Wireless Communications System for Low Earth Orbit: An Innovative Capstone Design Project

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ABSTRACT

With an increasing emphasis on microgravity scientific research being conducted in outer space comes a need for a turnkey architecture that is capable of supporting a wide variety of research experiments. In order to provide a solution to this problem, a CubeSat class vehicle called TSat has been designed and developed by Texas Space Technology Applications and Research (T STAR). As part of the Capstone Design Sequence performed by the Electronics Systems Engineering Technology (ESET) program within the Dwight Look College of Engineering at Texas A&M University; a student team, DVDT, has taken on the task to design, develop, document, and deliver a space qualified communications system prototype that will ensure reliable communication and data transfer from the TSat down to an Earth station.

This system will integrate into an existing compact rack-and-stack embedded system called the Modular Integrated Stackable Layer (MISL Stack) designed by the National Aeronautics and Space Administration (NASA) in conjunction with the ESET department. In this paper we will discuss in greater detail the hardware and software design, testing and verification methodology, and overall system requirements. Lessons learned and recommendations for future work will also be included.

INTRODUCTION

In the space industry, there has been a slow transition of projects from the public to private sector as spaceflight is becoming more affordable. “By the 2020’s, near the planned end of the life of the ISS, NASA’s intention is to transition low Earth orbit (LEO) from being government-led to significantly more private sector involvement” [1]. One specific focus in LEO commercialization is to create cost-effective satellites for conducting scientific research and data acquisition in microgravity. A CubeSat is a type of miniaturized satellite that typically utilizes commercial off-the-shelf components for its electronics which allows for exploration of new technologies in orbit at a lower price.

T STAR is a private business pursuing the entrepreneurial endeavor of commercializing LEO with CubeSats and collaborating with the ESET program to further innovate the product. The ESET program contains a very vigorous Capstone design experience that encompasses all areas of product development from the initial problem statement to a fully functional prototype [2]. Each capstone team is responsible for designing, developing, documenting, and delivering a fully functional prototype that meets all requirements set by the customer. Students in this capstone course typically form teams of three to five individuals that leverage their strengths to create solutions to real world problems. The quality of work that is produced through the capstone process continues to meet high standards and performs very well in satisfying the customer.

DVDT is a current team going through the Capstone experience to develop a functioning system for T STAR and their advancement in CubeSat technology. Understanding the rigorous path in front of them, DVDT set forth on their project during the summer months prior to their enrollment in Capstone to better understand the problem at hand, start acting as a pseudo start-up company, and begin early research and design. This paper will use DVDT as an example to provide insight into the ESET Capstone design experience. The team will discuss in greater detail the hardware and software design, testing and verification methodology, and overall system requirements. Lessons learned and recommendations for future work will also be included. Finally, the paper will illustrate the importance that working on real-world, customer driven projects has on students in engineering education.

BACKGROUND

Texas Space, Technology, Applications, and Research (T STAR) is designing a CubeSat class vehicle called the TSat. The current state of TSat operations is to be launched from the International Space Station, operate autonomously in low Earth orbit, and collect data until reentering Earth's atmosphere. Upon reentry to Earth's atmosphere, the TSat will burn up and lose all data acquired over the course of the experiment rendering a useless mission. Other CubeSat designs incorporate bulky untailored communication systems such as two way radios or other commercially available solutions with complex interfacing needs and high power consumption. The TSat is utilizing the Modular Integrated Stackable Layers (MISL Stack) to allow for a modular and scalable approach in CubeSat experiments. The MISL Stack is a compact computer system with interchangeable modules for rack and stack capabilities making experiments flexible without new designs. Each layer within the MISL Stack has a single purpose (e.g. power, intelligence, Wi-Fi, etc.).

A communications layer with the ability to transmit and receive data efficiently is a critical need for future development of the TSat because there is no value in conducting microgravity research without data transmission. A need exists for a communications system that can be merged into a turnkey TSat architecture to ensure reliable communications between the TSat and an Earth station. To solve this problem, DVDT will design a prototype communications system called the DVDTcomm board that integrates into the existing MISL Stack structure with a Real-Time Operating System (RTOS) architecture that allows for modular systems development in the future. This solution will focus on the design of a communications system while implementing the entire architecture in the lowest possible power requirements.

DESIGN

The design of the DVDTcomm board came into fruition through a sequence of product development stages. The first stage was a conceptual design in which a simple Conceptual Block Diagram (CBD) of the system was created in order for the basic functions to be visualized and then qualitatively defined into the functional requirements. The next stage was taking the functional requirements and creating their respective performance specifications. These specifications are quantitative measurable values for power, data rates, etc. for each of the functional requirements. Also, DVDT created detailed functional block diagrams (FBD) to showcase all the parts chosen with pins, signals, and all interfaces required for everything to function properly. Next, DVDT worked on defining the RTOS storyboard for how the software will run tasks on the intelligence layer of the MISL Stack. Lastly, the team worked on a plan for testing the DVDTcomm board to satisfy the functional requirements to their accompanying performance specifications. All of these stages, explained next, were vital in converting the problem into a solution.

