WIRELESS OPEN-SOURCE/OPEN-ACHITECTURE COMMAND AND CONTROL SYSTEM: MID-RANGE RF MODULE

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ABSTRACT

The main goal of the Mid-Range Radio-Frequency (RF) Module is to create a wireless data transmission channel over a distance of at least 100m. The system is designed to be incorporated in the Wireless Open-Source/Open-Architecture Command and Control System (WOCCS). The implemented design uses a 2.4GHz transceiver for wireless transmission, USB 2.0 for wired communication, and a customized protocol for data control. The system is based on the use of the Texas Instruments System-on-Chip (SoC) CC2531 and Power-Amplifier CC2591.

A design sequence consisting of creating planning documentation, electrical schematics, Printed-Circuit-Board (PCB) layout, protocol, and software was accomplished with a team of four electrical engineers. Test procedures confirmed a proof of concept despite a major design flaw with the PCB design. In this paper, the overall design and testing process is covered in detail.

INTRODUCTION

Data communication using wireless networks has increasingly gained importance. The main advantage driving this increase of popularity is the improved mobility of the communication modules. Nevertheless, cautions should be taken in designing such systems, considering instabilities of the wireless channel, bit error rate (BER), and transmission latency. Overall system performance can be severely affected by any of these detriments.

The WOCCS family of projects is intended to be used in wireless control applications. These applications could range from controlling unmanned land, air, or water vehicles or receiving wireless data from external sensors. This project's main goal is to be in the context of controlling land-vehicles indoors within 100m line of sight.

METHODOLOGY

The design process was divided into five different stages, including: identification of Customer Needs and Engineering Specifications, System Analysis, Decision Making, Detailed Design, and Software Development. Within these stages, tasks and goals were organized, managed, and tracked using a Gantt Chart.

Customer Needs and Engineering Specifications

The customer needs, as seen in Table 1, were evaluated based upon information issued from the customers, Dr. Hensel of RIT and Harris Corporation, and also the project completed by the senior design group 10205. The Engineering Specifications, which are quantifiable, measurable, and testable, were based off of analysis of the Customer Needs to convert the voice of the customer to the language of the engineer, shown in Table 2. In the Engineering Specification table, the marginal values and ideal values of metrics were determined through discussions with the other WOCCS senior design groups in order to realize the common objectives of the system level requirements. The marginal values were chosen as the Pass/Fail limit whereas the ideal value was a goal for achieving an optimal design.

Customer Need #	Description
1	Modularity
2	Wireless
3	Reliable Connection
4	Addressability
5	Configurable
6	Ergonomics
7	Lightweight
8	Maintainable
9	Economical

Table 1: Simplified Customer Needs

Spec #	Description	Ideal Value
1	Mass	0.2 [kg]
2	Configurable	OK [Binary]
4	Authorization	OK [Binary]
5	Channel #	15 [Unit]
6	Output Power	<30dBm [Watt]
7	Data Rate	56 [Kbps]
8	Range	200 [m]
9	Regulations	OK [Binary]
10	Bit Error Rate	0.001 [%]
12	Documentations	OK [Binary]
13	Interface	OK [Binary]
14, 15, 16	Dimension	9x7x3 [cm^3]
18	Cost	<300 [$]

Table 2: Simplified Engineering Specification

In order to verify the relationship between customer needs and engineering specifications, a relationship matrix was established. This tool allows for the analysis of the degree to which the customer needs are satisfied when the engineering specifications are achieved. In this matrix, the customer needs and engineering specifications are organized into rows and columns with metrics assigned at every cell within the matrix according to the degree of correlation. From the relationship matrix, the most important engineering specifications became prevalent: the number of available transmission channels, transmission power output, data rate, transmission range, bit error rate, and regulatory agency compliance.

These engineering specifications are directly related to the important customer needs of Wireless and Addressability. Wireless is defined as the ability to communicate wirelessly across line of sight at a certain range. The ability to communicate independently through multiple channels is defined as Addressability. From these calculations, future design decisions requiring a compromise between any customer needs or engineering specifications could be biased to most reflect the needs of the customer.

