Wireless Audio Control Interface (WACI)

Capstone Proposal - Team B9

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Abstract

WACI (Wireless Audio Control Interface) is a new means of controlling and mixing audio using conventional performance software.

The WACI system consists of a Hub and several Modules. The Hub will function as a 4-input, 4-output audio interface with MIDI support and acts as the base station for all wireless Modules. Each module has hardware user interface elements that allow each musician to remotely adjust settings in any MIDI-capable audio software in real time. The hardware elements in the Module interface may include but are not limited to push buttons, sliders, knobs, and foot pedals to allow for various modes of adjustment that feel natural to a musician.

WACI will be managed and controlled by a custom cross-platform desktop application, with the ability to connect Modules and manage settings including Module names, MIDI commands, and response maps. The desktop application will also be able to monitor critical Module states including charge level and signal strength.

Contents

1 Introduction

Many musicians use computers in studios to record and process sound. As computers have become more powerful, they have been adopted in live performances as well. Many musicians use low-cost computer programs such as MainStage, or one of its competitors, to produce sounds from MIDI keyboard information; process guitar signals through complex effects chains; and manage background tracks during live performances.

Performing these functions on computers provides many advantages compared to using dedicated hardware. Sophisticated music software can replace thousands of dollars of rack-mount hardware effects, like compressors and equalizers. Due to their size and sophistication, these effects panels are usually relegated only to expensive recording and mastering studios. These expensive, bulky devices are difficult to acquire and transport, and thus are not suitable for a traveling musician's use. It can also be difficult to change settings while performing with these devices, whereas software is instantly reconfigurable – certain programs are configured such that a single key press on a laptop can change settings for the next song. Computers can also emulate well-known instruments that might not ordinarily be accessible for most musicians, like clavichords and harps, or create entirely new sounds that could not be created by other means, broadening the creative options for a musical artist.

There are currently some devices on the market that are designed for mixing audio and altering sound settings and parameters. Most of these devices contain knobs or buttons as a means of controlling sound settings and effects and provide a way of altering sound during live shows or performances.

1.1 Korg NanoKontrol Studio

One such audio-mixing device is the Korg NanoKontrol Studio, a Bluetooth controlled 8-track mixing controller. It contains small linear faders, buttons and knobs to manipulate the tracks. This device wirelessly connects to a computer, but it has several drawbacks that make it inappropriate for live performances. These drawbacks will be discussed in the next section.

1.2 Palette Aluminum Expert Control Surface Kit

Another device currently on the market is the Palette Aluminum Expert Control Surface Kit. This product is a wired control surface that is reconfigurable and has its own computer software to assign control functions. The buttons and knobs are sub-modules that can be reconfigured and ordered in unique layouts to fit the user's desire, allowing for a customized experience. It interfaces with a computer via a wired connection and allows the user to change audio settings on the fly.

Figure 1: The Korg NanoKontrol Studio

Figure 2: The Palette Aluminum Expert Control Surface Kit

Figure 3: The HotHands Wireless Accelerometer

1.3 HotHands Wireless Accelerometer

The HotHands Wireless Accelerometer is a device that contains a wireless wearable ring fitted with an accelerometer. It measures the user's finger angle and converts it to a standard control voltage output, which controls other hardware like guitar pedals or synthesizers. The base of the device must get plugged into a guitar pedal or synthesizer to have an effect, as the HotHands device works purely as a control.

1.4 Mobile Device Applications

Subaqueous Wireless Midi Controller and Lemur are examples of mobile applications that communicate over WiFi to control MIDI devices using a cell phone or tablet device. These are free apps that are compatible with a variety of different software. They allow users to manipulate sound and effects while performing, using devices the user presumably already owns, thus saving the expense of buying single-purpose hardware.

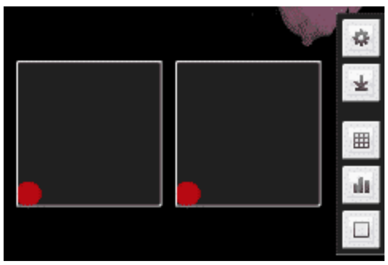

Figure 4: Screenshot of Mobile Application

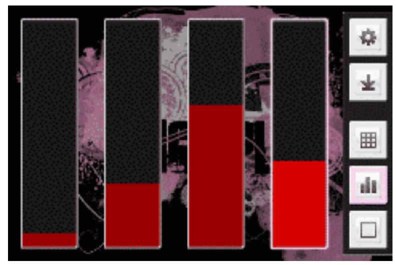

Figure 5: Screenshot of Mobile Application

2 Problem Formulation

Both amateur and professional musicians need to be able to manage effects and signal routing from the stage. Traditionally, this control is performed by physically changing instruments by running audio through hardware effects pedals or employing a dedicated mixing engineer to manage sound. This can be immensely limiting for performing artists, both in physical setup and needed level of expertise. Many products on the market attempt to patch at least one of these problems by either implementing a one-person wireless system, a wired distributed system, or an expensive customizable setup with significant feature limitations.

2.1 Shortcomings: Korg NanoKontrol Studio

Korg NanoKontrol Studio's advantages lie in its ability to set and adjust sound wirelessly; however, all the controls are on one centralized unit, designed for a single person to use and manipulate. This is limiting in a band setting, where it would be beneficial to have each instrumentalist have control over their own sound. In addition, the buttons and linear faders are rather small, which is acceptable for studio use, but would be difficult for a musician to use during a performance. An additional drawback is that the unit does not support audio input or output – additional hardware is required to connect any instruments.

2.2 Shortcomings: Palette Control Surface Kit

The Palette Control Kit allows for a more distributed control amongst musicians in a group, as a custom panel of controls can be wired from each musician back to a central computer. But, since these modules are not wireless, wired connections are required between the blocks of the module and the computer via USB. These connections may need to be lengthy for a real-world band application, which could introduce issues over the USB cable – this product is not designed for stage use, and would need some level of modification to be appropriate for use on a stage. In addition, the price of this product is rather prohibitive for musicians. This device also has no audio in or out capabilities and would require an additional product to manage audio in/out.