Conceptual Design

The conceptual design consisted of generating the CBD and the functional requirements. The CBD can be seen in Figure 1 showing a simple picture of the TSat in space communicating towards an Earth station.

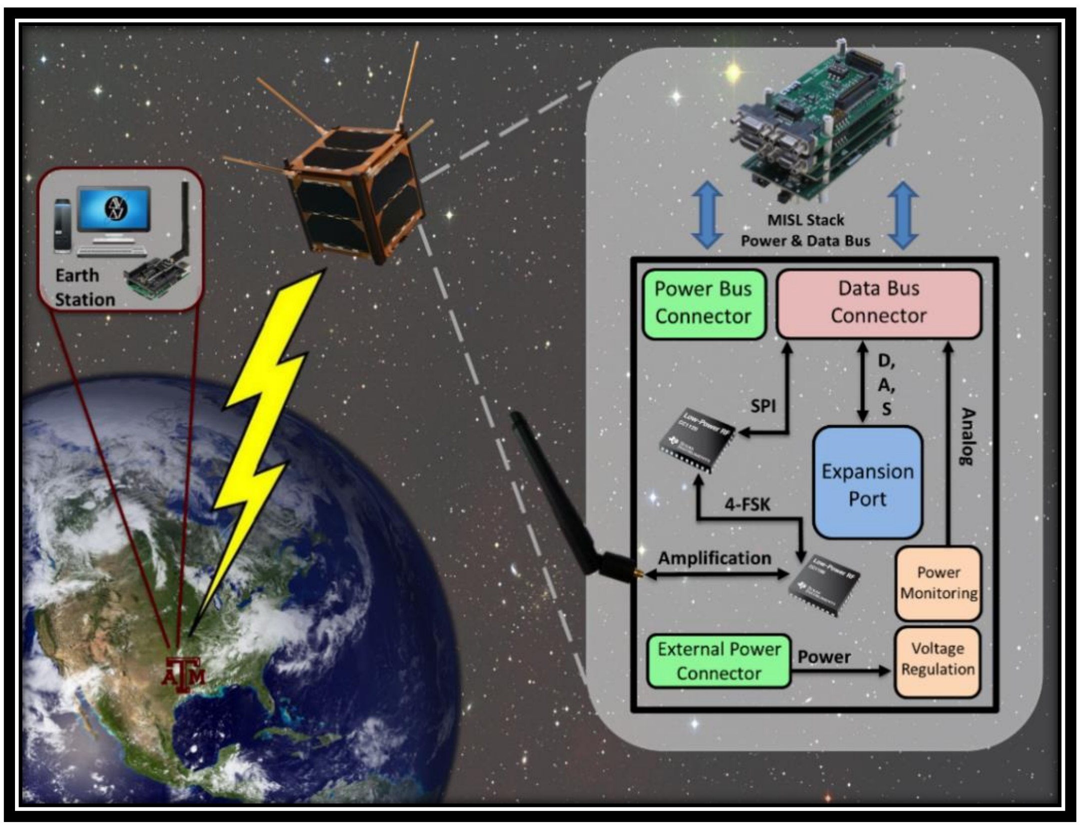

Figure 1 – Conceptual Block Diagram

The CBD shows the basic devices and their interfaces between each other to give a visual demonstration of how the DVDTcomm board works. The DVDTcomm board is outlined in black borders within the highlighted region. Notice how the DVDTcomm board connects to the MISL Stack through the blue arrows representing the MISL Stack power and data connectors. The entire MISL Stack, including the DVDTcomm board, is positioned within the TSat. There are two available power sources. The first power source is from the MISL Stack using the "Power Bus Connector" and the second from an external source using the "External Power Connector". The power coming from the power bus connector is regulated on a separate MISL Stack layer while the external power connector will be regulated onboard. The ability to monitor power is available for both sources.

All communications pass through the "Data Bus Connector" which has been strictly defined by NASA to ensure compatibility among MISL Stack layers. There is an "Expansion Port" on the DVDTcomm board that provides access to digital, analog, and serial signals on the data bus for use by the end customer. The last section of the CBD is the transceiver subsystem which contains the CC1120 and the CC1190. The CC1120 is a transceiver chip that can be configured for wireless communication at 915 MHz. The CC1190 is an RF Front End that will amplify the output of the CC1120 and allow the TSat to transmit at a greater power output. The CC1120 communicates over SPI to the MSP430 microcontroller to send and receive data packets. Once the CC1120 has the desired information, it sends the data through the CC1190 and out to the antenna where wireless communication down to the earth station begins [3].

