POLYMAP: A 64-CHANNEL POLYPHONIC GUITAR PICKUP SYSTEM

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ABSTRACT

In electric guitars, the vibrations of the strings are typically sensed by coils of wire combined with a magnet, called *pickups*. The pickups and their position along the strings contribute strongly to the instrument's sound. Most guitars feature one to three pickups, each spanning across all strings with fixed positions and generating a single mono output. The work of this Master's Thesis at ETH Zürich introduces a new pickup system called *PolyMap*, which senses each string individually and at multiple locations. The system is demonstrated with a custom-made eight-string guitar that contains eight pickups per string for a total of 64 pickups. The signals from these 64 pickups are individually digitized inside the guitar and transmitted over a multichannel audio digital interface (MADI), a low-latency digital audio interface, to a computer for further processing. PolyMap enables high-resolution sensing of an electric guitar's strings and enables extensive post-processing capabilities for musicians, audio engineers, and researchers. To the best of our knowledge, this is the first polyphonic guitar pickup system with such a complete feature set.

1. INTRODUCTION

What sets electric guitars apart from their acoustic counterpart is the pickup system and its influence on the sound. Depending on where the pickups are placed between the bridge and the neck, and how they are blended together, a vastly different output sound can be achieved. Still, with very few exceptions, the construction of electric guitar pickups has remained fundamentally the same since their introduction. They mostly sense all strings at once, and the guitarist can choose from a few predetermined positions while playing. The resulting mono signal is then sent out as an analog signal, fixing the choice of pickup position.

Hexaphonic pickups are available from a range of companies, allowing each string to be sensed individually. However, they sense the strings only at one location and typically feature six analog outputs, which complicates integration.

This Master's Thesis at ETH Zürich introduces a novel pickup system we call PolyMap, which not only senses every string individually, but also samples the strings at eight different locations. [1] These signals are then directly digitized inside the guitar and sent out over a single digital interface. In the recording software, e.g., a digital audio workstation (DAW), all 64 pickup signals can be monitored and recorded simultaneously. To choose which pickups are active and how they blend, a custom control plug-in, called PolyMap Studio, has been designed.

PolyMap moves the decision about the pickup position from the time of performance to the editing stage. Furthermore, the polyphonic nature enables a vast array of possibilities to creatively shape the sound that are simply impossible with conventional pickup systems. For example, because the strings are sampled individually, they can be spread in the stereo spectrum for an immersive sound. It is also possible to send different strings (or arbitrary combinations thereof) to their own effects or amplifiers. Furthermore, by enabling and blending multiple pickups per string, it is possible to create new, creative sounds by delaying some pickups or inverting their phase.

Figure 1: Photo of the custom-made eight-string electric guitar with the PolyMap Pickup System.

2. POLYMAP PICKUP SYSTEM

The 64 active pickups are arranged as an 8×8 grid across the eight strings. Their analog outputs are buffered and bandwidth-limited before being digitized by eight 8-channel ADCs sampling at 48 kHz and 24 bit resolution. A field-programmable gate array (FPGA) takes the digital signals and encodes them into a multichannel audio digital interface (MADI) [1] stream, which is then sent out of the guitar over a coaxial cable. A commercial off-the-shelf (COTS) USB MADI interface converts that stream into a standard multichannel audio device on the computer. Inside the DAW, a custom plug-in provides control and mixing functionality. The signal flow of the system is illustrated in Figure 2. The electric guitar is powered via the same coaxial cable by injecting power into it, eliminating the need for a separate power cable or a battery; the latter would severely limit playtime.

[1]The design files of the PolyMap Pickup System are available open-source here: https://github.com/IIP-Group/polymap

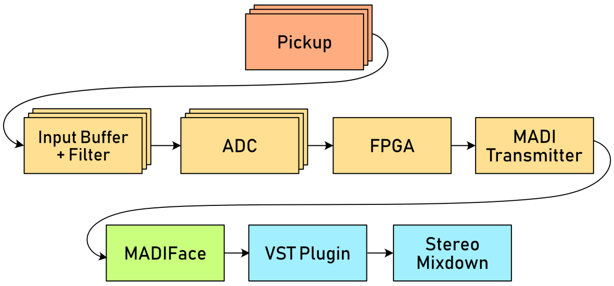

Figure 2: Signal flow of the PolyMap Pickup System.

