A Mechanically Robust Optical Data Backup System Using a Copper Data Pipe

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Submitted by

Yuvraj Jain

Reg. No: 180907124

Under the guidance of

Under the guidance of

Internal Guide

Dr. Priyanka Desai Kakade

Assistant Professor – Senior Scale

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

MANIPAL INSTITUTE OF TECHNOLOGY

(A Constituent Institution of Manipal Academy of Higher Education)

MANIPAL – 576104, KARNATAKA, INDIA

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MANIPAL INSTITUTE OF TECHNOLOGY
(A Constituent Institution of Manipal Academy of Higher Education)
MANIPAL – 576 104 (KARNATAKA), INDIA

Manipal
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CERTIFICATE

This is to certify that the project titled **A Mechanically Robust Optical Data Backup System Using a Copper Data Pipe** is a record of the bonafide work done by **Yuvraj Jain** (*Reg. No. 180907124*) submitted in partial fulfilment of the requirements for the award of the Degree of Bachelor of Technology (BTech) in **ELECTRONICS AND COMMUNICATION ENGINEERING** of Manipal Institute of Technology, Manipal, Karnataka, (A Constituent Institution of Manipal Academy of Higher Education), during the academic year 2021 - 2022.

Dr. Priyanka Desai Kakade	**Dr. Subramanya Nayak G**
Assistant Professor – Senior Scale	*HOD, ECE*
M.I.T, MANIPAL	*M.I.T, MANIPAL*

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ABSTRACT

During testing and prototyping volatile, high-energy systems such as boilers and rocket motors, test failures cause damage to the supporting data logging infrastructure in the vicinity. Data loss is possible due to shock damage from an explosion or occlusion of a wireless data link line of sight in such an event. Furthermore, data describing critical test parameters must be available to prevent such prototype failures in the future. Therefore, a highly reliable and mechanically robust system is required to back up the critical data. Due to the failure, the data acquisition system's electronics may be unusable for further tests, necessitating the system components to be cheap and ubiquitous. The authors design and simulate an optical communication system deploying a copper data pipe using the ray-tracing module provided in the COMSOL Multiphysics (Version 6.0) commercial code. The final system design emphasizes maximum data transmission speed, minimal transmission noise over a short distance, and reduced system cost. The authors practically implement the system and discuss deviations of the system performance from the results of the simulations.

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Developing and testing high-energy systems such as prototype boilers and rocket motors involve iterative testing, in which some tests can result in violent failure. To ensure such a loss does not occur again, the system designers require critical data in the short time before failure, which requires the sensor data acquisition systems to survive long enough to store the data safely. Hence, data backup systems duplicate critical data during volatile high-energy systems testing. In our setting, this backup system must be mechanically robust and capable of a high data rate while being cost-efficient in the event of damage due to an explosion.

Testing high pressure and energy systems involve data logging parameters such as system temperature, strain, forces, and vibrations. For other documentation purposes, audio and video capture of the test is gainful. In the proximity of the prototype, interfacing with the sensors, cameras, and microphone, the central data acquisition system acquires and records the data during a test. The researchers may lose the logged data if a prototype failure causes system destruction. Temperature, strain, and force data are critical in determining the physical processes occurring inside the system being tested and must have backups in the event of failure. In the case of rocket motors, the system must also backup the vibration sensor data, providing a detailed record of system processes during testing. An embedded backup system with a high data rate is desirable as it accommodates all requirements.

Vibration data sampled at 5 kHz accurately describes a sounding rocket solid rocket motor's acoustic power spectrum [1]. With each sample being 12 bits, each sensor axis requires 60 Kbps of bandwidth. For 3-axis vibration data, along with 32-bit floating-point data output at a rate of 50 Hz for the temperature, 3-axis strain, and 3-axis force sensors, the total approximate bandwidth requirement is 191.2 Kbps. If the system implements an error correction scheme, assuming a coding density of 0.9, the entire data throughput requirement is 212.4 Kbps. The system must support substantially larger data throughput if the experimenters wish to record audio or video.

1.2 Organization of this Report

The organization of this work is as follows. The following section provides a detailed overview of the system design and engineering choices. Chapter III discusses the COMSOL simulation setup, mesh characteristics, a system block diagram, selected electronic components, and details about the system implementation. Chapter IV presents the results of the simulations, the characteristics of the physically implemented system, the final choice for the length of the data pipe, and the performance figures of the physical system implementation.

CHAPTER 2
NEED FOR OPTICAL SYSTEM AND DATA PIPE

Optical communication systems have long been the standard for low noise, long-distance, and high throughput data transmission applications [2]. Their use in large data throughput and backup applications is well documented [3]. Optical communication systems may utilize fiber or function in free space using a laser without affecting the data transmission rate. However, in free-space optical systems, the link reliability is low if the line of sight between the two nodes is interrupted, which is not acceptable for the desired backup system [4]. Due to the low mechanical strength of the optical fiber and its high cost [5], the authors consider an optical communication system using a data pipe as an alternative in this work.

A light pipe is any macroscopic hollow structure that transmits light whose dimensions are much larger than the wavelength of the transmitted light. This work refers to a light pipe that carries data via optical pulses as a data pipe. The inner surface of the data pipe repeatedly reflects or refracts light to reduce losses during propagation [6]. Highly reflective materials, such as polished aluminium, copper, and silver, can be used to fabricate such pipes. However, only aluminium and copper alloys have the mechanical strength required for the desired backup system. Both metals also have good thermal dissipation and electrical conductivity, allowing the data pipe to carry power, data, and matter in the same physical link. A copper data pipe can carry power to the central data acquisition system and be used for data transmission, leading to further reductions in cost and improved battery safety. For a short-distance backup link, a data pipe is most suitable. It is mechanically robust and cost-efficient while not imposing any constraints on data transmission rates and allowing the use of high data rate optical transmission systems in proportion to the system costs. As far as the authors know, the academic community has not adequately explored this concept due to its niche applications. However, tests aboard military submarines have shown the concept to work [7].

CHAPTER 3
METHODS AND DESIGN CONSIDERATIONS

Two Arduino MKR Zero microcontrollers act as nodes in the network, connected by a single copper data pipe. The mother node is situated near the prototype to be tested and performs data acquisition. The daughter node receives the logged data, sent over using the data pipe, and stores it on a microSD card. Each node has a digital to optical interface for receiving or transmitting. A battery, situated safely away from the prototype to be tested, powers the entire network starting at the daughter node. The copper pipe acts as a low resistance channel through which the mother node receives current. A grounding wire, separately routed from the mother to the daughter node, completes the electrical circuit. Figure 3.1 shows each subsystem's system block diagram and the specific electronics. Further on in this section, the authors discuss each aspect of the system in detail.