2.3 Shortcomings: Motion-based Controls

Control hardware that relies on hand motions tend to have multiple shortcomings. In general, they are not very reliable or accurate as detecting motion can be a complicated task. The HotHands Wireless Accelerometer requires the user to wear a device on their finger to manipulate a control voltage while playing an instrument. This can be problematic for certain instruments, such as guitar, where both hands are required to play the instrument. The user may be limited in a way that does not allow the freedom to precisely move a finger to control the HotHands while still maintaining proper form and technique for instrument performance. The device also does not interface with a computer and therefore is very limited in customization options.

Overall, using wireless technology to control computers in live performances is still a relatively new idea, with high-profile musicians only beginning to adopt the idea in the last ten years due to the high price-points associated with the devices currently on the market. Imogen Heap and Ariana Grande have famously used "Mi-Mu" gloves, wearable devices that communicate control signals to a computer over WiFi. More information about the Mi-Mu gloves can be found at https://mimugloves.com, which includes links to videos demonstrating their use. These gloves are intended to be used for vocal performances and demonstrate great levels of accuracy but are available at a price point that is unattainable for lower-profile artists or hobbyists.

2.4 Shortcomings: Mobile Applications

App-only approaches, such as the Subaqueous Wireless Midi Controller and Lemur, provide a more accessible tool for low-profile artists and hobbyists, but with a non-monetary cost. Apps hosted on smartphones and tablets are at risk of interruption during a live performance for a multitude of reasons. Phones and tablets may "lock" during a performance due to a span of inactivity, making the app temporarily unusable and potentially interrupting app functionality. Outdoor performances are also not ideal environments for such controls, as touch screens are difficult to see outside. Other non-ideal lighting conditions, such as flashing stage lights, could also hinder the user's ability to see the screen. With free apps like these, it typically is not possible to interface with other hardware elements like foot pedals, which removes the ability for the user to use a more "organic" performance; it is typically more natural to control a sound my manipulating physical hardware like an instrument, and touch screens do not provide the same type of haptic feedback. Finally, not all major music software is capable of receiving MIDI data over a wireless connection, meaning that the phone or tablet would likely have to be connected and stationed directly next to a laptop computer.

2.5 General Shortcomings of Typical Live Audio Setups

When small music groups composed of 3-5 people perform in a venue, they typically do not have a dedicated audio engineer or funds for a large equipment setup. As such, they are often reliant on a house audio engineer who is unfamiliar with the band and their target sound, not knowing their preferences. This is the reason for the demand for a distributed control system that feels intuitive to a musician not necessarily trained in audio engineering. While some devices on the market try to solve the centralization issue, these products ultimately do not work well as they still require all devices to be tethered to a computer via wired USB connections. Most devices on the market are tailored more towards creative studio use and not concert use. While it may be possible to modify some of these tools to be suitable for a concert stage, it would ultimately be expensive and difficult to do this reliably. This is the motivation for our project, as we will attempt to build an affordable, distributed music control and processing interface to combine the best attributes of all devices currently on the market.

3 Project Overview and Block Diagram

Our system, dubbed "WACI" (Wireless Audio Control Interface), will consist of two main components. The central component of the system, the Hub, will serve as the main point of communication for all other devices in the system. The Hub is responsible for all direct communications with the computer, then relaying all communications to the Modules as necessary. The Modules are small, personalized controls that are paired with each musician's instruments and can be positioned near the musician due to their wireless capabilities.

The Hub will be an all-in-one USB interface for musicians. By integrating microphone inputs, line-level inputs, a MIDI interface, and wireless gateway functionality into one device, the Hub can manage an entire live performances with just one power cable and a USB connection to a laptop. The Hub will be designed in compliance with the USB and 802.11n specifications. FCC compliance for the wireless card is guaranteed by the wireless card vendor.

Each Module will be equipped with different controls to cater to different musicians' needs. For example, a pianist might get the most utility out of foot switches or pedals, while a singer might benefit more from hand-operated controls. Additionally, some Modules may be outfitted with low-power screens to display status messages to users. Module wireless cards are also guaranteed to comply with FCC emissions requirements.

