ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

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iPhone 13 with USB-C

Team #61

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May 4, 2022

Abstract

iPhones (and some other mobile Apple devices) have had the Lightning connector for almost a decade. While it has been the dream of many to have an iPhone with a USB-C connector, Apple will very likely not release iPhones with USB-C. A USB-C iPhone will increase interoperability and provide a universal charging standard (which is now used by iPads, MacBooks, Android Phones, many PCs and other devices). Our solution is to modify an iPhone 13-series smartphone. The modification entails removing the lightning receptacle inside the iPhone, adding electronics inside the iPhone for the proposed Lightning-to-USB-C conversion, and making mechanical changes to the iPhone chassis to accommodate and anchor a new USB-C receptacle.

Contents

1 Introduction

A general section looks like this. There is usually a blurb introducing the top-level section here.

1.1 Purpose

iPhones (and some other mobile Apple devices) have had the Lightning connector for almost a decade. While it has been the dream of many to have an iPhone with a USB-C connector, Apple will very likely not release iPhones with USB-C. This has multiple implications — it hinders the one-charge-for-all plan proposed by the EU to reduce e-waste, and it undermines the adoption of USB-C as a universal interface. The data transfer rate of USB-C can be significantly faster than lightning, and the power delivery of USB-C is also much more capable and universal.

1.2 Functionality

The solution we provide is to modify an iPhone 13-series smartphone. The modification entails removing the lightning port inside the iPhone, and replacing it with a USB-C receptacle (along with the added electronics). We plan to adding a lightning-to-USB-C conversation circuitry. We also planned on adding a micro-controller which provides slow-charging functionality. However, due to logistical issues (discussed later in the document), we were not able to implement it in time for the Final Demo. Finally, we modify the iPhone chassis to accommodate all the electronics and to anchor a new USB-C receptacle inside the iPhone.

1.3 Subsystems Overview

In this subsection, we will briefly go over all the subsystems (as initially planned). Figure 1 shows the block diagram with all these subsystems.

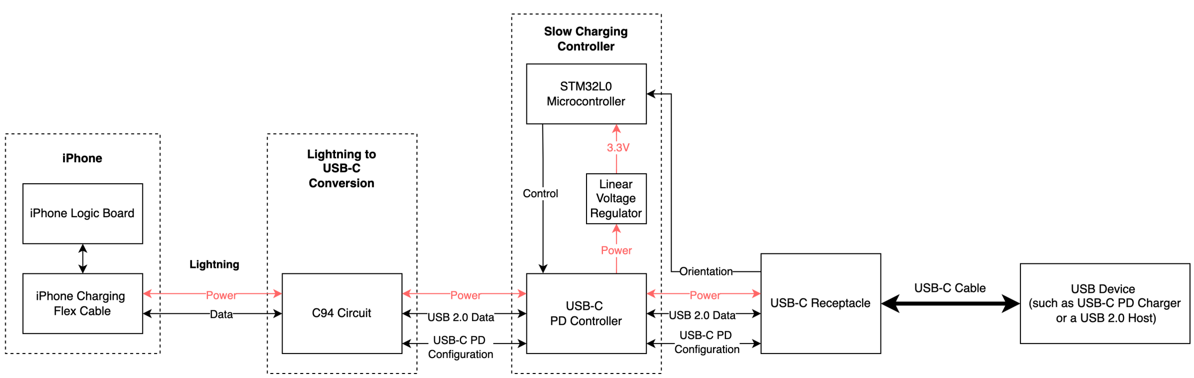

Figure 1: Initial Block Diagram.

1.3.1 Lightning to USB-C Conversion

This subsystem deals with converting all lightning logic to USB-C. It receives power and data from the slow charging subsystem, and passes it over to the Charging Flex Cable inside the iPhone 13, in its expected lightning protocol. This subsystem uses the C94 circuit from an Apple-certified Lightning to USB-C cable, which we have to add as a black-box. The components from an existing C94 circuit are extracted and used on our custom PCB.

1.3.2 Slow Charging Controller

This subsystem contains all the required circuitry to detect the orientation of the USB-C plug, and to perform a USB-C PD negotiation if necessary. It connects to the USB-C receptacle, and upon successful power negotiation, the incoming power is routed to the Lightning to USB-C Conversion subsystem for charging the iPhone. We have chosen the STM32L053R8T6 micro-controller and STUSB4500QTR USB-C PD Controller for their low power, small footprint and ease of use.