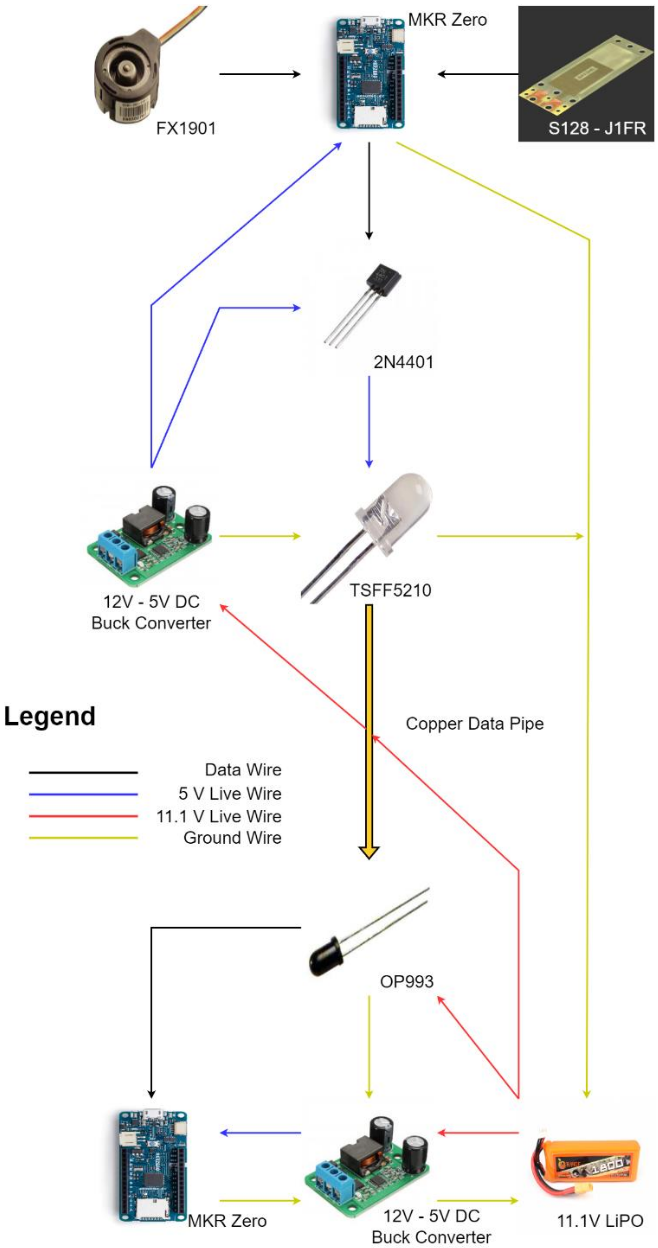

Figure 3.1: The Optical Data Backup System Diagram

3.1 Selection of Network Topology

Critical data backup systems employ multiple redundancies and fast data links to guarantee no data loss by deploying a mesh or a star topology network [3]. In this work, the authors assume that the daughter and mother nodes maintain a separate copy of data to provide redundancy. To minimize further costs in the case of prototype failure, a mesh network or star topology was deferred in favor of a simple point-to-point topology. The mother node in the system handles all data acquisition tasks and has an interface to an electrical to optical circuit coupled to a data pipe. This data pipe terminates at a safe distance from the prototype under testing at the daughter node's location, which creates a data backup.

3.2 Selection of Channel Media

Commercial fiber optical communication systems can achieve transmission speeds of around 100 Gbps [2]. It is also well known that optical fibers tend to be mechanically fragile [5] and hence, do not function in harsh environments. Research into improving the mechanical strength of optical fiber has progressed in the past few decades, with the introduction of plastic optical fiber and doped optical fiber. These variants do not see widespread adoption yet in commercial applications due to their higher cost today [8, 9]. However, in our application, the combination of extreme shock and heat in the case of a failure and its expensive nature make optical fiber an unattractive choice.

Free space optical communication systems (FOS) share similar data rate capabilities. However, they are susceptible to ambient atmospheric conditions [4]. In a violent prototype failure, such line of sight communication solutions might fail to communicate critical data saved before failure. Such failure is possible with other RF line of sight wireless transmission systems. Any non line of sight wireless system suffers from low data rates and transmission error challenges. While implementing error correction codes to minimize data acquisition system complexity is simple, having a near error-free channel is preferable to minimize the amount of overhead computation done by the microcontroller on each node.

Wired electronic communication media is a cheaper and more reliable alternative to wireless systems in such situations. The authors consider a Cat 5e Ethernet cable the best choice in this category. However, the system design does not use this medium due to its tendency to get damaged in harsh conditions easily. If easy damage to the wire is not a design concern, an ethernet cable is a lower-cost alternative to a data pipe. Such a system is limited to the Ethernet cable's data rate and signal attenuation specifications. In contrast, a data pipe's data transmission rate is realistically determined only by the transducer circuitry bandwidth at each node.

After considering all options, the authors chose a copper data pipe due to its resistance to mechanical and thermal damage, ability to achieve a high specular reflection percentage via electropolishing, and ability to provide data transmission rates comparable to fiber optic technology at low-cost. [10] shows that low loss optical transmission is possible in metal light pipes in the infrared spectrum, given that the radius of curvature approaches infinity. The 3 dB radius of curvature of a metallic waveguide in the infrared region is 75 m. The system considered here requires a direct connection between the mother and daughter nodes over a short distance for our application. Hence, there is little to no curvature. During system implementation and usage, experimenters must ensure that the data pipe does not have a radius of curvature less than 75 m at any point. The authors reserve 5 dB of link margin for the current physical implementation's design to account for any unintended curvature of the data pipe and signal attenuation.

3.3 Selection of Electronic Components

The mother node comprises a microcontroller interfaced via the Serial Peripheral Interface (SPI) and the I2C (Inter-Integrated Circuit) interface to communicate with various sensors mounted on the boiler or the solid rocket motor prototype. Table 3.1 provides the component specifications of the selected electronics.

Table 3.1: Relevant Electronic Component Specifications

Component	ID	Max Power Rating (mW)	Rise Time (ns)	Fall Time (ns)	Bias Voltage (V)
870 nm GaAlAs LED	TSFF5210 [11]	180	15	15	1.5
890 nm PIN Photodiode	OP993 [12]	100	5	5	-11.1
RF Power Transistor	2N4401 [13]	625	20	30	1.2

The Arduino MKR Zero microcontroller uses the SAM D21 ARM M0+ core [14]. The microcontroller is a part of the Arduino family of microcontrollers in a compact MKR form factor based on the ARM Reduced Instruction Set Computer (RISC) architecture. It has a native SPI interface to a microSD card onboard which the central data acquisition unit uses to log the sensor data at high speed. The microcontroller has a clock speed of 48 MHz and supports an SPI data rate of 12 Mbps [14]. The microcontroller interfaces with the IR LED via a Radio Frequency (RF) transistor to convert digital data to optical pulses and feed them into the data pipe.

Similarly, at the daughter node, an Arduino MKR Zero powered by the SAM D21 ARM M0+ core is used along with its built-in microSD card interface to back up the mother node's incoming data. The optical to electrical interface comprises a two-stage RF amplifier to convert the photodiode's optical pulses to digital data fed into the microcontroller's digital input pin. The selected optical components are about 1.5 USD, while the microcontrollers cost 25 USD, satisfying the low-cost criteria.

3.4 Computational Characterisation of Data Pipe

The authors simulated IR light propagation in a 1/4 inch 25 gauge hollow copper data pipe using the COMSOL Multiphysics (Version 6) commercial code's ray tracing module. Two cylindrical geometries, merged using a difference boolean operation with an absolute tolerance of 1E-8, are used to model the data pipe. This method keeps the input objects intact to produce a pipe with its interior space as another separate domain. The authors considered four lengths in a parametric study ranging from 1000 to 2350 mm for a straight pipe configuration. All geometry is of the Quartic Lagrangian order with an absolute tolerance of 1E-8.

The authors defined a mesh at the extremely fine size preset for the straight configuration mesh, with the maximum element size modified to 2 mm. A circle of radius of 1.5 mm splits the inlet and outlet ports in the air domain. Each of the 4 curves of each concentric circle was selected, and fixed element distribution of 4 elements was applied. Swept quadrilateral type mesh is assigned to both domains. Using a uniform refinement of one level, a refinement node generates the mesh used for the mesh dependence study. Tables 3.2 and 3.3 present the generated mesh characteristics. The authors contend that the mesh element quality is mainly influenced by the element skewness, with a value of 1 preferred. The coarse mesh for all data pipe lengths had a minimum element quality of 0.6321 and an average element quality of 0.8248.

Table 3.2: Coarse Data Pipe Mesh Characteristics

Length	No. Elements
1000 mm	38000
1450 mm	55100
1900 mm	72276
2350 mm	89300

Figure 3.2 illustrates the coarse mesh of a 1000 mm data pipe.

