETWORKING AND SECURITY

- Frequency range: ISM 902 – 928 MHz
- Spread Spectrum: FHSS (Frequency Hopping Spread Spectrum)
- Modulation: FSK (Frequency Shift Keying)
- Supported network topologies: Point-to-Point, Point-to-Multipoint, Repeater, Mesh (Mesh networking and 256-bit AES Encryption capabilities are currently only available in separate releases)
- Channel capacity: 10 hop sequences share 50 frequencies
- Encryption: 256-bit / 128-bit AES

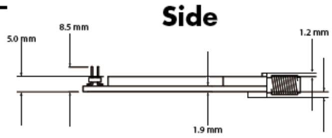
Network Architectectures



Top



Side



Power Requirements (Relative to Each Transmit Power Output Option)					
Transmit Power Output	1 mW	10 mW	100 mW	500 mW	1 W
Supply Voltage	2.8 - 5.5 VDC	2.8 - 5.5 VDC	2.8 - 5.5 VDC	3.0 - 5.5 VDC	4.75 - 5.5 VDC
Transmit Current (5V) Typical	110 mA	140 mA	270 mA	500 mA	730 mA
Transmit Current (3.3V) Typical	90 mA	100 mA	260 mA	600 mA	N/A

Visit www.digi.com for part numbers.

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6.7 *Radiometrix* NTX2 transceiver datasheet

http://www.*Radiometrix*.com/files/additional/ntx2nrx2.pdf

RADIOMETRIX

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Tel: +44 (0) 20 8909 9595, Fax: +44 (0) 20 8909 2233, www.radiometrix.com

NTX2 / NRX2 Issue 1, 30 July 2012

UHF Narrow Band FM TX & RX

The NTX2 transmitter and NRX2 receiver offer a low power, reliable data link in a Radiometrix SIL standard pin out and foot print. This makes the NTX2/NRX2 pair ideally suited to those low power applications where existing single frequency wideband UHF modules have insufficient range. NTX2 HP (25mW) variant can be used in applications where greater radiated power is desired (for example when space limitations dictate the use of small and inefficient antenna, or in countries where the extra power is permitted)

Figure 1: NRX2-434.650-10 NTX2-434.650-10

Features

- Conforms to ETSI EN 300 220-3 (radio) and EN 301 489-3 (EMC)
- Standard frequencies: 434.075MHz, 434.650MHz and 458.700MHz
- Custom frequencies available in 433MHz (EU) and 458MHz (UK) band
- Data rates up to 10kbps
- Usable range over 500m
- 25kHz Channel spacing
- Longer range compared to Wide Band FM modules

Available for licence-exempt operation in the 433MHz (EU) and 458MHz (UK) bands, the NTX2 & NRX2 modules combine effective screening with internal filtering to minimise spurious radiation and susceptibility thereby ensuring EMC compliance. They can be used in existing low data rate (<10kbps) applications where the operating range of the system using TX2 transmitter and RX2 receiver need to be extended. They are particularly suitable for point-to-point and point-to-multipoint wireless links where longer ranges are required at low data rates.

Technical Summary

Transmitter – NTX2

- 3 stage crystal controlled VCXO
- Supply 2.9V - 15V @ 18mA (internal 2.8V voltage regulator)
- Data bit rate: 10kbps max.
- Transmit power: +10dBm (10mW) or +14dBm (25mW HP variant)

Receiver – NRX2

- Double conversion FM superhet
- SAW band pass filter, image rejection: 50dB
- Intermediate Frequencies (IF): 21.4MHz, 455kHz
- Supply range: 2.9V - 15V @ 14mA (internal 2.8V voltage regulator)
- Data bit rate: 10kbps max.
- Receiver sensitivity: -118dBm (for 12dB SINAD) / -112dBm (for 1ppm BER)
- Local Oscillator (LO) re-radiation: <-60dBm
- Adjacent Channel: -70dBm
- Blocking: -84dB

Evaluation platforms: NBEK + SIL carrier

Functional description

The NTX2 transmitter consists of a Frequency Modulated (FM) Voltage Controlled Crystal Oscillator (VCXO) feeding a frequency multiplier with two stage amplifier and RF filter. Operation can be controlled by the EN (Enable) line, the transmitter achieving full RF output typically within 5ms of this line being pulled high. The RF output is filtered to ensure compliance with the appropriate radio regulations and fed to the 50Ω antenna pin.

