Optical Wireless Radio

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Introduction, Background and History

Optical communication is the use of light or laser as the medium with which to communicate between a transmitter and a receiver. In the past, optical communication was not used because the cost of implementing such a system was too high. Both the transmitter and the receiver were unreliable and there was a lack of proper technology and manufacturing capabilities. Since the time of the telegraph, the traditional electricity or copper lines have dominated the communication industry as the medium because it was cheap and well understood. For decades, copper lines had served as the channel for long distance communication and the network for information sharing across the globe.

In 1960, the invention of laser provided a new solution for the industry in the form of optical communication through optical fibers. In the late 1900s, the development of semiconductor lasers, low attenuation fiber optics line, and the capacity for virtually unlimited bandwidth using DWDM (dense wave division multiplexing) caused to the outburst of optical fiber communications. Nowadays, fiber optics unquestionably dominates long distance transmissions. It has ushered a new era of communication and has become one of the main components of the significantly improved Information Superhighway System.

Free space optical communication is a small niche in the industry where the laser is transmitted through the air (or free space) instead of fibers and is thus completely wireless. The obvious main constraint to this type of system is line-of-sight. Free space systems do not have fibers as waveguides and thus must be positioned such that there is no obstruction directly between the transmitter and receiver. This limits its realistic functionality and thus, though capable of much more efficient data transfer, free space optical communications will probably be restricted to applications such as space communications and not replace radio frequency systems. NASA currently uses optical wireless systems to communicate with both spacecraft and satellite systems.

Project Goal

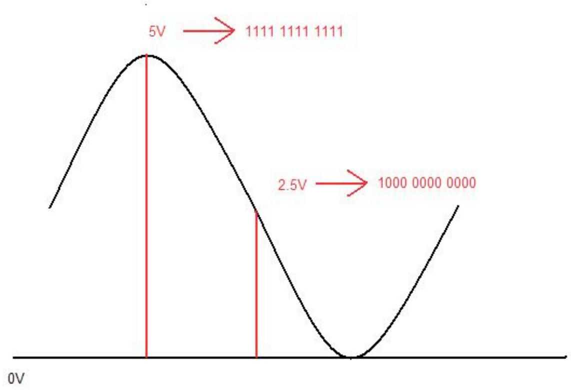
Our project is to design an optical wireless radio with two main parts. We will design a transmitter that will read and convert an analog signal into a digital signal. The digital signal will be sent to the laser pointer, which will send the data through free space. The second part of the project will be the receiver. The receiver will capture and read the digital signal and reconstruct the original analog input.

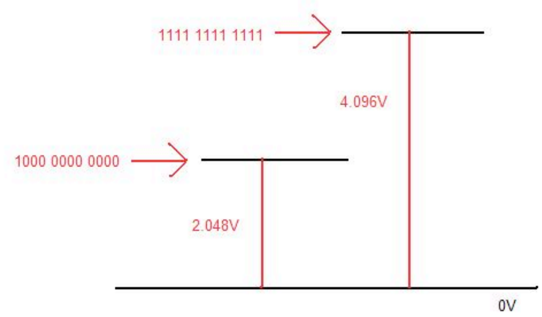
General Sampling and Data Communication Theory

Any analog signal can be converted to a digital signal through sampling. Signals are sampled by reading the amplitude at discrete and regular time intervals. These amplitude values are prescribed a digital (in our case, a binary string) value based on a predetermined voltage range and sample resolution. The input range is evenly divided by the sampling resolution. With a higher resolution, the conversion process can recognize more distinct amplitude values. In our case, our amplitude range is 0V to 5V and our resolution is 12 bits. With 12 bits, our converter can recognize 4096 different voltage values. Applied to our range, the 12-bit resolution implies that each bit increment is 1.22mV wide. Taken at a regular interval, these digital samples can represent the original analog signal.

Reconstruction of the analog is nearly the exact reverse process of sampling. The digital sample is read and prescribed an analog amplitude value based, again, on a predetermined voltage range and sample resolution. Our converter output range is 0V to 4.096V, and, for compatibility, our resolution is 12 bits. This implies that each bit increment is 1mV wide. The output of one sample is kept steady until the next sample is converted.

According to Nyquist, the maximum frequency of a signal that can be correctly reconstructed after sampling is half the sampling rate. In our project, our sampling rate is 1kHz. This means that the frequency of the input analog signal must not exceed 500Hz.