2 Design

2.1 Alternative Design

Our design was based on reverse-engineering the C94 Lightning-to-USB-C circuit. We planned to extract and use the components from the C94 circuit from a certified Lighting to USB-C cable. However, the wrong circuit arrived from our seller, and we did not have enough time to re-order the USB-C . Thus, we adjusted our design logic and decided to use the E75 circuit (which we recieved), which is a Lightning-to-USB-A circuit. We add another conversion logic from USB-C to USB-A in order to complete conversion from USB-C to lightning. All these electronics were housed on a flexible PCB in order to make use of the limited internal space in the iPhone, right below the battery.

2.1.1 Alternative Design Subsystem Overview

In this subsubsection, we will briefly go over all the subsystems in our modified proposal, based on the alternative design. fig. 2 shows the block diagram with all these subsystems.

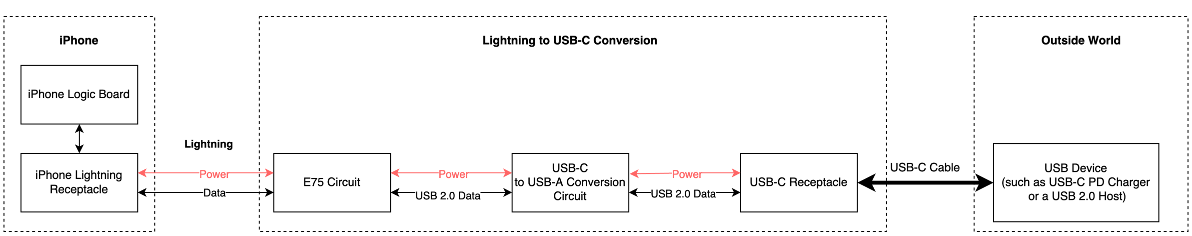

Figure 2: Modified Block Diagram.

Lightning to USB-A Conversion This subsystem deals with converting all lightning logic to USB-A. It receives power and data from the outside world and passes it over to the Charging Flex Cable inside the iPhone 13, in its expected lightning protocol. This subsystem uses the E75 circuit from an Apple-certified Lightning to USB-A cable. The E75 circuit receives power and data from the USB-C to USB-A conversion circuit, which makes the user can use a USB-C cable charging the iPhone directly.

USB-C to USB-A Conversion We implemented a basic circuit to convert USB-C to USB-A protocols, supporting up to USB 2.0 data speeds. This will be used as a bridge between the USB-C receptacle and the E75 circuit.

2.2 Design Description

2.2.1 E75 Circuit

The E75 circuit converts the power and data signals from USB-A to lightning protocols. There are two main chips inside the E75 circuit: one is C108 or C48 chip, and another is NX20P3. The E75 behaves as a negotiator between the power adapter and the iPhone. Once the cable is connected, the E75 informs the Tristar chip inside the iPhone that this is a MFI-certified cable, and wants to pass 5 volts charge to the battery. And the Tristar chip will request and receive the secret key from the E75. This is also the reason why we need to reverse-engineer the circuit of an MFI-certified cable, instead of making our own. The NX20P3 chip controls the current and voltage limit, protecting the iPhone from over-voltage and reverse polarity. If it detects any regulation discrepancies on the 5V charging, it will terminate charging by shorting the iPhone's `VBUS` line to `GND`.

2.2.2 USB-C to USB-A conversion circuit

A schematic of the USB-C to USB-A conversion circuit is shown in fig. 3. This circuit converts the power and data from USB-C to USB-A, and connects the USB-C receptacle with the E75 circuit. Since the USB-C has 20 pins of outputs but the USB-A only has 4 pins, we need to do a simplification while converting and connecting only useful pins. The V-bus, Data+, Data-, and GND are directly connected to the input pins of V-bus, Data+, Data-, and GND to USB-A. However, while USB-C can delivery four different level of voltage (Figure 3.), the USB-A can only support a 5 Volts input and output. Thus, we need to modify the input signal of the CC-channel, which is the configuration channel of USB-C, to control the power delivery of the USB-C. That's why we add a 5.1k resistor connected to CC1 and CC2.

2.2.3 PCB

Since we planned to fit the flexible PCB inside the iPhone, the first thing we need to do is measure the space inside the iPhone and check where we can put our PCB that can fit space well without changing the original internal layout of the iPhone. We tore down an iPhone 13 Pro Max, and a photo of the teardown is shown in fig. 5.