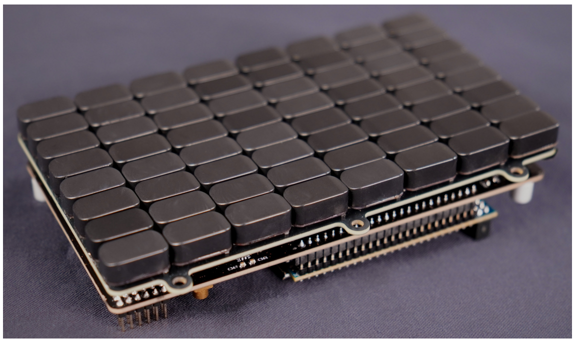

Figure 3: Assembled PolyMap Pickup System with the Pickup Array on top and the Control Board underneath.

2.1. Pickup Array

The pickups for this system need to be very small so they can be packed right next to each other for a separate pickup per string. The pickups also need to be directional so that they only pick up the string above them and not the neighboring ones. The Nu Capsules from Cycfi Research match these requirements very well, making use of very strong neodymium magnets as well as an active preamp below the pickup coil to compensate for their small size. The Nu Capsules also have a much wider bandwidth [2] compared to most traditional guitar pickups. This means that more information is recorded, which can be used to shape the desired tone using digital filters in the DAW plug-in.

2.2. Analog Frontend and ADC

For optimal performance, the signal from each pickup requires buffering, impedance matching, and bandwidth limiting before digitization. Digitization is performed by eight audio ADCs (CS5308P from Cirrus Logic) with eight channels each. Every ADC channel has a dedicated converter, and all channels per chip are sampled simultaneously, ensuring precise time alignment across pickup positions, which is essential since the plug-in may later blend signals from multiple locations along a string.

2.3. Digital Encoding on an FPGA

The FPGA is the central link that connects the individual ADCs to the MADI output and handles proper encoding. On the FPGA, we implemented custom logic on register transfer level (RTL) in System Verilog. Following the signal chain in Figure 5, the first logic block is the ADC buffer. It takes the eight serial TDM streams

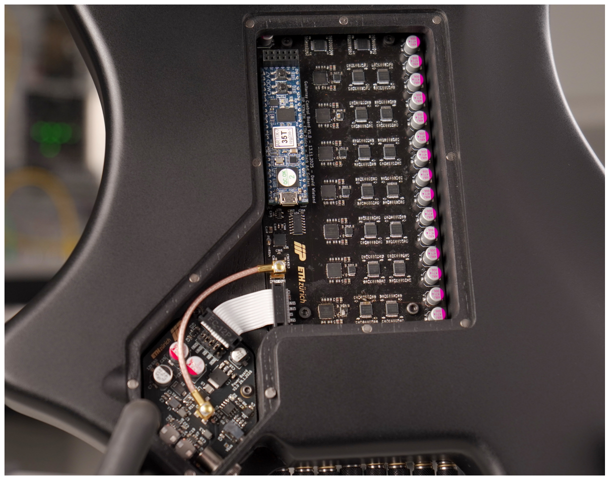

Figure 4: View of the back of the guitar, showing the control electronics (cover removed).

from the ADCs and converts them back to parallel words that are then buffered in a FIFO. The subframe assembler takes this 24-bit audio data and adds the MADI-specific status bits. This 32-bit subframe then gets converted to a 4B5B encoded 40-bit word. Because the transmission side of the logic requires a different clock, there is a clock domain crossing (CDC) FIFO to handle the transition. For the MADI receiver to correctly align with the 4B5B-encoded signal, synchronization symbols need to be inserted at a specific rate. They are unique 10-bit words that are interleaved between the 40-bit data words. The last stage is the serializer and the non-return-to-zero inverted-on-ones (NRZI) encoder. In addition to the direct signal chain, there is also a controller module that takes care of clocking as well as SPI for the MADI transmitter and the ADC reset signal.