Functional Design

Once the conceptual block diagram was complete the project transitioned further into the design phase with the generation of the functional block diagram. This block diagram is used to support simultaneous design and development of both hardware and software. The ability to have all part numbers, pin numbers, and interfaces referenced within a single document allows for the engineering team to have clearly defined specifications when completing their plan of action. The hardware engineer can look at the functional block diagram and understand all aspects of the design to a point where they can generate a schematic accurate down to the pin level. The software engineer can reference the functional block diagram when developing software to ensure the microcontroller and associated devices are consistent with those the hardware engineer is designing the board for. The system engineer uses the functional block diagram to accurately develop a test plan based on component selection and device interfaces. All aspects of the project are included within the functional block diagram including the user interface, features to be developed, and explicit definitions of what is not within project scope. Figure 2 depicts the DVDTcomm overview functional block diagram.

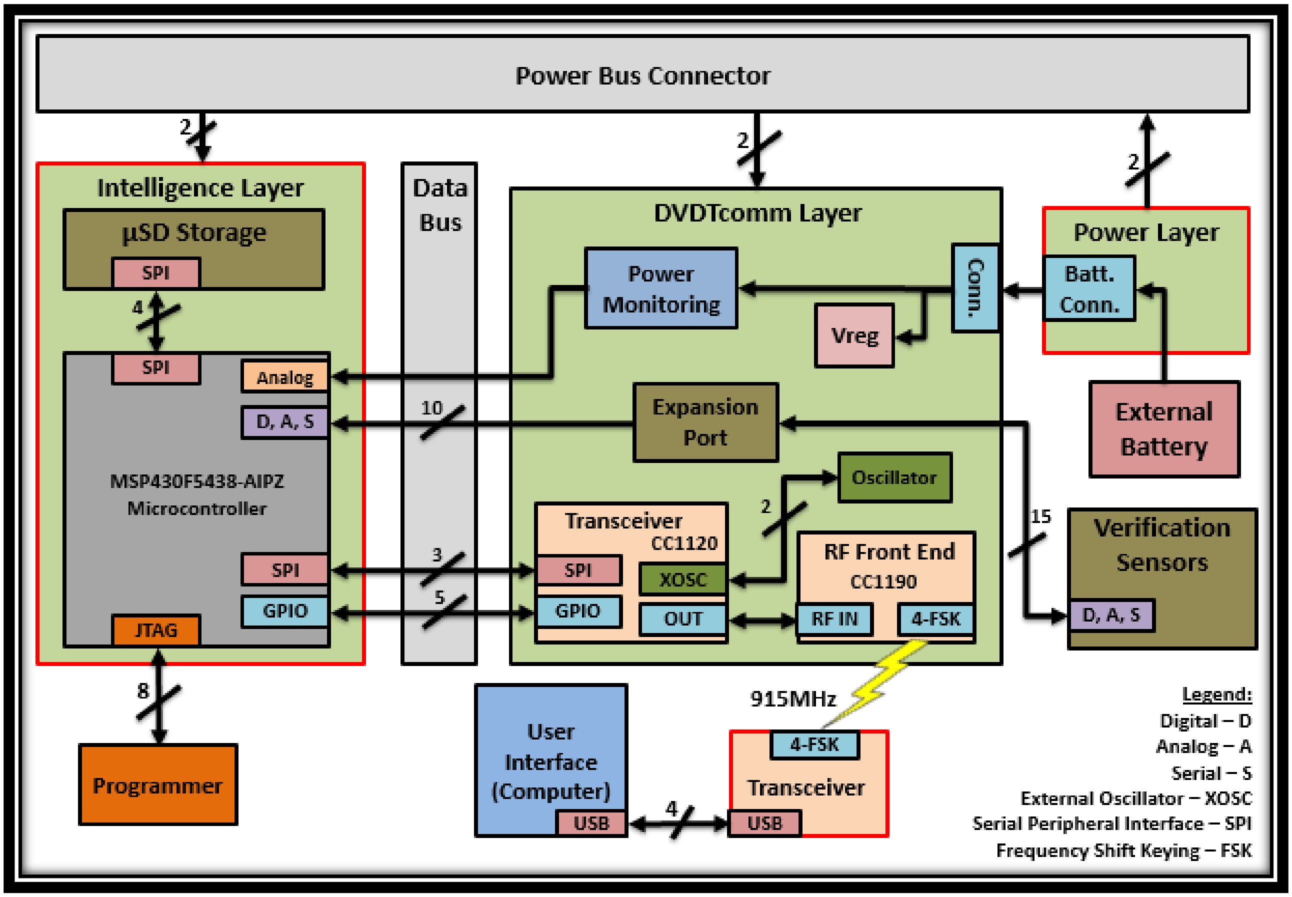

Figure 2 - Overview Functional Block Diagram

The MISL Stack contained within a TSat will require a minimum of 3 separate layers: the MSP430 layer which will provide onboard intelligence and contain all embedded code, the power layer which will regulate the battery voltage and transport necessary voltage levels throughout the system, and lastly the DVDTcomm layer which will translate embedded communication into a modulated waveform capable of line-of-sight communication with the Earth station.