Converter Timing Theory

Both A-D and D-A converters require 2 sample clocks to operate: a sample clock and a bit clock. For the ADC, the sample clock tells the converter when to sample the analog signal while the bit clock tells it when to send out each bit of the binary string. For the DAC, the sample clock tells the converter when the most significant bit (MSB) of the string is coming, and the bit clock tells it when each of the following bits arrive.

Alternative Solutions

1. Parallel vs. Serial

Pros

- Parallel laser communication will provide a faster transmission rate than a serial laser because multiple channels are used to operate

Cons

- Parallel laser communication would require as many lasers as the number of bits (eg. 8 lasers for 8 bit ADC conversion). This would increase the cost of the overall transmission. This does not calculate for components malfunctioning and photodiodes burning out.

- Aiming would be quite difficult for each independent laser and would require fixtures to hold each transmitter and receiver in place. This may diverge more of our time and attention to the mechanics of the project.

2. Labview & Labjack

Pros

- Would be able to compile multiple function generators, voltage supplies and oscilloscopes into one program.

- Would be able create a virtual output for easier access to testing purposes.
- Would be able to virtually lower the duty cycles for the clock

Cons

- Analog output limited to 50Hz on low-end Labjack modules.
- Would require the knowledge to program Labview.

3. Universal Asynchronous Receive/Transmitter (UART)

Pros

- Would solve problem of synchronous clocks. Includes start and stop bits.

- Create a true wireless communication by using two separate clocks.

Cons

- Would require programming a microcontroller, which we don't know how.
- Would require more time to work on the design.

Our Solution

We used the serial link because it is more efficient in terms of cost and time. If we were to use the parallel link, we would need to invest more money on the lasers. We would also have to spend time mounting the lasers onto the case, which will also be susceptible to mechanical vibration. Using Labview and Labjack were not the greatest solutions because we would need more time to learn the software, and we would also need to invest more money to purchase a high-end Labjack module. We could not implement UART into our system because we would also need additional time to learn the software of UART. We would also need to purchase the hardware, which would increase the cost of the system. Our optical wireless radio is considered to be the best solution due to the deadline constraint that we have and the cost constraint that we do not want to exceed.

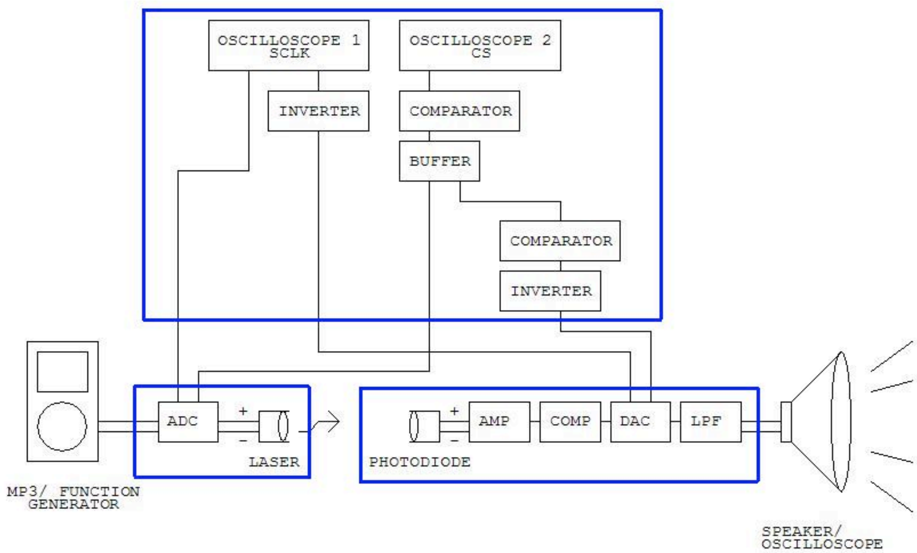
High Level Design

Starting from left to right, the apparatus is set up with a function generator sending its signal to an analog to digital converter (ADC). The data is then converted to bits and sent serially to a laser of visible wavelength. The "bits of light" are then picked up by the photodiode, amplified, and sent through a comparator in order to clean out the noise, which is finally sent to the digital to analog converter (DAC). The analog signal outputted from the DAC is then sent to a speaker or oscillocope.