The NRX2 module is a double conversion NBFM superhet receiver capable of handling data rates of up to 10kbps. It will operate from a supply of 2.9V to 15V and draws 14mA when receiving. A signal strength (RSSI) output with greater than 60dB of range is provided. The SIL style NRX2 measures 47 x 17 x 8 mm excluding the pins.

NTX2 Transmitter

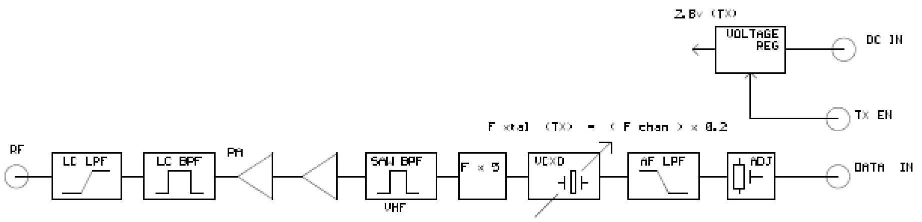

Figure 2: NTX2 block diagram

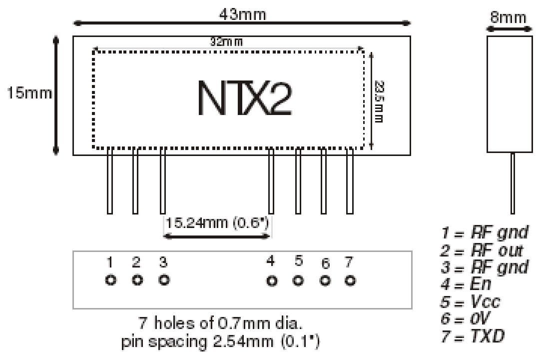

Figure 3: NTX2 pin-out and dimension

User interface

NTX2 pin	Name	Function
1, 3	RF gnd	RF ground is internally connected to the module screen and pin 6 (0V). These pins should be directly connected to the RF return path - e.g. coax braid, main PCB ground plane etc.
2	RF out	50Ω RF output to the antenna
4	EN	Pull high to enable Transmitter (3V CMOS logic)
5	Vcc	2.9 – 15V DC power supply
6	0V	Ground
7	TXD	DC coupled input for 3V CMOS logic. R_{in} = 100kΩ

Notes:

