Using AudioMoth with Piezoelectric Hydrophones and Contact Microphones

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AudioMoth comes with built-in support for external electret microphones through a 3.5 mm audio socket that can be added to the standard AudioMoth device, and is already fitted to the AudioMoth Dev and AudioMoth USB Microphone boards. This application note describes how this input can be used with other signal sources, including piezoelectric hydrophones and contact microphones, and various amplifiers.

1 AudioMoth External Microphone Circuit

The AudioMoth external microphone circuit consists of a non-inverting amplifier, using a Maxim MAX4466 microphone preamplifier integrated circuit, and an electret microphone bias circuit (see Figure 1). The microphone bias current is enabled whenever the AudioMoth detects that an external microphone is plugged into the 3.5 mm socket and a recording is being made. It is disabled when the AudioMoth uses the internal MEMS microphone and when sleeping between recordings.

The 1 µF DC offset capacitor and 10 kΩ input resistor of the non-inverting amplifier form a high-pass filter with a cut-off frequency of 16 Hz. The front-end has a voltage gain of ×11 and the calculated frequency-response is shown in Figure 2.

The output of this circuit goes through two further software-controlled inverting amplifiers (whose combined voltage gain is shown in Table 1), followed by the analog-to-digital converter (ADC). The ADC uses a 2.5 V reference such that a full-scale 16-bit WAV file recording corresponds to a peak-to-peak signal of 2.5 V at the input to the ADC. This is equivalent to a peak-to-peak signal of 15 mV at the input to the front-end when using medium gain in the normal gain range.

Electret microphones are sensitive, have a wide frequency response, and typically exhibit low self-noise. However, it is sometimes necessary to connect other types of microphones; such as piezoelectric hydrophones and contact microphones.

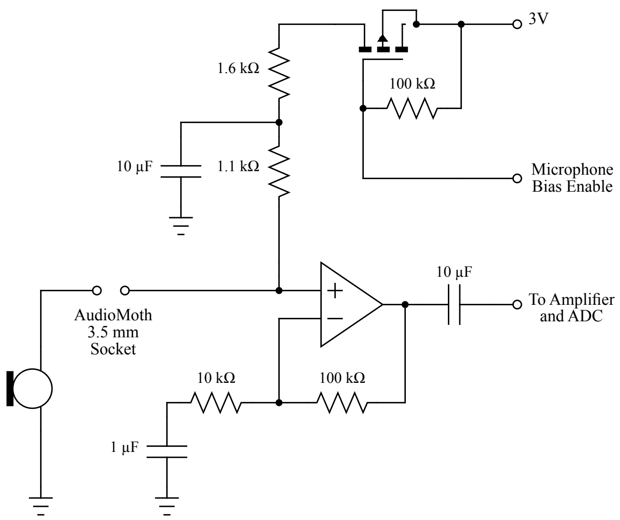

Figure 1: *AudioMoth external microphone circuit, incorporating a Maxim MAX4466 microphone preamplifier integrated circuit and software-controlled microphone bias circuit, connected to an electret microphone.*

2 Piezoelectric Hydrophones and Contact Microphones

Piezoelectric hydrophones and contact microphones are widely available and can also be connected to AudioMoth. Such devices most commonly consist of a bare piezoelectric transducer with no additional internal amplification.

2.1 Direct Connection

A bare piezoelectric transducer can be directly connected to the AudioMoth input by placing it in parallel with a 2.7 kΩ resistor to ensure that the positive input of the Maxim MAX4466 amplifier is at an appropriate DC voltage; approximately centered between ground and the 3 V supply voltage (see Figure 3).