System Analysis

A system block diagram was established to clearly show how the designed system would operate within the context of the other WOCCS teams, displayed in Figure 1. The designed RF module is placed within a mechanical housing with a second power module. The RF module must be able to interact with a peripheral to both transmit and receive data with a second RF module. Together, the pair of RF modules creates a bidirectional wireless link.

To create a more clear description of the overall functionality of the system, functional decomposition was used. During this procedure, the system was progressively broken down into functions and sub-functions using a functional tree, with a simplified version shown in Figure 2. From Figure 2, the broad

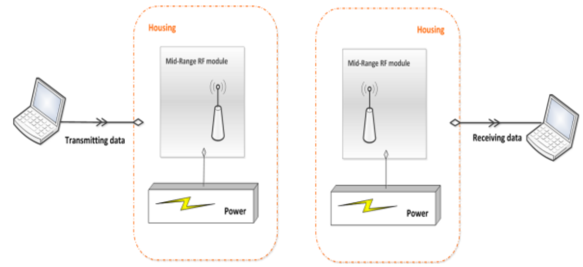

Figure 2: Simplified System Block Diagram

function definition of this system is to provide wireless communication. This function can then be broken down into further sub-functions: transmit data wirelessly, control data flow, provide structure, provide feedback, and receive data wirelessly. Further definitions of the functionality allow for a clear picture of the needed components and subsystems for accomplishing the overall system functionality.

The combination of the functional decomposition and system block diagram allowed for a great segue to concept generation. During this phase, four or five implementations were explored for each critical sub-function by literature research, group discussion, and further functional clarification. Tools such as morphological analysis and system path design were used to explore options and rank them according to varying parameters.

Decision Making

The use of morphological analysis was extended to sub-functions during the Decision Making phase, with concept selection matrices providing an unbiased way to choose implementations. Important decisions made include the implementation of Universal Serial Bus (USB) protocol for wired communication, the use of a micro-processor for controlling the flow of data, and status LEDs for providing feedback to the user. In addition, it was determined that a custom protocol

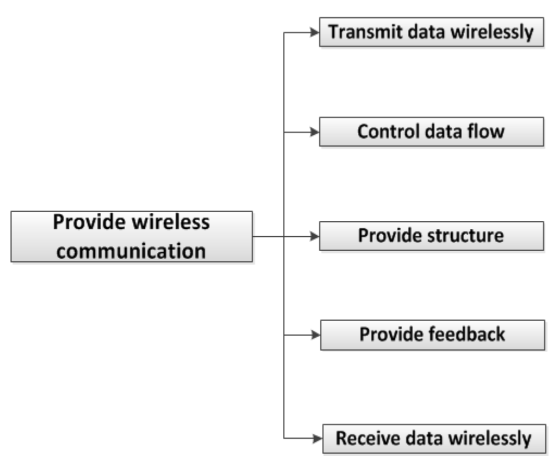

Figure 1: Simplified Functional tree

would be needed for sending control signals between boards and outside peripherals.

The last major decision made was to implement the IEEE Zigbee protocol for the wireless link. This choice influences the transmit frequency, data rate, and number of transmission channels; all important engineering specifications identified previously. After analyzing the available open-source protocols, the decision to use the Zigbee protocol was made for its high data rate, 16 available channels, and mesh style of addressing.

From this decision, the choice of transmit frequency and implementation of the protocol were needed. The two main transmit frequencies for Zigbee are at 2.4 GHz and 900 MHz, which led to a comparison between the two frequencies on the basis of availability of commercial products, portability, and range.

The availability of commercial products was determined on the basis of overall community support and documentation available for the given chipset. After investigation, Texas Instrument chips were considered due to their large online community presence, great customer support, and wide range of low power RF chipsets. From this vender, two System on Chips were considered, the CC1111 at 900 MHz and CC2531 at 2.4 GHz.