1. EN pin should not be left floating
2. Pinout footprint is as TX1H.
3. Compatible with RX2M, RLC2 and NRX2

NRX2 receiver

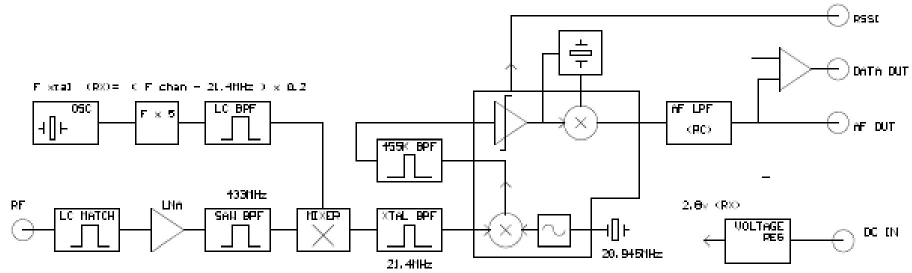

Figure 4: NRX2 block diagram

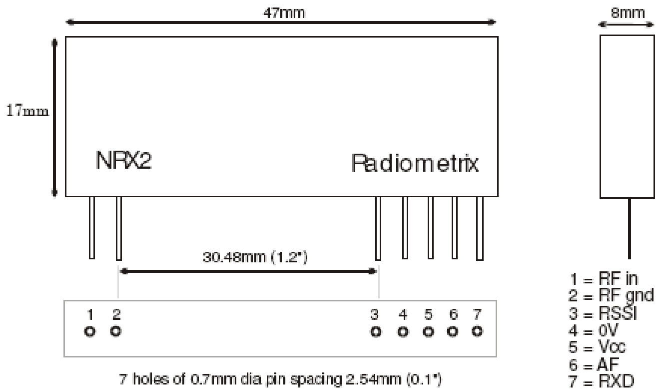

Figure 5: NRX2 pin-out and dimension

User interface – NRX2

NRX2 pin	Name	Function
1	RF in	50Ω RF input from the antenna
2	RF gnd	RF Ground is internally connected to the module screen and pin 4 (0V). These pins should be directly connected to the RF return path - e.g. coax braid, main PCB ground plane etc.
3	RSSI	Received Signal Strength Indicator with >60dB range. DC level between 0.5V and 2V
4	0V	Ground
5	Vcc	2.9 – 15V DC power supply
6	AF	500mV$_{pk-pk}$ audio. DC coupled, approx 0.8V bias
7	RXD	Received Data output from the internal data slicer. The data is squared version of the Audio signal on pin 6 and is true data, i.e. as fed to the transmitter. Output is "open-collector" format with internal 10kΩpull-up to Vcc (pin 5). Suitable for bi-phase codes

Notes:

1. Pinout is as our wideband RX2A receiver

Absolute maximum ratings

Exceeding the values given below may cause permanent damage to the module.

Operating temperature	-10°C to +60°C
Storage temperature	-30°C to +70°C
NTX2	
Vcc, TXD (pins 5,7)	-0.3V to +16.0V
En (pin 4)	-0.3V to +Vcc V
RF out (pin 2)	±50V @ <10MHz, +20dBm @ >10MHz
NRX2	
Vcc, RXD (pins 7,9)	-0.3V to +16.0V
En, RSSI, AF (pins 4,5,8)	-0.3V to +Vcc V
RF in (pin 1)	±50V @ <10MHz, +13dBm @ >10MHz

Performance specifications: NTX2 transmitter
(Vcc = 3V / temperature = 20°C unless stated)

General	pin	min.	typ.	max.	units	notes
DC supply						
Supply voltage	5	2.9	3.0	15	V	
TX Supply current (10mW)	5		18	-	mA	
TX Supply current (25mW HP)	5		28		mA	
Antenna pin impedance	2	-	50	-	□	
RF						
RF centre frequency		-		-	MHz	1
NTX2-434.650-10(-HP)			434.650			
NTX2-434.075-10(-HP)			434.075			
NTX2-458.700-10(-HP)			458.700			
Channel spacing		-	25	-	kHz	
Number of channels		-	1	-		
RF power output (10mW)	2	9	10	11	dBm	2
RF power output (25mW HP)	2		14			2
Spurious emissions	2	-	-	-40	dBm	7
Adjacent channel TX power		-	-37	-	dBm	
Frequency accuracy		-	-	±2.5	kHz	3
FM deviation (peak)		±2.5	±3.0	±3.5	kHz	4
Baseband						
Modulation type		-	FSK	-		F3D
Modulation bandwidth @ -3dB		0	-	5	kHz	
TXD input level (logic low)	7	-	0	-	V	5
TXD input level (logic high)	7	-	3.0	-	V	5
Distortion			TBA		%	6
Dynamic timing						
TX Enable to full RF		-	-	5	ms	