This solution is simple, but has two drawbacks. A

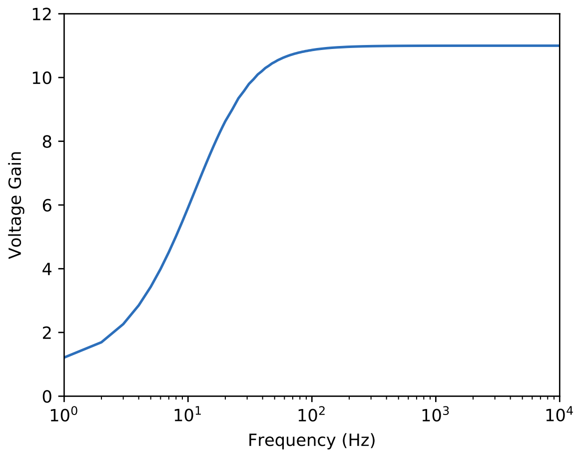

Figure 2: *Calculated voltage gain of the AudioMoth external microphone front-end against signal frequency.*

		Low Gain Range	Normal Range
0	Low	0.33	4.33
1	Low-Medium	0.55	7.00
2	Medium	1.00	15.00
3	Medium-High	1.67	25.05
4	High	2.20	33.00

Table 1: *Voltage gain applied by the software controlled gain stage, at each setting, when low gain range and normal gain range are selected.*

shock to the transducer may produce a large voltage that can damage the Maxim MAX4466 amplifier. This is theoretically possible, but seems to be rare in practice.

More significantly, the piezoelectric transducer presents its signal through a small series capacitance; typically 15nF or less. This capacitance and the 2.7 kΩ resistor combine to form a high-pass filter with a cut-off frequency of approximately 4 kHz. This removes most low-frequency sounds. This may be acceptable in some applications, while in others it will not.

2.2 High-Impedance Buffer Amplifiers

An alternative to direct connection is to use a high-impedance buffer amplifier between the AudioMoth and the piezoelectric transducer. A commercially available version that works well with AudioMoth is the Aquarian Audio PA1 buffer amplifier (`https://www.aquarianaudio.com/pa1.html`). These amplifiers typically consist of a junction field-effect transistor (JFET) and a small number of passive components. They provide a small amount of gain and prevent the loss of low-frequency sounds described above.

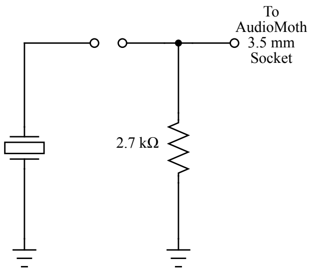

Figure 3: *Circuit to connect a bare piezoelectric transducer to AudioMoth incorporating a 2.7 kΩ resistor to ensure the correct DC voltage at the positive input of the Maxim MAX4466 amplifier.*

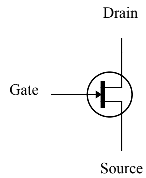

Figure 4: *Circuit symbol for a n-channel junction field-effect transistor (JFET).*

2.3 A Custom JFET Amplifier

In some applications, it is desirable to use a custom junction field-effect transistor (JFET) amplifier. This allows the amplifier to be placed very close to the piezo transducer. For example, see the custom piezoelectric sensor shown in Figure 16 where the amplifer is inside the sensor housing.

2.3.1 Principle of Operation

A JFET is a three-terminal semiconductor device in which the current flowing between two of the terminals, the drain and the source, is controlled by the voltage applied to the third terminal; the gate (see Figure 4). The gate has high impedance, which is key to avoiding the loss of low-frequency sounds described above.

The behaviour of a typical n-channel JFET, such as the Toshiba 2SK209 that we use here, is defined by two parameters: the drain-to-source saturation current, I_{DSS}, which is the maximum drain-to-source current that flows through the JFET when the gate-to-source voltage is zero, and the gate-to-source cut-off voltage, $V_{GS\ (OFF)}$, which is gate-to-source voltage necessary to reduce the drain-to-source current to zero.