2.4. MADI Transmisison

The PolyMap Pickup System uses AES10, better known as MADI [1, 3]. MADI is a mature professional standard capable of transporting up to 64 audio channels with 24-bit resolution at 48 kHz with a fixed 125 Mbit/s line rate. The FPGA formats the pickup data into a compliant MADI stream, which is then converted to USB externally using a commercial interface (RME MADIFace USB). Using MADI instead of native USB reduces complexity by delegating USB protocol handling to proven external hardware.

2.5. Control Software

The MADI interface exposes all 64 audio channels to the computer. While it would be possible to mix them manually in a DAW, this would significantly limit the usefulness of the PolyMap Pickup System due to the large number of individual parameters. For this reason, we developed a custom plug-in that provides a convenient interface to choose which pickups are active and apply various effects. Most DAWs do not support 64-channel tracks, which is why the current implementation of the plug-in has only been confirmed to work with Reaper, which allows for arbitrary channel counts [4].

The custom software plug-in offers two primary control paradigms. In *Manual Mode* (as seen in Figure 6), each pickup

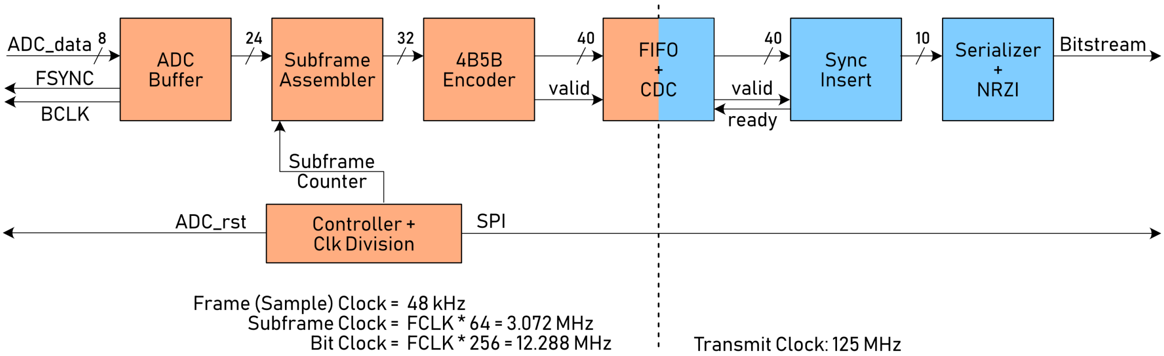

Figure 5: FPGA RTL Overview Diagram with the two clock domains shown in orange and blue.

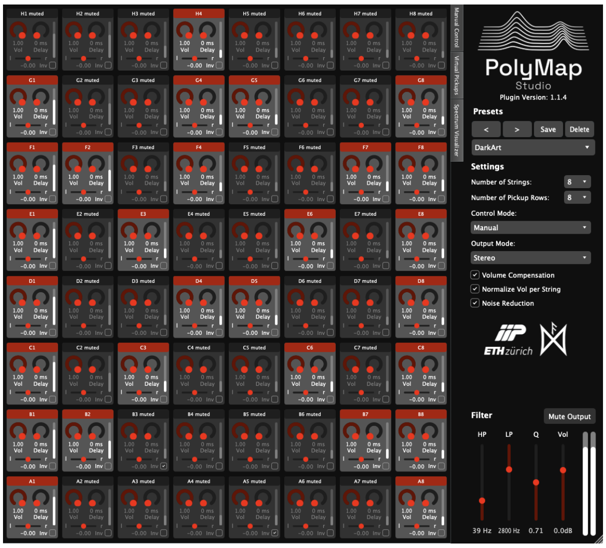

Figure 6: Manual Control Tab of the PolyMap Studio plug-in.

