P4XT Digital Multiplexing Transponder Project

Program Proposal

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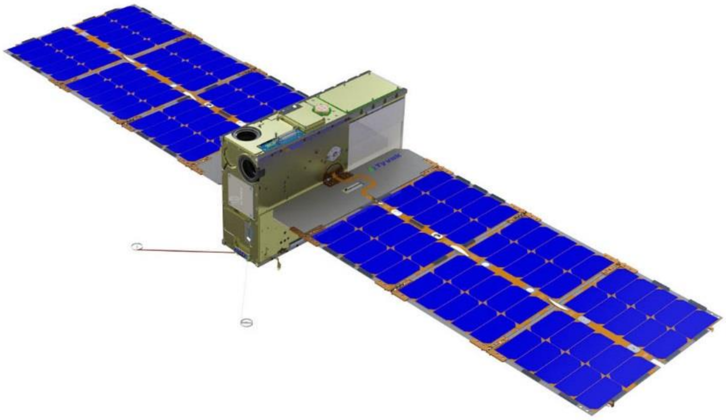

1/9/2020

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1 Executive Summary

1.1 Goal

The goal of this project is to produce open-source Digital Multiplexing Transponders (DMTs) for the Amateur Radio Service Microwave Bands. These DMTs will be suitable for deployment in Geostationary Orbit. In addition, the project will produce a low-cost modem for use with these transponders. The communications systems enabled by these efforts are intended to greatly enhance the purposes of the Amateur Radio and Amateur Radio Satellite services.

1.2 Open Design

This project is entirely open-source. All of the work product will be placed into the public domain. Participation in the project is open to all. The project will prohibit the use or incorporation of any technologies that are not already in the public domain or available for unrestricted use. All contributed work is intended to be classifiable as technical data in the public domain under the U.S. export control regime (ITAR 120.11).

1.3 Projects

The orbiting transponder in space and the modem on the ground are closely related in chicken and egg fashion. A functional system requires both and they must be fully compatible with each other. The engineering efforts required for implementing these two projects, however, involve largely different skill sets. Accordingly, the P4XT project will organize these two efforts as separate co-projects that will be closely coordinated. We refer to the transponder project as P4XDMT. We refer to the ground-based modem project as P4XM.

1.4 The Open Source Hardware Dilemma

Open source development can be fairly described as a free-for-all where talented people can find an “itch” and scratch it. This individual-centric process has produced phenomenal results. However, when the end-goal is a fully refined product, the open source process alone is often insufficient. There are many development tasks required to deploy a fully finished hardware product. Many of these tasks do not generate an itch that anyone is willing to scratch. This is the case with some of the state-of-the-art technologies involved in this project. Refining these technologies into fully productized form will require a highly focused multi-disciplinary engineering effort. The projects will have to be driven to the final goal – they won’t just arrive there on their own.

Stated another way, open source and commercial/aerospace/military development efforts have radically different definitions of “done”. In the open source world, “done” is when you throw it out to a git repository and let people start running it and playing with it. This is what drives open source. Put it out there; get feedback; refine it; put it out again; fork-it, etc. The end results can be great. But you just can’t throw something into space and wait for feedback. You can harness open source for various component pieces, but in the end, you need to deploy a fully working and tested system with very high confidence that it will work out of the box as desired, despite the hazards of space, for many years.

A major problem with complicated volunteer engineering projects is that while it is possible to find qualified individuals willing to volunteer significant amounts of their time, it is very rare to find those who are *also* willing to self-fund major projects or to contribute expensive equipment and software-based tools. This is especially true with complicated engineering activities that involve target equipment costing thousands of dollars and test equipment costing even more.

A second problem is that these engineers are often motivated only when the prospects for eventual success are high. The engineering mind is accustomed to accepting technical risk as this is something that is, at least theoretically, under its control. Financial risk, however, is another matter – something the engineering mind attempts to avoid. Engineers whose time is very valuable may enjoy building windmills – but they don't tilt at them. The likelihood that the project will be seen through to completion can be critical in motivating the volunteer engineering talent required to reach the final goal.

1.5 The Premise

The fundamental premise for this project is that given a commitment for the full funding of the necessary equipment, software tools, test equipment, purchased components and services to successfully complete the project goals - we can attract a more than adequate pool of volunteer engineering talent possessing the combined skill-sets required to complete the multitude of individual engineering tasks associated with this project. These resources will allow the project to proceed in a straightforward professional manner to successful completion.

1.6 Financial Summary

In the traditional complex engineering project, the vast majority of expense is associated with actual engineering salary & benefits. In contrast, with this project it is expected that all of the engineering work will be performed solely by volunteers. The volunteer engineers on the two project teams will each commit from 10 to 40 hours per week over the expected two-year course of the project. Many of these volunteers will have advanced engineering degrees. They will range in background from graduate students, to engineering academics, to retired professionals. Almost all of them will be Amateur Radio Licensees. In addition to the engineering volunteers, extensive important work will be carried out by non-engineer volunteers.

It should be noted that the market value of the engineering hours volunteered by these experienced engineers in their respective fields would be the equivalent of many millions of dollars in a commercial setting. Their no-cost contributions will greatly leverage the funding for the project.

The total budget for the two projects combined is expect to be less than US$ 500,000. The project performance will be spread over two years. Major performance milestones are defined and funding releases can be tied to the major milestones. Additional high level budget information is presented in the body of the proposal.

1.7 Technical Presentation

This project involves numerous technical details covering many specialized fields. The body of the proposal is general and tries to maintain a high-level view, although an engineering background is generally required to fully understand much of the material. Additional technical details are provided in the Appendices. Many of these details are provisional and subject to revision during the early stages of the project as detailed requirements are frozen.

2 Background

2.1 Introduction

Radiocommunication is regulated internationally, by treaty, through the International Telecommunication Union (ITU), an agency of the United Nations, which promulgates the ITU's Radio Regulations (RR). Each country generally regulates Radio Frequency (RF) emissions within its sovereign boundaries through a national administration. For example, in the United States the national administration is the FCC. In the U.K. the national administration is OFCOM and in Germany the national administration is the Bundesnetzagentur.

The ITU defines various radiocommunication services and the national administrations generally follow these definitions. One of these ITU defined services is the Amateur Service. ITU defines the Amateur Service as:

> *"A radiocommunication service for the purpose of self-training, intercommunication and technical investigations carried out by amateurs, that is, by duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest."*

The ITU also defines the Amateur Satellite Service as:

> *"A radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service."*

The Amateur Service is the oldest of radio services and pre-dates the regulation of radiocommunication. In the past 100 years, amateurs have contributed much to the technical arts. Many of the three million or so Amateurs across the globe continue to do so.

2.2 Amateur Service Satellites

Amateur Radio Satellites have operated in space since the dawn of the space age, 50 years ago. Called OSCARs - Orbiting Satellites Carrying Amateur Radio - more than 100 such satellites have been launched and operated. They have served and continue to serve the purposes of Amateur Radio – advancing the radio arts; advancing individual skills in the operating and technical phases of the art; and enhancing international goodwill.

In addition to the satellites built and operated by radio amateurs, amateur service equipment has also been piggy-backed onto satellites deployed for other purposes. These include the

International Space Station and the commercial Es'hail-2 communications satellite. These deployments are often referred to as ride-shares or hosted payloads.

Despite these significant successes, the population of Amateurs using these resources and the total time of actual use has been somewhat limited, especially when compared to the global population of Amateur Service licensees. This is mostly due to the very short time that a satellite in low earth orbit is in view from a particular location – typically a precise timeslot lasting up to 10 minutes a few times each day. The satellite must generally be tracked in some manner and two-way communication is limited to those with mutual visibility of the satellite. While these activities are enjoyable to many, they are not amenable to wide adoption by the Amateur community. They are also of limited use for the Amateur Services mission of providing support for relief operations in cases of emergency or disaster.

While nearly all amateur satellites operate in low-earth orbit, many commercial communications satellites operate from a much higher geostationary earth orbit (GEO), 36,000 km above the surface instead of a few hundred km. At this high altitude, the satellites are synchronized with the rotation of the earth and appear at a fixed point in the sky. This eliminate the need for tracking and provides a 24/7 coverage footprint of up to 1/3 of the globe. Due to the ability to use a simple fixed satellite dish, mass adoption of services using these satellites has occurred. There are presently 100's of millions of small earth stations receiving digital broadcast TV signals from more than 100 GEO (Geostationary Earth Orbit) satellites. In some countries such dishes hang from nearly every window. There are also hundreds of thousands of two-way VSAT (Very Small Aperture Terminals) terminals in daily use.

An amateur radio satellite in geosynchronous orbit has similar advantages. However, as with Satellite TV and VSAT, this requires compatible technology in both the satellite and the ground. The goal of this project is to deliver that technology in usable form.

2.3 Amateur Satellite Frequency Allocations

The frequency spectrum allocated to the Amateur Satellite services is a subset of the Amateur Service frequency allocations. There are restrictions on the frequencies that can be used for the Earth to Space and Space to Earth directions. These frequency allocations are not universally harmonized among the various national administrations within an ITU region or between the three regions.

2.3.1 Threats to Spectrum Allocations

Amateur Radio spectrum allocations have become very valuable resources that are coveted by commercial interests. Much spectrum has already been lost around the world to these interests. "Use it or lose it" is a reality that the Amateur Radio community continuously faces. The FCC in December 2019 proposed to "clear out" the 200MHz spectrum currently allocated on a shared basis to Amateur radio completely eliminating this allocation. There is no assurance that the other allocations will not be lost – especially if their utilization is minimal.

2.3.2 Current Allocations

In the US, the FCC has currently allocated the following microwave spectrum to Amateur Satellite service on a non-exclusive basis:

Table 2-1 US Amateur Downlink Allocations

US AMATEUR SATELLITE SERVICE MICROWAVE DOWNLINK ALLOCATIONS		
BANDWIDTH	**FREQUENCY**	**BAND**
3 MHz	435-438	UHF
50 MHz	2400-2450	S
10 MHz	3400-3410[1]	S
20 MHz	5830-5850	C
50 MHz	10450 - 10500	X
50 MHz	24000 – 24050	K

Table 2-2 US Amateur Uplink Allocations

US AMATEUR SATELLITE SERVICE MICROWAVE UPLINK ALLOCATIONS		
BANDWIDTH	**FREQUENCY**	**BAND**
3 MHz	435-438	UHF
10 MHz	1260 - 1270	L
50 MHz	2400 -2450	S
10 MHZ	3400 - 3410[2]	S
20 MHz	5650 - 5670	C
50 MHz	10450 - 10500	X
50 MHz	24000 - 24050	K

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[1] The FCC is currently planning to eliminate this allocation.

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2.4 Phase 4 Satellites

The various ARSOs[3] (Amateur Radio Satellite Organizations) around the world have adopted a so-called phase system to refer to types of amateur satellites. Phase 4 refers to satellites in geostationary orbit. The first of the Phase 4 satellites is P4A which is now known as QO-100[4]. QO-100 at this moment provides 24/7 coverage from 26E longitude which has visibility to Europe and Africa (but not North America or Japan.)

P4B is a planned mission over North America. This effort is led by Virginia Tech and involves a rideshare on a military satellite with a primary military payload. No other P4 missions have progressed much beyond the talk stage. In this proposal we use the term P4X to refer to any future Phase 4 satellite.

2.4.1 P4A QO-100

Built by Mitsubishi Electric Corporation (MECO) and owned and operated by Es'hailSat of Qatar, the Es'hail-2 commercial communications satellite was launched in November 2018. The satellite carries 24 Ku-band and 11 Kz-band transponders providing direct broadcasting services to the Middle East and North Africa region. A pair of the satellite's spare transponders were modified and configured to provide so-called narrowband (250 kHz) and wideband (8MHz) bent-pipe analog relay capability that operates on allocated Amateur Satellite Service frequencies (S-Band Uplink and X-Band downlink). These analog transponders have been in service for the past year under the designation QO-100 (Qatar Oscar – 100). The P4A project is a cooperative effort between AMSAT-DL (Federal Republic of Germany) and the Qatar Amateur Radio Society (State of Qatar).

Amateur operations through this satellite present a number of technical challenges. The narrowband transponder supports the traditional amateur SSB and other analog modes as well as the low-speed digital modes used for traditional amateur communications. Relatively expensive commercially manufactured HF rigs are used together with relatively expensive transverters. Despite these challenges, the transponder is continuously active.

The QO-100 operating rules allocate the 250kHz of so-called narrowband transponder bandwidth to various traditional analog and digital modes with bandwidths up to 2.7 KHz. This includes about 35 SSB channels in 105kHz. Another 50 kHz is allocated for mixed modes which may also include voice.

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[3] We use the term ARSO to encompass the various non-profit organizations around the world including AMSAT (a.k.a AMSAT-NA), AMSAT-DL, AMSAT-UK, JAMSAT, ARISS, and many others.