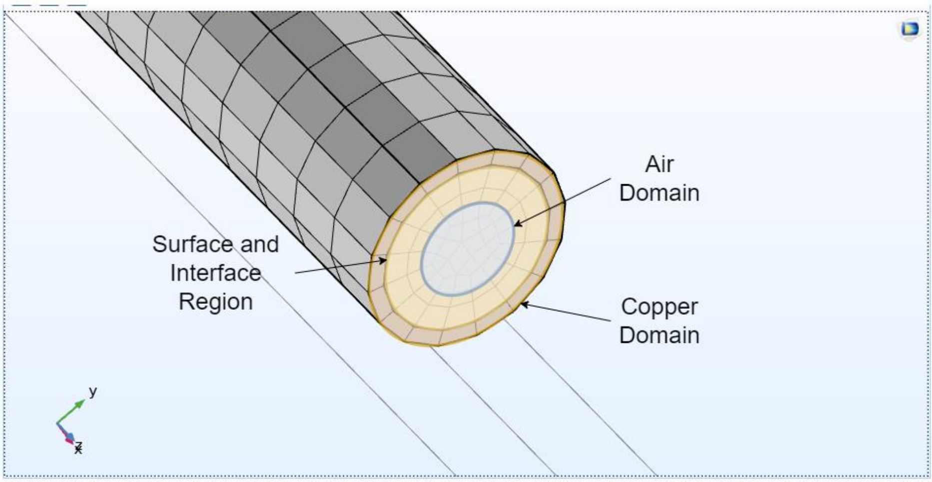

Figure 3.2: An Illustration of the Domains of Simulation in COMSOL Multiphysics and the Domain Meshes

Table 3.3: Refined Data Pipe Mesh Characteristics

Length	No. Elements	Min. Element Quality	Avg. Element Quality
1000 mm	304000	0.6321	0.8548
1450 mm	440800	0.6321	0.8548
1900 mm	578208	0.6321	0.8548
2350 mm	714400	0.631	0.8549

These simulations use a light ray wavelength of 870 nm. The option to use geometry normals while simulating was enabled. The software configuration selects the space inside the pipe as air [16] and the wall as copper [17]. Unmeshed domains outside the simulated domains default to the air material [18] at a temperature of 310 K. The inner surfaces of the pipe possess the "Mixed Specular and Diffuse Reflection Wall" boundary condition, along with a reflection coefficient value of 0.988 for both types of reflection [19]. For a worst-case scenario simulation, the authors use an average specular reflection percentage of 0.6 [20], the lowest possible value of an electropolished pure copper surface polished at 25°C [21].

The input port employs the "Release from Grid" boundary condition. The boundary condition creates a hexapolar grid of radius 2 mm with 5 layers, totaling 91 points. A conical release pattern with a 3° half-angle at random controls the ray trajectories from each point. Overall, the authors observe that this results in a 12° half-angle from the grid. At 100 rays per point, the simulation has 115,200 degrees of freedom. Both the inlet and outlet ports have a Freeze Wall boundary condition.

The simulation runs in steps of 2 m with the final maximum simulation path length of 8 m. The software tracks the outlet irradiance between iterations, stopping the run if the outlet irradiance had an absolute magnitude change of less than 1E-8 between iterations.

3.5 Selection of Communication Protocol

Synchronization between the two nodes is essential for any digital data transmission system. Software communication protocols, which rely on synchronization via precise assembly instruction counting or interrupts, have been proven unreliable due to internal hardware interrupts overriding the synchronization code [22]. Synchronization is possible via data modulation schemes, such as Manchester coding, albeit at the cost of reducing the effective throughput. The system communicates over a few meters using the hardware UART protocol on the chip to minimize the throughput penalty due to synchronization. The UART protocol is unaffected by any other hardware interrupts that can cause transmission disruption. The Universal Synchronous Asynchronous Receiver Transmitter protocol (USART) has a hardware implementation on the Arduino MKR Zero with a maximum transmission rate of 3 Mbps [14].

The microcontrollers use the hardware USART in asynchronous mode to communicate at a designed rate of 576 Kbps for increased reliability. Faster communication rates are possible by upgrading the microcontroller [15] and the transducer circuitry at both nodes, which leads to costlier components. As a demonstration, 576 Kbps is a satisfactory data transfer rate.

3.6 Data Pipe Manufacture

The backup system uses a soft annealed oxygen-free high conductivity (OFHC) copper pipe of 1/4 inch and 25 gauge diameter for physical testing, implementation, and verification of simulation data. Pipe segments of 45 cm were cut and straightened with vice and mallet. The copper develops tarnish and stains during handling and metalworking. For optical losses to be minimal, the surface finish of the procured pipe must not change, which means that quenching and tempering is not viable stiffening method.

To stiffen the segments against bending or denting, the authors initially wrapped the segments in carbon fiber glued on with commercial epoxy resin. A 10 mm region from each end of the segment was left uncoated so that it could interface with a copper pipe coupler. Figure 3.3 shows a finished data pipe.

Figure 3.3: Initially Manufactured Data Pipe Segments. The top article is a hand-straightened copper pipe segment. The below article is the segment after cutting, composite wrapping, and sealing.

Each sample underwent curing at room temperature for 24 hours. All samples exhibited sufficient stiffness. Next, the authors manufactured a sample with no carbon fiber reinforcement to reduce cost. This design demonstrated good bending and denting resistance. Figure 3.4 shows the final set of fabricated data pipes. The optical path length in these data pipes varies between 29 and 30 cm. To remove the tarnish and stains developed on the pipe during manufacturing, the authors treated the internal and exposed surfaces with 10 % v/v acetic acid solution for 10 minutes at 31 C [23]. The treatment reduces transmission losses before testing the system. The overall cost per meter of data pipe was approximately 2 USD.

Figure 3.4: The Final Set of 30 cm Data Pipe Segments. The top set is approximately 13 cm segments, and the top right shows the etched copper pipe couplers. A cured epoxy resin reinforcement coating is visible on the data pipe segments in the middle.

3.7 Mother Node Implementation

Practically, the mother node is responsible for acquiring sensor data, sending it over UART to the daughter node, and writing the acquired data to the local microSD card. The authors recommend using the onboard Analog to Digital Converter (ADC) peripheral to acquire 12-bit differential voltage readings on four channels simultaneously at a sampling rate of approximately 5 kHz. The Direct Memory Access (DMA) peripheral stores the ADC sampling results without CPU intervention into a buffer in the microcontroller's Static Random Access Memory (SRAM). The software can define three SRAM buffers to allow continuous data acquisition. The system designer can choose the buffer size such that the buffers require swapping at 50 Hz so that the microcontroller reads digital sensor data at every buffer swap. Then the complete data structure is sent in chunks of a byte to the UART data register using the DMA peripheral. Finally, the software must add a timestamp to the buffer and write it to a file on the microSD card. At node initialization, the software writes the initial timestamp to the file. Due to the precise timing of all processes running on the microcontroller, recovering the individual sample timestamps is possible by simply equally splitting the time difference between any two buffer timestamps.

The authors aim to show that communication is without error in this work. Hence, we do not implement the data acquisition part of the software. However, the circuit design of the node supports future work with integrated data acquisition. A string of random ASCII data generated using Random.org [24] provides the UART peripheral with data, and the UART transmitter (TX) pin generates the appropriate digital data waveform. The circuit supplies the output of the TX pin via a current limiting resistor to two RF transistors which switch the IR LED on or off to feed optical pulses into the data pipe. Figure 3.5 shows the electronics schematic of the mother node.