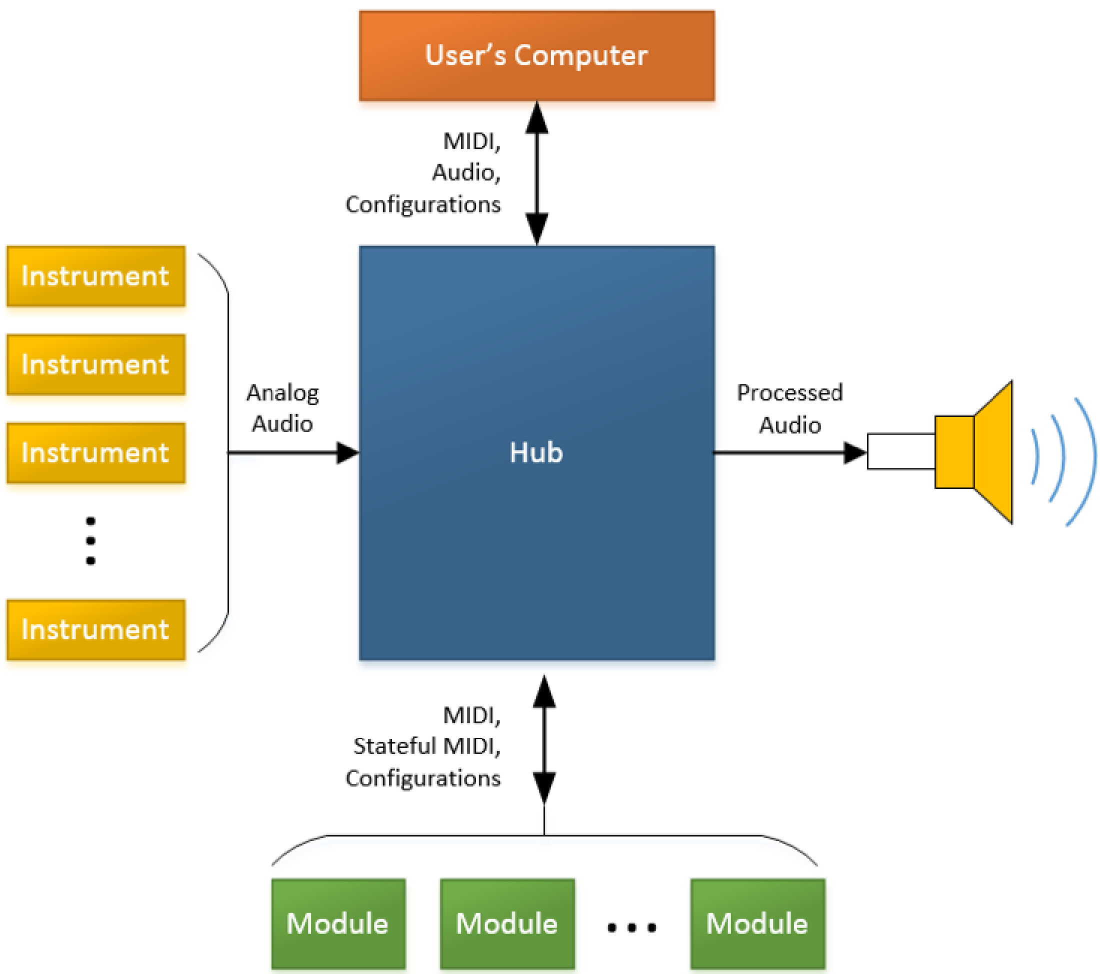

Figure 6: Simple System Block Diagram

4 Design Strategies and Analysis

4.1 Communications Link

Control modules will communicate with the central Hub wirelessly to send presets and preferences. In order to accomplish this, the project will make use of the ubiquitous ESP32 wireless module, which includes both Wi-Fi (802.11) and Bluetooth (802.15) functionalities. This module is designed specifically to be a good low-power solution for IoT applications, and it's low-power onboard IC will allow it to double as the main processing unit on the Modules (explained in more detail in the "Module" section of this report), and one can be used on the Hub as a slave device connected to the main IC. The ESP32 is capable of transmitting Wi-Fi with a transmit power between 13 and 15 dBm in 11n mode, or 19.5 to 20.5 dBm in 11b mode; and Bluetooth with transmit power and range of 0dBm (1mW) and -12 to 9 dBm. The onboard microcontroller on the ESP32 is an Xtensa 32-bit processor (either single or dual-core) with up to 600 MIPS, 448 KB of ROM, 520 KB of SRAM and 16 KB SRAM in RTC.

The ESP32 also supports the following microcontroller protocols and peripherals that may be useful in our application:

- External 2 MHz 60 MHz crystal oscillator (40 MHz only for Wi-Fi/BT functionality)
- Two timer groups, including 2 x 64-bit timers and 1 x main watchdog in each group
- One RTC timer
- RTC watchdog
- 34 x programmable GPIOs
- 12-bit SAR ADC up to 18 channels
- 10 x touch sensors
- Communications peripherals: SPI, I2S, I2C, UART
- LED PWM up to 16 channels
- Hall effect sensor

Each core of the ESP32 processor consumes about 40mA during normal operation, and the transmit power of the wireless antenna uses between 100-200mA when active.

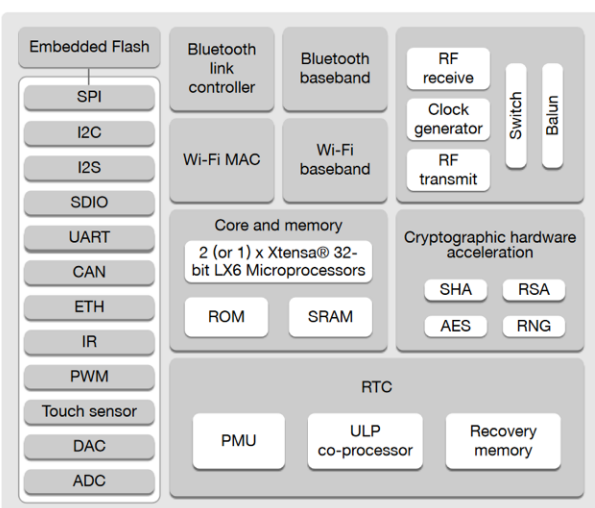

Figure 7: ESP32 Block Diagram

Figure 8: A Pre-assembled ESP32 Module

One of the major advantages of using the ESP32 module is its versatility and support community.

Libraries exist for the chip for every major embedded platform from Arduino up, and there are many open source libraries and Github repo examples readily available. The chip can be purchased on an inexpensive assembly that already includes components such as the antenna that would normally need to be routed on the PCB. The chip can be programmed using a standard AVR programmer (or even an Arduino), and runs on C-style code. Expected range of the chip can be as far as 150 meters in a standard configuration, and new iterations of the ESP32 also support the Wi-fi Long Range (LR) protocol with theoretical transmit distances up to kilometers.

4.2 Hub

The Hub will serve as the nexus of the system. It will be responsible for receiving the analog audio signals from wired instruments and wireless signals from Modules. The Hub will also be responsible for data conversion and routing of data between the computer, modules, and instruments. The main processing device in the Hub is an XMOS X-Core 200 multicore microprocessor.