The portability of these chips can be defined by the additional circuitry and components needed to accomplish transmission. Two main differences arose between the chipsets: the size of the antenna and the addition of further amplification to accomplish the transmission range. The size of the antenna was determined to be a large consideration with a typical length of 3.2 in at 2.4 GHz and 6.6 in at 900 MHz. A smaller antenna size was considered to be ideal for integrating the design board into a compact package.

To determine the effects of the frequency on the transmission range, the following formula can be used [1],

$$\frac{P_r}{P_t} = G_R G_t \left(\frac{c}{4\pi R f} \right)^2 \qquad \textbf{(1)}$$

where P_r is the received power in milli-watts, P_t is the transmitted power in milli-watts, G_R is the gain of the receive antenna and circuitry, G_t is the gain of the transmit antenna and circuitry, c is the speed of light, R is the radius in meters, and f is the frequency in hertz. The major consideration in Eq. 1 is the inverse relationship between the distance of the transmission and the frequency of transmission.

With all of these considerations, the choice of 2.4 GHz was determined by the large documentation available for the CC2531 and the significantly smaller size of the needed antenna. With this selection, the needed transmission power can be solved for by converting Eq. 1 to power ratio units, or dBm's, and solving for the transmit power,

$$P_t \approx P_R - 20\log\left(\frac{c}{4\pi R f} \right) \qquad \textbf{(2)}$$

with G_t and G_R being estimated as unity. Plugging in values, the power transmitted can be estimated as

$$\begin{aligned} P_t &\approx P_R - 20\log\left(\frac{\left(3\cdot 10^8 m/s\right)}{4\pi\left(200m\right)\left(2.4\cdot 10^9 1/s\right)} \right) \\ &= P_R + 86.246 dBm \end{aligned} \qquad \textbf{(3)}$$

A typical value extracted from the utilized system on the chip for a receive power, or sensitivity, is -97 dBm. With this number, a transmit power of -10.8 dBm would be required.

Using the commercially popular 2.4 GHz band, however, results in the noise floor becoming significant. Many routers, cellular devices, and general electronic devices utilize the band for their applications. As a result, estimates extracted from online data show that the noise floor could rest anywhere between -90 dBm and -60 dBm. To achieve a good signal to noise ratio (SNR), and thus an acceptable bit error rate, the received signal power should be at minimum above the noise floor.

Using the possible maximum power output from the SOC of 4.5 dBm, the noise floor allowed for a SNR of 1 would be,

$$\begin{aligned} P_R &= N_{Floor} = 4.5dBm - 86.246dBm \\ &= -81.748dBm \end{aligned} \qquad \textbf{(4)}$$

Any SNR above 1 would have to be achieved with a larger transmit power. Not knowing a good estimate for the noise floor of the areas of application, a power amplifier with a maximum output power of 20 dBm allows for a noise floor of,

$$\begin{aligned} P_R &= N_{Floor} = 20dBm - 86.246dBm \\ &= -66.246dBm \end{aligned} \qquad \textbf{(5)}$$

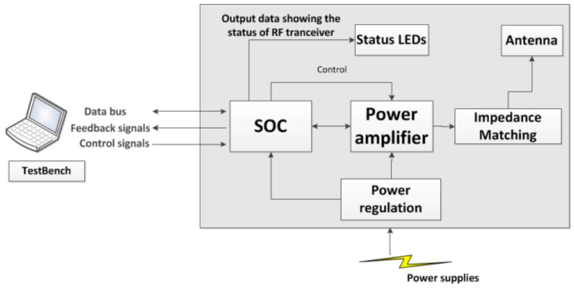

Figure 3: Simplified System Block Diagram

With this calculation, it was decided to use the CC2591 power amplifier chip in conjunction with the CC2531 system on chip to ensure proper data transmission. A system functional block diagram was created on the basis of the decisions made, as shown in Figure 3.

Detailed Design

A design provided from Texas Instruments with the CC2591 and CC2531 was used as a reference for determining the capacitor filters, impedance matching networks for the RF transmission lines, USB termination resistors and low pass filters, and crystal oscillator needed for implementing the two chips [2]. A power regulator was chosen to provide the 3.3V for both chips with a switch incorporated for choosing between USB power and the external power source. A bank of four green LEDs and corresponding current limiting resistors were picked out to allow for optical feedback to the end user.