These two parameters vary significantly between different devices of the same type due to manufacturing process variations. However, the relationship between the two parameters is well defined and fixed (see Figure 5 taken from the device datasheet[1]). Individual

[1] `https://toshiba.semicon-storage.com/info/2SK209_datasheet_en_20140301.pdf?did=19662&prodName=2SK209`

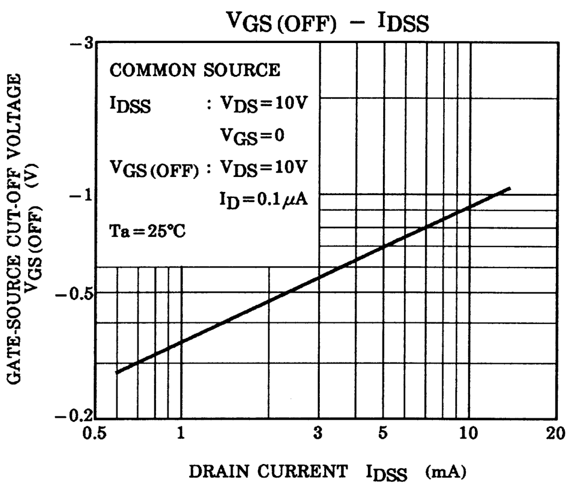

Figure 5: *Relationship between the drain-to-source saturation current, I_{DSS}, and a corresponding gate-to-source cut-off voltage, $V_{GS\ (OFF)}$, for the Toshiba 2SK209 n-channel JFET.*

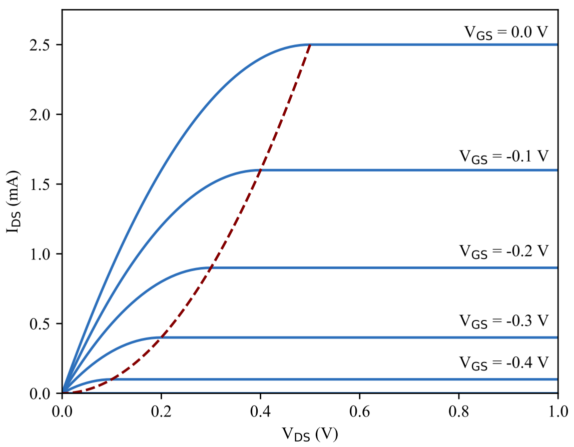

Figure 6: *Calculated relationship between drain-to-source current, I_{DS}, and drain-to-source voltage, V_{DS}, for a Toshiba 2SK209-Y n-channel JFET with drain-to-source saturation current, I_{DSS}, of 2.5 mA, and gate-to-source cut-off voltage, $V_{GS\ (OFF)}$, of -0.5 V.*

components are sorted into batches at manufacture, and here we use the Toshiba 2SK209-Y whose I_{DSS} is in the range of 1.2 to 3.0 mA.

Figure 6 shows the calculated relationship between the drain-to-source current, I_{DS}, and drain-to-source voltage, V_{DS}, for a typical Toshiba 2SK209-Y n-channel JFET with drain-to-source saturation current, I_{DSS}, of 2.5 mA, and a corresponding gate-to-source cut-off voltage, $V_{GS\ (OFF)}$ of -0.5 V. The plot shows the saturation region (to the right of the dark red dashed line) where a constant drain-to-source current flows, independent of the drain-to-source voltage.

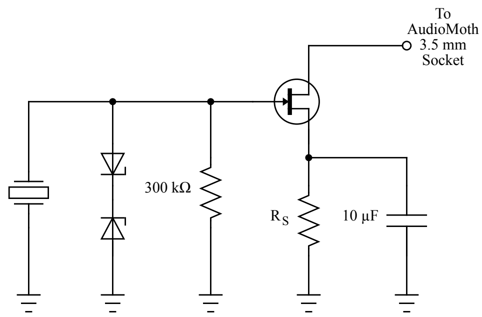

Figure 7: *Common source JFET buffer amplifier circuit.*

These components are unusual in that in normal use the gate-to-source junction is reverse-biased such that the gate is at a lower voltage than the source. As the gate-to-source voltage becomes more negative, the drain-to-source saturation current decreases, reaching zero at the gate-to-source cut-off voltage.

2.3.2 Biasing

Figure 7 shows the circuit diagram of the common source JFET buffer amplifier that we use here. The two Zenner diodes have a breakdown voltage of 5.1 V and protect the JFET against voltage spikes from the piezoelectric transducer. The signal from the piezoelectric transducer is applied to the gate of the JFET where it modulates the microphone bias current from the AudioMoth, generating an amplified voltage signal at the AudioMoth input.