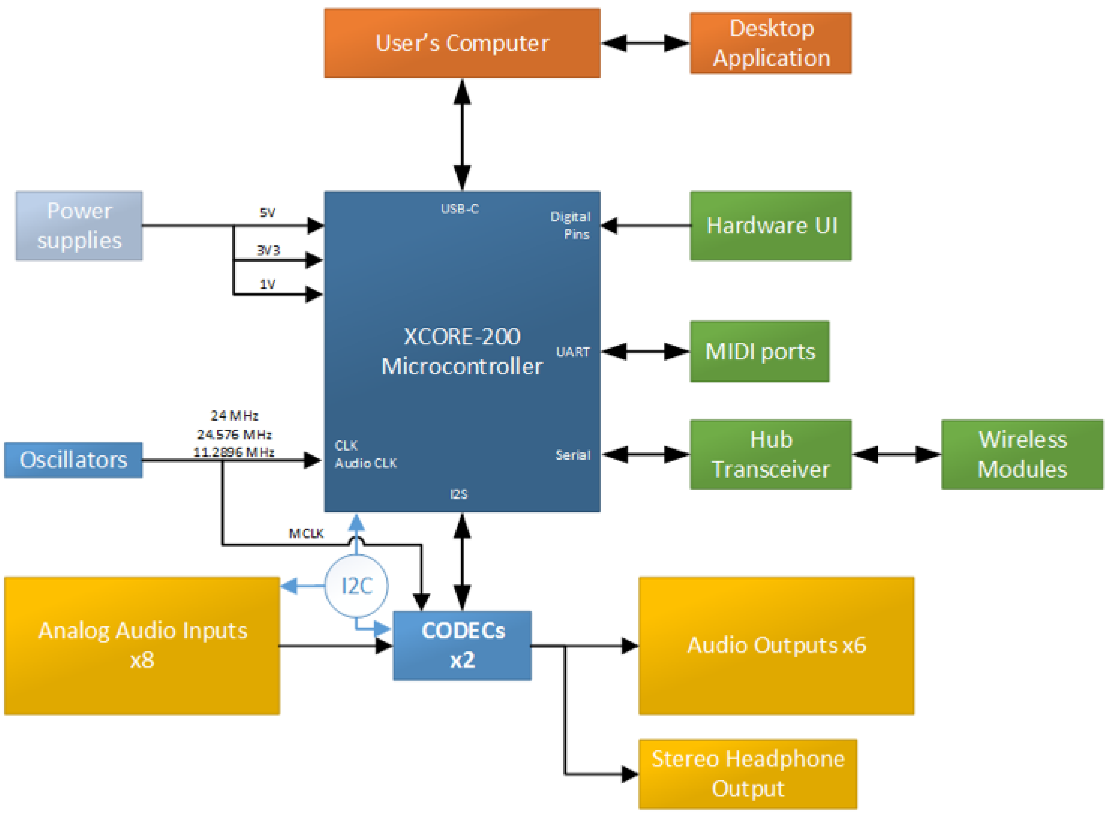

Figure 9: Block diagram of Hub circuit

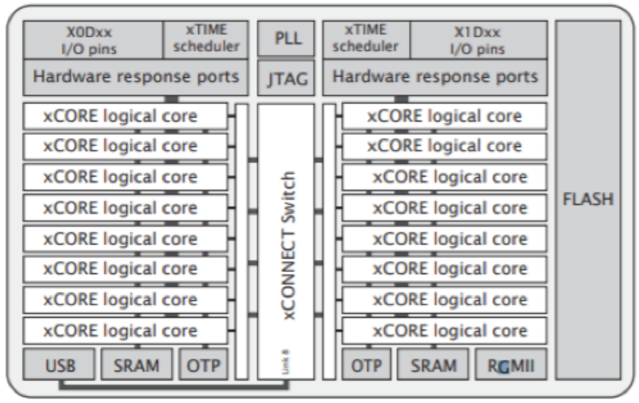

Figure 10: Block diagram of XMOS X-Core 200 Multicore Microprocessor

XMOS microcontrollers are optimized for high performance audio processing, with multiple independent processing cores, branded as "Tiles," that can each process several threads. The specific part number chosen for the Hub is the XUF216-512-TQ128-C20, which has two Tiles and a total of sixteen logical threads. It has guaranteed 2000MIPS performance. Open source libraries are available from XMOS for many critical audio protocols, including USB Audio Class 2.0, I2S, S/PDIF, and high dynamic range sample rate conversion. Each of these libraries consumes its own thread and thereby provides guaranteed throughput.

As stated above, we plan to use an ESP32 agile communications IC to manage the Module-side communications. Firmware stacks are available for WiFi, LR-WiFi, Bluetooth 4.2, and XBee, among others; this is convenient for our development because if a specific protocol does not work for us for any reason, we can simply update firmware on the Hub and Modules to adopt a different protocol.

The signal flow for audio inputs will be structured as follows:

Figure 11: Audio Input Signal Flow

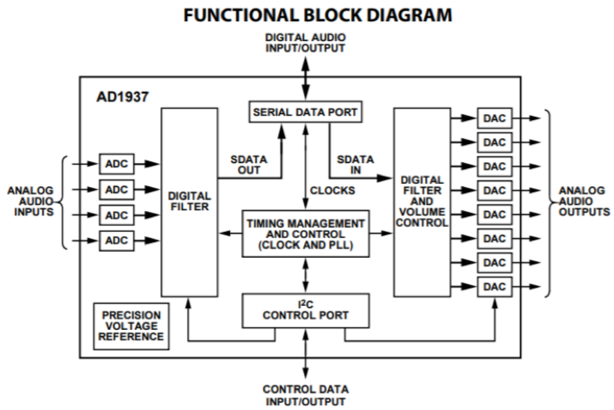

Figure 12: Block Diagram of AD1937 CODEC

"Combo XLR" connectors will be used as audio connectors. These connectors mechanically ensure that the user will not accidentally connect multiple devices to the same input circuitry at once. Input protection circuitry removes DC bias voltages, passively creates impedances required by the audio sources, and implements RFI mitigation. A preamp IC will provide adjustable gain of 0dB-60dB. Low gain levels will be used for line-level inputs, and high gain levels for microphone inputs. Preamp outputs feed into an ADC driver, which drive the input circuitry of the AD1937 CODEC. The AD1937 integrates high-performance sigma delta ADCs and DACs, as well as digital audio interface circuitry, on one monolithic IC. Digital audio from the CODEC is sent to the XCore-200 microprocessor over I2S and transmitted to the host computer over USB using class-compliant USB Audio Class 2. At this point, the computer takes over the signal chain and applies effects.