Four connectors were needed for interface to the other WOCCS components and peripherals for transmission. The power connector, as previously mentioned, allows the input of a battery to power the board without needing to draw power from the USB line. A USB type B female port was chosen with a SMA female port for the antenna. Finally, a ground clip allows for the ground plane of the board to be grounded to the metal housing.

The printed circuit layout was accomplished after the electrical schematics were complete, with a final design shown in Figure 4. A four layer board was chosen to minimize ground plane inductance, as recommended by the CC2531 and CC2591 datasheets [3][4]. The top and bottom planes are utilized for signal routing, with the second and third planes being dedicated to ground and power, respectively. Arrangement of the connectors was accomplished with discussions with the WOCCS housing team to ensure proper connectivity with systems integration.

A bill of materials was established for organizing all of the components and parts needed for ordering, with a quantity of eight boards, or four pairs, to be manufactured. Assembly plans were established to lay out the order of assembly and ensure needed resources were arranged to be available.

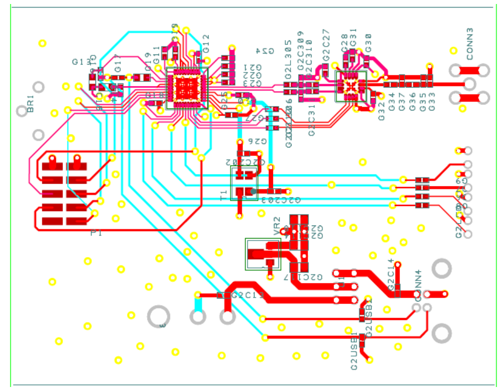

Figure 4: Printed Circuit Board Design

Software Development

To achieve a working protocol in the limited amount of time for development, a simple version of the TI Simplicity protocol was used in place of the Zigbee protocol. An example program was downloaded from the TI website and modified to include a custom protocol for data control. Table 3 shows the commands used between the computer and RF board, RF board to RF board, and RF board to computer.

Description	Header (ASCII)	Command (ASCII)	Options
PC to RF Board			
Set Channel	DC1	‘C’	Channel #
Transmission Time	DC1	‘R’	Time in ms
Normal Data	DC1	‘D’	Payload Length
Important Data	DC1	‘I’	Payload Length
Loopback Data	DC1	‘L’	Payload Length
RF Board to RF Board			
Normal Data	DC2	‘D’	Payload Length
Important Data	DC2	‘I’	Payload Length
Mirror Back Data	DC2	‘A’	Payload Length
RF Board to PC			
Acknowledge Data	DC3	‘A’	Payload Length
Raw Data	DC3	‘D’	Payload Length

Table 3: Software protocol

With this simple protocol, information and commands can be sent over the communication channel. Channels can be changed using the Channel command, with up to sixteen channels available for the user. A transmission time can be returned from the RF board to calculate the data rate of the previous transmission. Three types of data can be sent: Normal Data, Important Data, and Loopback Data. Normal data is simply passed from the first PC to its RF board, from the first RF Board to its pair, the second RF board, and from the second RF board to the second PC. Important data acts the same way, except that the information is sent back from the second RF board to the first and then from the first RF board to the PC. In this manner, the data can be confirmed to have been successfully transmitted. Loopback data can be used for testing the PC to RF board wired connection, with all data sent to the RF board being mirrored back to the PC.

RESULTS AND DISCUSSION

A manufacturing plan was created in order to provide an efficient way to produce the PCB with the designed components, with an abbreviated shown in Table 4. In this manufacturing process, it was decided to use the Surface Mount Technology lab in the Center for Integrated Manufacturing Studies (CIMS) at RIT.

In general, the manufacturing process consists of two phases. The first phase consists of placing all the non-integrated components onto the board using solder paste and soldering them using a heat flow station. During this process, the boards were inspected for any problems including misprinted traces, unmade connections, or schematic to layout errors. The second stage involves soldering the SoC and power amplifier integrated circuits onto the board. The board is then inspected using an X-Ray imaging machine to ensure all solder connections for the components are made with no bridging of adjacent pads.