The quiescent gate-to-source voltage is controlled by the value of the source resistor, R_S. Its value must be chosen to ensure that the JFET operates in its saturation region despite the variations between devices.

Figure 8 shows the calculated gate-to-source voltage, V_{GS}, the drain-to-source current, I_{DS}, and the overall gain of the amplifier, as the value of the source resistor, R_S, is varied. The left-hand plots correspond to a device with drain-to-source saturation current, I_{DSS}, of 1.2 mA, and gate-to-source cut-off voltage, $V_{GS\ (OFF)}$, of -0.37 V. The right-hand plots correspond to a device with drain-to-source saturation current, I_{DSS}, of 3.0 mA, and gate-to-source cut-off voltage, $V_{GS\ (OFF)}$, of -0.55 V. These two sets of values represent the extremes of the Toshiba 2SK209-Y range.

Note that the amplifier gain drops rapidly when the source resistor, R_S, is too small to maintain the JFET in its saturation region. This point varies from device to device. We use a value of 360 Ω for R_S to give a reasonable gain on all devices. If more consistent performance is required between devices, the drain-to-source saturation current, I_{DSS}, of individual devices can be measured. Note that the source capacitor is not critical to the circuit. It can be removed with some loss of gain. The resulting printed circuit boards, with 3.5

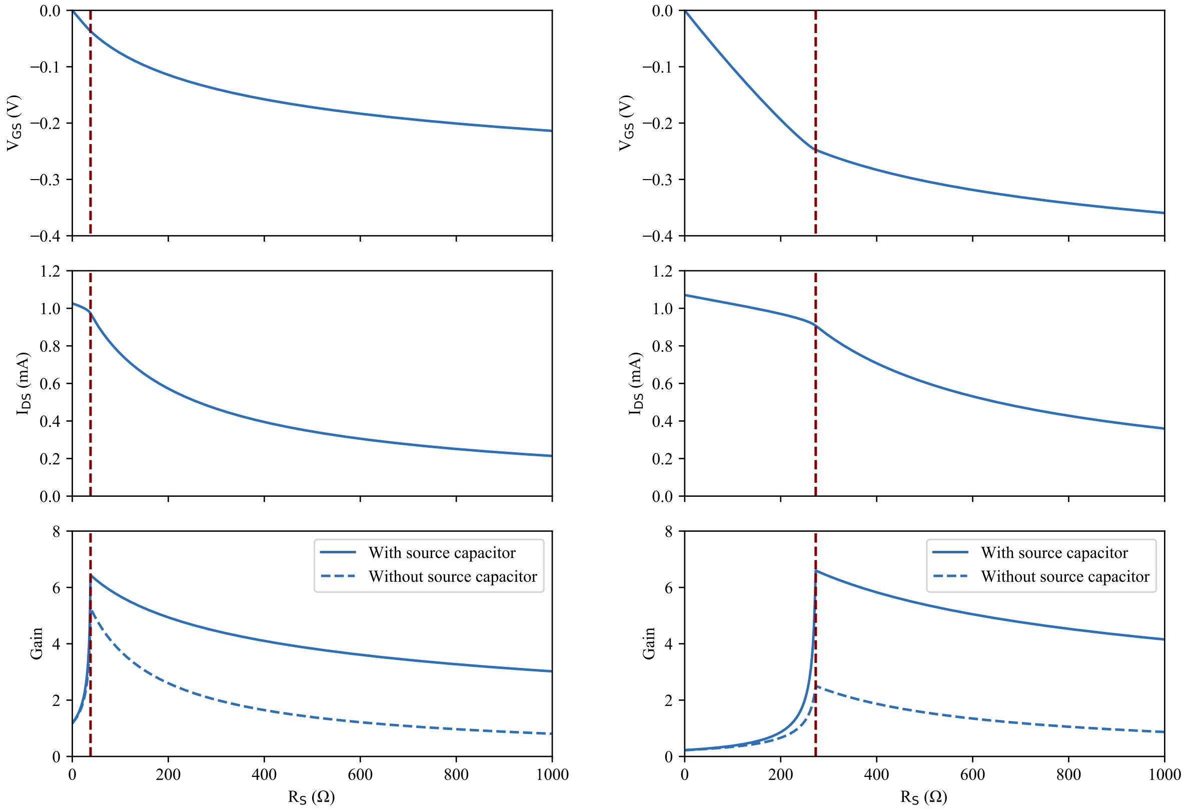