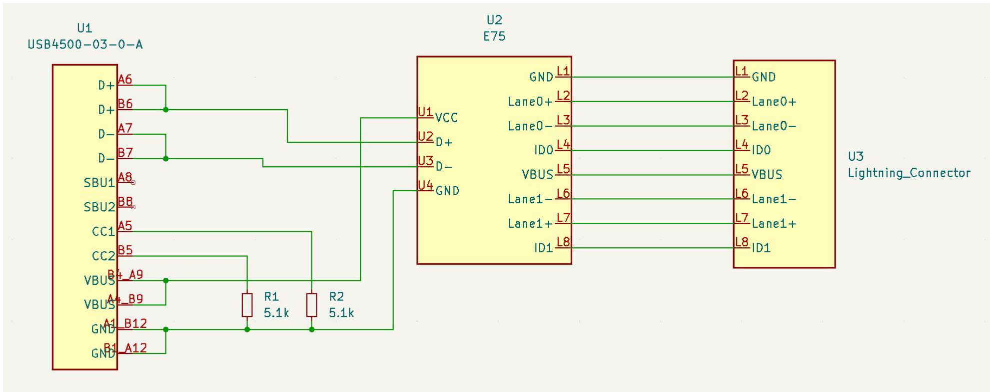

Figure 3: USB-C to USB-A conversion circuit.

Figure 4: A teardown of the iPhone 13 Pro Max.

We design a flexible PCB, shown in **??**, based on our measurements.

2.2.4 Changes to the iPhone Chassis

The hole at the bottom of the iPhone (that accomodates a Lightning plug) is not suitable for a USB-C plug. Thus, we had to increase the size of plugging hole according to the USB-C plug's size (according to [1]. We contacted the machine shop and they helped us enlarge the hole by using a CNC machine.

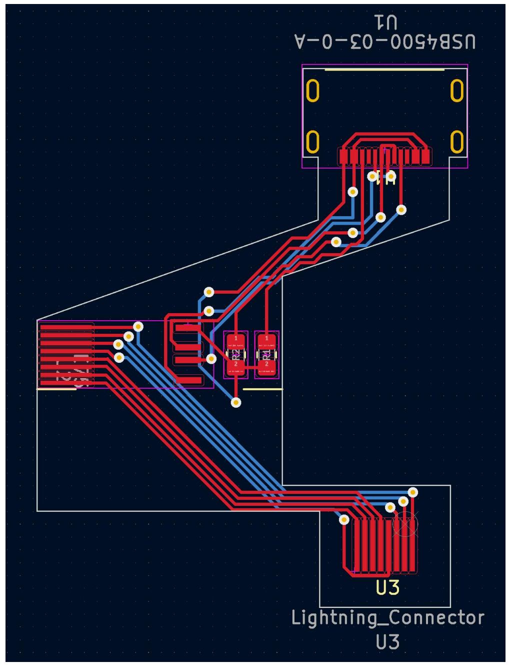

Figure 5: The custom-designed PCB.

3 Requirements & Verification

3.1 Requirements

This subsection details the three requirements of our project.

3.1.1 Charging

The first requirement was that our design should charge the iPhone at 5.0V with a minimum current of 1.2A.

This was verified using a USB Tester [2].

3.1.2 Data Transfer

Secondly, our design was required to perform USB 2.0 data transfer over the D+ and D- lines at ¿ 100 Mbps.

This was verified with a large 1GiB file transfer using a MacBook, and measuring the transfer speed.

3.1.3 Thermal

Last, we ensured that our design is able to meet both data and charging requirements simultaneously, while maintaining a temperature 60°C with only passive heat dissipation.

This was verified using a thermocouple attached to a fluke multimeter.

3.2 Completeness of Requirements

In the Final Demo of the project, we were able to verifiably meet all three requirements of the project.

4 Cost

4.1 Parts

Part	Manufacturer	Unit Cost ($)	Quantity	Total Cost ($)
USB-C Receptacle (USB4500-03-0-A)	GCT	0.83	1	0.83
E75 Lightning to USB-A Connector	Yitaiwei Ltd	0.53	2	1.06
TST001 USB Tester/Meter	Pimoroni Ltd	10.4	1	10.4
5.1k Ohm SMD Chip Resistor (RK73G2ATTD5101F)	KOA Speer Electronics	0.3	2	0.6
USB-C Breakout Board (BRK-USB-CV2.0)	Saiko Systems Ltd.	8.92	1	8.92
iPhone 13 Pro Max	Apple	1599	1	1599
Total				1620.81

Table 1: Cost of individual parts.