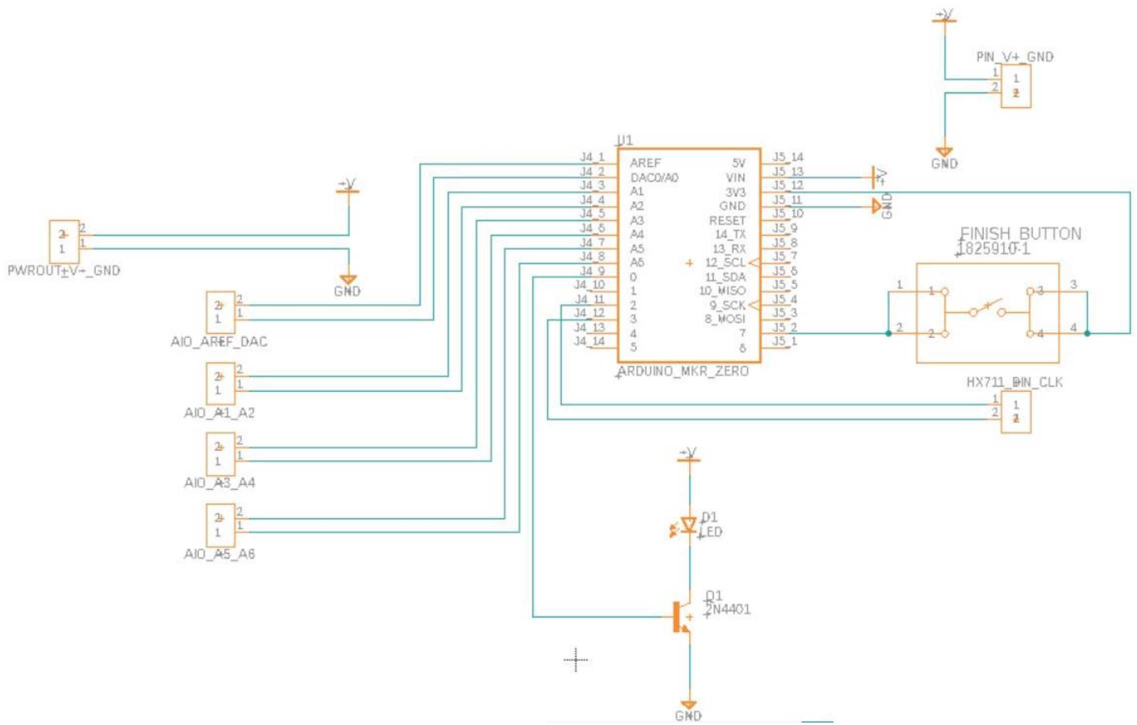

Figure 3.5: The Electronics Schematic of the Mother Node

The authors require that future implementations extensively use the DMA peripheral to offload data acquisition and UART transmission from the CPU of the microcontroller because the CPU must be available to handle the filesystem and read/write operations on the microSD card. The software must also implement a priority structure, where microSD card operations are the least priority, and ADC data acquisition is the highest priority. This priority structure ensures consistent sampling, minimal system jitter, and a simple software structure.

3.8 Daughter Node Implementation

In the field, the daughter node is responsible for the waveform reception, signal conditioning, signal recovery, and backup of the incoming data on its local microSD card. The authors specify that the system must be mechanically robust and only aim to show error-free data transmission in this work. The system must receive variedly attenuated optical pulses from the data pipe in real-time to achieve the required robustness. However, if the authors design a signal conditioning system using physical hardware, the daughter node can not adapt to the variation in reception strength. Hence, this design deploys a software-defined system to convert the analog optical waveforms to digital data.

The authors deploy the Analog Comparator (AC) peripheral to continuously sample the output of the photodiode and generate a digital waveform. The AC peripheral compares the input to a reference level provided by the onboard Digital to Analog Converter (DAC). At node initialization, the mother node sends a preamble which the daughter node samples using the ADC to obtain a threshold value for the DAC. After initialization, the software writes the threshold value to the DAC and instructs the AC to start comparisons. The microcontroller can convert a sample within 120 ns in the high power configuration of the peripheral [14]. The circuit feeds the AC's digital output waveform into the UART receiver (RX) pin. Unfortunately, the MKR Zero does not provide the AC digital waveform output on a physical pin on the board. This board design forced the authors to reroute the signal through the Event System peripheral and use a Timer Peripheral to reproduce the digital output on a pin accessible on the board. The rerouting adds additional delay to the system leading to a total delay of 400 ns. This delay provides a maximum bandwidth of 2.5 MHz. The authors also enable digital filtering in the AC peripheral, using the consensus of 5 samples technique [14], to improve the reliability of the conversion process. After accounting for the filter delay, the maximum bandwidth is 625 Kbps. The node is programmed to send data at 576 Kbps, allowing for some margin. Figure 3.6 shows the electronics schematic of the daughter node.

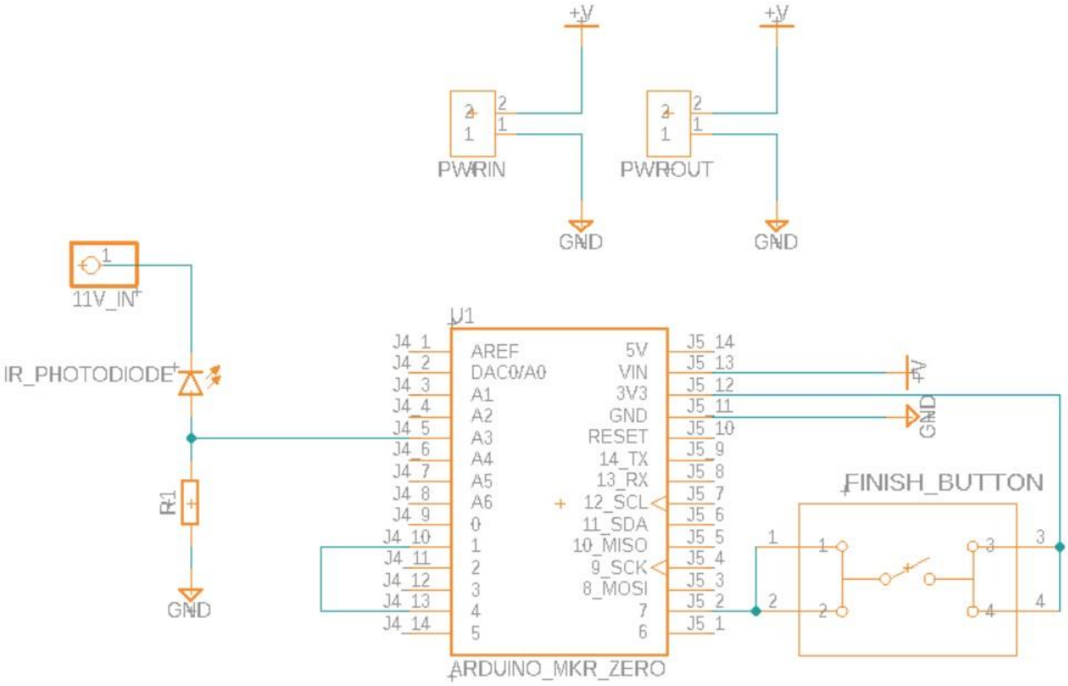

Figure 3.6: The Electronics Schematic of the Daughter Node

Again, future implementations must use the DMA peripheral to reassemble the buffer transmitted by the mother node in the SRAM and write it to a file on the microSD card. Like the mother node, the daughter node should offload all UART operations onto the DMA peripheral, leaving the CPU to deal with the filesystem and read/write operations. The authors suggest defining two buffers in the SRAM, one for UART reception and the other for microSD card writing. The software can then swap the buffer after a data structure reception.

CHAPTER 4
RESULTS

Using the results of the ray-tracing simulations performed in the COMSOL Multiphysics commercial code, the power at the inlet and outlet ports has been tabulated in Table 4.1.

Table 4.1: Port Irradiances for Refined Mesh Simulation

Pipe Length	Inlet Power (mW)	Outlet Power (mW)
1000 mm	104.38	22.330
1450 mm	104.41	12.015
1900 mm	104.46	7.608
2350 mm	104.14	4.653

The authors also performed a mesh refinement study to study the mesh dependence of the results. Figure 4.1 shows the mesh errors as a function of pipe length. The authors observed no trend in the error data as the direction of the rays in the simulation was random. The fineness of the mesh also contributes to the error as software computes the reflection normals using the mesh element faces. However, enabling the simulation to use geometry normals for computation minimizes the mesh contribution to the error.