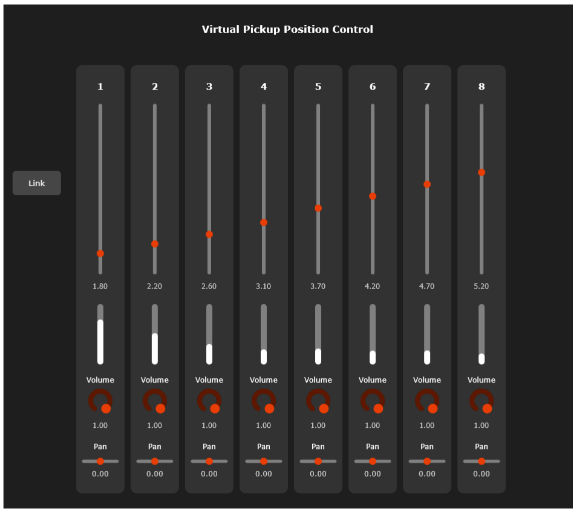

Figure 7: Virtual Pickup Control Tab of the PolyMap Studio VST plug-in.

can be enabled, level-adjusted, inverted, panned, and optionally delayed. This allows detailed spatial control and experimentation. In *Virtual Pickup Mode* (as seen in Figure 7), a continuous pickup position is selected per string. If the chosen position lies between two physical pickups, the plug-in blends them proportionally. Per string pickup position can be linked for global movement or controlled independently.

Because the Nu Capsules output a fair amount of high-frequency noise (hiss), we employ two countermeasures: (i) active noise reduction at the input and (ii) a resonant band-pass filter on the plug-in output, which is also used to shape the pickup sound. Noise reduction is implemented using a moving average filter and a noise gate, which mutes the signal whenever the input level is below -55 dBFS. Up to an input level of -32 dBFS, the filtered signal is blended with the dry signal.

Additional features of the plug-in include preset management, MIDI mapping for all parameters, and a real-time multichannel spectrum analyzer.

3. RESULTS

3.1. Latency

End-to-end latency was measured from the pickup to the headphone output of the computer. With a buffer size of 32 samples and a sample rate of 48 kHz, the total end-to-end latency is only 259 samples or 5.4 ms. The PolyMap hardware itself contributes only little delay, i.e., around five samples. The MADI interface adds another 27 samples, with the dominant factors being DAW buffer size and operating system audio buffering. As a comparison, using a Presonus Audiobox USB 96 with the same DAW buffer size, an end-to-end latency of 6.1 ms was measured.

3.2. Noise

The noise performance of the PolyMap Pickup System was evaluated by measuring the output of the pickups without any strings vibrating, showing the total noise of the system, including the pickups, the buffering circuit, and the analog-to-digital conversion.

The RMS noise lies in the range of -73 dBFS to -67 dBFS depending on the channel. The majority of the noise enters the

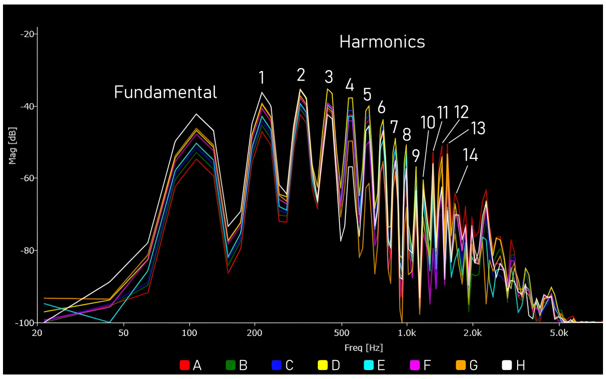

Figure 8: Spectrum of the open A string right after plucking. Pickup A (red) is closest to the bridge, and Pickup H (white) is closest to the neck.

signal directly in the pickups, which can be clearly seen when the pickups are disabled by not providing them with power, resulting in a noise floor of −90 dBFS. A significant source of noise in the pickups is power supply noise that couples into the signal.