Notes:
1. Available in 25kHz channel steps on other custom frequencies in 433MHz/458MHz band
2. Measured into 50Ω resistive load.
3. Total over full supply and temperature range.
4. With 0V – 3.0V modulation input.
5. To achieve specified FM deviation.
6. For $1V_{pk\text{-}pk}$ signal biased at 1.4V
7. Complies with spurious emission limits of ETSI EN 300 220-1 (SRD) and ACMA (LIPD)

Performance specifications: NRX2 receiver
(Vcc = 3V / temperature = 20°C unless stated)

	pin	min.	typ.	max.	units	notes
DC supply						
Supply voltage	7	2.9	3.0	15	V	
Supply current	7	-	14	-	mA	
RF/IF						
RF centre frequency	1,6				MHz	
NRX2-434.650-10			434.650			
NRX2-434.075-10			434.075			
NRX2-458.700-10			458.700			
RF sensitivity @ 12dB SINAD	1, 6	-	-118	-	dBm	
RF sensitivity @ 1ppm BER	1, 7	-	-112	-	dBm	
RSSI threshold	1, 3	-	-125	-	dBm	1
RSSI range	1, 4	-	55	-	dB	1
IF bandwidth		-	TBA	-	kHz	
Blocking	1	-	84	-	dB	
Image rejection	1	-	55	-	dB	
Adjacent channel rejection	1	-	70	-	dB	
Spurious response rejection	1	-	55	-	dB	
LO re-radiation	1	-	-	-60	dBm	2
Baseband						
Baseband bandwidth @ -3dB	6	0	-	5	kHz	1
AF level	6	-	500	-	mV_{p-p}	3
DC offset on AF out	6	-	0.8	-	V	
Distortion on recovered AF	6	-	TBA	-	%	
Dynamic timing						
Power up with signal present						
Power up to valid RSSI	5, 3	-	3	-	ms	
Power up to valid AF	5,6		2		ms	
Power up to stable data	5, 7	-	TBA	10	ms	
Signal applied with supply on						
Signal to valid RSSI	1, 3	-	2	-	ms	
Signal to valid AF	1,6		1		ms	
Signal to stable data	1, 7	-	TBA	5	ms	4
Time between data transitions	7	0.1	-	TBA	ms	

Notes:

1. See applications information for further details.
2. Exceeds EN/EMC requirements at all frequencies.
3. For received signal with ±3kHz FM deviation. AF output is inverted with respect to TXD input.
4. For 50:50 mark to space ratio (i.e. squarewave).

Applications information

Power supply requirements

Both modules have built-in regulators which deliver a constant 2.8V to the module circuitry when the external supply voltage is 2.9V or greater, with 40dB or more of supply ripple rejection. This ensures constant performance up to the maximum permitted rail, and removes the need for external supply decoupling except in cases where the supply rail is extremely poor (ripple/noise content >100mV$_{pk-pk}$).

The Enable pin allows the TX module to be turned on or off under 3V logic control with a constant DC supply to the Vcc pin. The module current in power-down mode is less than 1µA.

The Enable pin should be tied directly to the Vcc pin if this facility is not required.

TX modulation requirements

The module is factory-set to produce the specified FM deviation with a TXD input to pin 7 of 3V amplitude, i.e. 0V "low", 3V "high

If the data input level is greater than 3V, a resistor must be added in series with the TXD input to limit the modulating input voltage to a maximum of 3V on pin 7. TXD input resistance is 100kΩ to ground, giving typical required resistor values as follows:

Vcc	Series resistor
≤3V	-
3.3V	10 kΩ
5V	68kΩ
9V	220kΩ

NRX2 Received Signal Strength Indicator (RSSI)

The NRX2 receiver incorporates a wide range RSSI which measures the strength of an incoming signal over a range of 55dB or more. This allows assessment of link quality and available margin and is useful when performing range tests.

The output on pin 3 of the module has a standing DC bias of <0.5V with no signal, rising to 2V at maximum indication.