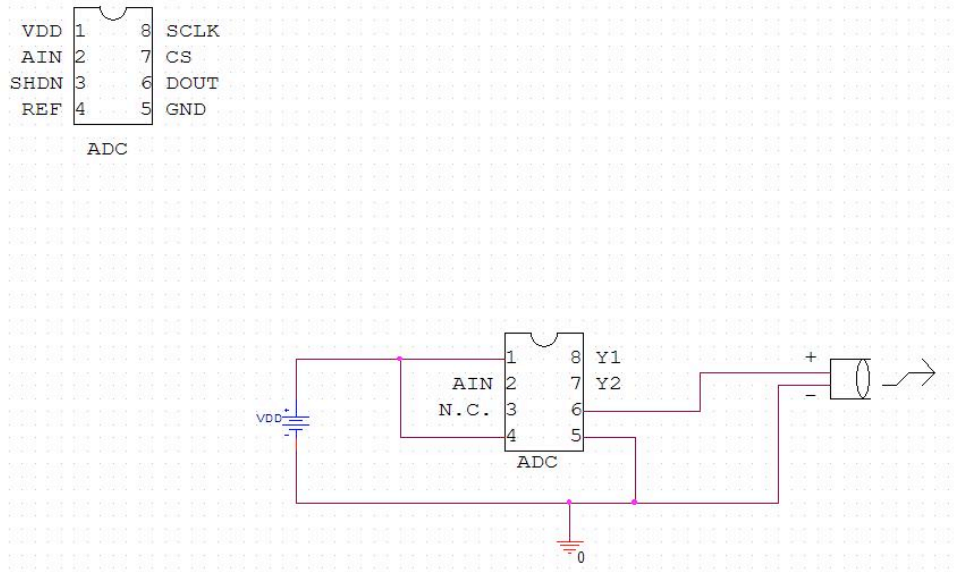
Parts

Item	Part Number	Item Description
1	DAC7611PB-ND	Digital to Analog Converter
2	MAX189CCPA+-ND	Analog to Digital Converter
3	PNZ300-ND	Photodiode
4	TT7300CP	Laser Pointer
5	497-2309-5-ND	Comparator
6	497-1384-5-ND	Op Amp
7	HCF4007UBEY-ND	Inverter