[4] Amateur Satellites receive an "OSCAR" number designation only after they achieved actual transmissions from orbit. QO-100 is the 100th satellite to meet this requirement.

2.5 Phase 5 Applications

The various ARSOs use the designation Phase 5 to refer to satellites used on Lunar or Planetary missions. With the recent funding of the Lunar Orbiter Platform Gateway (LOP-G) there will be numerous opportunities where Amateur Radio Service communication payloads may play a role.

3 Statement of Need

3.1 There is No Ready to Fly Payload

There is presently no operational digital multiplexed transponder of any significant capability available for deployment in GEO – nothing even close. If a ride-share to GEO opportunity should present itself tomorrow – there is nothing the community has on offer. Something would have to be cobbled together or a crash development program would have to be whipped up with the hope that it could be completed before the opportunity vanished. This situation is clearly *unacceptable*. The Amateur radio community *must* have a *proven* transponder payload ready to fly.

3.2 Analog Repeaters have Serious Shortcomings

While the traditional analog bent-pipe transponder approach, similar to QO-100, can provide 24/7 capabilities, such transponders do not scale to hundreds or thousands of simultaneous users. Neither do they offer any reasonable immunities to abuse. A single bad actor can hi-jack the transponder at any time. The only effective responses to such actions are to turn off the transponder or jam the offending signal.

3.3 Lack of Disaster Capability

Amateur radio has a long history of providing communications to assist disaster relief efforts. This includes communication within local areas through simplex VHF/UHF and repeaters and communication to the outside world through HF. The number of long-range channels available is extremely limited and the reliability of HF is highly dependent on variable ionospheric conditions. There is a clear need for a rapidly deployable multi-channel 24/7 long-distance capability that is reliable and easy to operate under any conditions and independent from any infrastructure on the ground.

3.4 Paper Designs and Demos are Not Enough

It is not sufficient to have paper designs or live GNU Radio-based[5] demonstrations. These are surely valuable tools that serve well to demonstrate feasibility. But they do not provide high confidence that a working payload or operational system can actually be delivered. What is needed to enhance the confidence level of potential space platform partners is a demonstration of real hardware and real operational capabilities in an environment that can be extrapolated with high confidence to the target space environment. We cannot just say “give us a ride to GEO and we will build something”. Rather we have to be able to say “here is what we have built that is ready to go – help us get it deployed to GEO”.

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[5] GNU Radio is an open source framework for Software Defined Radio development.

3.5 Fulfilling the Need

The P4XT project is designed to fill the above needs. The project will produce ready to fly Digital Multiplexed Transponders (DMTs) for deployment on future rideshares and/or future amateur built GEO space platforms. These will be all digital designs except for their RF front-ends and they will be able to serve large numbers of simultaneous users. The project will produce both the Digital Multiplexed Transponder, easily adaptable to multiple missions and the low-cost modem for earth station terminals suitable for wide adoption by the Amateur Radio community.

In order to enhance confidence with potential space platform partners, the technical and operational characteristics of the system will be demonstrated on the ground using live space segments provided by the wideband analog transponder of QO-100. This demonstration will use the actual hardware and software but will utilize space segments provided through QO-100. This configuration will have double the hops and twice the delays. But it will clearly demonstrate a level of performance that can easily be extrapolated to the space-borne digital transponder configuration.

3.6 Why Digital?

A bent-pipe analog transponder is well suited for broadcast applications where the signal is generated centrally on the ground and simply relayed by the satellite without processing. The uplink transmitter can have high EIRP and be precisely adjusted and controlled and continuously monitored in the downlink. Pointing accuracy is easily confirmed in order to minimize interference to adjacent satellites which typically use different polarizations and staggered channel assignments.

When a transponder is shared by multiple users, especially a diverse community with a wide range of technical skill levels, numerous problems arise. With multiple uplinks in the same transponder bandwidth, all of the signals add linearly in the time domain and the statistical peaks can easily saturate the downlink power amplifier. So, the downlink normally has to be operated with a so-called back-off from its maximum power output. An otherwise authorized uplink using excessive power can essentially rob all other channels of their share of the available power and may introduce non-linearities that affect other users. In addition, since the transponder merely repeats anything it receives within its bandwidth, any bad actor can easily hijack a portion of the transponder by simply transmitting without authorization.

A digital multiplexing transponder approach completely separates the uplinks and downlinks. As the uplinked analog signals are not blindly repeated, the uplinks are useless to bad actors not following the precise digital protocols necessary for information forwarding. With effective access control, authentication, and authorization, the channels cannot be used by such bad actors. The transponder can be maliciously jammed – as can any communication channel – but it cannot be hijacked for a nefarious purpose by an unauthorized user.

The digital protocols also minimize the interference from cooperating stations not able to meet the required performance requirements. Stations can be initially limited to very short transmission burst in channels with having extra wide guard bands in order to verify the stations capability and performance before being allowed by the protocol to proceed. They can continue to transmit only as long as they maintain the required performance. Such protocols can thus ensure that there is minimal interference between the many uplink carriers. This allows the number of uplink carriers to orderly scale up to the hundreds and thousands.

Digital protocols can also make efficient use of the available spectrum. They can use multiple digital uplinks on different bands and with different polarizations. None of these interfere with existing non-amateur satellites which operate in different frequency bands. As the uplink and downlink bandwidths are not tied together, the total uplink bandwidth can exceed that of the downlink.

Using the latest DVB-S2(X) digital technologies, a single aggregate downlink can provide quasi-error free channels. Using multiple modulations and coding that can be continuously changed frame by frame, the downlink can serve multiple classes of terminals supporting hundreds of simultaneous narrowband users and dozens of wideband users.

Forward Error Correction on the uplinks can provide low payload error rates. Voice quality, even at the low-end, can far exceed that of traditional analog amateur voice modes.

There are many more advantages to digital. Non-digital communications modes are nearing extinction in commercial, government and military domains. It makes little sense to invest time or effort in any new analog bent-pipe transponder approach when viable digital alternatives are practical.

4 Proposed System Architecture

The subsystems to be produced by this project are components of an overall communications system that includes several additional subsystems. The complete communication system includes all of the major subsystems discussed in the following sections.

4.1 Space Platform

The space platform is the host for the Digital Multiplexed Transponder (DMT) payload. This platform may be a military, government, or commercial platform - or a dedicated Amateur Built Platform from P4 Space or another organization. In any case, the platform will provide power and cold plate (cooling) as well as uplink and downlink antennae. While the primary focus is on GEO, the platform may alternatively be used in LEO, HEO, or Lunar orbits.

The space platform may provide various inputs to control the operation of the DMT as well as facilities for loading the FPGA binaries, firmware and control data. If such facilities are not available from the platform, the DMT can be self-sufficient in these respects.

The DMT may provide supplementary communications services to the space platform. These could include operations in frequency bands allocated to non-amateur services. Such non-amateur band communication services as well as the space platform itself are outside the scope of the P4XT project. However, the project will maintain close cooperation with those involved in space platform development to maximize the potential opportunities for ride-share.

It should be noted that since this an open source project, anyone is free to adapt the design for other uses. A potential partner or non-partner may load their own FPGA binaries and firmware to support their specific mission. In some cases, the DMT may be turned over to Amateur use only at the end of the primary mission. Many other mission scenarios are possible. The flexibility of the programmable FPGA based SDR architecture enables many of them.

4.2 Control Stations

The control stations are earth stations equipped to control DMT operation. Control stations are capable of generating encrypted communications for these control links as permitted under FCC Part 97.211(b). These links permit the uploading of FPGA binaries, firmware, and control data. Control stations may also perform functions during transit to geosynchronous (or lunar) orbit. Generally, these activities require relatively large tracking dishes and their associated control systems. Doppler correction of uplinks is also generally required. Multiple control stations may be required to support such activities but the total number is relatively small.

4.3 RO Earth Stations

Receive Only (RO) Earth Stations are receive-only systems capable of receiving some of or all of the non-control transmissions of the satellite. Since the down link is a DVB-S2(X) carrier, the

RO Earth Station is very similar to a commercial DVB dish/receiver and incorporates the same type of mass-produced ASIC decoder chipsets used by the Digital Satellite Broadcast industry. RO Earth Stations use dishes identical to the satellite broadcast industry and use low cost mass-produced LNB's slightly modified for operation at the 10.45 GHz downlink frequency band. RO Earth Stations can be thought of as equivalent to shortwave receivers. They can listen and lurk – but not transmit. They present a very low-cost entry point for beginners – even before they have become licensed amateurs.

4.4 TX/RX Earth Stations

TX/RX Earth Stations are similar to RO Earth Stations but include a transmit capability at a supported microwave uplink frequency. They can be used only by Amateur Service licensees. The stations are similar in most respects to commercial VSAT terminals.

TX/RX Stations have a modem (a.k.a transceiver) in place of the receiver (demodulator). The vast majority of amateur Earth Stations will transmit narrowband digital modulations in bandwidths on the order of 5kHz to 25kHz. TX/RX Earth Stations will require dishes with suitable dual TX/RX feeds. A Block Uplink Converter (BUC) will typically be used to translate the modem output (Low Power L-Band) to the uplink frequency at power levels appropriate for the transmit bandwidth (nominally on the order of 1W). TX/RX Earth Stations will require high quality timing which will typically be derived from a GPS disciplined clock with fallback to timing from the downlink signal itself. This high time-base precision is required to ensure that the uplink output frequency stability is maintained. This is particularly important with the very narrow channel assigned dynamically to each transmit station.

4.5 Global Earth Relay Stations

When multiple P4X satellites are deployed, there will be an opportunity for links that traverse two or more satellites to provide a global circuit. Such links can be created through earth-based relay stations that have the two satellites in view. Generally, these locations will be on the fringe of the coverage areas of both satellites. Global Links will most likely use wide band channels to aggregate a bundle of multiple low data rate channels between the two satellites. Generally, there will be only one or two active Global Relay Stations in service for each pair of satellites.

4.6 Space Relay Stations

In some applications a satellite might relay data from another satellite to the ground. As an example, a DMT aboard the LOP-G[6] could relay uplinks from the moon to a tracking station on the ground. That station on the ground could in turn relay the data through a GEO to global users.

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[6] LOP-G, also known as the Lunar Gateway, is a NASA-led project to provide a space station in lunar orbit. The project includes all of International Space Station (ISS) partners.

4.7 Amateur Radio Access Points (ARAPs)

ARAPs are similar to Global Relay Stations but serve to interwork traffic from non-satellite stations, for example a local terrestrial FM repeater. ARAPs can link one or more channels from a local handheld transceiver or repeater to other TX/RX Earth Stations. ARAPs can support multiple local channels allowing the inter-connection of multiple repeaters within an area. ARAPs can also serve as a new generation of digital multi-channel repeaters that can utilize P4XM equipment in a terrestrial environment.

ARAP's may form the core of future disaster response communications. There are thousands of deployed VHF repeaters in the existing amateur infrastructure and many already operate independent of local infrastructure. An ARAP deployed to a local area can be used to link many of the repeaters in a disaster zone to the unaffected outside world.

It should be noted that P4XT project will not provide ARAP designs. The DMT will provided the facilities that support ARAPs; but the actual ARAP designs will remain separate efforts. Simple ARAPs may incorporate the low-cost modem provided by the P4XM project. More complex ARAPs will likely be FPGA based modems outside the scope of this project. The projects, however, may re-use the work product from the P4XM project and visa-versa.

5 P4X Digital Multiplexed Repeater DMT Functional Requirements

5.1 General

This section provides a brief high-level overview of the functional requirements of the DMT. Additional details regarding the current baseline design to meet these requirements are provided in Appendix E. It should be noted that neither the requirements nor the design have been frozen. All details are preliminary and subject to revision during the initial stages of the project.

5.2 Purpose

The primary purpose of the DMT is to provide an aggregate DVB-S2(X) downlink signal that can contain a very wide range of digital payloads for quasi-error-free (QER)[7] transfer to the ground. The DMT essentially multiplexes many diverse payloads and combines them into a single aggregate downlink. The content of all payloads must be of a nature that conforms to the regulations for the amateur services. Specifically, the payloads must be unencrypted and must be for a purpose without pecuniary interest.

5.3 Software Defined Radio

Fundamentally, the DMT is an orbiting SDR (Software Defined Radio). Its function is largely determined by the specific load of firmware and FPGA binary code. The DMTs function can be any set of functions within the parameters established by the RF/IF hardware. Generally, the DMT will always provide at least one aggregate DVB-S2(X) downlink. The uplinks will depend on the specific mission as described below.

5.4 Aggregate Downlink

The DMT downlink will use the DVB-S2(X) standards. This family of standards was originally developed for the direct-to-home satellite TV broadcast industry. The latest standards support many other non-broadcast applications. The DMT will use the S2 version of the standard and the so-called Generic Stream Encapsulation (GSE). Additional ‘X’ extensions may also be used in some DMT configurations.