In contrast to manufacturing plan, the test plan was designed to examine whether or not the boards were functional after manufacturing. Shown in Table 5, the test plan is divided into five different procedures with each sub-test being performed using similar testing equipment and environments.

Procedure Description	Condition
Cut mounting boards to fit the casing requirements	Width: 7+/- 0.127 cm
	Length: 9 +/- 0.127 cm
Pour solder paste on the designated pads	Solder paste should match the pads as accurately as possible
Place Surface Mount Components on PCB based on the schematic/PCB layouts	Components should match the pads to avoid short circuits and other malfunctions
Use the reflow station on the surface mount pads to solder components	Ensure the components are placed correctly and are stable then apply the heat until you see the paste melt.
Let the board and the parts cool down before removing the board from the station	Wait at least 2min
Place through-holes components and solder them with a soldering iron.	Ensure not to short circuit the leads while soldering

Table 4: Manufacturing Plan

From the initial inspection, it was found that one of the connections to the SoC's crystal oscillator was grounded. This mistake arose from combining the developed board layout with other WOCCS teams for ordering. During this combination, a naming conflict

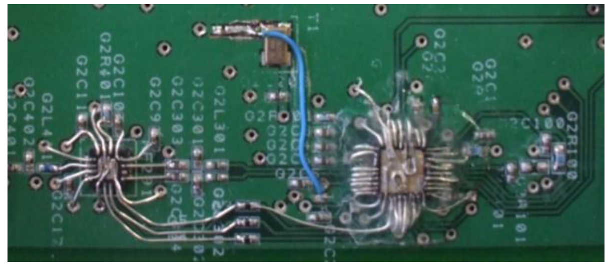

Figure 5: PCB Rework

between components replaced the needed footprint for the oscillator with a different footprint. As a result, the layout file was corrupted with the net being shorted to ground. To solve this problem, a trace was cut to isolate the oscillator's signal path from the ground. This solution brought large concern due to the high frequency of the oscillator. Any undesired capacitance or inductance coupled into the circuit could have potentially caused significant performance issues to the system. After probing the line, however, it was found that the solution worked with a clear clock signal being provided to the SoC.

A more major problem, however, was found during the initial testing. It was realized that the 40 pin SoC and 16 pin power amplifier were laid out in their "dead bug" version; a mirroring of the pin assignments. This caused a total failure in the system's configuration as every pin from the two chips was connected to the wrong node.

The solution for this problem was to flip the chips upside down and glue them in place. Each pin was then soldered to their respective pad individually using 30 gauge wires, as shown in Figure 5. It took two members a combined total of 30 hours rework two boards, with each board requiring 56 pin to pad connections. If there were no limits on budget or time, alternative solutions could have been to buy a dead bug adaptor or to simply fix the layout and repurchase the boards.

Among the two boards that were made, one was fully functional and the other was partially functional. The partial functionality of the second board could be due to two problems. The first is the grounding problem of the crystal, as it was found that the SoC could not self-generate the system clock when the programming debugger was disconnected from the SoC. The second was most likely due to a connection error made during the hand-wiring of the pins to pads; the power amplifier did not operate at all. With limited time and human resources, production of additional boards could not be realized for testing. Consequently, test procedures suffered failures with many of the requirements.

The test plans consist of a transmission test, dimension test, channel validation test, output frequency and power test, and documentation test. In the transmission test, the range, bit error rate, and data

Distance	Test Description	Pass Requirement	Status
1 m	BER[%]	< 0.12	Passed
1 m	Data Rate [kb/s]	> 40	Passed
1 m	Successful Transmission	Yes	Passed
50 m	BER[%]	< 0.12	Failed
50 m	Data Rate [kb/s]	> 40	Failed
50 m	Successful Transmission	Yes	Failed
100 m	BER[%]	< 0.12	Failed
100 m	Data Rate [kb/s]	> 40	Failed
100 m	Successful Transmission	Yes	Failed
250 m	BER[%]	< 0.12	Failed
250 m	Data Rate [kb/s]	> 40	Failed
250 m	Successful Transmission	Yes	Failed

Table 5: Transmission Test Results

rate are tested. From the results, three specifications were passed at one meter range with failures occurring beyond one meter, as seen in Table 5. The reason for this is due to, as mentioned above, the failure in one of the board's power amplifier. The test procedures, especially for transmission test, require two fully functional boards for communication.