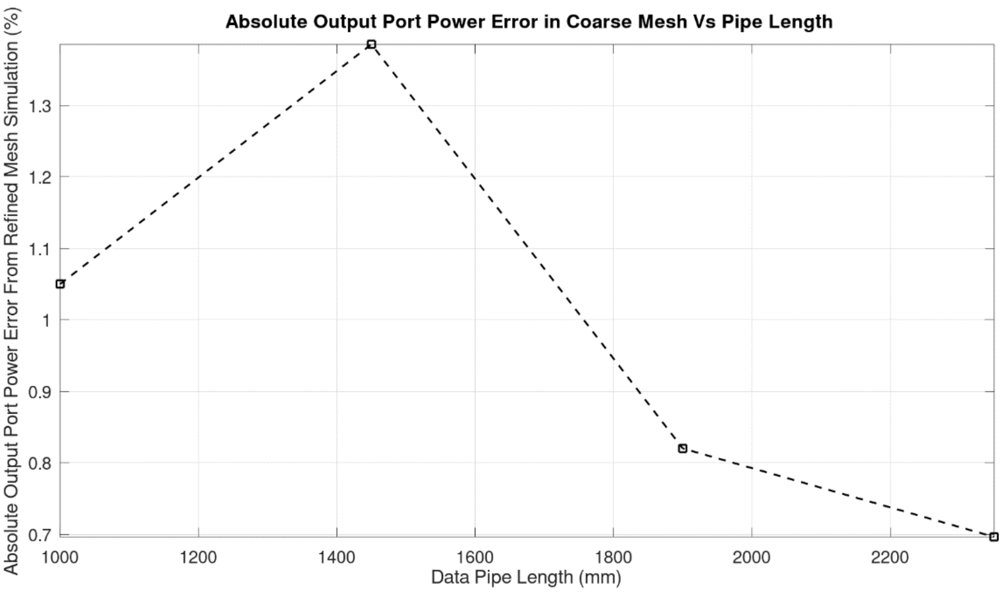

Figure 4.1: Mesh Errors Versus Pipe Length

Using the above path loss numbers results, the authors defined a path loss model for the copper data pipe. Figure 4.2 plots the 1st order fitted curves and the original data. The path loss shows a stable trend with a proper fit of the first-order model. The photodiode has an irradiance threshold of 2.3 mW for a light current of 100 µA [13]. Allowing for a link budget of 5 dB and calculating the length of the data pipe based on the fitted curves, the authors found that a straight data pipe of length 2260.2 mm was required to achieve the irradiance threshold at the daughter node. A total of five segments of the manufactured data pipes equal a length of 2200 mm. Figure 4.2 depicts the optimum calculated data pipe length alongside the fitted path loss model. Hence, the authors selected a net length of 2200 mm for practical system implementation.

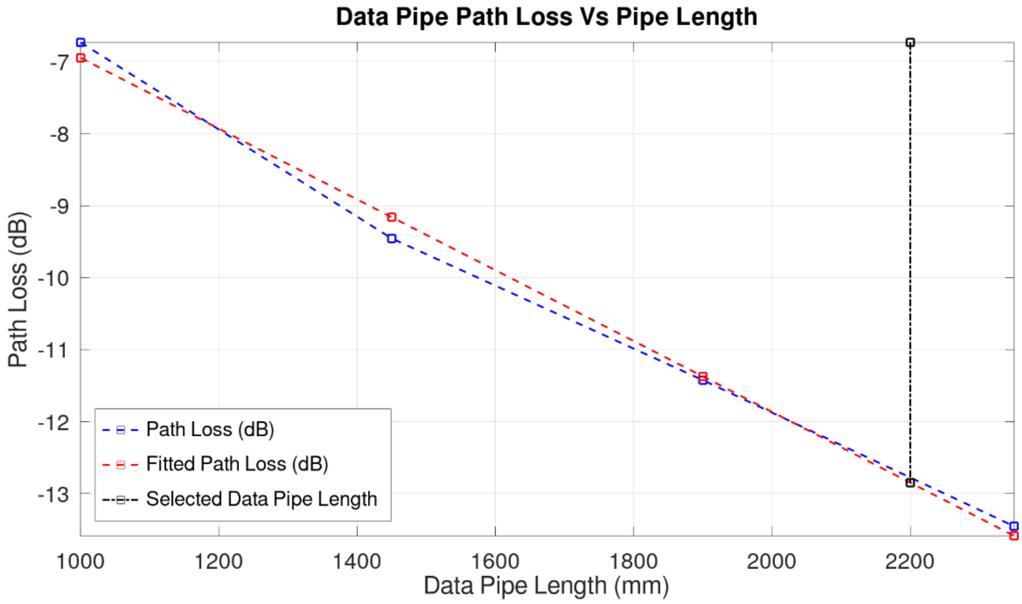

Figure 4.2: Simulated Pipe Path Loss and the Fitted Path Loss Model. The black marker line marks the pipe length for which 5 dB of Link Margin exists.

This geometry is finally simulated, with all other simulation settings kept the same as the previous simulations. The authors also included a mesh refinement study. The simulation results showed that the relative mesh error of the coarse mesh from the refined mesh is -0.753 %. There was an error of -2.91 % from the path loss model, implying the model slightly over-predicts the path loss in the data pipe. Table 4.2 shows the final optical link's simulation results.

Table 4.2: 2200 mm Data Pipe Simulation Results

Type	No. Element Quality	Avg. Element Quality	Avg. Element Quality	Input Port Power (mW)	Output Port Power (mW)
Coarse	83600	0.6321	0.8248	104.36	4.914
Refined	668800	0.6321	0.8549	104.51	5.035

As discussed in the previous section, the authors fabricated the mother and daughter node designs and tested them. Figure 4.3 shows the tabletop CNC milled copper-clad circuit board for the daughter node and Figure 4.4 shows the same for the mother node.