The DMT DVB-S2(X) downlink will have a symbol rate in the range from 80kbaud to 8Mbaud in an occupied bandwidth of 0.1 – 10 MHz and will fully conform to the ETSI DVB-S2(X) standards. The DMT RF output will be capable of operating on any of the microwave bands authorized to the Amateur Radio Satellite Service for space to earth or space to space communication (listed in Table 2-1). Note that the DVB-S2(X) standard allows the modulation and coding to be changed on a frame by frame basis. This allows the downlink to simultaneously support spectral efficiencies ranging from 0.5 to 6 bits per hertz over a 34 dB range of C/N (-10 to +24dB). As an example, a single aggregate 8 Mbaud downlink may include a mix of 2 Mbps

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[7] QER is defined as frame error rate less than 1 in 100,000 frames.

of data that is receivable by very simple stations combined with 16 Mbps of data that requires a larger and more capable earth station.

The DVB-S2(X) aggregate will transport data originating within the host platform and data received on its digital uplinks. These uplinks may receive data from earth stations and/or data from other space stations.

5.5 Earth to Space Uplinks

Earth to Space Uplinks are used to implement a repeater relay service from a potentially large number of earth stations. This is the primary application for the amateur GEO satellites. The DMT will receive an entire band segment and processes multiple uplink channels. These will include narrowband channels on the order of 2400 bps and wideband channels on the order of 25 kbps.

All narrowband channels will be isochronous at a rate of 25 frames per second. This will provide compatibility with many voice codecs. All of the narrowband channels will be demodulated, error corrected, and then multiplexed into a single downlink GSE stream. The wideband channels will be separately multiplexed onto one more additional GSE streams.

The narrowband channels will be universally accessible to all stations. Their associated data will normally be carried using the most robust operational coding available on the downlink. Wideband channels, however, will generally be carried in separate GSE streams using more spectrally efficient coding. Higher performance stations will generally be required in order to receive these high data rate streams. However, all stations can automatically skip past these streams if they are not capable of decoding them (this is a core feature of DVB-S2(X)).

5.6 Space to Space Links

Space to Space links are highly mission specific. Generally, these links will be similar to earth to space links. Data received from a space to space uplink will be multiplexed onto the aggregate downlink in the same manner as the high-data rate earth to space links. Generally, these links may be used to relay data from other spacecraft in earth orbit or from space stations in lunar orbit or on the lunar surface. Space to space links may use bands and modes that are highly specific to the mission and spacecraft involved.

5.7 Host Data

Host data consists of data that originates within the host platform. This can include telemetry or data that is related to the mission, e.g. images, scientific or educational data. Such data must fall within the scope of permissible transmissions over Amateur Radio Satellite Service allocations and must otherwise comply with regulation.

Host data can be transferred from the platform CAN bus , or LVDS (Spacebus) interfaces depending on the platform. CAN bus is suitable for telemetry and other low rate data. The LVDS Spacebus interfaces are suitable for higher rate data e.g. Image and Compressed Video. The DMT will be able to buffer local host data and insert it into the aggregate downlink along with uplinked data.

5.8 Form Factor

The DMT will be designed for deployment in space. It will have a form factor suitable for installation in a typical cube-sat card cage. It will most likely consist of two 90mm x 90mm PC boards. Additional boards may be added where additional RF capability is required.

The design is expected to be compliant with Next Generation CubeSat Bus (NGCB) and 6U CubeSat Design Specification Rev 1.0.

5.9 Power

The power consumed by the DMT during normal operation may range from a few watts to a few tens of watts. Most of the power will be consumed by the FPGA based baseband processor although significant power will also be consumed in the ADC/DAC chain and/or integrated radio subsystem. Power dissipation is primarily a function of the individual switching speeds of the logic elements within the FPGA and it’s I/O pins. This is determined by the specific hardware implementation. Power management is a significant factor throughout the design.

Note that the DMT power does not include the transmitter RF drivers and final amplifiers. These are expected to also be in the range from a few watts to a few tens of watts. The total DC power in operation is expected to be on the order of 5 to 100 watts depending on the application. There will, however, be low power standby modes and perhaps some low power operational modes using FPGA binaries highly optimized for low power. Lower power can be achieved by placing various external components and internal processing blocks in sleep or standby modes.

In space, all power must eventually be radiated as this is the only mechanism available for heat transfer. Power dissipation in the electronics is essentially converted to infra-red radiation.

5.10 System Partitioning

The DMT is expected to be used primarily in 6U or larger platforms. Absolute minimum volume is not expected to be the primary concern although the electronics should remain under 0.15U in volume. Removing dissipated power and maximizing radiation tolerance are large concerns. These concerns, together with the desire for maximum flexibility, favor a multi-board design.

5.11 Digital IQ Basebands

Nearly all modern digital communication systems are based on the processing of digitized quadrature baseband signals generally referred to as IQ basebands. Quadrature (IQ) Basebands are digital numeric representations of signals sampled by clocks in quadrature (90 degrees out of phase). Once an RF or Intermediate Frequency (IF) signal has been converted to a digital IQ baseband it can be processed completely in the digital domain.

Digital IQ Basebands can be transported over high speed serial links generically referred to as SERDES (Serializer/Deserializer) links. These digital links are similar to the PCI lanes in personal computers, SATA disk drives, USB 3.x, and HDMI. Such serial links have all but replaced high pin count parallel interfaces in modern high-performance equipment.

Due to the much small number of circuit traces, the use of SERDES links make it easier to partition the baseband processing and the RF/IF on separate boards. Note that this partitioning also makes it practical to evolve the baseband processor and the RF/IF sections somewhat independently. It also allows the core baseband board to be used for a wider variety of missions by changing only the RF/IF board.

A set of SERDES links (or Lanes) is conceptually similar to a PCIe slot in a personal computer. The user can plug in different boards to accomplish different functions. Similarly, the DMT baseband board can accommodate different IF/RF boards for different applications. Unlike PCIe, the interface is not general but highly specific to transporting digital basebands.

5.12 Baseband Processor (BBP) Board

The baseband processor (BBP) board processes IQ data stream of the uplink(s) and produces the IQ baseband stream(s) of the transmitter(s). This board will operate entirely in the digital domain (except for power supplies). The baseband IQ streams are transferred to the RF/IF boards over the high speed SERDES lanes. Each lane can transport one or more IQ baseband streams. Additional serial SPI and I2C interfaces are provided for control. A CanBus interface will be also available for interface to the space platform. LVDS and RS422 Spacebus interfaces will also be available for interface to Host Systems or other payloads.

The BBP board is expected to contain a mid-sized FPGA. The control processor will most likely be a multi-core ARM integrated within the FPGA. The provisional FPGA/SoC device is one of three pin compatible members of the Zinc 7000 family. These devices range from 275k to 444k logic elements, 17.6 – 26.5 Bits of Block RAM, and 900 – 2020 DSP Slices (36 x 36-bit multipliers).

The BBP will provide 4 to 8 pairs of high speed SERDES channels capable of JESD204B operation at rates up to 12.5 GHz. JESD204B has become the de-facto standard method for connecting ADC and DAC converters and integrated RF radios to the FPGA core. This partitioning will keep the BBP completely digital. The 8 high speed transceiver lanes provide a flexible interface. In most applications it will also enable a degree of redundancy.

5.13 IF/RF Board

The IF Board converts analog RF or IF to/from digital IQ baseband. The digital interface will be JESD204B together with SPI and I2C for control. The analog side will be IF/RF covering the microwave bands.

Three initial baseline designs are under consideration. One uses either one or two AD9371 integrated radio devices. Another uses a single ADRV9026. The third uses one AD9371 and one ADRV9026. The latter can be populated with either or both chips.

5.13.1 AD9371

The AD9371 device is capable of supporting up to two simultaneous transmit IF/RF outputs driven from a common internal transmit LO. The device also supports three simultaneous receive IF inputs based on two independents receive LO's. Each device is a 12mm x 12mm package. With two devices these resources are doubled (at twice the power consumption).

5.13.2 ADRV9026

The ADRV9026 supports roughly double the resources of the a single AD9371 in a package the same size as a single AD9371. There are four transmit, four receive, and 2 observation receivers. The device resides in a 12mm x 12mm package.

5.13.3 RF Outputs

The RF Outputs from both devices are similar. They cover a range from UHF to 6GHZ. Generally, frequency specific filtering is required to keep spurious emissions within design specifications. For X-BAND output, a further up-conversion is required and this is provided on the RF board.

5.13.4 RF Inputs

The RF Inputs to both devices are also similar. They also cover a range from UHF to 6GHZ. A low noise amplifier (LNA) is required at the input followed by a band pass filter to minimize interference from strong signals in other bands.

Both the AD9371 and ADRV9026 devices are small 12mm x 12mm devices. This leaves sufficient board real-estate to implement most of the RF front end on the same board. On the transmit side, this will include the upconverter (IF to 10.5GHz) and driver amplifier. On the receive side it may include the LNA's and filters for one or more bands. Where additional RF inputs and outputs are required, one or more additional boards may be stacked.

There may be several similar IF/RF Board designs to accommodate a range of frequencies for uplinks and downlinks. In some cases, several different bands may be provisioned by installing appropriate hybrid passive filters. It is expected that the standard primary downlink will be 10.45 – 10.50 GHz. The standard primary uplink will be 5.65 GHz. The primary control uplink will be

1.260 – 1.270 GHz. Some application may use a 24 GHz downlink and 10.45 uplink. It must be noted that the IQ basebands are nearly identical for all of these applications. The downlinks are generally a single DVB-S2X carrier although in some platforms there may be two different DVB-S2X carriers on different bands or on the same band using different antenna (with crossed polarizations).

The uplinks are wideband band segments of several megahertz. Low data rate channels within a band are derived through the digital signal processing.

5.14 Downlink Power Amplifier (PA)

The final RF power amplifier and Downlink Antenna will normally be part of the supporting platform as these are expected to vary widely with the platform depending on available DC power, physical antenna configuration, and cooling requirements. Similarly, the uplink Antennae and LNB (if any) will also be part of the platform.

The platform will provide DC power and cold-plate. All of the dissipated power will need to be conducted through the thermal system for radiation into space.

5.15 Transmit Subsystem

The transmitter will produce a single downlink with DVB-S2(X) modulation. The transmitter will FEC code and modulate the baseband frames produced by the formatter. When no frames are available, a dummy frame will be transmitted to maintain synchronization. The output will be digitally filtered with the selected rolloff to comply with the DVB-S2 specifications.

5.15.1 Symbol Rate

DVB-S2(X) modulation requires a fixed symbol rate that is maintained continuously. These rates generally range from 1 Mbaud to 30 Mbaud. Both lower and higher symbol rates are possible.

For amateur radio applications the downlink symbol will typically generally range from 800k baud to 8M baud. This corresponds to a downlink bandwidth between 1MHz and 10MHz.

5.15.2 Modulation and Coding

Tradeoffs exists between bandwidth, downlink power, and receive antenna effective aperture. Together, these determine achievable performance. DVB-S2(X) uses a very powerful forward error correction coding that performs within about 1 dB of the theoretical limit. The error rate vs. required C/N curve is very steep meaning that the difference between quasi-error free and useless is only a few dB.

The most robust modulation and coding in DVB-S2 is QPSK with ¼ FEC. This provides a spectral efficiency of about 0.5 bit/Hz. QPSK ¾ provides 3 times the spectral efficiency but requires approximately 6dB greater C/N.

5.15.3 GSE Streams

The DMT will transmit data formatted into GSE Streams. GSE Streams are specified in the DVB standards. GSE is designed to support many types of data including IP.

Wideband uplink receivers will generally demodulate GSE Streams that are formatted by the ground-based transmitter. These streams may be transported in BB frames using any supported modulation and coding. Note that uplinks are not DVB-S2.

5.15.4 Narrowband Multiplexor

In order to scale to a large number of channels, a narrowband multiplexor (NBM) entity is provided. The NBM very efficiently packs the individual bits from each narrowband channel into an aggregate UDP packet that be transported over a single GSE stream. The NBM stream has a fixed isochronous rate of 25 packets per second and is interleaved with other GSE streams. The NBM stream carries channels that are an integer multiple of 800 bps. To maximize efficiency, the spare capacity (e.g. momentary pauses in speech) are packed with alternate downlink data e.g. telemetry and messages.

It should be noted that the NBM payload is transparent. Any payload in a publicly described format that complies with FCC rules may be carried.

5.16 Receive Subsystem

The uplink passband can be filtered into multiple band segments, for example a band segment containing a large number of narrowband channels, and a band segment containing a relatively small number of wideband channels. There may also be multiple uplink bands (e.g. 3.4 and 5.6 GHz). In any case, one or more digitized band segments may be presented to multiple receiver blocks.