The power and intelligence layers are not within the scope of the project and have been previously designed. The DVDTcomm layer is the focal point of design, development, and delivery by DVDT. Onboard the DVDTcomm layer will be an external connector to allow the battery voltage to be passed directly to the board without being regulated through the power layer. This voltage will then be regulated and monitored on the DVDTcomm board to provide extra functionality to the customer. The DVDTcomm layer will have an RF transceiver as well as an RF front end chipset. The transceiver is responsible for communicating with the microcontroller over SPI and taking the incoming packets and modulating them into a waveform. The RF front end then takes this input and amplifies the radiated power from +10dBm to +27dBm and passes the waveform along to the antenna on the outside of the TSat.

The DVDTcomm layer will communicate with an Earth station that is not within the scope of DVDT's design, however, a commercial off-the-shelf Earth station will be implemented for testing and verification purposes. As mentioned earlier, the intelligence layer is not within the scope of the project but there is a µSD card reader on that layer that will be utilized for data storage and therefore the software aspect for communicating with the µSD card is within the project scope. Lastly, an expansion port will be included on the DVDTcomm layer to provide flexibility in design and development as well as flexibility in interfacing capabilities to the end customer.

Real-Time Operating System

Creating embedded software for a system that can be implemented in various ways was a major challenge DVDT had to overcome. Due to the expandability of the system, DVDT decided to implement a RTOS architecture on the MSP430 intelligence board. The ability for multiple tasks to run, as well as the ability to have dedicated tasks for communication is the focal point of the RTOS architecture.

Figure 3 shows the RTOS Architecture and how different tasks communicate and interact with one another.