The signal flow for audio outputs will be structured as follows:

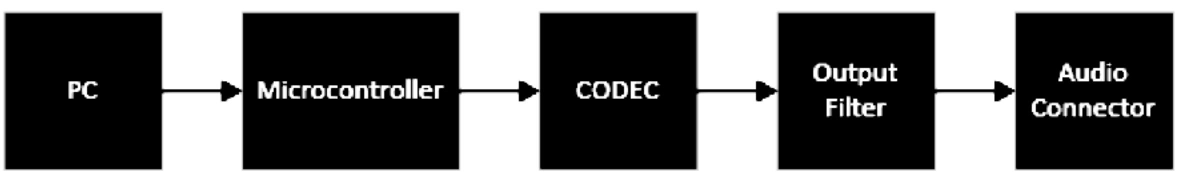

Figure 13: Audio Output Signal Flow

After the audio undergoes processing and alteration on the computer, it will be sent back to the microprocessor over USB audio and then to the AD1937 CODEC where it will undergo digital-to-analog conversion. Once the audio is back in analog form, it will be passively filtered to remove high-frequency noise and output over standard audio connectors.

The Hub will have a barrel jack port to interface with a standard 9V pedalboard supply or wall adapter.

The microprocessor requires two low voltage supplies to be derived from the power input: 3.3V and 1V. The 3.3V supply powers the I/O buffers and the 1V supply drives the cores. Buck converters will derive both supplies.

An additional 1V analog rail is required to drive the XCore-200's internal PLL, which generates the main processor clock. This rail should have low noise. XMOS application circuits derive this rail from the 1V buck converter, cleaning the supply with an RC filter. This will be done in place of a linear regulator to accommodate the chip's start-up sequencing needs.

A custom four-layer circuit board will be developed to house all these components and required supporting circuitry, such as reset generators, memory ICs, clock distribution ICs, and oscillators. A daughterboard may be implemented to house the power components separately to more easily parallel development of the PCB's.

4.3 Module

Wireless controls, currently referred to as "Modules," compose the novel idea of this project. These devices are wireless control interfaces made up physical user interface elements, wireless communications circuitry, and a power management system. These devices are designed to mimic traditional analog musical controls such as guitar "stompboxes" and mixer panels. Originally, this form factor makes use of fundamental electronic controls such as switches and potentiometers to control onboard filters implemented through analog and digital circuitry. In the WACI system, these same controls will be paired with a microcontroller to communicate analog signal levels from each Module to the Hub. Modules should last for at least 24 hours of meaningful use while running off an off-the-shelf Li-Ion battery pack, and they will be able to be charged either with a USB-Type C connector or an industry standard 9V barrel jack connector typically used for existing pedals on the market. Internally, the Modules will be driven by the microcontroller inside the ESP32 wireless module, with firmware tweaks made to accommodate the different possibilities of user-facing controls, potentially including control knobs and sliders, switches and buttons, display or touchscreens/touchpads, and other creative ideas.

Communications will be transcoded from analog and digital captures – derived from knob positions and button presses – to MIDI commands by the various Modules and transmitted wirelessly to the Hub. The Modules themselves will have no physical connection to the instrumental hardware an individual performer is using; rather, the commands that the Module creates will be passed from the Module to the Hub, then into the connected computer's processing software to change specific effects on the user's sound, then back out to the Hub to be passed to speakers or amplifiers. From the musician's perspective, the experience using the WACI module should not be drastically different from using an inline effect device – once mapped appropriately to their equipment, the module will be a less tangled, wireless direct replacement for the controls they are already accustomed to. By only sending commands to the central effects processor, these modules will also have the advantage of being able to be spread apart from each other conveniently as there are no cables connecting them, allowing a musician or stage technician to carry one around as a remote to perform a sound check at various locations or when moving around the stage. This is another interesting possible use case that adds a clear advantage to the proposed WACI system over current devices on the market.

Figure 14: A Typical "Stompbox" Guitar Effects Pedal

Due to their simple configuration, the Modules will be able to be controlled by the microcontroller onboard the wireless communications hardware. The firmware of the communications IC can be modified to support the few signals each module will be responsible for transmitting. This will allow the Module hardware to have fewer discrete components and less power consumption, helping to meet performance goals and enabling battery-powered design. With an estimated total consumption of 300mA — 250mA for wireless transmission at an approximately 1% duty cycle, 50mA for microcontroller and peripherals consumption — the required minimum battery size for each module is 2,000mAh.

4.4 Software

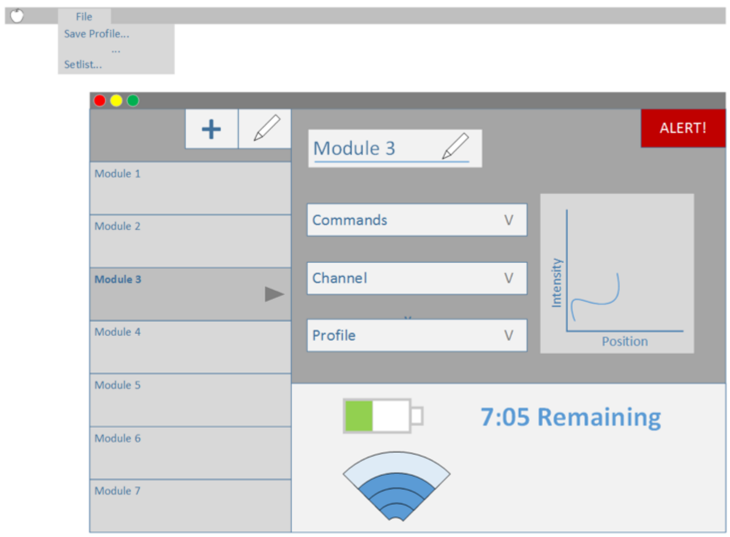

Figure 15: Desktop Software GUI Mockup

The Modules will be configured using a desktop application. The application will allow creating and naming a new Module, pairing the Module, configuring response with an input/output response map, and will have MIDI command and channels. The response map will be an interactive visual, which can be used to add transformations or scaling to the Module response. The GUI will contain a "Command" panel where the user can send MIDI messages to the Modules through the Hub. The application will also monitor and display Module charge, signal strength, and alerts for status changes. The app will communicate with the Hub through USB.