Circuit Schematics

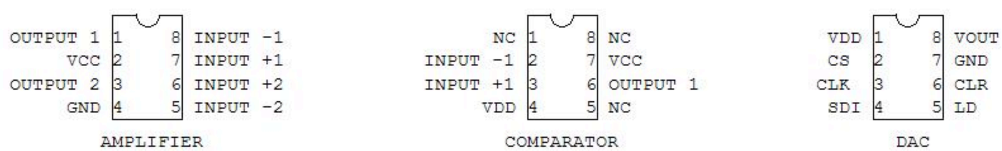


Transmitter

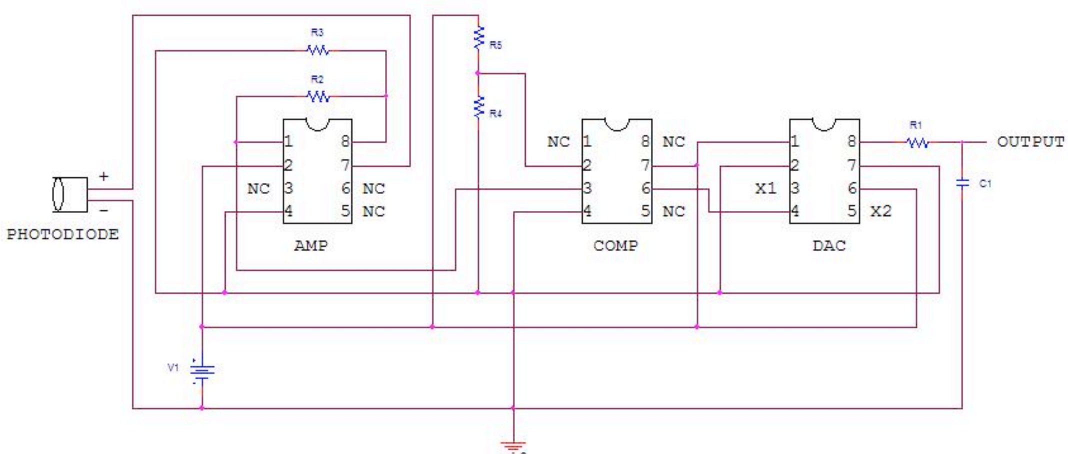


VDD
AIN
SHDN
REF
SCLK
CS
DOUT
GND
ADC
AIN
N.C.
Y1
Y2
VDD
ADC
0

Receiver

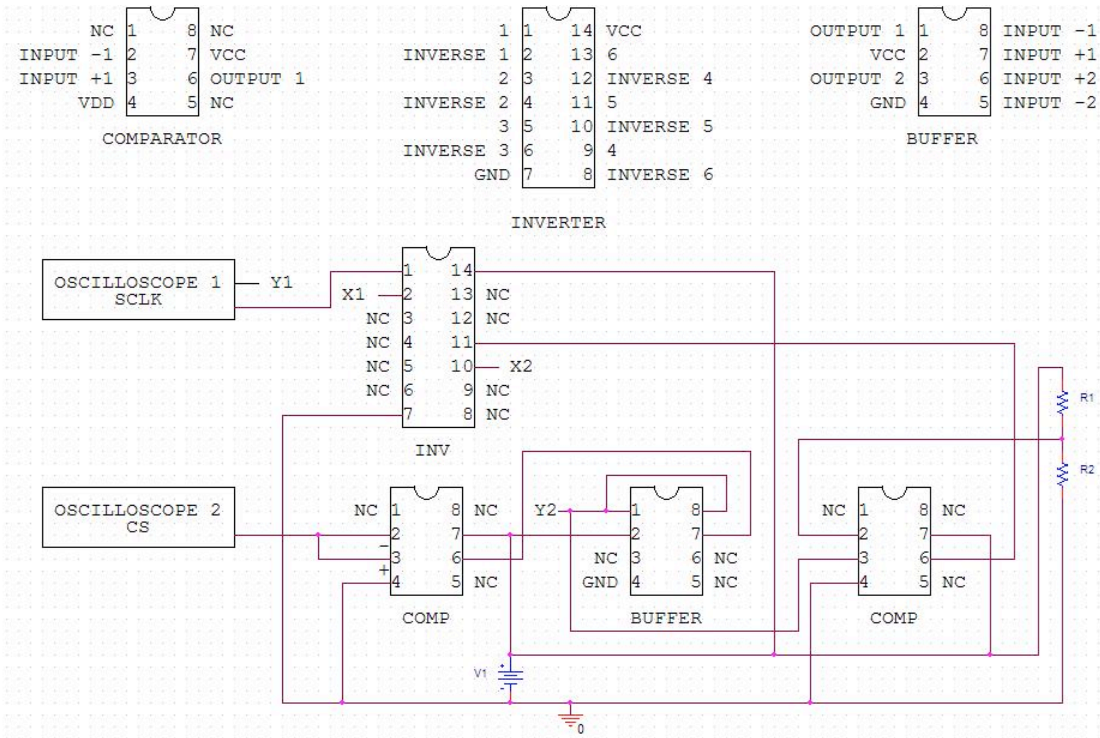


OUTPUT 1
VCC
OUTPUT 2
GND
INPUT -1
INPUT +1
INPUT +2
INPUT -2
AMPLIFIER
NC
INPUT -1
INPUT +1
VDD
NC
VCC
OUTPUT 1
NC
COMPARATOR
VDD
CS
CLK
SDI
VOUT
GND
CLR
LD
DAC



R3
R2
R5
R4
R1
C1
V1
PHOTODIODE
NC
NC
NC
AMP
NC
NC
NC
COMP
X1
X2
DAC
OUTPUT
0

Clock Box



Individual Components

Transmitter

- Analog to digital converter: The ADC we decided to implement in our circuit was a 12 bit serial dual inline packaging (DIP) chip. It has a 75 kHz sampling rate, which is well above the audible frequency range of humans. The chip initiates its conversion on the falling edge of the chip select clock (CS), and operates as an active low. The serial clock (SCLK) should be set twelve times the chip select clock in order for us to distinguish between each set of bits.
- Laser: We decided to use a simple laser pointer as suggested in the guidelines. This reduces complications in a couple of ways. First, we do not need to collimate our own laser, which would require its own apparatus to hold the lens in place. Secondly, the circuitry is pre-defined with a turn on voltage of ~4.5V. The simple on/off switch saved us time to work on the main portion of the project. Its wavelength is 650nm (red), which is in the visible range.