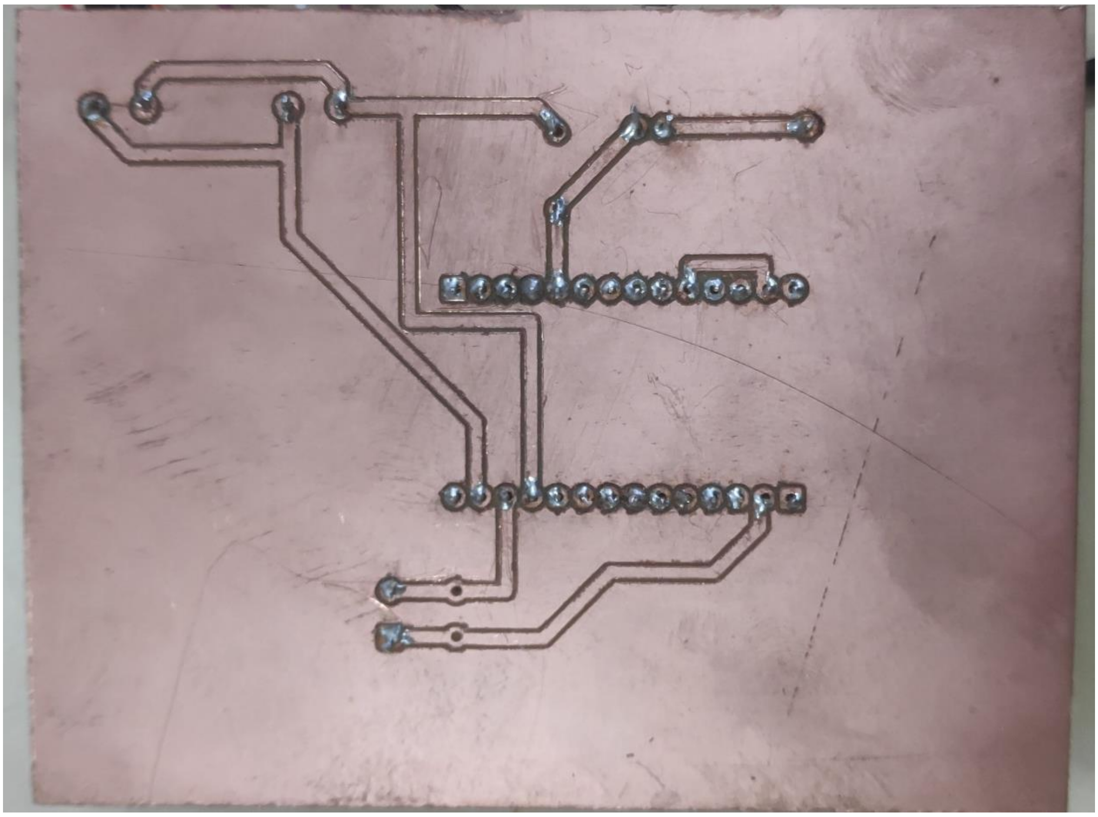

Figure 4.3: The CNC Milled Daughter Node Copper-Clad Board

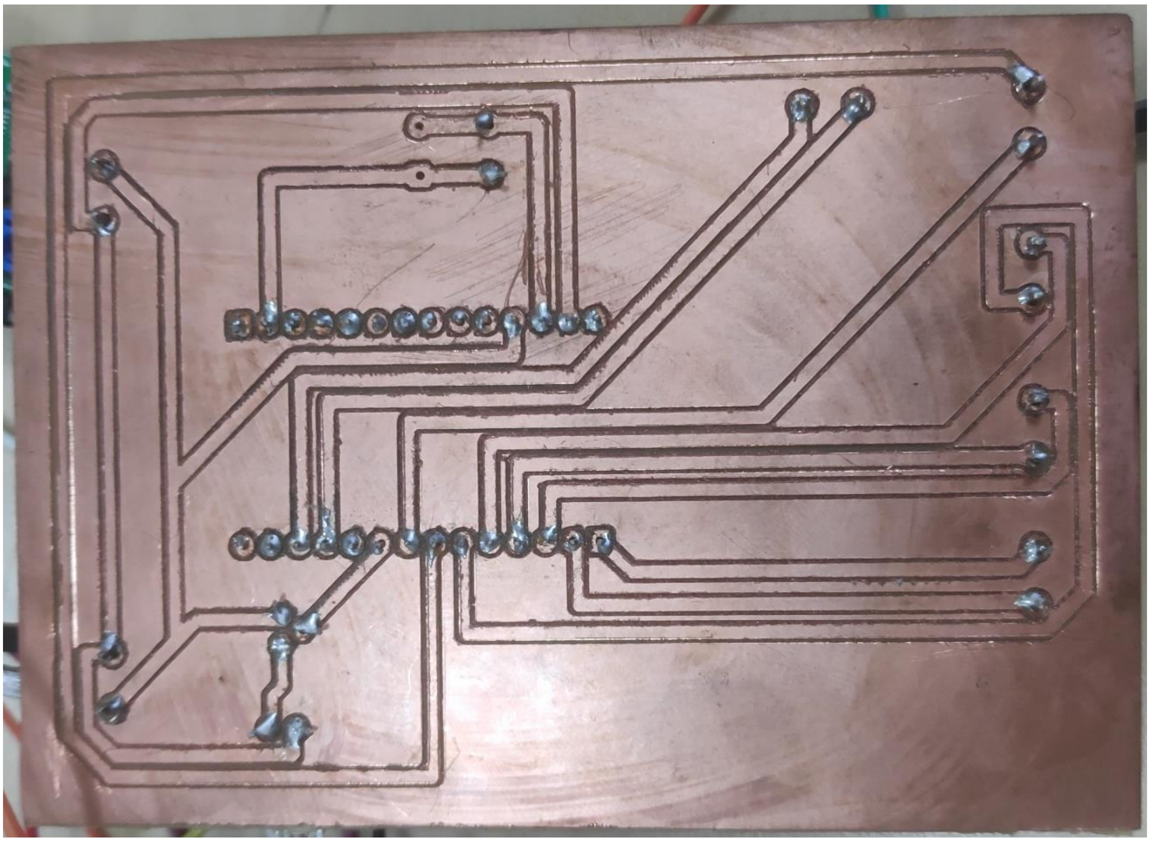

Figure 4.4: The CNC Milled Mother Node Copper-Clad Board

Before final system integration and testing, the authors disjointly tested data acquisition at the mother node and data transfer using UART between the nodes. For the data acquisition test, the authors interfaced six Analog to Digital Converter (ADC) channels of an MKR Zero to a known frequency and amplitude waveform. Figure 4.5 shows the logged data parsed into GNU Octave (Version 6.4), verifying the sampling rate and accuracy of the acquired waveform.

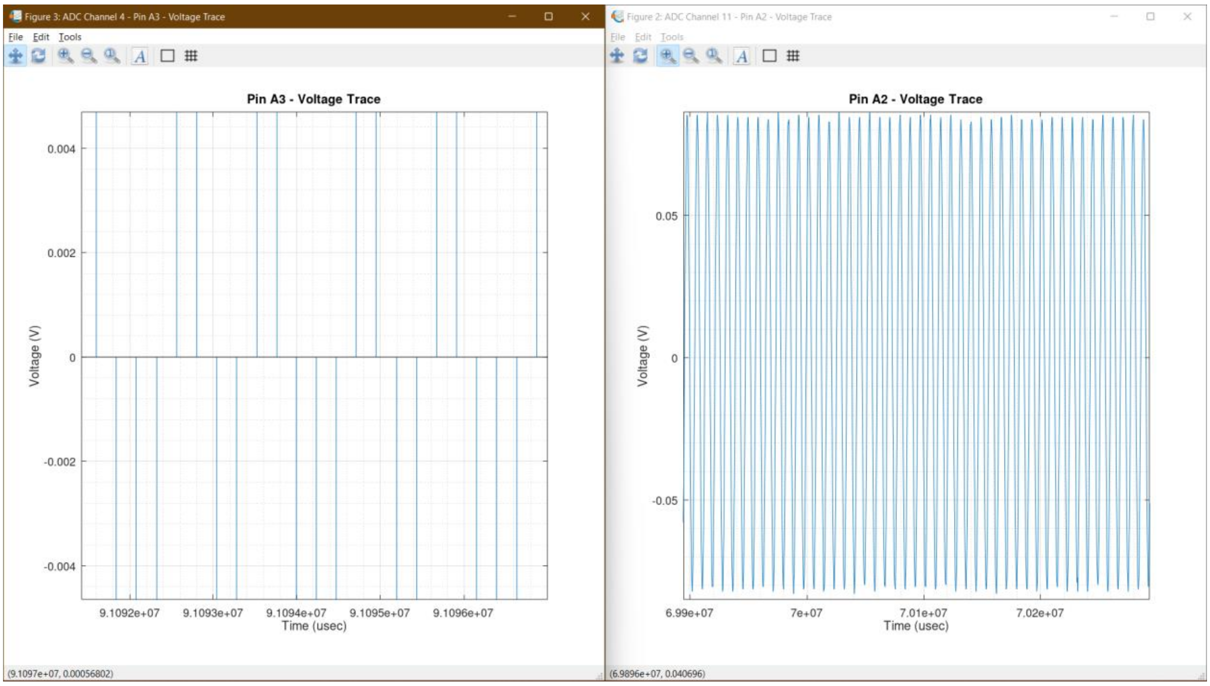

Figure 4.5: The Acquired Data from the Data Acquisition Test. The stem plot on the left shows the sampling rate of the system. Note that each label on the x-axis corresponds to one millisecond. The plot on the right shows the acquired waveform for a known input of 1kHz triangular wave of peak to peak voltage of 200 mV.