The desktop application should be used along with an existing audio software, which will provide all the actual audio tools. While the desktop app can communicate through MIDI channels or configure a response map, no actual recording of audio is taking place on the desktop app. The existing software, such as Mainstage, will handle all the recording and editing of the audio. The audio software will communicate with the Hub through USB. A notable benefit of this setup is if the user already has configurations on whichever audio software they are using, they would still be able to use those with WACI and would not have to learn an entirely new system.

The application will be developed with Proton Native, a cross-platform framework for desktop applications using native tools and a React environment. React is preferred because it is component based and state for each component is self-contained, which allows for simplicity in creating interactive user interfaces. The component-based structure of React is especially helpful for this GUI, which will need to dynamically create, update, and delete Modules as the user needs. Proton Native will allow the creation of a small desktop application with a simplistic and elegant GUI.

5 Cost Analysis

WACI Cost Analysis

Number of Hubs Built:	3
Number of Modules Built:	8

Hub Cost Analysis	Cost per Hub	Cost per Hub from Donations	Cost per Hub from Budget	Budget Cost for all Hubs
Integrated Circuits	$122.66	$95.26	$27.40	$82.20
Passive Components	$45.00	$0.00	$45.00	$135.00
Connectors	$30.00	$0.00	$30.00	$90.00
Circuit Board	$10.00	$0.00	$10.00	$30.00
Total	$207.66	$95.26	$112.40	$337.20

Module Cost Analysis	Price per Module	Cost Covered by Donations	Cost Covered by Budget	Budget Cost for all Modules
Integrated Circuits	$30.15	$18.14	$12.01	$96.08
Passive Components	$10.00	$0.00	$10.00	$80.00
Battery	$10.00	$0.00	$10.00	$80.00
Circuit Board	$1.50	$0.00	$1.50	$12.00
Enclosure	$2.00	$0.00	$2.00	$16.00
Total	$53.65	$18.14	$35.51	$284.08

TOTAL COST FROM BUDGET:	**$621.28**
Total Cost From Donations:	$430.86

Figure 16: Estimated Budget

Additional cost breakdowns will be provided in the appendix.

6 Division of Tasks

Jess and Phil will both design power and battery management circuits for both the Hub and the Modules. The Hub will receive its power from a barrel jack, which will be bucked down to various voltages as described above. The Hub also needs to boost the initial power rail to a 48V rail to supply phantom power to microphones. The Modules require battery charging and management circuits, which will be specified more clearly as the project progresses.

Schematic capture and layout for the non-power applications in the Hub are assigned to Josh and Phil—this task includes laying out high-speed lines for the USB 2-HS signal pair, the analog audio lines, communications, and peripheral circuits for the XMOS Audio Microcontroller, etc. Andrew and Jess will support Hub design as needed.

Andrew and Matan will design the schematics and layout for the wireless Modules, excluding power and battery management. This includes microcontroller circuits and laying out the board to be generalized over several sensor types. This will allow only one PCB spin for all Module variants.

Andrew and Matan will write Module firmware, and Josh will write Hub firmware. Louisa and Matan will write the desktop companion application, which communicates with the Hub microcontroller and administers Module profiles.

7 Proposed Timeline

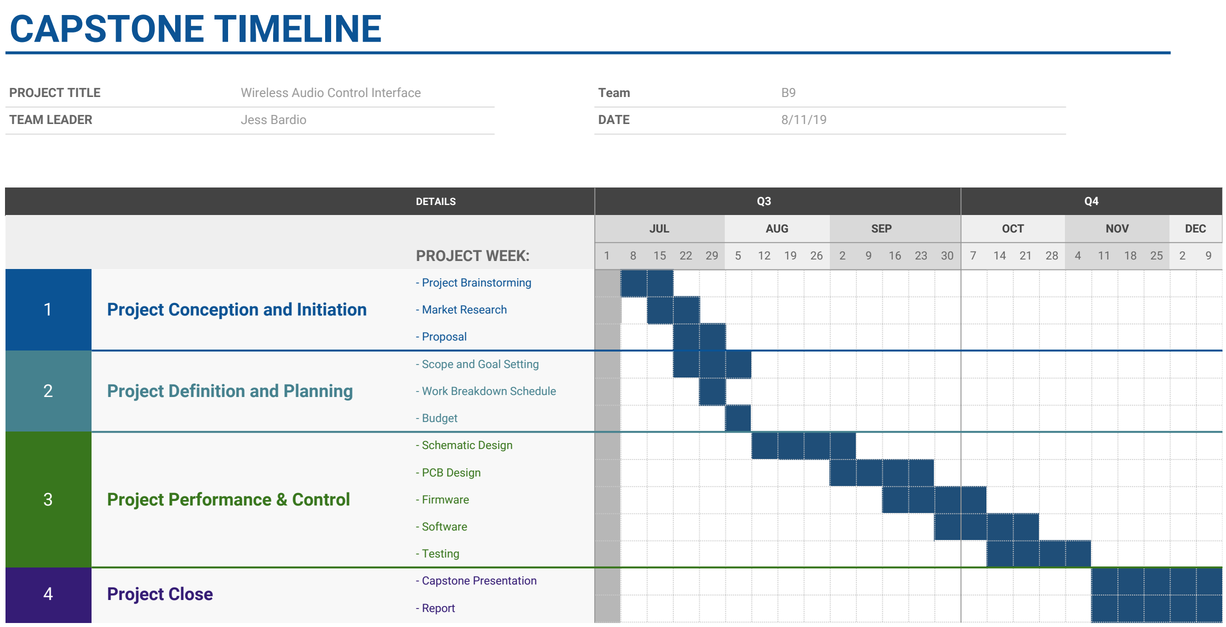

Figure 17: Estimated Development Timeline

8 Conclusion

We propose an audio processing system that allows distributed control by multiple performers. By integrating audio, MIDI, and wireless physical interfaces, WACI functions as a complete sound processing solution for small performing ensembles. Introducing wireless distributed control allows many musicians to tailor their sound without the hassle and cost of managing multiple processing systems. Hub and Module circuit boards will be designed, fabricated, programmed, and tested as part of this project; a project breakdown and cost analysis show that WACI can feasibly be completed within Capstone time and budget requirements.