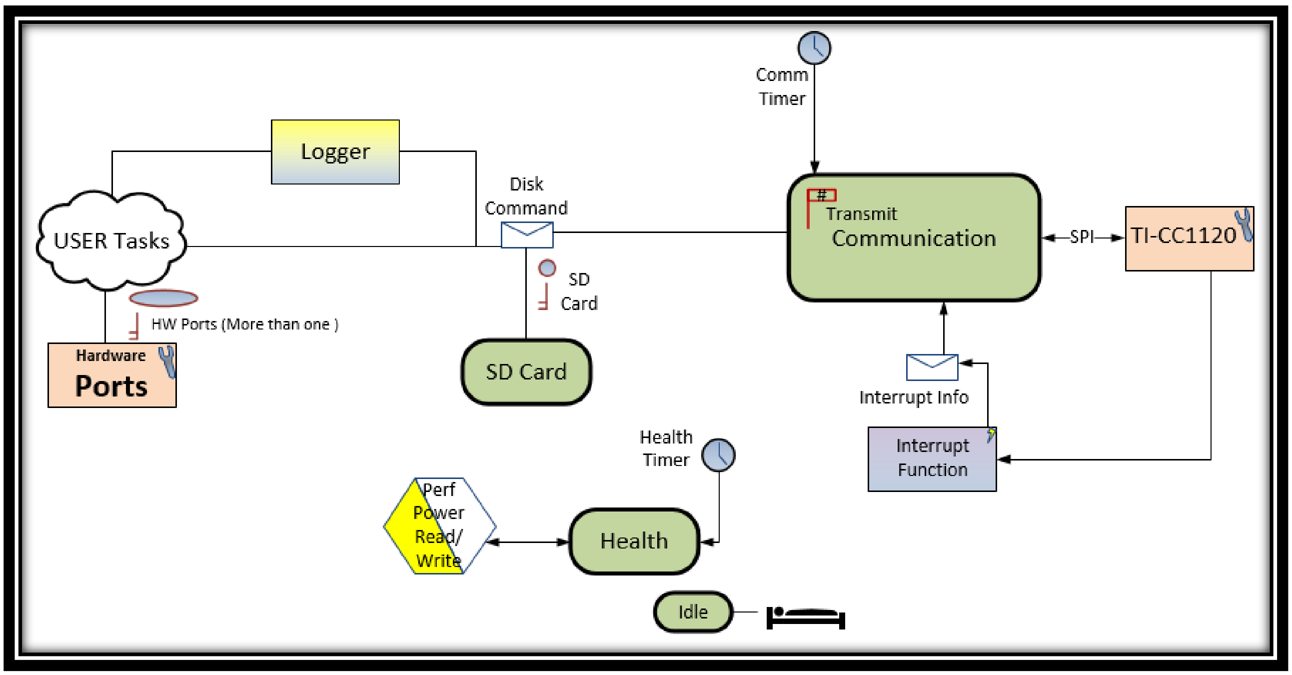

Figure 3 - RTOS Architecture Storyboard

There are three main parts of the architecture: the User End Tasks, Communications, and the Health Task. The combination of these sections make up the real-time operating system which will allow the DVDTcomm board to operate in the lowest power mode by putting the system to sleep when a task does not need to be executed.

All experimental code will be written in the User Tasks. This encompasses all code written to operate any experiment. One major concern for any RTOS implementation is multiple tasks be able to use the same port. For example, a task might send Temperature data over UART to a device, and a different task sends Humidity Data to the same device with the same UART connection. If a task is interrupted in the middle of sending a packet by another task that starts sending data, the end result will be a mix-up of different information and it won't be useable. To correct this, the code written by the end users will have access to all hardware ports but will be locked while in use. This prevents multiple access to the same ports. If a port is locked, no other task can use it until the task that locked it is done. Also, the software will have access to a logger function and access to the µSD card to save data. The logger will save all data that is given to it, and only information passed through the logger will be transmitted to the Earth station.

The Communications task was created by DVDT and will control all communication from the TSat to the Earth station. The initial setup of the transceiver and strategies of data handling will all be implemented in this task. To send information, the Communications task will do the following tasks. First, the Communications task will be in idle mode until a packet is received from the Earth Station. Once the start transmit packet has been received, the communications task will begin transmitting all information that is contained in the logger file on the uSD card. Every minute, the communications task returns to idle mode and waits for another clear to transmit signal from the base station. This cycle will continue until the TSat is out of range of communication.

Lastly, the Health task in the RTOS architecture allows for our system to be monitored and have the ability to reset itself incase errors occur. All tasks are required to ping (talk) to the health task. If any task does not ping the health task after a certain number of attempts, that task will be restarted. If the task is a mission critical task, and the task still does not respond, a complete reset of the TSat can be done.

TESTING

DVDT created a test matrix to map functional requirements of the DVDTcomm board to tests that will validate all of their performance specifications. Once all of these tests are passed, a final demonstration can be performed to show the customer that the DVDTcomm board is capable of communicating data from the TSat to an Earth station. The test matrix is seen in Table 1 with requirements located in the columns and tests inside the rows.

Table 1 – Test Matrix

Test	Data Bus Connections	Power Bus Connections	External Power Connector	Power Monitoring	Expansion Port	Wireless Communications	SPI	Delete µSD	R/W to µSD	Small Form Factor	RTOS Architecture	Mockup Earth Station
Power		■	■		■							
Integration to MISL	■	■										
Wired Signal Testing				■			■		■			
Wireless Signal Testing						■						■
Continuity to uC	■		■		■							
µSD								■	■			
RTOS				■	■	■	■	■	■		■	
Wireless Signal Attenuation						■						■
Size Measurements										■		
Battery Life		■	■								■	
Earth Station Connectivity						■						■

The filled in boxes within the row and column intersections show which test is used for verifying which requirement. These help confirm that DVDT does not miss testing any functional requirement. Note that almost all functional requirements are tested in more than one way for extra verification or in the case that a test does not get the results as planned. Next, each test will be explained with the questions it will be used to answer.

Power

- Is the MISL Stack power bus supplying expected voltages to the correct pins?
- Is the external power connector able to supply power correctly?
- Is the expansion port receiving power on the two designated pins?

Integration to MISL

- Can the DVDTcomm board fit on the MISL Stack?
- Are all the power and data bus pins mapped correctly?

Wired Signal Testing

- Can the MSP430 read the correct power monitoring signals?
- Are the SPI signals between the CC1120 and MSP430 correct?
- Are the SPI signals between the µSD card and MSP430 correct?

Wireless Signal Testing

- Is the Earth station receiving packets from the DVDTcomm board?

- What is the received signal strength at the Earth station?
- What is the bit rate, error rate, etc.?
- What is the transmit power of the DVDTcomm board?
- Can the DVDTcomm board be initialized by the Earth station?

Continuity to Microcontroller
- Does the expansion port successfully communicate with the MSP430?
- Are the external power pins not shorted?

µSD
- Can the µSD read, write, and erase data successfully?

RTOS
- Can the RTOS monitor the power successfully?
- Can the RTOS send and receive data to the expansion port?
- Can the RTOS send and receive data to the transceiver?
- Are all SPI logic signals correct?
- Can the RTOS use the µSD successfully?
- Is the RTOS energy efficient?