5.16.1 Multi-Channel Narrowband Receiver

A Multi-Channel Narrowband Receiver (MNBR) demodulates and forward error corrects the narrowband uplinks from the individual stations in a narrowband band segment. There will typically be several hundred fixed narrowband channels, each on the order of 5k – 12.5 kHz wide.

The MNBR first digitizes the band into multiple narrowband segments (typically using FFT and overlap-add methods). After channelization, each channel has a relatively low sample rate that can be processed sequentially for each channel through a common demodulator error/correction block. The end result is a recovered bitstream for each channel.

5.16.2 Multi-Channel Wideband Receiver

A Multi-Channel Wideband Receiver (MWBR) is similar to the MNBR but handles a relatively small number of channels of higher bandwidth on the order of 100 kHz. The high-speed outputs will generally be formatted as either IP packets carried by a common GSE stream, or individual GSE streams.

5.17 Signaling Subsystem

The signaling subsystem implements the protocols used to gain access to the satellite. These include commissioning protocols (establishing the ability to deliver a conforming uplink), authentication, authorization, and channel acquisition.

6 P4XM Modem Functional Requirements

6.1 General

An Amateur Satellite Service TX/RX Terminal (a.k.a. Earth Station) is the end-point of the system – much like a satellite dish and receiver are the end-points of a Digital Satellite TV Broadcast Network. While there may be a single operational P4X DMT in space, there may eventually be tens of thousands of terminals. It is therefore critical that the terminal be very low in cost, very easy to install, and very easy to operate. There must be very low risk of adverse interference to other services. There must also be very low risk of harmful RF Electromagnetic Radiation. All of these conditions are prerequisite to wide adoption within Amateur community.

It must be noted that while the target of the project is a very low-cost terminal (<$500) that can be purchased off the shelf and operated much like an appliance, the amateur service is fundamentally about self-learning and experimentation. The availability of a low-cost terminal in no way precludes the use of “home-brew” earth stations with greater or lesser capabilities. The proposed system will accommodate any station that complies with the specifications. In fact, some of the capabilities of the system, e.g. high data rate uplinks, may not be possible from the very low-cost terminals.

It must also be noted that the proposed system is fully digital. There are no analog modes. There is no SSB – no FM, no CW, no PSK31, no RTTY, and in fact no analog modes whatsoever. Forward error corrected digital links are the only transmission modes. This means that all equipment and design experience with these traditional modes will have little practical value in this new communications environment. However, the learning opportunities in the various disciplines of modern digital communications technologies will be immense. This digital world has an even greater number of possible modes of operation that can be explored and mastered.

The space-borne DMT will be reprogrammable in orbit. This means that over its lifetime the system can evolve in many ways. The heart of the low-cost terminals, the P4XM Modem, is also to a large extent programmable. This allows both modem and DMT to evolve together. With programmable equipment at both ends, it will not always be necessary to retain backward compatibility. Transmission modes can be replaced by improved technology. For example, the channel spacing and modulation and coding formats of the uplink may be entirely replaced with a new more advanced system. Modems will only need to be upgraded to the latest firmware images to become compatible. These updates could even be distributed Over-The-Air (OTA) through the satellite itself.

6.2 Antenna

Commercial VSAT's operating in Ku-band have a minimum dish size of about 1.2 meters[8]. This is dictated by the narrow beam width required to direct the output to a single satellite. Observed from the ground, geostationary satellites all appear along a curved line (the Clark-belt) extending from horizon to horizon with a maximum elevation that depends on the observer's latitude. Satellites are spaced with separations of 1 to 2 degrees in orbit with observed separations even smaller. The beam width of a dish antenna is a function of both diameter and frequency of operation.

Commercial Ku band VSATs have uplink and downlink frequencies that are fairly close. Uplinks are typically in the 13.7 – 14.5 GHz range and downlinks are in the10.9 – 12.7GHz range. An OMT[9] is used to separate the transmit and receive signals in the feed. Transmit and receive use orthogonal linear polarizations.

The commercial downlink frequencies are close to the amateur X-Band (10.45 – 10.5). This makes it relatively easy to adapt downlink equipment with only minor modification. However, as the Amateur space allocation is only 50 MHz, uplinks and downlink within the same band are not practical for the typical full-duplex mode of operation. This requires the use of an uplink in another band. Options exists in the 2.4, 3.3[10] and 5.6 GHz bands.

Amateur GEO satellites will be relatively few in number and their spacings will typically be very wide. This means that the dish beam widths can be wider if necessary. This allows use of dishes in the 600cm to 1M range. The uplink beam widths will be much larger with smaller dishes, but there will be no interference issues with adjacent satellites.

6.3 Block Up Converter (BUC)

Commercial VSAT terminals generally locate the transmitter near the antenna to minimize the cost of very expensive waveguide[11]. Coaxial cable delivers an L-Band signal from the modem to a device called a Block Up Converter (BUC). The BUC translates this frequency to the desired uplink band and amplifies the signal to the required power level. P4X terminals may use the same approach. To permit direct use on the 23cm amateur band, the P4X modem's L-Band outputs will normally cover the 1100 – 1300 MHz frequency range. The BUC design will upconvert this IF to S-Band or X-Band depending on the uplink frequency. X-Band will typically be used in North America.

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[8] Operation in Ka band can use smaller dishes.

[9] An OMT or Orthogonal Mode Transducer is a waveguide structure that separates horizontal and vertically polarized signals.

[10] In December 2019, the FCC proposed the elimination of all 3.3 GHz amateur radio allocations.

[11] Waveguide is rectangular tube that conducts microwaves with very low loss.

The BUC design will typically mix the modem L-Band output with a 4.4 GHz local oscillator. This normally produces outputs in the 5.6 and 3.4 bands. The desired output is filtered and then amplified to the desired power level typically on the order of 500mW to 1W for narrowband stations. A high precision local oscillator is required to ensure that the final transmit output meets the accuracy requirements for a narrowband channel. The modem provides a timing reference on the same cable as the transmit output. The LO in the BUC maintains locks to this reference.

6.4 Baseline Modem Design

6.4.1 Form Factor

The basic form factor for the modem is approximately 7 x 4 x 2 inches. A small graphic display and touchscreen will be fitted to provide basic controls.

6.4.2 Application Processor

The modem will incorporate a Raspberry Pi-4B which attaches to the main transceiver board inside the case. This approach will eliminate any dependence on an external PC by essentially incorporating the PC within the modem box. This will avoid potential issues with the type of PC platform, Operating System, Driver compatibility, etc. The approach will also eliminate the separate expense of the PC. The modem essentially embeds a PC with dual 4k capable display outputs, GigE Ethernet, USB 3.0, Wi-Fi, and Bluetooth. All software, drivers, applications, etc. will be pre-installed and will work as a fully configured system out of the box. It will not be necessary for the individual Amateur to deal with software installation.

True to the amateur radio spirit, however, everyone will be free to experiment to their heart's content. Hardware and software will all be completely open source. The GigE, Wi-Fi, USB 3, and USB 2 connections will permit attachment of many kinds of peripheral devices on the digital side. As the design is open, a wide range of hardware accessories can be developed for use with the platform. All of this is intended to improve the value proposition to the full amateur radio operator population.

The performance of the Raspberry Pi-4B hardware (Quad-Core 64 Bit ARM Cortex A72 at up to1.6GHz) is high enough to subsume some of the key modem functions. Two complete cores can be dedicated to specific modem functions. Each ARM A72 core has significant floating point, SIMD, and DSP capabilities. This allows many of the audio codec and transmit modulator functions to be handled within the Raspberry Pi-4, reducing the cost and complexity of the modem.

6.4.3 Radio/Processor Interface

The radio hardware will interface to the Pi-4B through a 40 pin so-called Pi Hat connector. This connection is fully within the enclosure. The main modem board will contain a small FPGA which interfaces with the multiple high-speed SPI interfaces provided on the Pi-4B version of the

Pi-Hat connector. The FPGA will provide the logic to map and route between the ASIC DVB-S2 receiver and the Pi-4B. These interface resources are more than adequate to support all of the features of the transceiver without consuming any of the Pi-4B's external interfaces – GigE, 2x USB 3.0, 2x USB 2.0, and 2x HDMI.

6.4.4 DVB-S2 Receiver

The baseline receive system is provisionally based on an ST-910ADB DVB-S2 decoder ASIC and its related tuner chip. (this may be switched to a DVB-135 or another DVB-S2X ASIC in the final design). The use of a low-cost ASIC DVB-S2 chipset will keep the cost of the modem very low. The receiver will support up to two simultaneous channels of DVB-S2 from unencrypted commercial satellite transponders. It will also be capable of receiving DVB-S2 from other sources, e.g. NOAA weather feeds from Galaxy 28. The modem receiver will provide power to the external LNB through the coax, similar to commercial satellite receivers, and will support industry standard LNB switching.

The L-Band RF tuner's IQ baseband will be enhanced with an optional programmable narrow band filter in one of the channels in order to provide enhanced performance with multiple, relatively narrow DVB-S2 carriers in minimal spacing.

6.4.5 Modem Transmitter

The L-Band transmit subsystem will produce the RF signal that drives an external BUC for the configured Microwave band - C-Band in Region 2 and S-Band in all other regions. The modem will convert the quadrature baseband signal from the Raspberry Pi-4 to L-Band. This will be a low-power signal that is intended to drive the BUC. The modem outputs are not intended for direct output to an antenna without signal conditioning to ensure compliance with spectral limits.

BUC timing reference (at 10 MHz) will be optionally superimposed on the transmit signal. TA timing reference is required to meet the tight tolerances required for low data rate microwave operation. BUC Power will be provided by a separate 20V DC power feed.

6.4.6 Station Clock

Precision timing will be provided through an TCXCO disciplined from an internal built-in GPS timing receiver subsystem. A separate antenna connection will be provided for the GPS including LNB power.

The GPS derived clock will be distributed via the L-Band outputs to the BUC. It will also be available on an external connector. For emergency operation in the absence of GPS, timing can alternatively be disciplined to the downlink symbol rate. The BUC will provide the recovered clock for use by the co-located BUC. This will eliminate the usual errors in downlink frequency, expanding the ability to work narrow carriers.

6.4.7 Display

The transceiver will include a 1.8-inch diagonal monochrome display with touch screen. This will provide basic setup and configuration of the system (e.g. setting the WiFi address for wireless operation.) Simplified appliance like channelized voice operation will be possible without the need for a high resolution display.

6.4.8 Input Devices

USB keyboard and/or mouse can be added as well as other input devices e.g. jog dials and tuning knobs.

6.4.9 Power

The modem will be powered from a standard USB-C power delivery supply up to 90W or 11 – 15V DC. The transceiver will provide power to the LNB and BUC. (High powered BUC may require their own power supply.

6.4.10 User Interface

The device may be operated using an external HDMI monitor and keyboard/mouse (either USB or Bluetooth). The device may alternatively be operated through a VNC connection to a local or remote machine (wired or WiFi). The device can also be fully controlled through an HTML-5 based browser-based SSL interface to the internal webserver. The software is also expected to support wired or wireless operation through standard mass produced VOIP terminals. The USB ports will allow the use of high quality gaming headsets for wideband audio.

6.4.11 Cost Target

Despite all of these capabilities, the cost of the modem is expected to be in the US$ 200 - 300 range in modest volumes. This does not include the LNB, BUC, and Antenna. When low cost versions of these components are added the total cost should remain below the $500 target.

6.5 FCC Emission Compliance

All radio transmitting equipment produces radiofrequency electromagnetic fields. The various national administrations regulate the limits of maximum human exposure to such fields. In the US, transmit station licensees, including Amateur Service licenses, are required to evaluate compliance with these limits. Manufacturers of unlicensed equipment are also required to evaluate their equipment and in some cases the equipment, e.g. outdoor WiFi equipment with hi-gain antennas must be professionally installed.

At microwave frequencies, very high gains can be achieved with relatively small antennae. A signal with power as low as a few hundred milliwatts, may be amplified to hundreds or thousands of watts. This can create fields that easily exceed the current limits for human exposure.

In order to permit safe installation, the BUC and antenna configurations designed as part of the P4XM project will be fully pre-evaluated for human electromagnetic exposure and the installation instructions for the equipment will provide all of the data necessary to install the equipment such that the exposure limits can be easily calculated by the licensed amateur.

7 Goals and Objectives

The primary goal of this project is to produce a fully operational digital multiplexed transponder (DMT) ready for deployment as the payload of a geosynchronous satellite - together with a very low-cost earth station package capable of using the DMT. Realization of the primary goal involves several intermediate goals which are each described in the following subsections. This development effort is not a research project or a technology demonstration. The goal is to develop a complete system that is ready for deployment – both the space-borne repeater and thousands of low-cost terminals.

7.1 Project Plan

The broad outlines of the requirements and major development activities are known. However, these need to be refined into a detailed plan – taking full account of the available engineering resources. This will be the first formal activity of the project. A professional approach to the project planning is expected to have the side benefit of increasing confidence by the participants that the end-goals of the project remain within reach.