Typical RSSI characteristic is as shown below:

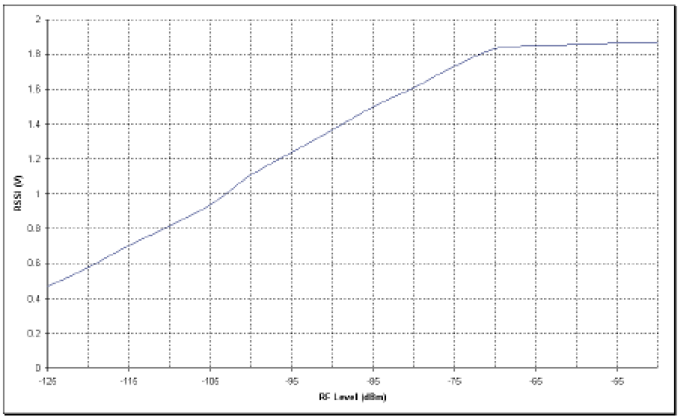

Figure 6: RSSI response curve

Expected range

Predicting the range obtainable in any given situation is notoriously difficult since there are many factors involved. The main ones to consider are as follows:

- Type and location of antennas in use
- Type of terrain and degree of obstruction of the link path
- Sources of interference affecting the receiver
- "Dead" spots caused by signal reflections from nearby conductive objects
- Data rate and degree of filtering employed

The following are typical examples – but range tests should always be performed before assuming that a particular range can be achieved in a given situation:

Data rate	Tx antenna	Rx antenna	Environment	Range
10kbps	¼ wave	¼ wave	urban/obstructed	300m
10kbps	¼ wave	¼ wave	Rural/open	500m
10kbps	helical	helical	in-building	100m

Data formats and range extension

The NTX2's TXD input is normally driven directly by logic levels but will also accept analogue drive (e.g. 2-tone signalling). In this case it is recommended that TXD (pin 7) be DC-biased to 1.2V approx. with the modulation ac-coupled and limited to a maximum of $2V_{p-p}$ to minimise distortion over the link. The varactor modulator in the NTX2 introduces some 2^{nd} harmonic distortion which may be reduced if necessary by predistortion of the analogue waveform.

Although the modulation bandwidth of the NTX2 extends down to DC as does the NRX2 it is not advisable to use data containing a DC component. This is because frequency errors and drifts between the transmitter and receiver occur in normal operation, resulting in DC offset errors on the NRX2's audio output.

The NRX2 in standard form incorporates a low pass filter with a 5kHz nominal bandwidth. In conjunction with similar filtering in the NTX2 an overall system bandwidth of 5kHz is obtained. This is suitable for transmission of data at raw bit rates up to 10kbps.

Antennas

The choice and positioning of transmitter and receiver antennas is of the utmost importance and is the single most significant factor in determining system range. The following notes are intended to assist the user in choosing the most effective antenna type for any given application.

Integral antennas

These are relatively inefficient compared to the larger externally-mounted types and hence tend to be effective only over limited ranges. They do however result in physically compact equipment and for this reason are often preferred for portable applications. Particular care is required with this type of antenna to achieve optimum results and the following should be taken into account:

1. Nearby conducting objects such as a PCB or battery can cause detuning or screening of the antenna which severely reduces efficiency. Ideally the antenna should stick out from the top of the product and be entirely in the clear, however this is often not desirable for practical/ergonomic reasons and a compromise may need to be reached. If an internal antenna must be used try to keep it away from other metal components and pay particular attention to the "hot" end (i.e. the far end) as this is generally the most susceptible to detuning. The space around the antenna is as important as the antenna itself.