4.2 Labor

	Hourly Rate ($)	Hour	Total ($) / Person	Actual Cost ($) Total x 2.5
One member	30	160	4800	12000
Total For the team				36000

Table 2: Cost of labor.

4.3 Grand Total

Section	Total ($)
Materials	1620.81
Labor	36000
Grand Total	37620.81

Table 3: Total cost.

5 Conclusion

5.1 Accomplishments

Overall, our project has met two of the three high-level requirements we have stated in the original design document. Since the PCB was not delivered, we integrated all the circuits on an USB-C breakout board and connected it to the iPhone 13 so that it can replace the PCB to perform the Lightning to USB-C conversion. The modified iPhone 13 can now be charged through a USB-C charging cable and is able to perform USB 2.0 data transfer through the USB-C connection. After learning and understanding the USB Type-A and Type-C's specifications, we were able to convert the USB-C bus from the charging cable to the USB-A bus in our charging subsystem; and by using the E75 circuit, we can then convert the USB-A bus to the Lightning bus that the iPhone's built-in charging circuit uses. At the same time, by seeking help from the machine shop and using a CNC machine, we successfully modified the iPhone chassis so that it can fit the USB-C connector.

5.2 Uncertainties & Future work

There were some parts of the device that did not meet our expectations. Looking into the future of the project, there are also many things that could be improved upon. One uncertainty of our project is that currently we only used a modified USB-C breakout board to accommodate all our circuits instead of using a PCB that can be put inside of the iPhone as what we designed originally. Even though the circuit on the PCB is the same as that we are currently using, and we have made a paper version of the PCB to verify that the shape of the PCB we designed can fit inside the iPhone, we still cannot guarantee that after our ordered PCB arrive, it can function as what we expected. Therefore, our next work is to test the PCB once it arrives and solder it inside the iPhone. By doing this, our modified iPhone can finally function like a brand-new iPhone, without any external circuits connected.

Another uncertainty of our project is that the modified iPhone now didn't support different charging speeds when changing the orientation of the charging cable connector. This is one feature we expected in the earliest version of the design document, but we found that we cannot realize it after we changed our design to use the E75 Lightning to USB-A circuit. Therefore, in our future work, we hope to reverse-engineer a C94 Lightning to USB-C circuit. By doing this, we can directly make use of the CC-channel of the USB-C bus. Unlike the USB-A bus we currently use in our circuit, this channel supports four different levels of voltage, thus can be used to realize different charging speeds.

Apart from all the uncertainties above, one improvement we can make is to redesign our PCB to make it more compact and integrated. Currently our design takes the E75 circuit as a single component on the PCB, and we plan to directly solder it on the PCB. In our future work, we hope we can desolder all the components from it, measure them one by one, and make footprints for them in the CAD tool so that we only need to add those smaller components in our PCB design. By doing this, we can make our PCB more integrated, and look more like a real business product.

5.3 Ethical considerations

There can potentially be some electrical and heat hazards with our project since we modified the charging unit inside the iPhone and it is connected to the battery. The battery should not be overcharged and should be handled with care as they might explode if the temperature is too high. Throughout our project, our team followed the IEEE Code of Ethics section 6 to make sure that "the safety, health, and welfare of the device's user are held paramount" [3]. Therefore, we designed our charging subsystem as it will maintain the charging speed of 5.0V and 1.2A, which is within the safety range of the iPhone battery. Throughout the testing, we also used a digital thermometer to inspect the temperature on all ICs at 1 minute intervals and made sure that the temperature never exceeds 60°C.

A source of concern could be about personal privacy, since we modified the USB 2.0 data channel on the iPhone. However, we can ensure that our design would not bring any new risk of privacy breaches because we will use the components from the E75 circuit on a certified Lightning To USB-A cable. Thus section 1 of the IEEE Code of Ethics [3], "to protect the privacy of others..." is upheld.

References

[1] USB Implemeters Forum, *USB Power Delivery*, May 2021. [Online]. Available: https://usb.org/document-library/usb-power-delivery.

[2] Chargerlab, *Power-Z KM001 USB power tester voltage current ripple dual type-C meter*, Aug. 2021. [Online]. Available: https://www.chargerlab.com/power-z-km001-usb-power-tester-voltage-current-ripple-dual-type-c-meter/.

[3] IEEE. “”IEEE Code of Ethics”.” (2016), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 02/08/2020).