Figure 8: *Plot showing the gate-to-source voltage, V_{GS}, the drain-to-source current, I_{DS}, and the overall gain of the amplifier as R_S is varied. Left-hand plots correspond to a device with I_{DSS} of 1.2 mA, and $V_{GS\ (OFF)}$ of -0.37 V. Right-hand plots correspond to a device with I_{DSS} of 3.0 mA, $V_{GS\ (OFF)}$ of -0.55 V. The right of the red dashed line represents the saturation region.*

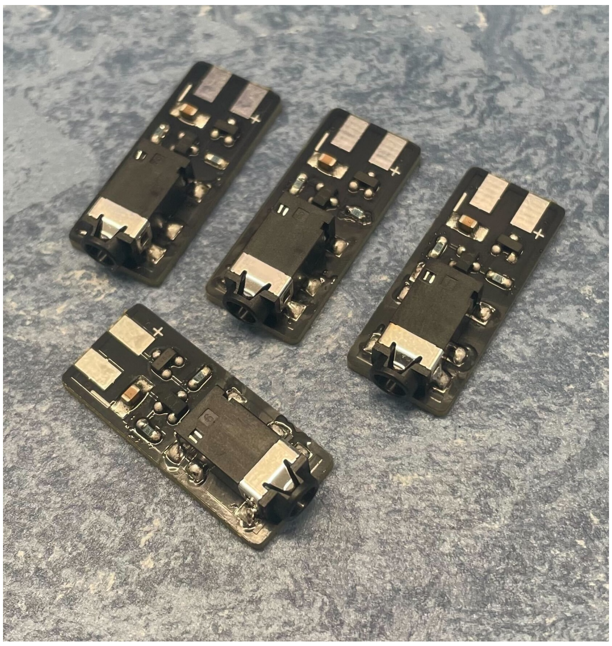

Figure 9: *Custom JFET amplifiers built on printed circuit boards with a 3.5 mm sockets.*

mm sockets to allow connection to AudioMoth with a male-to-male 3.5 mm audio cable, are shown in Figure 9. These small amplifiers can be mounted alongside the piezoelectric transducer (see Figure 16).

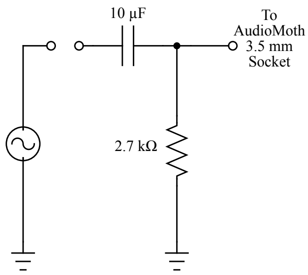

Figure 10: *Circuit to connect a hydrophone amplifier (or any other signal source) to AudioMoth.*

2.4 Other Hydrophone Amplifiers

Sensitive oceanographic hydrophones are often available with purpose-built amplifiers that exhibit more consistent gain between devices than the JFET buffer amplifier described above. These amplifiers can be connected to AudioMoth by placing them in series with a 10 µF coupling capacitor, to remove any existing DC offset, and in parallel with a 2.7 kΩ resistor to ensure that the correct DC offset is applied to the positive input of the Maxim MAX4466 amplifier (see Figure 10). Some amplifier outputs will already incorporate a coupling capacitor in their output and will only require the 2.7 kΩ resistor.