The transmission test aimed to test the software framework used by the final system to relay data between the nodes. Figure 4.6 shows the mother node and daughter node setup.

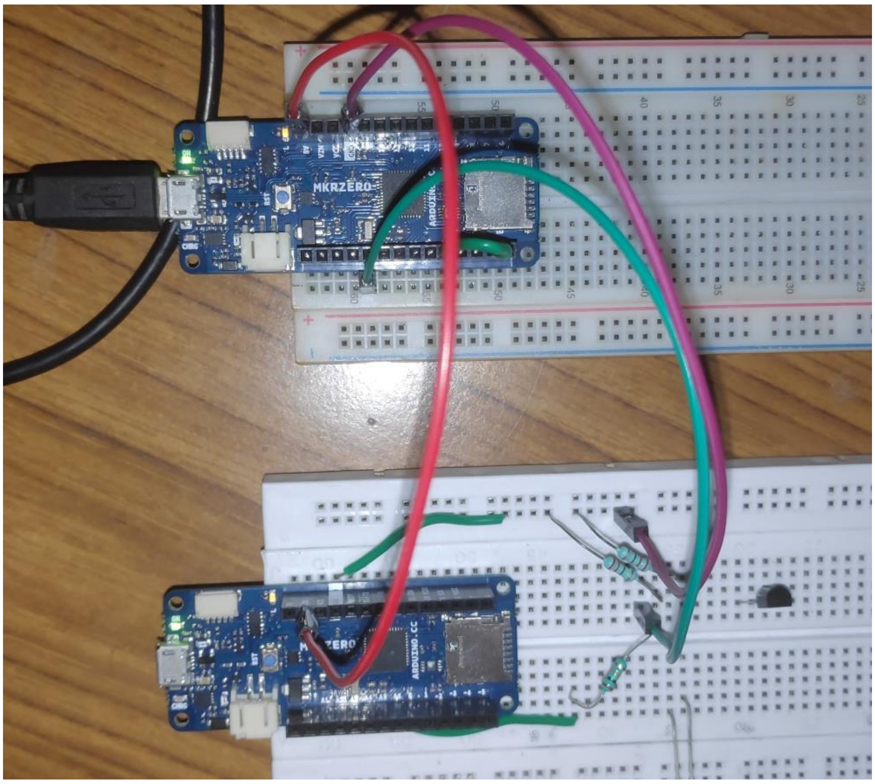

Figure 4.6: The UART Transmission Test Rig. The top is the daughter node mockup, and the bottom is the mother node. The red and purple wires supply power from the daughter to the mother node. The green jumper between the nodes and the voltage divider simulates the data pipe transmission channel. Digital pin 0 outputs the UART waveform on the mother node, which is attenuated and fed via the green jumper into the input of the AC at the daughter node.

A PC powered the daughter node, which powered the mother node. The resistors on the mother node create a voltage divider that scales the UART output waveform down by approximately a factor of 10, simulating a worst-case scenario of 20 dB noise-free attenuation encountered by an optical pulse while propagating through the data pipe. During this test, the system continuously sent 4096 random bytes on a loop in ASCII format generated using Random.org [24] from the mother to the daughter node. The daughter node compared the received data to determine if an error had occurred, halting transmission if it detected one. The authors found that the first-bit error consistently occurred around the 700 second mark when the UART peripheral on the microcontroller was running at 1.5 Mbps. If the peripheral sent data at 1 Mbps, no bit error occurred for up to 90 minutes, after which the authors terminated the test.

Armed with the above results, the authors manufactured the 2200 mm optical link in segments of 300mm and fabricated the electronics for both nodes. Figure 4.7 shows the configuration used as a reference for range and reception strength.

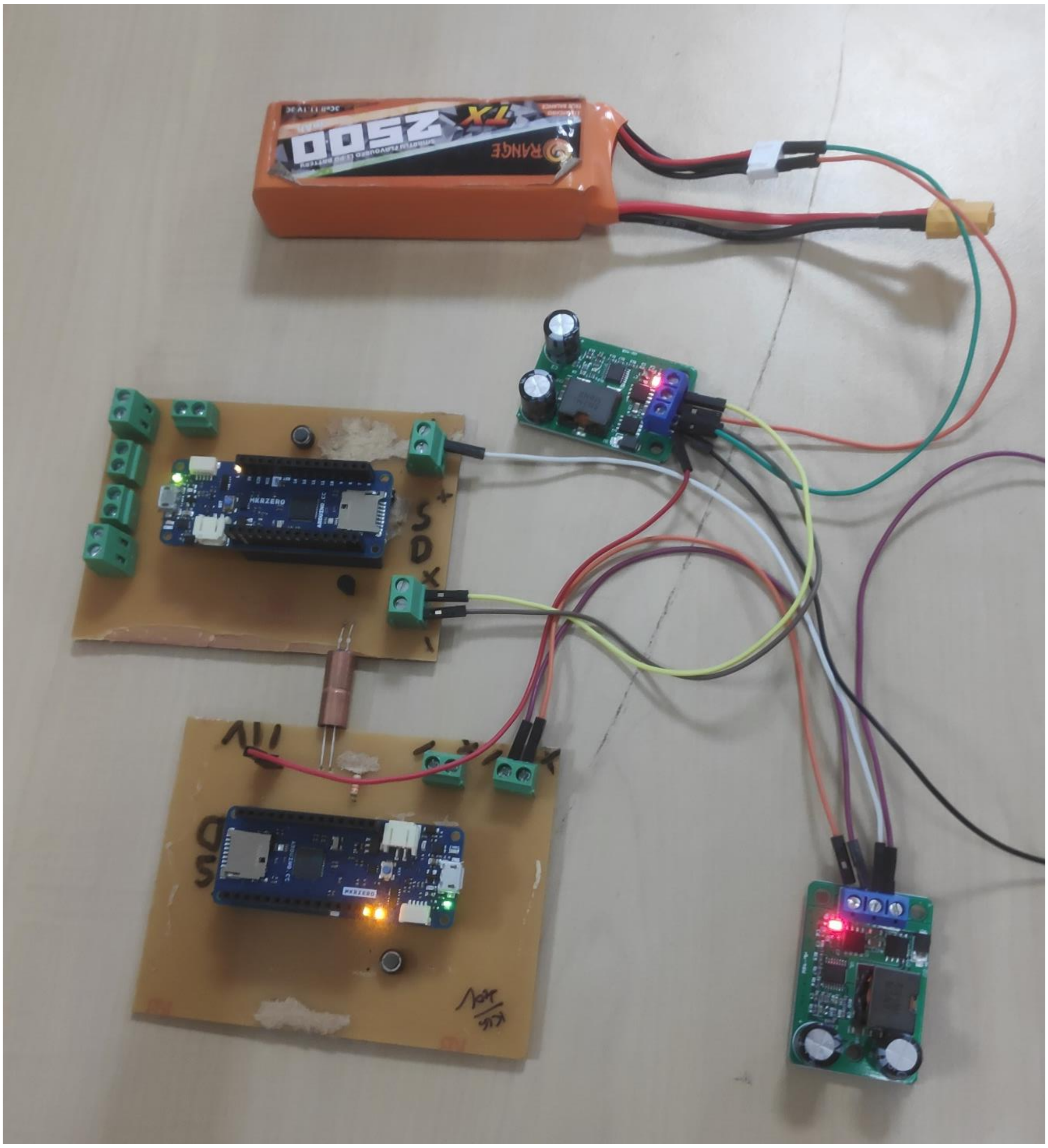

Figure 4.7: The Test Setup for Calculating the Reference Optical Reception Parameters

The PIN Photodiode provides a reading of 2V for a logical HIGH in this configuration. The authors found that the maximum reception strength for a typical configuration with a single 300 mm segment is 0.3V for a logical HIGH. Hence, the experimental path loss in the system is 20 dB/m, three times what the path loss model predicted. Several factors explain these results. Firstly, the path loss model assumes smooth internal surfaces and straight data pipes. The simulation also does not account for passivation. The authors found that passivation contributes to an additional 6 dB/m attenuation after exposing the data pipe for 60 minutes to ambient conditions after treatment with the acetic acid solution.