2. Microprocessors and microcontrollers tend to radiate significant amounts of radio frequency hash which can cause desensitisation of the receiver if its antenna is in close proximity. The problem becomes worse as logic speeds increase, because fast logic edges generate harmonics across the UHF range which are then radiated effectively by the PCB tracking. In extreme cases system range may be reduced by a factor of 5 or more. To minimise any adverse effects situate antenna and module as far as possible from any such circuitry and keep PCB track lengths to the minimum possible. A ground plane can be highly effective in cutting radiated interference and its use is strongly recommended.

A simple test for interference is to monitor the receiver RSSI output voltage, which should be the same regardless of whether the microcontroller or other logic circuitry is running or in reset.

The following types of integral antenna are in common use:

Quarter-wave whip. This consists simply of a piece of wire or rod connected to the module at one end. At 434MHz the total length should be 164mm from module pin to antenna tip including any interconnecting wire or tracking. Because of the length of this antenna it is almost always external to the product casing.

Helical. This is a more compact but slightly less effective antenna formed from a coil of wire. It is very efficient for its size, but because of its high Q it suffers badly from detuning caused by proximity to nearby conductive objects and needs to be carefully trimmed for best performance in a given situation. The size shown is about the maximum commonly used at 434MHz and appropriate scaling of length, diameter and number of turns can make individual designs much smaller.

Loop. A loop of PCB track having an inside area as large as possible (minimum about $4cm^2$), tuned and matched with 2 capacitors. Loops are relatively inefficient but have good immunity to proximity detuning, so may be preferred in shorter range applications where high component packing density is necessary.

Integral antenna summary:

Feature	whip	helical	loop
Ultimate performance	***	**	*
Ease of design set-up	***	**	*
Size	*	***	**
Immunity to proximity effects	**	*	***

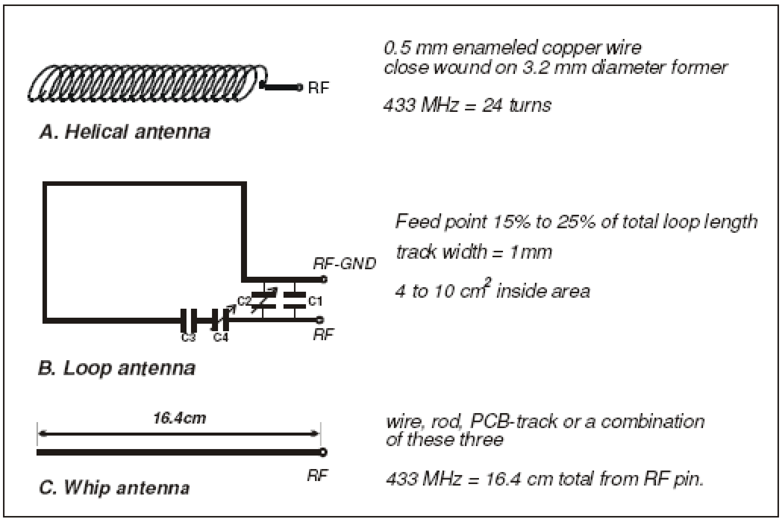

Figure 7: integral antenna configurations

External antennas

These have several advantages if portability is not an issue, and are essential for long range links. External antennas can be optimised for individual circumstances and may be mounted in relatively good RF locations away from sources of interference, being connected to the equipment by coax feeder.

Helical. Of similar dimensions and performance to the integral type mentioned above, commercially-available helical antennas normally have the coil element protected by a plastic moulding or sleeve and incorporate a coax connector at one end (usually a straight or right-angle BNC/SMA type). These are compact and simple to use as they come pre-tuned for a given application, but are relatively inefficient and are best suited to shorter ranges.

Quarter-wave whip. Again similar to the integral type, the element usually consists of a stainless steel rod or a wire contained within a semi-flexible moulded plastic jacket. Various mounting options are available, from a simple BNC/SMA connector to wall brackets, through-panel fixings and magnetic mounts for temporary attachment to steel surfaces.