Receiver

- Photodiode: The photodiode we chose is optimal for the wavelength of 800nm but has a 65% relative sensitivity for the 650nm wavelength. This photodiode will suffice since we could not find a photodiode with optimal sensitivity in the 650nm wavelength.

- Amplifier: Once the signal is received from the photodiode we used a simple op-amp amplifier circuit to boost the signal in order to make the high-low voltage straddle .5Vref for our comparator. Instead of fixed resistor values, we decided to use a potentiometer to adjust the gain. The fixed resistor value was 82k Ohms and the potentiometer impedance range was 0-100k Ohms. By having an adjustable amplifier, we could design a robust adaptable receiver for different distances.

- Comparator: The comparator cleans up digital data. When the input is above a predetermined Vref, the comparator outputs Vdd. When the input is below the Vref, the comparator outputs 0V. This creates a clean 1 and 0 for the DAC.

- Digital to analog converter: The DAC we decided to implement in our circuit was also a 12 bit serial dual inline packaging (DIP) chip. It has a 132 kHz sampling rate, which is also more than sufficient to convert bit rates above the audible frequency range of humans. The chip initiates its conversion on the rising edge of the chip select clock (CS), and operates as an active high. This chip uses the same clocking schematic as the ADC but is inverted. Using the same clocking schematic ensures that both the ADC and DAC are sending and receiving the same amount of information at the same time.

- Low Pass Filter: This is a simple RC low pass filter that smoothes out the output of the DAC. The R value is 160 Ohms and the C value is 1 uFarad. This gives a cutoff frequency ofn 530Hz. This pushed the bandwidth capabilities of our project to near the max defined by Nyquist.

Clock Box

- Comparator: The comparator generates a very low duty cycle square wave from a triangle wave that is required for our sample clock. We also have another comparator after the buffer to bring the voltages back to Vdd and 0V for the inverter.

- Buffer: Because of the long wires, we decided to introduce a near unity gain buffer after the comparator for the sample clock. This maintains the high and low even on longer wires.

- Inverters: Since both the ADC and DAC are receiving the same clock signals but are inverted from one another, we placed two inverters in front of the two clock signals going into the DAC. This is crucial to synchronizing the ADC and DAC chips.

Design Problems and Solutions

Throughout the course of this project we came across many different problems and challenges that forced us to bring out the best in our abilities to design the optical radio. Among the earliest problems encountered in this project lied in attempting to decipher the timing diagrams and understand the timing methodology that most ADC and DAC manufacturing companies use in designing their chips. This was the main hurdle for us to overcome since the crux of our design rested in the ADC and DAC chips and the syncing of their bit and sample clocks.

Once we came to understand the methodology behind the clock signals of the two chips, we developed a solution built around the manner in which the chips sampled incoming data and with what bit resolution that the data was sampled. Since our chips were 12-bit converter chips, we had to have two separate clocks; one for the sample clock (called the Chip select, which controlled the timing of the output of the sampled binary data) and one clock for the bit resolution of the sampled data (which this clock ran at 12 times the speed of the sample clock). By similar reasoning, the DAC chip had one clock that was effectively the sample clock and another clock that was designed 12-times the frequency of the sample clock so that the incoming 12-bits of data could be de-converted back into the analog domain at the proper de-sampling rate.

Another major hurdle in this project was in dealing with the laser because the initial laser that we had obtained in the mail was not of the correct type for the circuitry we planned on employing. Due to this apparent constraint, we could not get the first laser diode to laze properly and so we had to obtain a different type of laser to transmit our digital data signal. We then obtained a simpler red laser that was relatively simpler to implement and we constructed the circuitry to get this laser to laze.

In implementing this simpler laser, another design constraint became immediately apparent through the nature in which we chose to transmit the digital data. We had chosen to transmit our data through the laser using a very simple method, given our very limited level of knowledge about modulation techniques in communications. Our digital data was going to be transmitted by each 1-bit turning the laser on and causing it to laze and each 0-bit corresponding to the laser turning off and not lazing. As we tested different frequency signals in the laser, we began to realize that this laser couldn't transmit signals of a frequency greater than or equal to 10 kHz with enough resolution. This limitation could be overcome by either using a faster laser diode and more sensitive photodiode that can completely resolve a very rapidly oscillating laser signal, which has a cost of a higher price tag associated with this project when viewed from an economic perspective.