DEVICE	QUANTITY/HUB	PART NUMBER	PACKAGE	MANUFACTURER	PRICE (1)	PRICE/HUB QTY 1	Price (10)	Digi-Key Part Number	RATIONALE/NOTES
Microcontroller	1	XUF216-512-TQ128-C20	TQFP128	XMOS	$16.13	$16.13	$14.66	880-1122-ND	XMOS Multicore Microcontroller, 16 Logical Cores
CODEC	1	AD1937WBSTZ	LQFP64	Analog Devices	$11.63	$11.63	$10.51	AD1937WBSTZ-ND	Provided by ADI- High SNR, I2C Controlled, 24-192 Sigma Delta Converters
Buck Regulator	2	ADP2303ARDZ	SOIC8	Analog Devices	$3.32	$6.64	$2.98	ADP2303ARDZ-ND	Provided by ADI- High efficiency, high output current, used before on projects
Linear Regulator	2	LT3088	SOT-223-3	Analog Devices	$5.38	$10.76	$5.38	LT3088IST#PBF-ND	Provided by ADI- 3.3V to 1.0V Linear Regulator
Phantom Boost Converter	1	LT8330ES6#TRMPBF	TSOT23-6	Analog Devices	$6.36	$6.36	$6.36	LTC3872ETS8#TRPBFCT-ND	Provided by ADI- Phantom Power Boost Converter
Preamp Supply	1	LTC3265EFE#PBF	TSSOP20-EP	Analog Devices	$9.21	$9.21	$9.21	LTC3265EFE#PBF-ND	Provided by ADI- Inverting Charge Pump With Dual Pos/Neg LDO
Audio Opamp	4	ADA4891-4ARZ	SOIC14	Analog Devices	$2.97	$11.88	$2.67	ADA4891-4ARZ-ND	Provided by ADI- Fast slew, high output, wide GBW opamp
Reset Generator	1	LTC2900-1CMS#PBF	MSOP8	Analog Devices	$4.49	$4.49	$4.49	LTC2900-1CMS#PBF-ND	Provided by ADI- Quad supply monitor/reset generator, adjustable timing
Health and Welfare ADC	1	LTC2309CF#PBF	TSSOP20	Analog Devices	$7.14	$7.14	$7.14	LTC2309CF#PBF-ND	Provided by ADI- 8ch ADC, SAR, multiplexed
Mic Preamp	4	SSM2019BRNZ	8SOIC	Analog Devices	$5.41	$21.64	$4.86	SSM2019BRNZ-ND	Provided by ADI- single resistor set preamp
Headphone Driver	1	SSM6322ACPZ-R7	LFCSP24	Analog Devices	$5.51	$5.51	$4.95	SSM6322ACPZ-R7CT-ND	Provided by ADI- stereo HP amp
Wireless Card	1	ESP32-WROOM-32D	38-SMD	Espressif	$3.80	$3.80	$3.80	1965-1003-ND	ESP32; module; SMD
24.000MHz Crystal	1	KC2520K24.0000C1GE00	4-SMD	Kyocera	$1.36	$1.36	$1.30	1253-1531-1-ND	Crystal oscillator, 50ppm, low phase noise
24.576MHz Crystal	1	KC2520K24.5760C1GE00	4-SMD	Kyocera	$1.36	$1.36	$1.30	1253-1532-1-ND	Crystal oscillator, 50ppm, low phase noise
22.5792MHz Crystal	1	KC2520K22.5792C1GE00	4-SMD	Kyocera	$1.36	$1.36	$1.30	1253-1530-1-ND	Crystal oscillator, 50ppm, low phase noise
Logic Buffer Push-Pull	5	74LVC1G125GW,125	TSSOP5	Nexperia	$0.25	$1.25	$0.21	1727-3488-1-ND	Single-element buffer
Logic Mux Push-Pull	2	NC7SZ157P6X	TSSOP6	ON Semi	$0.44	$0.88	$0.32	NC7SZ157P6XCT-ND	Used as clock mux, 3.3V supply
ESD Protection TVS	2	TPD2E2U06QDBZRQ1	SOT23-3	Texas Instruments	$0.63	$1.26	$0.54	296-40695-1-ND	Used to prevent transient voltages from killing the XMOS chip