A significant improvement in performance is obtainable if the whip is used in conjunction with a metal ground plane. For best results this should extend all round the base of the whip out to a radius of the length of the whip used (under these conditions performance approaches that of a half-wave dipole) but even relatively small metal areas will produce a worthwhile improvement over the whip alone. The ground plane should be electrically connected to the coax outer at the base of the whip. Magnetic mounts are slightly different in that they rely on capacitance between the mount and the metal surface to achieve the same result.

A ground plane can also be simulated by using 3 or 4 quarter-wave radials equally spaced around the base of the whip, connected at their inner ends to the outer of the coax feed. A better match to a 50Ω coax feed can be achieved if the elements are angled downwards at approximately 30-40° to the horizontal.

Module mounting considerations

The modules may be mounted vertically or bent horizontal to the motherboard. Note that the components mounted on the underside of the NTX2 and NRX2 are relatively fragile – avoid direct mechanical contact between these and other parts of the equipment if possible, particularly in situations where extreme mechanical stresses could routinely occur (as a result of equipment being dropped onto the floor, etc).

Good RF layout practice should be observed. 50Ω microstrip line or coax or a combination of both should be used to connect RF pin of the module to RF connector or antenna. It is desirable (but not essential) to fill all unused PCB area around the module with ground plane.

Variants and ordering information

The NTX2 transmitters and NRX2 receivers are manufactured in the following variants as standard:

At 434.650MHz:	NTX2-434.650-10	10mW	Transmitter
	NTX2-434.650-10-HP	25mW	Transmitter
	NRX2-434.650-10		Receiver
At 434.075MHz:	NTX2-434.075-10	10mW	Transmitter
	NTX2-434.650-10-HP	25mW	Transmitter
	NRX2-434.075-10		Receiver
At 458.700MHz:	NTX2-458.700-10	10mW	Transmitter
	NTX2-458.700-10-HP	25mW	Transmitter
	NRX2-458.700-10		Receiver

Other frequency variants can be supplied to individual customer requirements in the 433MHz (European) and 458MHz (UK) licence exempt bands

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Limitation of liability

The information furnished by Radiometrix Ltd is believed to be accurate and reliable. Radiometrix Ltd reserves the right to make changes or improvements in the design, specification or manufacture of its subassembly products without notice. Radiometrix Ltd does not assume any liability arising from the application or use of any product or circuit described herein, nor for any infringements of patents or other rights of third parties which may result from the use of its products. This data sheet neither states nor implies warranty of any kind, including fitness for any particular application. These radio devices may be subject to radio interference and may not function as intended if interference is present. We do NOT recommend their use for life critical applications.
The Intrastat commodity code for all our modules is: 8542 6000

R&TTE Directive

After 7 April 2001 the manufacturer can only place finished product on the market under the provisions of the R&TTE Directive. Equipment within the scope of the R&TTE Directive may demonstrate compliance to the essential requirements specified in Article 3 of the Directive, as appropriate to the particular equipment.
Further details are available on The Office of Communications (Ofcom) web site:
http://www.ofcom.org.uk/