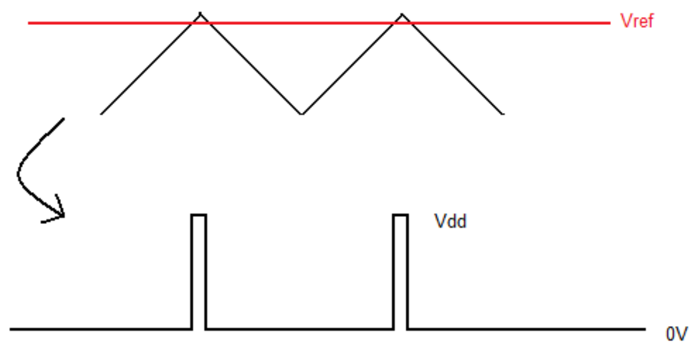
Once the project was working on the bread boards, we began to think about partitioning the circuitry into separate modules so that we could present the project in a simpler and more attractive image. Because of the number of circuit components that required power and clock signals, merely separating the circuitry into two discrete boxes would make it look less appealing by having a large quantity of tangled cables running about the boxes. To combat this, we broke the design into three blocks; one consisting of the clock and power circuitry, from which the receiver and transmitter portions of the project would obtain their sample and bit clocks and their power and ground sources, while the other two blocks consisted of the receiver and transmitter circuitry. This module design technique simplified the external, visual layout of the cables and the boxes so that we used as few cables outside of the boxes as possible.

We began to notice that due to our chosen sampling rate we were noticing that our signal became choppy once we approached the limit of our input analog signal frequency imposed by the Nyquist Theorem. Through discussions with our mentor, Professor Boyraz, and experimental trial and error, we discovered that our signal aliasing was due to a lack of an output low pass filter to attenuate the harmonic, high frequency contributions of the de-sampling process. We then implemented a simple RC filter with a cutoff centered about 1 kHz (our sampling rate) and the signal became clearer and we were able to resolve signals closer to our sampling rate. In the end, we were able to clearly demonstrate the functionality of the project by sending in various signals from the function generator as our analog input and reading the outputs on the oscilloscope.

Clocking Issue

One of the biggest issues we had for this project was the clocking and timing issue. Both the ADC and the DAC require two clocks to function. One of the clocks is the bit clock which provides the converters with a way to recognize the frequency and time of each outgoing or incoming bit. The other clock is the sample clock. In the ADC, the sample clock tells the converter when to start the conversion and send out the data, most significant bit first. In the DAC, the sample clock tells the converter when the sample string starts, also MSB first. The three issues that we had were: 1) we need to generate a sample clock with a very small duty cycle, 2) we needed to synchronize the bit clock and the sample clock at a very specific phase, and 3) we needed to generate a 180 degrees phase shift between the ADC bit clock and the DAC bit clock.

1) Our ADC and DAC operate on different sample clocks. The ADC operates on an active-low falling edge sample clock, meaning that the clock initiates a conversion on the falling edge and must stay low during transmission. Thus the clock looks like a square wave with a very small (5%) duty cycle or a short pulse. On the other hand, the DAC operates on an active-high rising edge sample clock, meaning the clock initiates a conversion on the rising edge and must stay high during the conversion. This looks like a square wave with a very large (95%) duty cycle, again a short pulse but inverted. Because our waveform generators can only generate duty cycles between 20% and 80%, we had to find a way to externally create the necessary cycles. Our solution for the ADC side is a comparator circuit with a triangle waveform. With the reference voltage (set by a voltage divider) near the peak of the triangle, the output of the comparator will be a short pulse at every peak. To generate the DAC clock, we will use a digital inverter circuit on the ADC clock.



2) Our ADC and DAC are both 12 bit converters, meaning each sample transmitted is 12 bits of digital data. Consequently, our bit clock rate must be twelve times the rate of our sampling rate. For testing purposes, we have our sampling clock at 1kHz and thus our bit clock must be at 12kHz for the data transmission to function. Because phase is the integral of frequency, any imprecision in frequency would mean a phase shift after some time. The waveform generators we work with in the labs are not 100% precise and thus a 1kHz signal from one generator and a 12kHz signal from another generator will drift away from each other. Furthermore, the sample clock needs to be locked in such a way that the pulse is during a bit clock low. To resolve these problems, our group will adjust the frequency of the sample clock in minute increments to get the phases to line up. For instance, if the sample clock is lagging, we will increase the 1kHz signal in increments at the mHz magnitude until the pulse occurs during the bit clock low and the phase stops drifting.