For a proof of concept, however, a Texas Instrument evaluation board for the SoC was used in conjunction with the fully functional board. With modified software for the evaluation board, data was transmitted successfully over a distance of 100 meters with the required data rate and bit error rate measured. Most of the remaining other tests were successfully completed, with exceptions where two fully functional boards were needed. Table 6 shows a summary of the status and results of the different tests.

CONCLUSIONS AND RECOMMENDATIONS

The main goal of this project was to acquire engineering experience through following a design process of a RF transceiver. Communication with the main customers of this project, Harris Corporation and Dr. Hensel from RIT, led to the development of customer needs. With these needs established, Engineering Specifications with precise metrics were defined. System analysis techniques, such as functional decomposition, allowed for the overall system to be analyzed at a fundamental level with morphological analysis and selection matrices aiding in design decisions. The IEEE 2.4 GHz Zigbee protocol was chosen for its high data rate, 16 available channels, and its advanced mesh network addressing. The higher frequency allowed for a smaller antenna and a more compact design.

After calculating the needed transmission power for the given transmission range, it was decided to use

Test Description	Pass Requirement	Status
Mass	<.3kg	Passed
Configuration	Licensed technician can successfully configure device without outside instruction	Failed
Tx Frequency	Frequency Complies with FCC Regulation	Passed
Number of Channels	Three operating sets with Passable BERs	Passed
Transmit Power	<30dBm	Passed
Data Rate	>40kbps	Passed
Range	<.12 at 100m	Failed
Regulatory Compliance	Test results meet regulatory compliances	Passed
BER	<.12	Passed
Printed Documentation	A document exists	Passed
Interface Specification Compliance	Interface requirements are met	Passed
Width	9 +/- .127 cm	Passed
Length	7 +/- .127 cm	Passed
Height	<3cm	Passed
Price Per Board	<$300	Passed

Table 6: Summary of Test Results

the CC2591 power amplification chip in conjunction with the CC2531 System-on-Chip CC2531 from Texas Instruments. These chips were chosen for their ability to handle the Zigbee protocol for wireless transmission, USB for the wired communication, and compact size. The electrical designs for the two chips were based on a reference design from TI with several adjustments made to include a power regulator, status LEDs, and power switch. All components used were complied in a bill of materials with the total expenses within the allocated budget.

Under the programming time constraints, it was decided to use a simple version of the TI Simplicity protocol instead of the initial Zigbee protocol. After customization, commands and data can be sent over one of the 16 available communication channels.

The manufacturing and testing phases of the design process were heavily modified from the original project plan to accommodate errors in the PCB layout. Two boards were manufactured, with one board being fully functional. Although all the tests were not passed, it was proven that the design/concept worked using a fully functional board and an evaluation module from Texas Instruments. With modifications to the PCB layout to fix the mirrored chips and the grounding problem of the crystal clock pad, a fully functional design can be realized. These modifications have been added in the latest version of the design.

The problems encountered could have been avoided by more in depth analysis of the layout, especially the connections of all pads and developed footprints for each chip. An incomplete or unworking layout was actually predicted during a risk assessment of potential problems, with the actions taken to mitigate the problems being rechecking the layout and delaying the ordering of the boards. These actions were executed, but a more thorough check list should have been developed to ensure a proper PCB design.

Overall, it was demonstrated that the design implemented could accomplish wireless transmission at a distance of 100m. The developed design could be used immediately in a wide range of applications, including the ability to send telemetry and control data between a base station and a robot. Future applications and improvements could improve the amount and speed of the data transmission to include higher bandwidth applications, such as video feeds.

ACKNOWLEDGMENTS

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