Figure 18: IC Cost Breakdown for Hub

MODULE ICs

DEVICE	QUANTITY/MODULE	PART NUMBER	PACKAGE	MANUFACTURER	PRICE (1)	Price (10)	PRICE/MODULE (QTY 10)	Digi-Key Part Number	RATIONALE/NOTES
Analog Mux	1	ADG728BRUZ-ND	TSSOP16	Analog Devices	$5.59	$5.02	$5.02	ADG728BRUZ-ND	Provided by ADI- sensor mux for Modules
Battery Charge IC	1	LTC4053EMSE-4.2	MSOP10	Analog Devices	$4.62	$3.06	$3.06	LTC4053EMSE-4.2#PBF-ND	Provided by ADI- battery charger IC
Reset Generator	1	ADM6713ZAKSZ-REEL7	SC70-4	Analog Devices	$0.93	$0.83	$0.83	ADM6713ZAKSZ-REEL7CT-ND	Provided by ADI- reset generator for wireless module
Buck Regulator	1	ADP2302ARDZ	SOIC8	Analog Devices	$2.88	$2.59	$2.59	ADP2303ARDZ-ND	Provided by ADI- High efficiency, high output current, used before on projects
Buck-Boost Converter	1	LTC3440EMS#PBF	MSOP10	Analog Devices	$6.63	$6.63	$6.63	LTC3440EMS#PBF-ND	Micropower, high-efficiency buck-boost converter
Wireless Card	1	ESP32-WROOM-32D	38-SMD	Espressif	$3.80	$3.80	$3.80	1965-1003-ND	ESP32; module; SMD
Analog to Digital Converter	1	MAX11645EUA+	MSOP8	Maxim	$1.91	$1.72	$1.72	MAX11645EUA+-ND	ADC; 12 bit; relatively good specs; low cost
Power Mux	1	TPS2113PW	TSSOP8	Texas Instruments	$2.80	$2.52	$2.52	296-14205-5-ND	Auto-switching power mux
Dual Buffer Open Drain	1	NC7WZ07P6X	TSSOP6	ON Semi	$0.37	$0.28	$0.28	NC7WZ07P6XCT-ND	Dual buffer for battery charging logic
Logic Inverter	1	NC7WZ14P6X	VSOP8	ON Semi	$0.39	$0.29	$0.29	NC7WZ14P6XCT-ND	Dual inverter for battery charging logic
Dual AND Gate	1	NC7WZ08K8X	VSOP8	ON Semi	$0.46	$0.37	$0.37	NC7WZ08K8XCT-ND	Dual AND gate for battery charging logic
Dual OR Gate	1	NC7WZ32K8X	VSOP8	ON Semi	$0.46	$0.37	$0.37	NC7WZ32K8XCT-ND	Dual OR gate for battery charging logic
USB Comms IC	1	FT231XS-R	SSOP20	FTDI	$2.12	$2.12	$2.12	768-1129-1-ND	USB to UART, battery charge port detect, status outputs, handshake
ESD Protection TVS	2	TPD2E2U06QDBZRQ1	SOT-23-3	Texas Instruments	$0.63	$1.36	$0.54	296-40695-1-ND	Used to prevent transient voltages from killing the FTDI chip

Figure 19: IC Cost Breakdown for Modules

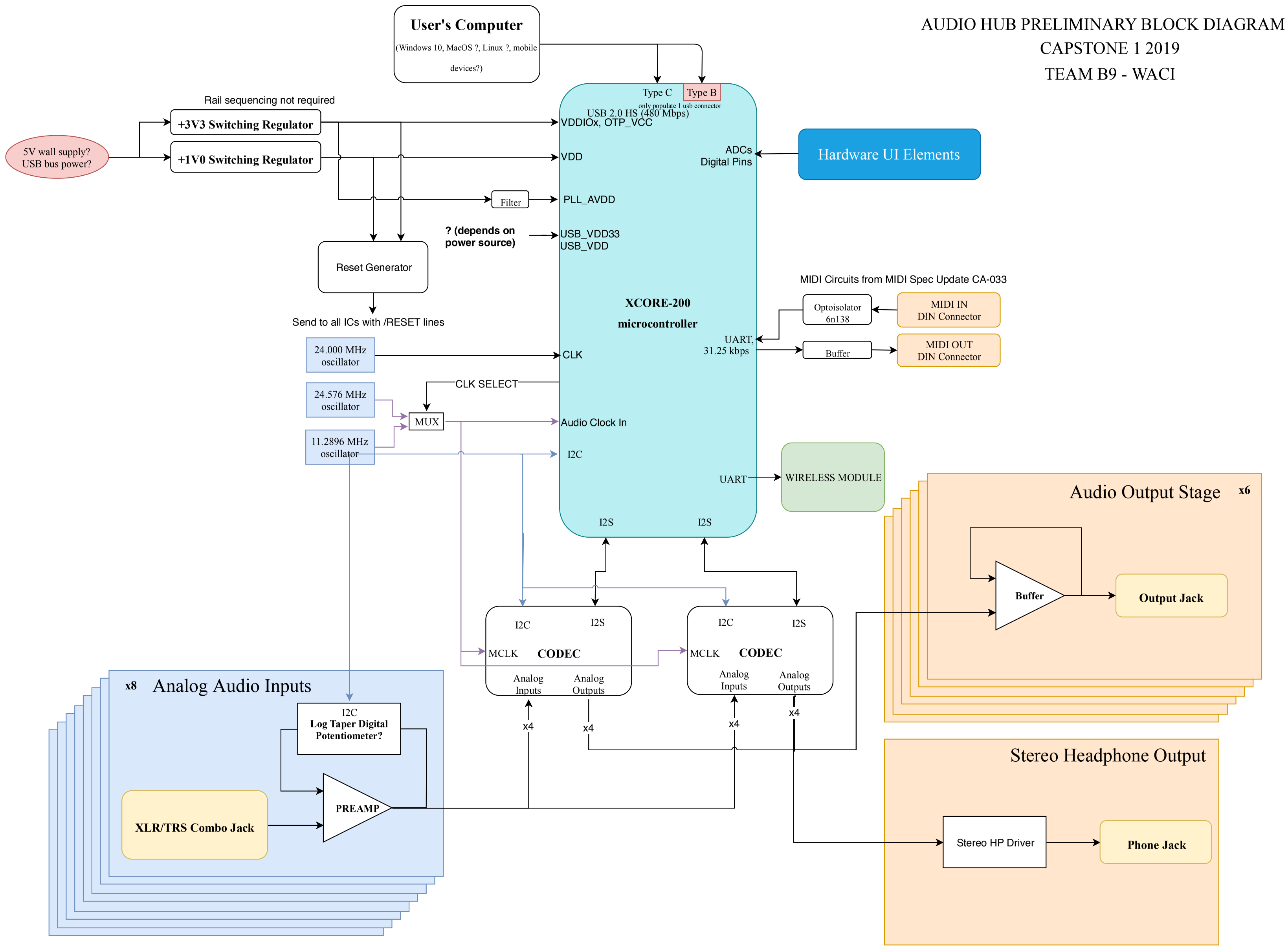

Figure 20: Detailed Block Diagram of Hub Circuit