3) The ADC and DAC operate on the same bit clock principle. The ADC outputs a bit at every falling edge of the bit clock while the DAC inputs a bit at every falling edge. However, because there is a conversion delay on the ADC side, the two converters cannot have falling edges at the same time. To remedy this issue without having a second bit clock, we will send the clock through an inverter before the DAC, giving it a 180 degree phase shift. This will give the ADC ample time to convert and then send.

Possible Improvement for Future Design

The optical wireless communication that we have designed has its physical limitation. For example, our range barely spans out to one meter, the system cannot regenerate an audio signal higher than 1 KHz, and the product is not a true wireless system. For future improvement, we will utilize a faster laser, in order to transmit a true audio signal. The current laser that we used is an ordinary cheap laser pointer; therefore the pulse resolution lies in between 13 KHz to 15 KHz. However, if we were to design a true optical transmitter using a 12 bits ADC, then we would need the laser to pulse at the rate of 12 x 44 KHz (equivalent to 528 KHz). Not only a better laser in terms of faster pulses, but we will also need a powerful laser to increase the optical range for our product.

For future design, we will also use UART, Universal Asynchronous Receiver/Transmitter, to implement in our optical wireless product. The product that we made for senior design is not a true optical wireless communication product since we used the same bit clock for both our transmitter and receiver. By using UART, we will be able to transmit a 12 bit data through the laser carrier without time synchronization between source and destination. UART is achieved by utilizing a microcontroller to transmit a known bit to show the beginning and ending of a data string.

A stereo signal capability will also be added to our future design. In order to do this, we will need a new stereo ADC and DAC chips. With the stereo capability in the chips, the ADC will alternate the left and right channel signal to produce a stereo signal, and the DAC will follow the same process when it converts digital signal back to analog signal. We will also implement a better low pass filter for our next design. By utilizing a better low pass filter, we will be able to smooth out the output signal by filtering out all the unnecessarily high frequency and noises above audio frequency hearing range. In order to make our product more appealing, we will need to use a printed circuit board and a smaller housing to reduce our product size.

These are just problems if we have more time to work on the product, learn to use UART, and more time to play around with the chips. Money is also an issue to create a true optical wireless radio too because we would need an expensive laser emitter which would then increase the price of our product.

Various Impacts of Optical Communications Systems

The field of Optical Communications offers many benefits to society, the economy and is environmentally sustainable. Not only can society and the economy benefit from optical communications, but the manufacturing industry can gain from the field of optical communications. But these benefits come with added responsibility and without proper usage and ethical issues in mind, optics can bring potential pitfalls.

Optical communications has a faster data rate than radio communications and because of this increase in information exchange, society benefits by having that speed ready and at their fingertips to keep up with our rapidly growing world. Precisely because of this increase in information exchange, the individual's quality of life increases as well because the faster people get their information, the faster they get on with their everyday lives. It is for this reason as well that the general education can increase because the wealth of information available in the world through the internet can become that much more easily accessible at an even faster rate. Optical communications can also much more rapidly bring the otherwise geographically isolated societies of the world closer together.

The low cost of building and maintaining optical communications has obvious economic benefit. In the case of our project in particular, our device is not terribly expensive and would be cheap to implement. Optical devices are easy and cost efficient to maintain in the long term, although in the short term the expenses for converting many different systems to an optical method of data communication could cost a considerable amount. In the process of implementing and maintaining optical communications systems many more jobs can be opened up in the economy and this can correlate with economic growth. The reliability of optical communications also benefits economically due to the fact that a more reliable product can entice the public to buy it and to take stock in the offers of optical communications.

The design of our project facilitates manufacturability of the circuit because the unit as a whole is based upon smaller components that perform individual functions that when considered as a whole, constitute the optical wireless digital radio. These smaller components could be assembled together on a printed IC board and placed within container boxes for distribution. Through our projects modular design, it is simple to translate this device onto an assembly line for manufacture and distribution. This modular design also facilitates the troubleshooting process should any components fail or any attachments go bad in the device. One pitfall of our design that we began to notice was the susceptibility of the chips to fail and so the modular design was helpful in troubleshooting any device malfunctions.