Wireless Signal Attenuation
- Can the DVDTcomm board transmit successfully to the Earth station at long distance LOS?
- How is the signal strength with added signal attenuation?
- What is the bit rate, error rate, and signal strengths with these tests?

Size Measurements
- Does the DVDTcomm board meet the size requirements to fit on the MISL Stack and inside the TSat?

Battery Life
- How much power does the DVDTcomm board use to perform the RTOS tasks?
- How long will the battery be able to power the DVDTcomm board?

Earth Station Connectivity
- Can the Earth station successfully transmit to the DVDTcomm board and interrupt RTOS tasks?
- Can the Earth station successfully receive packets from the DVDTcomm board?

Earth Station Test Plan
The Earth station mockup is one of the major tools used to verify wireless communication tests in the test matrix and is very important for simulating and verifying the end goal of the DVDTcomm board to communicate data at long distances in line-of-sight.

The system engineer uses the functional block diagram to accurately develop a test plan based on component selection and device interfaces. An Earth station is needed to test the DVDTcomm signal strengths and packet error rates. DVDT chose the CC1120 Development Kit (dev kit) from Texas Instruments (TI) to serve as the mockup version of the Earth station. This dev kit contains the exact same transceiver chip as the DVDTcomm board and is capable of running transceiver tests through USB on a computer with an already designed graphical user interface (GUI). Figure 4 shows the development kit that DVDT used to test communications and gather various data points.

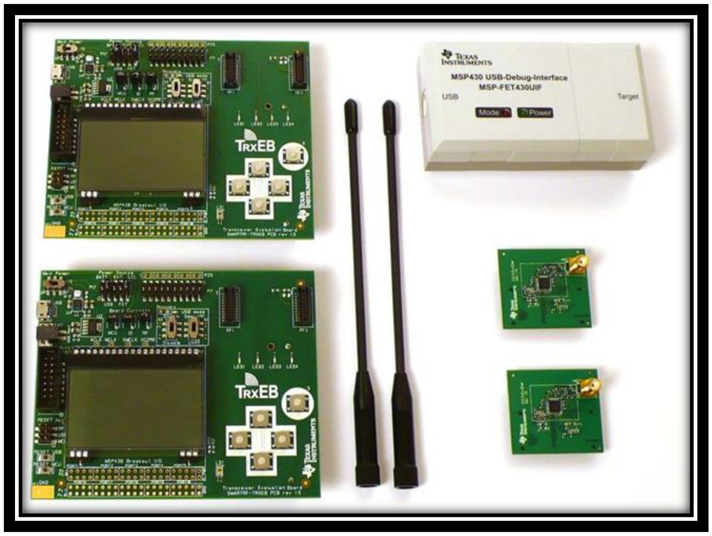

Figure 4 - CC1120 Performance Line Development Kit [4]

This dev kit will be used for two major tests to demonstrate the functionality of the DVDTcomm board. The first test is to transmit data from the DVDTcomm board to the dev kit Earth station and the second test is to transmit specific data from the Earth station to the DVDTcomm board. Transmitting data from the DVDTcomm board will consist of using the dev kit in master mode to receive signals and display packets on the GUI. These packets will be sent from the intelligence layer and through the DVDTcomm layer on the MISL Stack with the help of the RTOS architecture. This test will be done at the longest line-of-sight distance possible and also be done separately with added attenuation to simulate the losses that will be experienced when located in low Earth orbit. The purpose of this test is to simulate the TSat sending experimental data while in range of the Earth station. The second test of transmitting specific data from the Earth station to the DVDTcomm board will be done by putting the Earth station in slave mode sending data to the DVDTcomm board. The purpose of this test is to simulate the Earth station pinging the TSat to identify if the TSat is in range for data transmission.

These two tests are very important to demonstrate how the DVDTcomm layer is designed to work with the Earth station. The Earth station will first ping the TSat and then listen for an acknowledgement to signify that the TSat is in range. If there is no acknowledgement then the Earth station knows the TSat is out of range and will continue pinging and listening. While this is going on the TSat is orbiting the Earth in idle, a sleep power saving mode, on the RTOS architecture but also listening for a wake up ping from the Earth station. Once the TSat is in range and receives that Earth station ping, then the RTOS will send an in range acknowledgement to the Earth station to begin transmission of the experimental data. The DVDTcomm board will keep sending data until the RTOS discovers that the TSat is out of range which then restarts the entire process.