7.2 System Design

While the outlines of the design concepts have been presented in previous sections, more work is required to determine the optimal component specifications. For example, it is currently believed that 250K to 500K logic elements will be required for the core FPGA device. Since power is a major consideration (and its related cooling), the power requirements for the implementation approach will have to be evaluated through simulation tools. FPGA implementation is an interactive process with many factors that affect the floor planning of the device and the resulting power consumption. Raw logic elements counts are only a guide. Something close to the final design has to be analyzed and tested to determine the ultimate feasibility of a given design on a particular FPGA.

7.3 Specifications Development

Some early work on specifications has been performed. This needs to be extended and finalized. A complete specification is required for the uplinks and downlinks before the DMT and modem designs can be finalized. In addition, a feasible design for the narrowband multiplexor and the access control, authentication and authorization protocols needs to be finalized. While these can be changed in the future, a feasible first solution is required to be able to perform all-up testing of the system – both in simulation and real implementation.

7.4 Development Environments

The methods and strategies for development are covered in chapter 8. The full tool-chains to support these strategies must be specified and then deployed. This includes both tools for development and simulations and their supporting tools. Note that it is not uncommon to find activities associated with test and simulation comprising the bulk of the total development effort. All of the basic tools must be in-place for the design work to proceed in earnest.

7.5 Simulation Environments

A number of simulation environments will be used to support the development of the various components of the system including the user interface and application layers and the various protocols used for access control, authentication, and authorization. These various simulation environments are discussed in Chapter 8.

7.6 Live Test Environment

A live test environment is planned that will use fully functional prototype modems in conjunction with a development DMT deployed on development hardware. Both of these will be used with QO-100 providing the space segments. This means that all of the equipment for this test environment will need to be located within the foot-print of QO-100 (Outside of North America). This effort will also require coordination with AMSAT-DL and QARS.

For this live test environment, the uplinks will actually be bent-pipe downlinked through the transponder to a relatively large earth station (>2.4M) on the ground. The input to the ground-based DMT will be an analog signal with a C/N representative of a P4XDMT deployed in space. Note that the link in this case involves two hops so it has twice the delay. The signal will otherwise be almost identical at the L-Band input to the DMT core. This will provide a useful real-world surrogate for the target uplinks.

The downlink to the terminals will be through the QO-100 wideband transponder. It will be similar to the existing DVB-S2 beacon and the existing Digital ATV signals that several stations currently experiment with. The DVB-S2 coming from the P4XDR DMT(on the ground) will appear in the 10GHz wideband downlink from QO-100 where it can be received by any earth station in the coverage area.

While the primary goal of this test environment is to support the development of the P4XDMT, it may significantly extend the usefulness of QO-100 and could remain in use indefinitely. P4XM modems acquired by QO-100 amateurs will be useful as well on any future P4XDMT deployed over Europe and Africa.

7.7 P4XDMT Hardware Realization

One of the final steps in the program will be the final realization of the P4XDMT hardware. This involves the actual PCB layout and assembly and integration of the final FPGA image and firmware loads. These will need some adaption from the configurations used in the test environment as the PCI and Ethernet interfaces and other instrumentation will no longer be present. Once the P4XDMT hardware is realized, the P4XDMT hardware and its associated RF boards will completely replace the test environment hardware. Real-world tests can then be continued using real DMT hardware and software. At that time further environmental testing can be performed in preparation for deployment of the design to the space environment.

7.8 P4XM Terminal Deployment

While perhaps 100 or so prototype modems may be deployed during development, some minor refinements may be required as the result of real-world testing. In addition, it will be desirable to produce a complete terminal solution including a low-cost dish, LNB, BUC, and low-cost dual feed for the C band and S band uplink regions. This will allow a complete turn-key Tx/Rx earth station that only needs to be assembled, mounted, and pointed. Such a package is expected to cost well under $500 delivered anywhere in North America.

8 Methods and Strategies

8.1 General

Both of the development projects involve hardware and software development. The P4XDMT hardware includes programmable logic devices programmed using Hardware Design languages (VHDL or Verilog) and other design inputs (timing constraints, etc.). Both the P4XDMT transponder and the P4XM Modem also involve ARM Cortex firmware programmed in C and in some cases Assembly Language (for SIMD instructions and DSP).

8.2 Hardware Development

As the direct hardware development tasks are a small proportion of the total effort, they will be handled by a small team using standard off-the-shelf PCB design tools (e.g. Eagle). As most of the development cycle will take place using simulation tools and off the shelf evaluation boards and modules, the actual hardware PCB design and layout of the P4XDMT will be completed rather late in the program as described in Chapter 7. A baseline PCB board design and mock layout will track the project as development proceeds to provide an early warning of potential PCB layout issues.

The P4XM Modem design will proceed as soon as specifications can be frozen. This can occur rather early in the program. Prototype terminals using the P4XM modem will be necessary during real-world testing of the DMT. They can also be useful in the simulation environment.

8.3 FPGA Design Flow

FPGA hardware functions are specified in a Hardware Design Language (HDL) e.g. Verilog or VHDL. The required performances are specified through separate timing constraint specifications. All of these source codes are then synthesized to the hardware elements of a particular FPGA device type through synthesis and implementation tools. The resulting binary image is then loaded into the real FPGA device to program the low-level device interconnections inside the device. What makes an FPGA so flexible is that these binary images can be changed to produce, in effect, an entirely different hardware device.

FPGA’s are often used as an intermediate step in the design of an Application Specific Integrated Circuit device (ASIC). The development tools produce RTL (Register Transfer Logic) than can be synthesized to either FPGA’s or ASICs. FPGA’s are thus a solution to verify designs that will ultimately be implemented in an ASIC. In the case of this project, the FPGA represents the final target as the DMT unit volume is way too low to justify the use of an ASIC.

8.4 Algorithm Development

The functions of the DMT involve signal processing algorithms that will be implemented with hardware elements that must operate in real-time. Generally, algorithms are first developed as mathematical expressions. These are typically verified using MATLAB and Simulink commercial software or their open source equivalents. They can alternatively be written in C/C++, Python, or other languages. Ultimately, the goal is to be able to verify that the algorithm will operate correctly with the expected inputs including corner cases. This is often done using simulated inputs. Simulated inputs can be mathematically generated offline together with artificially generated impairments e.g. noise and interference. Recorded live signals can also be played back off-line or in real-time. In either case the inputs used to drive the simulations can later be used as test vectors for real-time hardware verification.

8.5 HDL

Once algorithms are verified, they must be converted to a form capable of being synthesized to the FPGA. This generally begins with a hardware design language (HDL) such as Verilog and/or VHDL. Just as C/C++ provides an abstraction for data and procedural steps that can be translated to binary machine instructions, HDL is an abstract description of hardware that can be translated into hardware logic elements. FPGA's, in contrast to processors, are highly parallel and many operations can be simultaneous performed throughout the device. This is especially true for devices with hundreds of thousands of logic elements.

Design tools allow the HDL to be simulated and verified in non-real time. This process is very slow. HDL verification also involves a "timing closure" process which verifies that the implementation as expressed in the HDL can meet the worst-case performance requirements of the individual building blocks in a particular FPGA. The final step is to synthesize the final images and test them on an actual device.

8.6 Cloud Based Simulations

A recent industry development is the availability of cloud-based instances of very powerful server platforms that also include high end FPGA's boards. Amazon EC2 provides these as so-called F1 instances. Related tools allow the development of the images that can be loaded into these FPGA's. These tools run on separate preconfigured virtual machine (VM) instances that include the bundled FPGA design tools e.g. Vivado.

By structuring the project's FPGA development work-flow around these capabilities, it is possible to synthesize and implement major portions of the HDL to actual representative hardware and verify and test the design in real time on an F1 cloud instance. Simulated or recorded IQ streams can be fed in real-time to the FPGA and the outputs can similarly be recorded in real-time for later analysis. The FPGAs in F1 instances are much more powerful than the likely target devices. They are a different family (ultrascale Virtex instead of Kintex). However, since the same synthesis tools are used the conversion to the actual target hardware is relatively straightforward. Using these cloud-based resources, the bulk of FPGA development will not require the actual hardware. Only a few hardware test platforms will be required when the implementations are transferred to the final target hardware and integrated with the RF components. In addition, the cloud-based approach allows many more developers and potential developers to participate as they require little financial support.

The cost of a complete development toolchain in the cloud, including the Vivado license, running on an 8 core VM with 64 GB RAM, 300GB of SSD and 10G Ethernet is less than $1 per hour. The billing is pay as you go with no upfront costs. On demand pricing for an f1 image with the hardware FPGA is less than $2 per hour. Again, there are no upfront charges. These prices are low enough that the resources can be made available to those who may not already have direct experience with FPGA development in general and Vivado in particular.

8.7 Personal Development

The only predictable thing about technology is that it is always advancing. Engineering school doesn’t teach people how to do much that is of immediate value to employers. What it teaches is how to apply math and physics to real world problems. The successful engineer’s education is never complete. He or she has a lifetime of continuous learning ahead as technologies change and the tools to use them continuously evolve.

A specific engineering project will be undertaken using the tools that are available at the time. For this project we are organizing the tools necessary to build high-end software defined radios for space. This is a rather specific skill set. Learning curves are high. Learning curves exist for just about every experience level - they differ only in slope.

One of the key success factors for this project will be to leverage the skill sets of a few professionals with direct background in the specific arts to mentor those who have the ability to do the work once equipped with the current tools of the art. Not everyone has the native abilities and background to be able to do the required work. Few are ready to step in and produce immediate results. But many, with a bit of mentoring, can quickly rise to the occasion.

There is a symbiotic relationship between the volunteer and the project. The volunteer gains both education and experience with the tools used in a real-world project. The volunteer, in so doing, becomes valuable to the project. But the volunteer also gains a valuable marketable skill. This is a win-win-win; a win for the volunteer; a win for the project; and a win for the project sponsors who gain leverage for their financial contributions.

8.8 Design Reviews

The success of a complex project often depends on the effectiveness of the various design decisions that are made during the course of the project. Experience has shown that such decisions are much more likely to be effective when formal review stages are incorporated into the project plan. Reviews provide the opportunity to harness the experience of professionals who are unable to contribute significant time to the project but are willing to make available the limited time required for a design review. Reviews provide the opportunity for course corrections or tweaks. They can sometimes lead to the entire abandonment of an approach. In short, they provide one of the bests ways to ensure that project will be successful and that the minimum amount of resources will be squandered.

9 Plan of Evaluation

Ultimate success of this project will be one or more operational DMTs in GEO being accessed by thousands of ground terminals. This result cannot be promised by the project alone as the availability of a host for the payload is uncertain. The project can make sure that the lack of a GEO transponder in orbit is not due to the lack of a ready to fly transponder and its associated ground-based systems.

9.1 Final Milestone

The project goals will be considered to have been met will when the team delivers P4XM modems to the community that work effectively with a P4XDMT accessed through a space segment provided by QO-100. This will effectively demonstrate that the Amateur Radio community is ready to effectively utilize GEO DMTs in space in furtherance of the purposes of Amateur Radio, including in particular, to provide an unprecedented Amateur Radio response to disasters. Governments, Commercial Enterprises, Militaries, educational institutions, and NGO's will all be able to clearly see that helping to get these payloads into space is a worthwhile endeavor with little risk and very high return.

9.2 Operational Milestone

Prior to the final milestone involving the actual P4XDMT hardware, the team will demonstrate fully operational capability through QO-100 in Europe. This will involve the operation of a DMT prototype at a mid-sized Earth station. This operational system will be running using FPGA's of the same type, and RF A/D D/A converters of the same type as the production DMT. They will also use the same control software as the production articles.

9.3 Design Verification Milestone

This milestone will be reached when the team demonstrates every required signal processing component of the system operating in real-time at scale.

9.4 Simulation Milestone

This milestone will be reached when the team demonstrates all of the major functionality of the DMT from IQ baseband input to IQ baseband output in real time using cloud-based FPGA resources. The baseband inputs will be composites of multiple uplink transmissions each with various simulated transmission impairments e.g. frequency offsets, noise, interference, etc. The output IQ baseband will be validated by decoding the baseband offline to verify the digital packet streams that contain the outputs of the Narrowband Multiplexor operating in a configuration that provides the outputs of each channel in a prearranged test configuration.

9.5 Specification Milestone

This milestone will be reached when all of the specifications of the P4XDMT and the P4XM modem have been finalized including all uplink and downlink specifications. This will require that the feasibility of each of the component parts of the subsystems have been demonstrated. This will involve component demonstrations and test results either from offline or real-time simulation. This is an evaluation that the specifications are those of a system that is likely to ultimately work.