3.3. Analysis of Different Pickup Positions

This guitar offers a unique opportunity to study the effects of pickup position on the sound in a very controlled and reproducible manner. Because the position can be changed after the fact, and all the pickups are the same, the only variable is the sound.

The first aspect standing out is that, without any compensation, the pickups further away from the bridge produce a higher output amplitude. This is to be expected, as the string amplitude there is greater. Inspecting the harmonic frequencies in Figure 8 reveals that the fundamental does not have the highest amplitude. It can also be seen clearly that the pickup closest to the neck (Pickup H) has the highest amplitude for the fundamental and first harmonic. For subsequent harmonics, the pickup with the highest amplitude moves closer to the bridge. Another interesting observation is that Pickup H has a significantly lower amplitude at the fourth harmonic, which then increases again at the fifth, likely corresponding to a standing-wave node near the pickup position. The same effect can be seen in the fifth harmonic for pickup B. This pattern matches a comb filter, which is commonly used to model guitar pickups [5].

4. APPLICATIONS

A clever technical music system is only as good as the sonic expressions it enables. We now outline what might be possible, but it is by no means an exhaustive list. [2]

4.1. Spatial Audio

An impressive effect that is simply not possible with a traditional guitar is to spread the strings in space. By panning every string slightly differently in the stereo field, the result is a sound that feels immersive. This effect is especially pronounced when playing things that move across the strings, like arpeggios.

4.2. Delay Effects

By enabling multiple pickups per string and selectively adding delay to some of them, an effect similar to reverb or a fast delay pedal can be achieved. The difference is that the timbre also changes with the delayed parts, without the need for any effects.

4.3. Split Processing

With polyphonic pickups, multiple amplifiers can be used for different strings. The possibilities with this are endless, but one example would be to send the lower strings to a bass amplifier while sending the upper strings to a guitar amplifier. Adding delay or reverb only to the higher strings but not the lower ones, or using clean versus distorted sounds, would be another idea.

4.4. Fractional Blending

Instead of enabling multiple pickups per string at full volume, adding a second one with reduced volume allows for much finer control of the resulting sound. One application of this is to invert one of the pickups, adding it 180 degrees out of phase. Blending an inverted pickup will cancel a lot of the fundamental frequency, accentuating the higher harmonics and attack that are significantly different between the two positions.

5. DEMO EXPERIENCE

Visitors of the demonstration will have the opportunity to try out the entire signal chain, from the guitar to post-processing in the DAW. The guitar can be played while listening to how different configurations in the plug-in affect the sound. Visitors can also try the software plug-in and explore the PolyMap Pickup System's interesting musical applications by working with pre-recorded audio in the DAW. The plug-in and a sample audio file are also publicly available for download [3] so that anyone interested can experiment with them at home.

6. ACKNOWLEDGMENTS

The authors would like to thank Marc Schaffo for recording the guitar demos, which can be heard in the demo video as well as in the available audio sample.

7. REFERENCES

[1] *AES Information Document for Digital Audio Engineering, AES10 (MADI)*, Audio Eng. Soc. Std. AES-10id-2020, 2020.

[2] J. Guzman, "Lo-Z: Let's clear a misconception," *Cycfi Research*, Jun. 2021. [Online]. Available: https://www.cycfi.com/2021/06/lo-z-lets-clear-a-misconception/

[3] *AES Recommended Practice for Digital Audio Engineering*, Audio Eng. Soc. Std. AES10-2020, 2020.

[4] *REAPER User Guide*, Cockos Inc., New York, NY, USA, Mar. 2026.

[5] Z. Mohamad, S. Dixon, and C. Harte, "Digitally moving an electric guitar pickup," in *Proc. 18th Int. Conf. Digital Audio Effects (DAFx)*, Nov. 2015.

[2] A recorded demo can be heard here: https://youtu.be/6SRUF4_frlk

[3] The audio file and VST plug-in are available here: https://iis-people.ee.ethz.ch/~datasets/PolyMap/