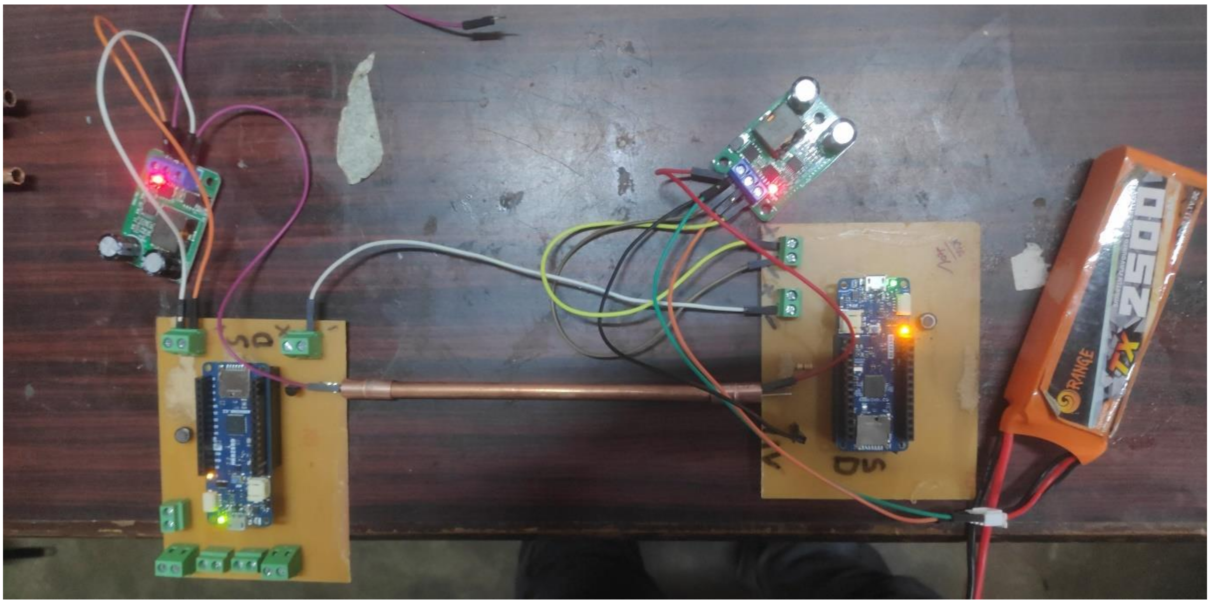
Figure 4.8: 14 cm Data Pipe Test Rig

Figure 4.8 shows both nodes operating at 576 Kbps without error for 15 minutes using a 14 cm data pipe. The daughter node powers the mother node in this test using the data pipe. This test shows that the node design and software functions appropriately and that the fabricated PCBs are of good quality. The extreme attenuation is due to manufacturing irregularities of the internal surface of the copper pipes. The acetic acid solution can only remove surface tarnish. The authors suggest that future work can investigate the effect of electropolishing [20] on path loss. Further, the effect of electroplating the inner surface with Aluminium or Silver can also change the data pipe's wavelength-based attenuation-reflection profile. The authors conclude that the future must increase data transmission distance by order of magnitude for a practical backup system.

CHAPTER 5
CONCLUSION AND FUTURE SCOPE OF WORK

5.1 Work Conclusion

The authors analyzed the challenges faced during volatile, high-energy system design and prototyping, focusing on data acquisition and backup. They evaluated Various channel media based on their cost, mechanical robustness, and link reliability. Two media satisfied the requirements: a wired data transmission medium (a Cat 5e Ethernet cable) and an optical data hollow pipe made of annealed chemically polished epoxy reinforced copper. The authors selected the data pipe due to its durability and the independence of the data transmission rate on the channel properties.

The authors conducted preliminary ray-tracing simulations of optical propagation in a copper data pipe using the COMSOL Multiphysics commercial code. The results of the simulations helped establish a path loss model of the channel, with the input variable being the pipe length. The pipe length ranged from 1000mm to 2350 mm in the model. The authors found that the optimal straight data pipe length was 2260.2 mm, factoring in the minimum irradiance requirement to produce a high signal-to-noise ratio at the daughter node. The authors selected a straight data pipe with a length of 2200 mm for the final ray-tracing simulation. The output port power obtained from the simulations agreed with the evaluated path loss model. The authors also showed that the output port power was mesh-independent.

The system implemented cost less than 100 USD. The authors tested the system using random binary data streams to find its data transmission rate and reliability. A tabletop CNC milling fabricated copper clad boards for the mother and daughter nodes. The authors found that the system did not have any bit errors at the data transmission rate of 1 Mbps for 90 minutes with a wired channel. The authors fabricated 300 mm segments and found that the path loss after treatment with an acetic acid solution was 20 dB/m, three times higher than the simulations predicted. The nodes achieved reliable optical transmission at 576 Kbps using a 14 cm data pipe. The extreme attenuation was due to irregularities in the internal surface of the data pipe.

Finally, the authors conclude that the future must increase data transmission distance by order of magnitude for a practical backup system. Electroplating the inner surface with Aluminium or Silver and electropolishing it may help reduce path loss.

5.2 Future Scope of Work

Workers interested in continuing this work can look to the following claims for study. The authors claim the mechanical robustness of the system in this report. Future investigations can drill the data pipe and observe if holes in the data pipe degrade the link quality and if a software reset of the nodes remedies the problem. The authors also claim that the designed system has a low noise channel and a low bit error rate. However, they do not test the system with a prototype boiler or rocket motor. Future work can test a similar system with a prototype rocket motor or boiler to verify the above claim. Finally, the authors claim that a data pipe can transport power, data, and mass in this work. The work here demonstrates power and data transport. Future researchers may aim to achieve transport of all three on the same physical link. Such a technology demonstration is a landmark in systems engineering, enabling vast simplification of turbofan design and aerospace avionics design.

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DATA AVAILABILITY STATEMENT

The COMSOL Multiphysics 6.0 ray-tracing simulation files, node electronics schematics, and the board Computer Aided-Designs (CAD) are available from the authors upon request. All software used during the operation and testing of the systems is available on Github at https://github.com/nutcasev15/OBS_Project_Code, and the custom SPI SDCard driver with the Greiman's SdFAT library is available at https://github.com/nutcasev15/SdFat/tree/HWDrv.

PROJECT DETAILS

Student Details			
Student Name	**Yuvraj Jain**		
Register Number	180907124	Section / Roll No	A, 12
Email Address	yuvraj.jtlr@outlook.in	Phone No (M)	96426 45520
Project Details			
Project Title	**A Mechanically Robust Optical Data Backup System Using a Copper Data Pipe**		
Project Duration	6 Months	Date of reporting	10^{th} January, 2022
Organization Details			
Organization Name	**Manipal Institute of Technology, Manipal**		
Full postal address with pin code	Department of Electronics and Communication Engineering, Manipal Institute of Technology, Eshwar Nagar, Manipal, Udupi, Karnataka - 576104		
Website address	https://manipal.edu/mit/program-list/btech/btech-electronics-and-communication-engineering.html		
Internal Guide Details			
Faculty Name	**Dr. Priyanka Desai Kakade**		
Full contact address with pin code	Dept. of E&C Engg., Manipal Institute of Technology, Manipal – 576 104 (Karnataka State), INDIA		
Email address	priyanka.kakade@manipal.edu		

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