9.6 Organization Milestone

This milestone will be reached when there is a comprehensive project plan of all of the project's tasks and a detailed plan for the volunteer engineering resources available to complete the tasks in a timely manner. This means that all of the individual engineering resources required have committed some minimum pledges of future time that will be devoted to the project. The individual resources will be vetted for prior experience, formal and self-education in the required disciplines, and their ability and willingness to learn the toolchains required by the project.

10 Budget

The detailed project budget will be developed in early 2020. The budget is expected to be less than US$ 500K. Budget items are expected to include

- Tool Licenses
- Purchased FPGA IP (Contingency)
- Test Equipment.
- FPGA Cloud Resources
- Simulation Cloud Resources
- Prototype Hardware
- Prototype Fabrication Services (PCB’s, assembly, etc)
- Necessary Travel
- Space Segment (NA Testing)

11 Program Schedule

11.1 Planning

Plans for the project will be fully developed during 1Q2020. Volunteer engineering resources will be recruited from the open source communities e.g. Phase 4 Ground. Commitments from partners in the AMSAT-DL, AMSAT-UK, and AMSAT-J communities will be obtained. The project will formally kick-off in a session in early February 2020 – timed to be adjacent to Hamcation, the second largest amateur radio festival in North America.

11.2 Specifications and General Design

11.3 Tool-Chain development

11.4 Major Subsystem Development

11.5 Transceiver Prototype Run

11.6 Test System Deployment in NA

11.7 Test System Deployment in Europe

11.8 P4XDR Board Layout and Prototype Fabrication

11.9 Full Operation in Europe through QO-100

12 Organizational Background

Open Research Institute (ORI) is a non-profit research and development organization which provides all of its work to the general public under the principles of Open Source and Open Access to Research

Appendix A. FPGA Primer

This Appendix provides a brief discussion of Field Programmable Gate Array (FPGA) technology for those who may be unfamiliar.

A.1. FPGA Devices

The P4XT Digital Multiplexed Transponder (DMT) is essentially a digital signal processing system implemented mostly in hardware (rather than software). The heart of the DMT is a medium size Field Programmable Gate Array (FPGA) device. An FPGA is generally the optimal device for such processing in terms of parallel signal processing capability, power, and interface capability.

An FPGA is basically a programmable integrated circuit with a very large array of low-level building blocks that can be configured and interconnected to perform virtually any digital hardware function. FPGA's differ from usual integrated circuits in that they are built from building blocks e.g. lookup tables (LUTS), multipliers, and memories and a fabric of flexible interconnection logic. Most integrated circuits, on the other hand, are built from low level silicon elements like transistors and resistors with direct interconnections. Integrated circuits built for a specific application, e.g. DVB decoding, are often referred to as ASICs (Application Specific Integrated Circuits). ASICs use the same manufacturing processes used to produce general purpose integrated circuits.

ASIC's are generally not practical in quantities less than tens of thousands of units because of the high costs of generating the required silicon fabrication masks ($50K and up) and the high costs of the tools necessary to synthesize a design (hundreds of thousands of dollars per seat). FPGA's, on the other hand, can be feasible at Quantity 1. So, although they cost hundreds of times more per unit than ASIC chips, their life cycle costs are far lower in smaller quantities. FPGAs also consume far more power compared to ASIC's performing the same task. However, they are the only viable solution for complex hardware designs in small volume.

A.2. FPGA Types

The types of FPGA's under consideration for the P4X DMT cost $1K to $2K per chip. The FPGA represents by far the majority of the repeater component cost. However, the FPGA also provides the majority of the functionality.

The particular FGPAs under consideration for the DMT are the upper-end of the Xilinx Kintex family. This family is designed for lower cost applications. Xilinx has other families positioned below and above (and well above) the Kintex family. Other manufacturers e.g. Intel (Altera) also have comparable devices and families.

The baseline design uses a hybrid device that also includes on on-chip dual-core ARM processor with good internal direct connectivity to the FPGA core. This sacrifices about ¼ of the FPGA resources in return for a very capable general purpose processor system. FPGA can also use a portion of their resources to implement general purpose processes.

Both FPGA and ASIC Digital IC designs are specified using a High-Level Design language like Verilog or VHDL. These are used to generate an intermediate form of logic representation called RTL (Register Transfer Logic). The RTL is then synthesized to produce the target for the chip – programming bits in the case of an FPGA and ultimately silicon layer mask layers in the case of an ASIC. In both cases there are many more steps, a lot more in the case of the ASIC. Other types of design inputs, e.g. timing constraints, are always part of the flow.

In the case of FPGAs, the vendor (or third party) provides the design tools. In the case of Xilinx, their current toolset is Vivado Design Suite. Vivado works across all the current families of Xilinx FPGAs with much commonality between the families.

For the low-end FPGA families, Vivado is free. For the mid-range chips of interest, the tools are several thousand dollars per year per seat.

A recent development in the industry is the appearance of FPGA hardware resources in the cloud, available for rent on an on-demand basis. These use very high-end multiple FPGA boards mounted in powerful machines within the cloud datacenters. Virtual machine instances are available with the pre-configured tool-chains. There are no extra charges for using the tools – just the normal VM instance charges. Charges for use of the FPGA resources and their supporting VM's are about $2 per hour. These FPGA VM's are designed for heavy computational loads where FPGA's can seriously outperform General Purpose processors or Graphics Processing Units. But they can be used as well for the RF simulation and verification tasks reqSuired by this project.

Appendix B. Link Budgets

B.1. General

A Link Budget accounts for all of the gains and losses in a communication system from transmitter to receiver. This includes transmit power amplifiers, cable and connector losses, transmit antenna gain, path losses, rain attenuation, receive antenna gain, and receiving system noise etc. The budget normally covers everything from the transmitter output to the receiver input. The final result is the ratio of Signal to Noise at the input of the receiver. In satellite engineering, this is typically referred to as the Carrier to Noise or C/N and is usually expressed in dB. For example, 10 dB C/N means the signal is 10 times stronger than the noise. 20 dB C/N means the signal is 100 times stronger than the noise.

In a traditional satellite link the signal extends from the ground-based transmitter uplink, through spacecraft receive antenna, receive LNA, and bent-pipe satellite transponder and then from the spacecraft downlink transmit antenna output to the ground. This is typically modelled as a single link with every element in the chain.

With a DMT, however, the uplink and downlink are completely separate. Only fully recovered digital signals are transferred from uplink to downlink. Accordingly, the uplink and downlink link budgets are separately engineered.

B.2. EIRP

The performance of a transmitting system (Modulator, Power Amplifier and Antenna) can be characterized with a single metric known as Effective Isotropic Radiated Power (EIRP). A GEO satellite will typically have a global beam antenna that covers the entire globe. At GEO altitude, the earth appears in a 17-degree field of view. An antenna to cover this field with 3 dB loss at the edges with typically have a gain of 20dB at beam center and 17dB at the edge of coverage. A 10-Watt transmitter with 1 dB of connector and cable losses will have an EIRP of about 29 dbW output at beam center and 26 dbW at the edge of coverage (EoC).

B.3. G/T

The performance of a receiving system (Antenna and LNB) can be characterized with a single metric known as G/T. G/T has units of 1/Degrees Kelvin. G/T expresses the gain of the system divided by the noise temperature. An amplifier will always amplify both signal and noise. Real amplifiers will also add internal noise of their own. We are normally concerned only with the ratio of our desired signal to noise, or C/N. G/T can be improved with a larger antenna which collects less noise (due to its narrower beam width). G/T can also be improved by reducing the noise added by the amplifier (within limits). Noise is normally significant in the early amplifier stages where the signal is low compared to internal amplifier noise. Amplifier noise can usually be neglected after the signal ihas been amplified to a level well above the internal amplifier noise.

G/T can also be influence by elevation angle of a ground-based dish. When the dish is pointed upwards, the antenna collects mostly sky noise which has a low noise temperature (about 10° K). However, when pointed at lower angles closer to the horizon, the antenna will collect a portion of the earth noise which has a much higher temperature (approx. 150° K at the horizon). So, G/T will depend on the operating frequency, dish size, LNB Noise, and Elevation angle.

Typical G/T performance at 10.425 GHz for various dish sizes is provided in the table below.

B.4. Required C/N

The C/N required to decode a signal with a specified error rate depends on the type of modulation and the type of noise. For satellite channels, the noise is typically Additive White Gaussian Noise (AWGN) and with this type of noise the decoding performance is easily predictable. For DVB-S2 downlink signals, we are generally interested only in Quasi-Error-Free (QEF) channels, i.e. those with block error rates below 10 e-5. The required C/N for DVB-S2 signals in the presence of AWGN noise have been well-characterized are provided in the table below.

B.5. C/N Margin

Good engineering practice requires that the system provide additional margin beyond the minimum required determined by calculation. Such margin can ensure that the system will still perform when assumptions regarding the various factors, including neglected factors, are different from the expectation. A margin of 6 dB is usually considered to be the minimum for satellite links. So generally, we want to engineer the system so that it will have a C/N of at least 6 dB above that required by the design parameters.

B.6. Link Budget Equations

The Link Budget is basically (Transmit EIRP * pathloss * receive gain)/Noise Power. The resulting C/N is a single dimensionless ratio normally expressed logarithmically in dB.

By expressing the receive gain/Noise using G/T, and Boltzmann's constant to relate noise temperature to noise power in 1Hz, we can simplify this to EIRP + 228.6 – 204.3 + 228.6 + G/T or EIRP + 228.6 -10logHz – 204.3 + G/T or:

EIRP + G/T + 24.3 dB - 10logHz.

B.7. Downlink Link Budget

For the downlink, we can simply further to a normalized configuration. For this we assume a 10W Satellite transmitter, 0.9 Meter receive dish, and 1.25 MHz receive bandwidth (1 Mbaud symbol rate). Substituting these in the simplified formula above we get:

C/N = 9.3

The required C/N threshold for DVB-S2 QPSK ½ is 4 dB. So, the normalized system has 5.3 dB of margin with a 10W transmitter and 1 Mbaud symbol rate.

The effective of various changes from the normalized parameters can be easily calculated from the following:

- Each Doubling of Downlink Power (e.g. from 10W to 20W) will add 3 dB.
- Each Doubling of the symbol rate (e.g. from 1 Mbaud to 2Mbaud) will subtract 3dB.
- Increasing the Dish from 0.9 Meter to 1.2 Meter will add approximately 2.5 dB.
- Reducing the Dish from 0.9 Meter to 0.6 meter will subtract approximately 3.5 dB.
- Operating at the EoC will subtract 3dB.

B.8. Uplink Link Budget

The same general equations apply to the uplink. However, the parameters are significantly different. The transmitter is now on the ground. Its gain is a function of dish size and efficiency. The path losses are about 5.5 dB lower (due to the lower operating frequency) and there is little impact from rain. The uplink receiver in the satellite will still have a beamwidth of the full earth but it will see the noise temperature of the earth which is 288K. Accordingly the G/T at the receiver is much lower than a receive antenna on the ground. Fortunately, the receive bandwidths are much lower and this makes up for most of the differences. For the uplink we use a normalized bandwidth of 6250 which corresponds to the minimum practical channel.

Path Loss = 199 dB BW = 6250 = 38 dB/Hz -8.4dB + G/T + EIRP.

The expected G/T is – 8 dB. For a .9M Dish the gain is about 32 dB so the EIRP at 1W output power is 32 dbW. Cable losses for a dish mounted LNB and connectors should be less than 1 dB.

31 – 16.4 = 14.6 dB.

The required C/N for the uplink depends on the modulation and coding. Unlike the downlink, which much be engineered to be quasi error free, the uplink is more flexible. For speech frames, a frame error rate as high as 10e-2 may be acceptable for coded speech. We use here the C/N required for uncoded QPSK at a BER of at 10e-3. This requires a C/N of about 9.6. This provides a link margin of approximately 5 dB, about the same margin as the downlink. Note that in practice, the uplink with likely use a modulation e.g. GFSK and FEC coding.

Changes from the normalized uplink with 1W transmit, 0.9 M dish, 6250 Hz would be as follows:

- Each Doubling of Power (e.g. from 1W to 2W) adds 3 dB
- Each Doubling of the channel size (e.g. 6.25 kHz to 12.5kHz) will subtract 3dB.
- Increasing the Dish from 0.9 Meter to 1.2 Meter will add approximately 2.5 dB.
- Reducing the Dish from 0.9 Meter to 0.6 meter will subtract approximately 3.5 dB.

- Operating at the EoC will subtract 3dB.

Note that these changes are similar to those on the downlink. Like the downlink, of greatest importance are dish size and channel size. For example, a 100 kHz channel size (i.e. receiver bandwidth) requires about 12dB greater transmit power for the same dish size, e.g. 16W vs 1W.

Note that the EIRP power levels are significant. Even a 1 Watt transmitter will have an EIRP of 1,563 Watts. These power levels are comparable to commercial VSATS and are potentially hazardous to humans. Refer to Appendix for additional information regarding the mitigation of potential radiation hazards.