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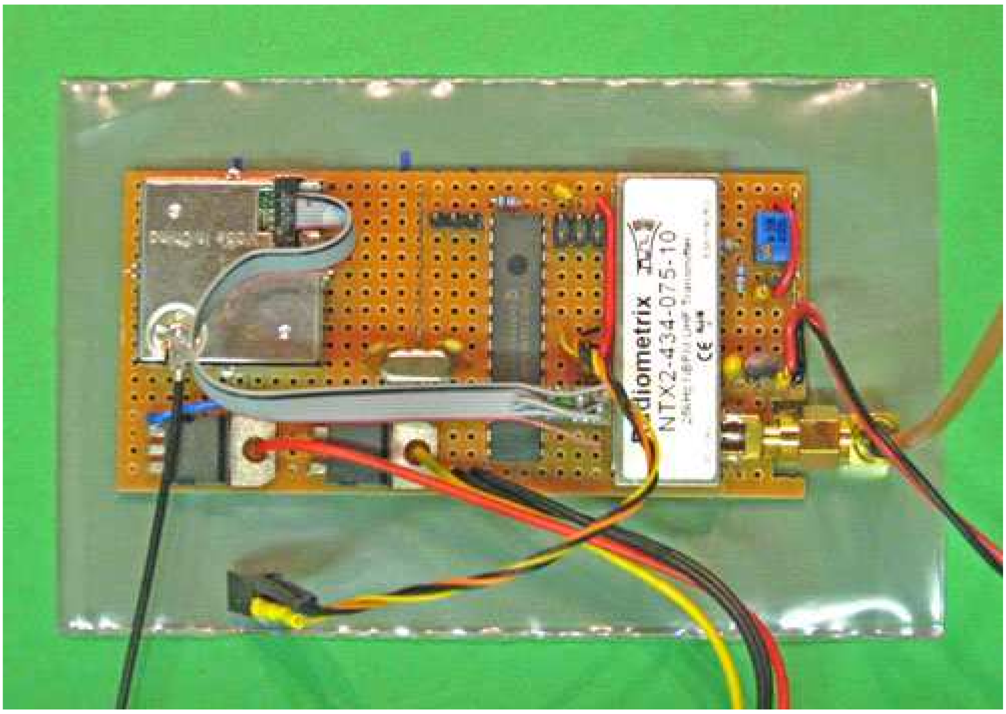
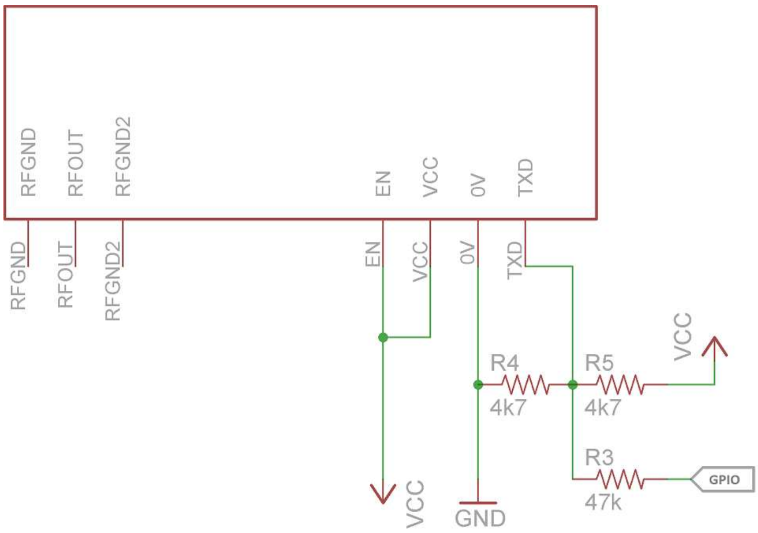


Example of amateur implementation
Source: http://www.*Radiometrix*.com/files/additional/Bang-goes-the-theory-2.jpg



$$V_{cc} = 5V$$
$$GPIO_{low} = 0V$$
$$GPIO_{high} = V_{cc}$$
$$R4 = R5 = 4.7k$$
$$R3 = 47k$$
$$\text{NTX2 deviation} \approx 2000Hz/V$$

$$TXD_{low} = \frac{R4||R3}{R4||R3 + R5} V_{cc} = 2.38V$$

$$TXD_{high} = \frac{R4}{R5||R3 + R3} V_{cc} = 2.62V$$

$$TXD_{high} - TXD_{low} = 0.24V$$

$$shift = 0.24 \times 2000 \approx 480Hz$$

Example of Arduino connection
Source: http://ukhas.org.uk/guides:linkingarduinotontx2

6.8 SMA connector family

http://i01.i.aliimg.com/photo/v0/256281235/SMA_connector.jpg