The nature of light in different mediums provides an environmental constraint upon wireless laser communications. Weather conditions between the path of the laser beam and the receiver can impede successful data transmission and can affect the environmental sustainability of the laser. In addition to weather conditions, different environments and geographies can provide substantial, if not impossible, challenges for line of sight laser communications within the atmosphere of Earth. It is for this reason that laser communications systems are used so extensively in satellite and space communications systems. In addition to the varying geography of Earth, the wired optical communications systems can affect the environment through the laying of fiber optic cables in the oceans and across land.

As with all laser devices, there is a certain level of responsibility and care that is required when dealing with the health and welfare of the general public. Improper use of lasers can damage a person's eye and depending on the strength of the laser can blind a person. In the case of our project, since the transmitting laser is in the 5 mW power range and is within the same power rating as a handheld laser pointer, then there is a certain level of danger in using this laser around people's eyes and care must be taken when using any laser based communications system. Despite this, most laser communications systems are within the infrared spectrum of light and do not pose quite the same dangers as visible lasers.

Conclusion

After completing this project, we have seen how effective laser communications can be and how limited they can be as well. We can say that through this project we have gained an understanding of the technicality and intricacies that revolve around clocking mechanisms in wireless systems and in sampling systems (and DSP systems as well). This project has also underlined the important idea of synchronization and the importance of matching circuits and components so that everything can properly work together. Overall, this project was a success in that we were able to transmit an analog signal over a wireless laser channel and receive it at a photodiode and reproduce the image at the output. Although we did not achieve audio, this could be accomplished by modifying the current circuitry slightly be adding a few buffer stages, a better low pass filter, and by obtaining a faster laser.

Throughout this project, we had to rely on our ability to obtain resources and research the topic of optics and laser communications in order to tackle this design. Many sources were based off of the internet and off of specification sheets of the chips, components, the laser and the laser diode but we also used textbooks from our classes to obtain relations and formulas for the buffer stages and amplifiers used in our design. This project has emphasized the idea that you are always learning in whatever you are doing and that you are always reaching back into the techniques and the resources that you've had in the past in order to push forward into the future. We've also learned a lot of new topics and ideas through this project, which also underlines the lifelong learning idea that no matter what you do, you will need to research a new idea or further your own knowledge in a field in order to accomplish your goals.

Timeline

Fall Quarter

Week 3	Began initial research on project
Week 4	Met with Professor Boyraz, discussed project details and group breakup. Decided to work on AD and DA conversion first.
Week 5	Met in groups to collaborate and share sources and research.
Week 6	Met in groups to find and order DAC/ADC from Analog Devices
Week 7-8	Waited for shipping
Week 9	Chips came in. Packaging too small to test pins. Ordered pc board adapters
Week 10	Adapters came in. Tested, wrong chips. Timing/compatibility issues. Searched for new chips and ordered samples from Maxim.
Winter break	

Winter Quarter

Week 1	Chips came in. Tested, wrong chips. Soldering/Control-bit issues and still too small. Searched for new chips in DIP packaging. Ordered from Digikey
Week 2	Chips came in. Tested, wrong chips. Control-bit/timing issues incompatible for application. Searched for new chips. Ordered from Digikey 12-bit for timing solution. Decided to research and work on laser at the same time. Ordered laser and photodiode.

Week 3	Laser and photodiode arrive. Laser is uncollimated and requires extra circuitry. Decide to use laser pointer. Search for solution to "clean up" highs and lows and order comparators.
Week 4	DAC/ADC arrive. Tested individually. Timing issue and function generator limit testing compatibility. Comparators arrive. Tested with photodiode. Successfully send/receive clean square wave through optical. Tested maximum resolvable frequency to be ~15kHz.
Week 5	Discuss solution for clock timing and synchronizing. Search for timers/counters. Decide to use comparator/triangle wave. Order comparators.
Week 6	Comparators arrive. Test, synchronize issue and duty cycle issue resolved. Timing issue with clock low/high. Order digital inverters.
Week 7	Inverters arrive. Breadboard circuit tested successfully.
Week 8	Soldered to circuit board. Housing and enclosure installed. Laser engraved modules. Tested successfully
Week 9	Met with Prof. Boyraz and discussed LPF. Installed LPF
Week 10	Comparator failed, replaced by extra. Demo to Boyraz. Presented project and complete report.

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