Appendix C. Non-Ionizing Radiation Exposure

C.1. General

Radio Frequency transmitters emit energy in the form of photons. This is also known as non-ionizing radiation. Most transmitters e.g. cellphones, Bluetooth devices, and WiFi devices, etc. produce relatively low levels of such radiation. Due to potential hazards from higher levels of radiation, the FCC requires evaluation of the hazards caused by RF sources exceeding certain levels in order to limit exposure to its so-called Maximum Permitted Exposure limits.

Recently, the FCC has amended its rules related to the evaluation of such hazards. Where under previous rules, amateur transmitters were subject to certain exemptions, the new rules subject Amateur Service and Amateur Satellite Service transmitters to the same rules that apply to all devices. This requires evaluation of devices for the exposure levels and imposes restriction on the location of the emitters with respect to the public and operating personnel.

The current FCC limits are 1 mW/cm2 for the general public uncontrolled exposure and 5 mW/cm2 for occupational/controlled exposure. The FCC applies the latter limits to the Amateur and his family at a residential location.

C.2. Satellite Receivers

Generally, satellite receivers do not emit any power levels that require evaluation. Neither do receive only Amateur stations. It is generally safe to install such receiver dishes at any location, including on the ground, outside windows, etc.

C.3. Uplink Transmitters

Transmitting stations, such as uplink transmitters, produce significant levels of RF energy in the transmitting direction of the dish antenna. The parabolic dish essentially focuses the RF energy. A normally safe output of a few hundred milliwatts can be focused to the equivalent of a 1000 Watts or more. This high power will be concentrated in a narrow beam in front of the dish. Generally, this area must be kept clear of human contact.

Uplink Transmitters must generally be installed in a location that ensures that MPE limits will not be succeeded by members of the amateur licensee’s family or members of the general public. Different limits are adopted for each of these categories of persons.

Generally, meeting the limits will require the installation of the dish at a location where the beam is installed above the level where members of the public or family members may be exposed. Commercial VSAT transmitters, installed in many locations e.g. gas stations, provide examples of compliant installations. Note that many dish antennas use an offset feed to the direction of the emissions is at an angle

Generally, it will be necessary to evaluate both the beam center and side lobes of the particular antenna. In order to do this, it is necessary to have an accurate characterization of the antenna. Otherwise, it may be necessary conduct actual measurements using calibrated equipment.

Appendix D. Simulation Environments

This appendix provides a brief summary of the various environments that will be used for simulation.

D.1. Narrowband Multiplexor NBM Simulation

The transponder downlink ultimately produces a DVB-S2 GSE packet stream. At the packet level, this stream can be easily produced by a simulator running on a cloud server. For the narrowband multiplexor that will relay the vast majority of uplink channels, this simulator stream will be identical to that produced by the DMT. This packet stream can be transferred to test stations through the Internet with delays below those of the actual satellite. This allows the narrowband capabilities of the system to be completely simulated in real-time, including the access, authentication, and authorization protocols and the complete live two-way audio channels.

While the downlink NBM simulation can provide one-to-many channels, the simulator can also be used for the uplink simulation. At the DMT's Multi-channel Narrowband Receiver input, each of the individual narrowband links will be demodulated and error corrected into a framed bitstream of about 100 bits per frame (at 25 frames per second). This bitstream will be identical regardless of the modulation and forward error correction. Unlike the simulated downlink that must be transferred individually to every terminal, the simulated uplinks are a single one to one packet stream directed to the simulated DMT NBM input. The DMT simulator can simply use these simulated bits in place of those that will come from an actual multichannel narrowband receiver implementation. This permits the evaluation of all of the digital protocols, codecs, and operational modes in real-time using the Internet for transport.

The NBM simulation environment will be extended to the application processor of actual P4XM modem hardware. As the application processor for the Modem is a standard off-the-shelf Raspberry Pi-4B, connecting an ordinary Pi-4B to the internet will provide a complete simulation of the application layer of the system. A driver in the Pi-4B will provide an interface to the application layer that will be virtually identical to the of the modem. But instead of transferring to the Modem hardware through Pi-4B SPI ports, the simulator driver will transfer packets through the Internet. The driver will delay data as necessary to match the timing characteristics that will be seen from the real modem hardware.

The simulation environment can also be extended to the wideband channels subject to internet bandwidth limitations.

It should also be noted that P4XM transceivers will be capable of receiving a DVB-S2 carrier transmitted through an existing satellite transponder over North America. This can be done using unmodified commercial TV dishes and LNB. This allows a real space-segment downlink to be used together with a simulated uplink. This hybrid configuration would have additional latency but would be otherwise similar to the space-borne repeater configuration.

D.2. DMT FPGA Component Simulations

The DMT will be composed of a number of hardware components defined by HDL and timing specifications. These components can be very complex. To verify that each component is working per its design specifications, test vectors can be used to simulate inputs and evaluate outputs of the design using the standard tools of the development environment. In typically FPGA development activities, the development of these verification components can represent the bulk of the development effort. Eventually, following such design verification, the hardware will need to be run in real time on real hardware.

Real-Time verification of an FPGA hardware component typically involves some type of test harness hardware to feed inputs to the component in real-time and collect the outputs of the component also in real time. The outputs can then be evaluated off-line to verify that the component produces the expected outputs when operating in real-time on real FPGA hardware. For components that are designed to work across the various FPGA products of a particular vendor, the component can be initially verified using a different family member. For example, an HDL with full timing specifications that will initially be run on a Xilinx Kintex device, can be initially verified using Virtex device. This allows the features of the larger devices to be used as test harness, even where the final target FPGA is not large enough to accommodate both the component set and its test facilities. This approach depends on having the full specification of the design, both HDL and timing specifications, to allow the design to be synthesized properly to the specific hardware. Generally, if full timing closure is achieved, the designs will work on any device in the supported families.

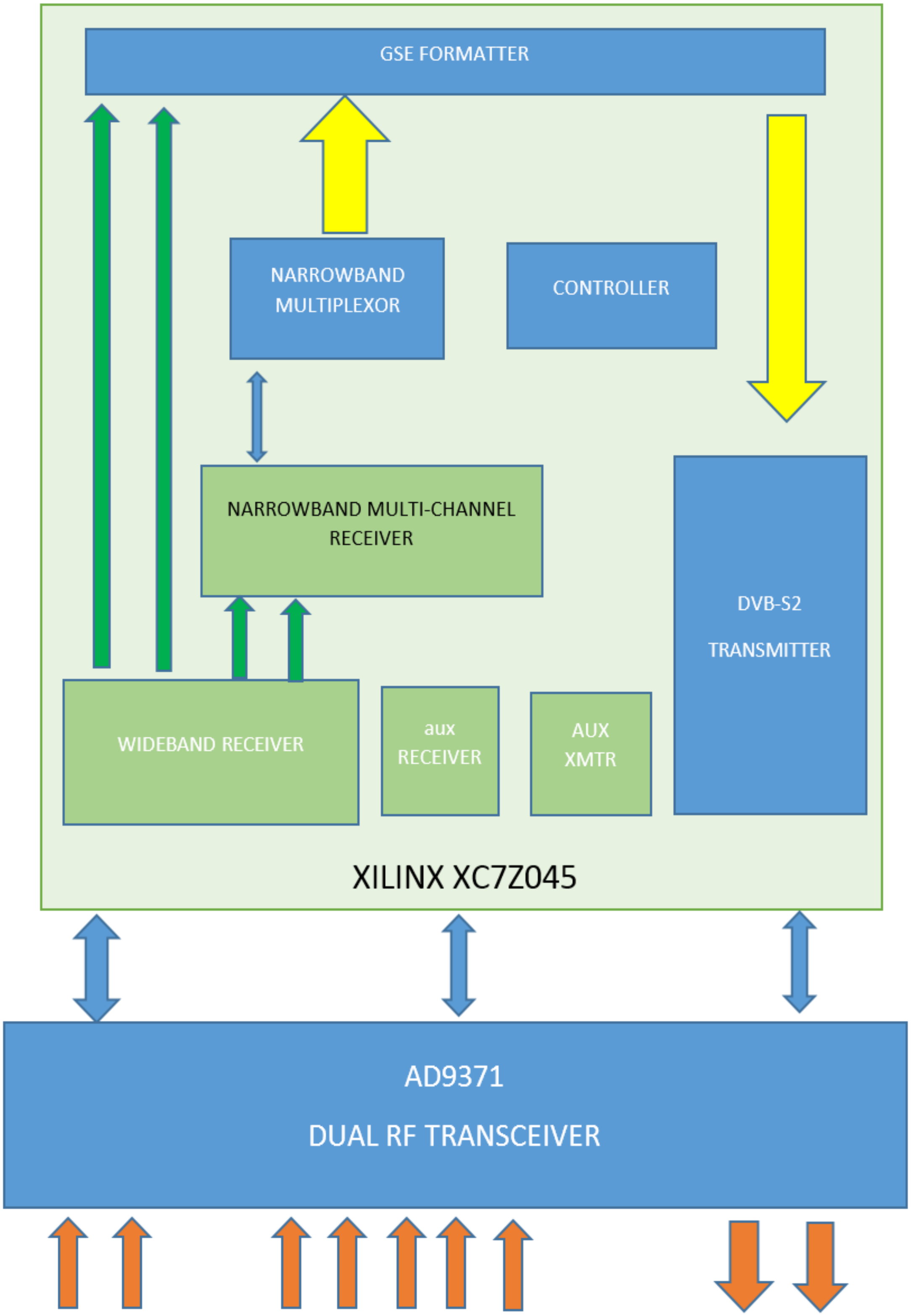
Appendix E. DMT Baseline Design

The baseline design uses a Xilinx XC7Z045 SoC as the core of the system. This is the 2nd largest device in the Xilinx Zync-7000 (Kintex-7) SoC family. The device has 218,600 Lookup Tables, 437,200 Flip-Flops, 19.2Mb of Block RAM, and 900 DSP Slices. Both larger and smaller devices are available should either prove optimal. The design trade-offs involve not only the processing capability of the device but the power consumption in this particular application. FPGA power dissipation can vary over a ten to one or more range depending on the specific activity within the device.

Initial prototyping activities will use the Xilinx ZC706 Evaluation kit ($2922) which is available off-the-shelf. This is large PCI-e board that can be installed in a PC platform or operated in a standalone configuration.

The Digital RF subsystem is provisionally based on an AD9371 device. This device is AD’s second generation which provides higher performance and improved feature set over the more common AD9361. Initial prototyping will be performed using an off-the-shelf ADRV9371 ($1250) evaluation board. This board plugs into the FMC connector on the XC7Z045 FPGA development boards which results in a complete package that includes most of the functionality of the target SDR core board.

Appendix Figure E-1 DMT Block Diagram



RF connections will include 2 Main Tx, 2 main Rx, and 5 auxiliary RF inputs any one of which can be selected as an additional receiver. These all operate from 300 MHz to 6GHz. The two TX chains share a common LO. Similarly, the two main RX chains share a common LO. The third RX chain is independent.

Generally, 10.5 GHz output will require an upconverter. With careful choice of frequencies, it is possible to generate independent downlinks on X-Band and another band (2400, 3400, 5600) or independent outputs of different polarizations.

The auxiliary receiver can be configured on the fly to work with any of 5 RF inputs. Two of these inputs may be connected to the corresponding transmit chains to support calibration. The others are available to support any band.

It is possible for the 2nd main receiver to support an uplink band with careful choice of IF frequencies and the use of a converter. It could also independent polarizations of the name band.

The RF connections to the ADRV9371 board used during development will accept connection from the actual frequency converter boards in the final configuration. This will allow these boards to be developed directly and fully tested and characterized using the prototype environment.

The chassis housing the test platform will include a remote JTAG capability that can be used to program the board remotely. The development systems will be configured with Linux-based software and development tools. The systems will be designed to be remotely accessed by members of the FPGA development team on a shared basis. The physical systems used for development will be installed in locations that also have remotely accessible test equipment e.g. spectrum analyzers.

Appendix F. P4XM Modem Baseline Design

This appendix provides a brief discussion of the baseline P4XM Modem Design. This is provisional and subject to revision as the project proceeds. It should be noted that the P4XM modem can be used in earth terminal with many variations in antenna size and output power covering a wide range of performance.

F.1. General

The P4XM Modem is intended to provide a low-cost solution for widespread adoption by the Amateur Radio community. It is not intended to provide the lowest possible cost solution but rather a low-cost solution that addresses most of the needs of a very wide range of operators.

F.2. Standalone Appliance Solution

While it is possible to perform certain functions of the modem within an associated personal computer, not all amateurs have a suitable machine. In addition, as the PC environments are highly varied, there is a large potential for troublesome software and hardware issues.