CURRENT PROGRESS

DVDT has successfully completed the first semester of the Capstone Design Sequence in which all project planning has been completed as well as initial designs for the DVDTcomm board. The planning phase consisted of using many project management tools to accurately define the scope, time, and cost of pursuing the project for the customer. This first stage of Capstone positioned DVDT with a clearly defined and agreed upon solution to the problem T STAR needs solved. The project has now transitioned into the development and verification phases of the project's work breakdown structure. DVDT plans to have a fully developed and tested platform ready for use by T STAR in early April, much earlier than the required mid-May deadline.

Hardware Development

Hardware development has seen significant progress by generating solutions for every subsystem of the DVDTcomm board. DVDT was able to begin the initial designs for this solution using the functional block diagrams to then create a schematic capture of the desired solution. After creating a schematic, DVDT was able to successfully pass their Alpha Schematic Review which included both their technical advisor and the Capstone design director. In addition to completing the schematic, DVDT has designed a 4 layer printed circuit board which had been printed out at actual size and verified for each component. DVDT successfully passed their Alpha Layout Review on January 9th, 2016 and the board was sent out for manufacturing. The first revision of the printed circuit board can be seen in Figure 5.

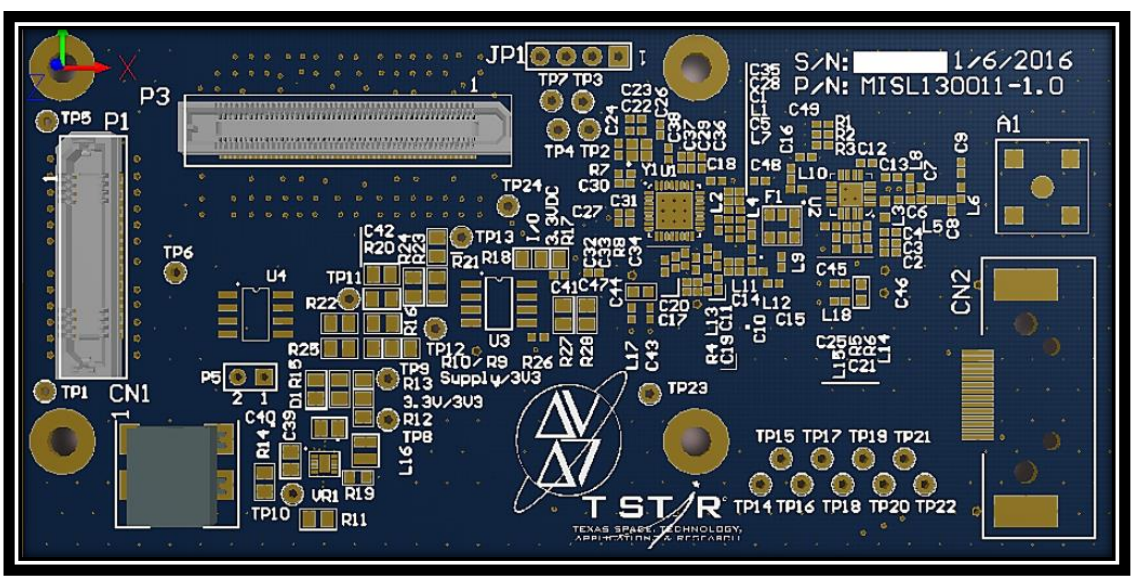

Figure 5 – Alpha PCB

The printed circuit board was designed to separate different subsections from one another to aid in performance. The lower left-hand corner of the board is a switching power supply which is used to regulate the incoming battery voltage. The lower right-hand side of the board is the expansion port with various test points to help with debugging. The upper right-hand section of the board is the CC1120 and CC1190 chipsets and antenna which are used for 915 MHz wireless communication. The center of the board is used for power monitoring and various configuration settings of the hardware layer. Lastly, on the far left and top of the board are the power and data connectors to interface with the other MISL Stack layers.

Along with the design of the printed circuit board, the procurement of individual components was completed to help verify the board layout as well as ensure stock of all devices. The components will be installed on the alpha board for testing to ensure all simulations and circuits have been correctly designed and implemented.

Software Development

Current progress for the RTOS embedded code is ahead of schedule. DVDT has successfully configured TI-RTOS on the MSP430 MISL Stack layer and has shown functionality with simple tasks that blink LEDs. The major hurtle of the RTOS system has been overcome by connecting the Intelligence layer of the MISL Stack with a CC1120 transceiver. The RTOS on the MISL Stack has communicated over SPI to the CC1120 transceiver and successfully communicated packets wirelessly at 915 MHz. Current progress is being made in creating the other secondary features, including saving data to the uSD card and expansion port drivers. More development needs to be made in making the software libraries for the end user to utilize to make creating code easier.