In the past several years, very low-cost PC platforms e.g. the Beagle Bone and Raspberry Pi have appeared. These single board computer devices have a very high level of price performance. The latest Raspberry Pi, for example, has a Quad Core processor, 1 GB of RAM, Gigabit Ethernet, USB-3.0, and dual 4K capable mini HDMI ports – all on a board that cost $35 retail. Accordingly, the baseline P4XM design embeds a Raspberry Pi 4 and provides a complete standalone appliance like solution for the Modem portion of the terminal. The only external components required are the Dish, LNB, BUC, and associated cables. The LNB and BUC functions may be integrated with a single unit including the dual band feed allowing simple final assembly and installation.

F.3. Application Processor

As indicated above, an internally mounted Raspberry Pi 4 functions as the application processor of the terminal and handles the user interface and certain radio related tasks. The Pi 4 has a quad core processor and two of these cores are dedicated to modem functions. The remaining two processors provide the application user interface as well as interconnections with optional systems.

F.3.1. External Interfaces

The external interfaces available to the application include the following:

- 2X Micro HDMI ports, each capable of 4K resolution.
- 1 Gigabit Ethernet Port
- 2X USB 3.0 Ports
- 2X USB 2.0 Ports

Note that both the USB 3.0 and USB 2.0 ports can be extended through low cost off-the-shelf hubs.

F.3.2. Wireless Interfaces

Both Dual Band WiFi (802.11n) and Bluetooth Interfaces are provided. These use an internal antenna. The modem enclosure is designed to pass this RF with performance equivalent to typical plastic Raspberry Pi cases. The WiFi can operate either as a terminal or an access point. The Bluetooth Interface can be used for wireless input devices and audio devices e.g. headsets.

F.4. Internal Interfaces

The 40 Pin so-called PI-hat connector of the Pi-4 connects internally to the main modem board. Power for the PI is provided through this connector as well as 5 SPI interfaces. All data between the modem and the Pi-4 are passed through the SPI interfaces.

F.5. Modem Board

The Modem Board contains Power Supplies, the Satellite Receiver Front End, the DVB-S2 demodulator, a GPS Derived Oscillator, a Narrowband Modulator and IF driver and various glue logic. An internal microcontroller manages the modem functions and communicates with the application processor through one of the SPI ports. The other SPI ports are connected to a small FPGA which provides glue logic for the formatting. The SPI interfaces will support Digital Television streams from commercial satellites as well as the GSE streams from the DMT.

F.6. ASIC DVB-S2 Demodulator

The P4XM Modem will be based on an off-the-shelf DVB-S2 Demodulator IC. These types of devices are designed primarily for broadcasting applications in consumer satellite receivers. These devices perform all of the baseband processing for the DVB-S2 receiver including demodulation and FEC decoding.

The provisionally selected device has advanced non-broadcast features including demodulation of all DVB-S2 MODCODs and support for Generic Stream Encapsulation. The device is fully characterized for symbol rates from 1MBaud -to 45Mbaud. The device also has the internal machinery for operation at lower baud rates. In addition, the device supports bypassing its internal demodulator which allows the processing FEC decode and BBFRAME decoding using an external demodulator.

F.7. GPS Timing Receiver

The device contains an integral GPS Disciplined Oscillator that generates the high timing precision required for narrowband satellite links. An external GPS antenna is required and connects through an SMA connector. Antenna LNA power is provided through the connector. A 10MHz timing reference is provided through a BNC connector to support other equipment. The 10MHz reference is also supplied through the IF Output to the Block Up Conververter (BUC).

F.8. RF Front Ends

The modem provides 4 RF inputs. All 4 inputs use industry standard 75 ohm F connectors for compatibility with existing satellite receive equipment and to prevent the inadvertent connection of the transmit Outputs LNBs. LNB power is provided on all 4 inputs. The four inputs can be routed to two IQ channels. One channel is wideband with a selectable passband from 5 – 45 MHz and is always supplied to one channel of the DVB-S2 demodulator. The second channels is narrowband with a programmable Low Pass Filter selectable passband from 50kHz to 1 MHz. This channel is passed both to the DVB-S2 demodulator and to an ADC of the DSP.

F.9. Modulator

The modem contains a Quadrature Upconverter that generates IF/RF in the range from 440 – 2500 MHz from IQ basebands. The IQ baseband is generated from a 12-bit DAC.

F.10. Modem Software

The complete modem software distribution, including the Linux operating system and all necessary drivers is contained on a single SD-Card image that is inserted into the SD-Slot of the PI 4. A complete open source software distribution and build system will be maintained to ensure the full appliance-like operation of the system can be maintained. This distribution will be derived from the Raspbian and Debian upstreams.

Appendix G. DVB-S2(X)

This appendix provides a very brief summary of DVB-S2(X) which is the underlying technology for the high-speed digital downlinks provided by the P4DMT.

The use of a geosynchronous orbit for communications was first proposed by British science fiction author Sir Arthur C. Clarke, in 1945. In 1962 the first television signals were relayed between North America and Europe and several commercial satellites were launches in the sixties. By the early 1970, transponders were more or less standardized with 36 MHz channels in 40 MHz spacing.

In the late eighties, medium powered satellites operating in Ku band were able to provide direct to home service to small dishes (under 1 meter) in Europe. By the mid-nineties, several direct to home services were in operation using digital standards, both proprietary (DSS) and open (DVB-S). Since its introduction in Australia in 1995, DVB-S eventually became the dominant world-wide standard. Since the mid 2000’s, the second version of the standard, DVB-S2 has begun to replace DVB-S throughout the world. The P4DMT uses the DVB-S2 version of the standard and some of its extensions (DVB-S2X).

DVB-S2 uses a powerful forward error coding (BCH and LDPC) to provide the quasi error free performance required for digital television and Internet Protocols. The performance is very close to theoretical limits. Given a signal meeting the threshold C/N, quasi error performance will be delivered. Adding additional C/N will not significantly increase the performance. A signal even 2 dB below the threshold will be essentially useless.

Unlike earlier systems, DVB-S2 supports variable modulation and coding on a frame by frame basis. A DVB-S2 carrier consists of a continuous sequence of back to back frames. The modulation can be different for each frame and is indicated by a MODCOD sent at the start of each frame. All receivers, even those with the minimum performance level, are able to decode the MODCOD and determine the modulation, coding, and size of the frame. Only stations that have the C/N required for the specific MODCOD are able to correctly decode the frame. All stations, however, are able to maintain synchronization and will be able to receive the MODCOD for the next frame. Variable modulation and coding let a single carrier serve a broad range of users with different C/N performance.

Appendix H. Amateur Radio Access Points

A P4X Digital Repeater in space has the potential to drastically enhance Amateur Radio's response to natural disasters. There are thousands of amateur radio VHF repeaters with many of them conducting net operations every day in preparation for future emergencies. Unfortunately, each repeater provides only a single channel which quickly becomes saturated with priority traffic related to the disaster response. This usually leaves little capacity to carry any health and welfare traffic of any significance. In the developed world, the direct casualties from natural disasters are fortunately very few. However, there are significant health aspects to the emotional stresses caused by worries about the safety and whereabouts of loved ones and worries that family members don't know where their loved ones are. Health and welfare messages can greatly reduce such unnecessary stress while showcasing the benefits of the amateur radio services.

ARAPs provide the means to link each local repeater in a disaster zone to a global network – independent of any other infrastructure within the disaster area. This can be done with even a single very-low-cost earth station. Even a simple ARAP link can provide a duplex voice channel to a repeater as well a digital channel capable of moving store and forward digital message traffic to and from the disaster area.

In addition, an ARAP can host digital microwave links between emergency shelters and the ARAP location. These links can use L-Band or VHF/UHF frequencies operating in point to multi-point mode. The P4XM Transceivers can be configured to operate in this manner to move digital messages from a shelter site to the repeater site where they can be forwarded to and from network traffic stations in unaffected areas. Advanced terrestrial ARAPs using PC's and off-the-shelf hardware can provide functions similar to those of the P4XT DMT without requiring the expensive FPGA based hardware. This can allow a central repeater to move high volumes of traffic and multiple voice channels between all of the emergency shelters in a local area.

In addition, even the very-low-cost P4XM transceivers can host a local WiFi hotspot and wired ethernet networks providing a built-in local web server that provides browser based two-way message access from any WiFi enabled mobile phones operating in the shelter. Shelter occupants could register and then send and receive short message type traffic both between shelters and between the shelter and the unaffected world. These messages can be held locally and reviewed locally in the shelter prior to forwarding to ensure that they comply with applicable regulations.

Appendix I. Amateur Built GEO Platforms

The P4X Digital Repeater may eventually be deployed on any of several types of platforms. One of these possibilities is an Amateur Built Platform dedicated to the repeater.

Preliminary studies suggest that a 6U CubeSat less than 10kg would be of sufficient size to hold the required systems, including power, propulsion for station keeping, and propulsion for maneuvering to a disposal orbit at end of life.

An interesting possible configuration would involve a cluster of 3 or 4 satellites that could be piggy-backed on a mission launching a military, government, or commercial satellite to GEO. This might involve a launch into a Geosynchronous Transfer Orbit (GTO), followed by a circularization burn placing the payload and it’s piggy-backed CubeSat into GEO. The Amateur Radio satellites would be released sometime prior to the primary payload’s final orbit. Each of the satellites would then be independently maneuvered into their final GEO slot. As the combined size and mass of the 3 satellites is very small compared to the typical primary payload, such an approach appears to be feasible.

Another possible approach is to use a similar sized satellite with ion propulsion capable of slowly raising the orbit from LEO to GEO over a period of 1 to 2 years. Preliminary indications are that this approach may also be feasible. The big disadvantage is the long duration within the inner Van-Allen belts which is a rather unfriendly environment for electronics.

Appendix J. QO-100 Ground Based Repeater

A concept for a ground based digital repeater for the QO-100 based on the early P4B work was presented at the TAPR/ARRL 2017 Digital Conference. The presentation and a paper presenting this concept are available on the web.

The early experience with QO-100 suggests that this concept remains feasible and may also be able to provide an interim digital solution for QO-100. While this solution involves twice the delay of space borne repeater and does not fully address transponder hi-jacking issues, it could nevertheless expand the useful capacity of QO-100 by providing many more voice channels.

At present the QO-100 narrowband transponder of 250kHz serves the analog modes. The wideband transponder with 8MHz of bandwidth provides an uplinked DVB-S2 beacon of 2MHz and several uplinked channels that are used for experimental modes, typically 333kHz to 1MHz. By allocating a portion of this spectrum to low data rate digital repeater uplinks and a portion to carry a DVB-S2 carrier transporting the low data rate multiplexor GSE output, the number of digital voice channels supported by the satellite could be expanded by 5X or more.

The P4XM transceiver design will specifically support all of the necessary requirements for this ground-based repeater operation while remaining fully capable for use on any future space-borne DMTs deployed over Europe and Africa.

Appendix K. Narrowband Uplinks

While the P4XDR repeater will support many types of digital uplinks, the low data rate uplinks are critical as they determine the number of stations that can ultimately be supported.

The C/N of digital signals is generally inversely proportional to bandwidth. So, the narrower the receive bandwidth, the less power is required to achieve a particular C/N. Required C/N for a particular BER is a function of the modulation employed and the FEC coding used.

The baseline characteristics of the low data rate uplinks are described below. These are only provisional. They are subject to change.

The baseline modulation is GMSK with a symbol rate of 2000 Hz and WTb=0.3. This waveform has an occupied bandwidth that will fit within a 5KHz channel spacing. Very high timing precision is required in the complete transmit chain as 1ppm at 5.6 GHz is equivalent to more than an entire channel. Stations must maintain a frequency accuracy of plus or minus 400Hz which requires a timing precision on the order of 0.06 ppm.

Transmissions are framed in 40ms frames. Each frame contains 80 symbols. 13 symbols are dedicated to a preamble for each frame. Three symbols are dedicated to control. This leaves a payload of 64 symbols or 128 bits.

The payload is FEC coded at Rate ½ using a convolutional encoder to produce a corrected payload of 64 bits. This corresponds to a 1600 bps payload rate. The code can be punctured to produce other rates included a standard 2400bps payload rate using an FEC ¾ code. These rates (as well as the frame rate) are selected for compatibility with evolving open-source low bit rate codecs e.g. Codec 2.

Waveforms will be generated in an over-sampled baseband IQ form which will then be converted to analog and upconverted to the intermediate frequency.

Transmissions will be precisely timed to arrive at the satellite in their designated timeslots. Transmissions are always back to back frames. Short bursts of 2 or 3 frames are used for control functions. Stations are not permitted to transmit long continuous bursts until they have demonstrated that their signals are within spec. This will be an automatic process that is part of the protocol. Once authenticated and authorized, stations may transmit as directed by indications provided in the downlink. Performance is continuously monitored and non-performance is indicated in the downlink causing the station to cease transmission.

Multiple stations may be “parked” on an uplink channel, transmitting a single packet a few times per minute as directed by downlink indications. This permits dozens of stations to participate in net like operations. For ordinary two way QSO’s, the stations will alternately share the same channel.