The Graphical User Interface (GUI) is going to be handled completely by TI RF Studio which is free software given by TI to configure the evaluation boards. The GUI has been completely configured for the data rates, frequency, modulation schemes and CRC checks. The GUI has successfully received packets sent from DVDTs RTOS. The GUI is considered complete with the option to edit some settings if testing proves that changes need to be made.

LESSONS LEARNED

The main technical lesson learned over the project came from the decision on what frequency the transceiver would be operating. The CC1120 transceiver works at many different frequency bands but narrowing it down to a specific frequency to be used took a lot of thought. First of all, there are many regulations nationally and internationally on what frequencies are available for use with research and which frequencies require a license. DVDT decided on using 915 MHz because it is allowed by the Federal Communications Commission (FCC) for Industrial, Scientific, and Medical (ISM) research. Using the 915 MHz ISM band was chosen because it is allowed for use in research just like DVDT is doing, but there are lessons learned here for the customer’s use of the DVDTcomm layer. The FCC reserves these ISM bands for research, so this can get complicated when a private company like T STAR is wanting to use it for commercial gain. This will cause T STAR to eventually need their own frequency and a license when the DVDTcomm layer is used for profit. Another lesson learned is that, because the 915 MHz ISM band is readily available for research without licenses, there are numerous radios currently using this frequency which causes unwanted interference and can potentially mess with the transmitted packets.

Extensive planning skills and the ability to effectively communicate with the customer are a critical skill to have in the real world. If lucky, the customer will know exactly what they need and already has realistic and achievable functional requirements and performance specifications. In the real world, the customer may or may not know exactly what is needed and these critical requirements of the project need to be extracted through multiple and frequent conversations with the customer. The project planning phase of a project helps greatly in understanding the needs of a project.

They say the customer is always right, but the customer may not always know everything that goes into product development. Scope, cost, and time are the 3 critical points of the project triangle, never let the customer control all three of these. By allowing the customer to control two, an obtainable solution can be generated that meets the project deadline and stays within budget.

When designing a new product there are typically no current solutions that meets every one of the customer's needs. Generally there will be reference material for each of the subsystems that are to be designed. Heavy use of these reference designs will minimize mistakes and aid in the development of a working solution.

Required curriculum will not teach an engineer everything they will ever need to know. Typical college coursework goes a long way to prepare a future engineer for product and system development but each project will have their own nuances. Therefore, the most important thing to learn in college is the ability to teach yourself new material. DVDT has learned first-hand the importance of building upon material from their typical coursework whether it be learning how to use a printed circuit board layout software to the overall design of a satellite communication system.

One of the greatest lessons learned from the ESET Capstone experience is taking ownership in ones work. If a team does not take ownership in a project that is being completely designed, developed, documented, and delivered by them, no one will. Taking ownership of your works means not having excuses for missing deadlines or unsatisfactory work as well as having the drive to complete a project to the best of the team's ability.

The last main lesson DVDT learned deals with the rapid approach of project deadlines. No matter how small a task may be, there will always be more work required than anticipated; therefore the team will be at risk of missing the deadline if they procrastinate. The best course of action for staying ahead of schedule is to dedicate time throughout the week and early on in the life of a project. Once one deliverable has been successfully completed ahead of schedule, do not wait to start the next task. By moving all deadlines up to meet the new schedule the team will be better prepared when an unavoidable delay occurs in the project.

CONCLUSION

The DVDTcomm board presented in this paper details a novel capstone project that shows the level of capability present in ESET graduates today. Capstone students learn how to effectively communicate with a customer, how to use time management skills, and gain technical knowledge in creating real world solutions. The capstone experience encompasses all of product development from the initial problem statement to a fully-functional prototype. The knowledge gained by ESET students who complete the course allow them to become more prepared for industry and give them insights into project management.

The communications board that will be created will have real world impact as T STAR continues to develop their TSat. With the scalability of the RTOS environment and the hardware expansion capabilities, the DVDTcomm board is conveniently positioned for future improvements and extensions with the MISL Stack. T STAR will be taking this product into their current TSat design to pursue the venture of commercializing low Earth orbit and contribute to the exploration of the final frontier.

REFERENCES

1. Dunbar, Brian. *NASA Commercial LEO Workshop*. *NASA.* Webb, Carlyle, 30 January 2015. Web. 22 December 2015.

2. Porter, J.R., et al. *Project EVIS: An Example of an Innovative Capstone Process*. in 2006 IJME - INTERTECH International Conference. 2006. Newark, New Jersey: The International Journal of Modern Engineering.

3. CC1120-CC1190EM 915MHz Reference Design. Texas Instruments. Web. 11 Jan. 2016. <http://www.ti.com/tool/cc1120-cc1190em915rd>.

4. Tomar, Ankur. CC1120DK Performance Line Development Kit. Digital image. Element14 Community. 26 Aug. 2013. Web. 22 Dec. 2015.