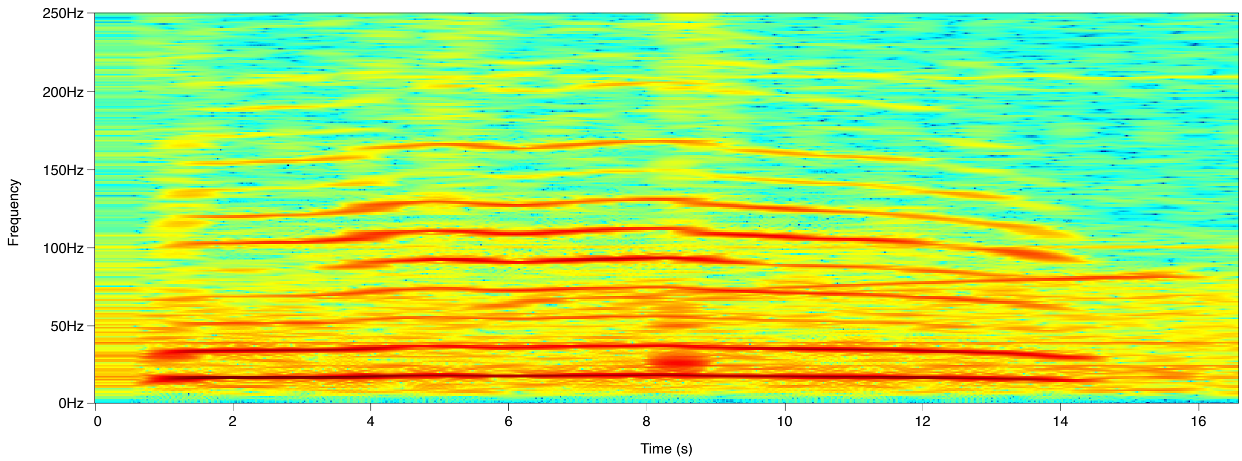

Figure 11: *Example recording of an elephant rumble using the low-frequency amplifier and a Primo EM419N electret microphone.*

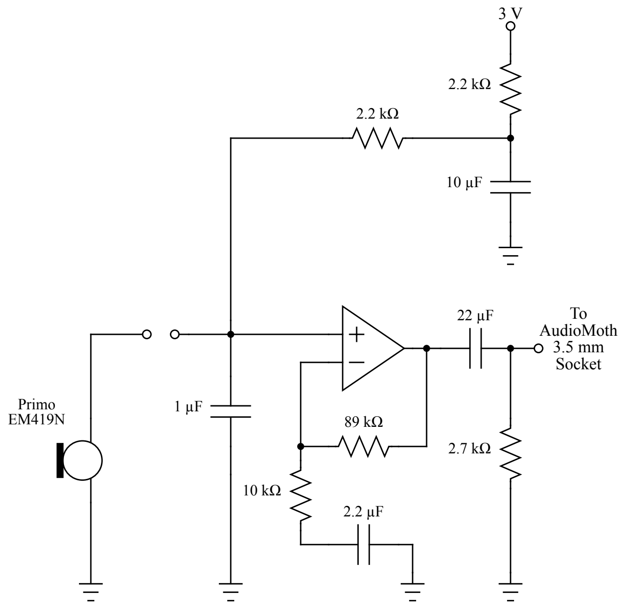

Figure 12: *Low-frequency amplifier circuit.*

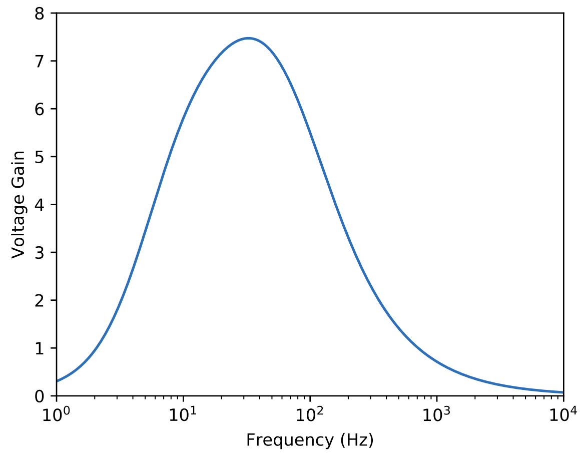

Figure 13: *Calculated frequency response of the low-frequency amplifier circuit.*

3 Other Amplifiers and Signal Sources

The use of a coupling capacitor to remove any existing DC offset on the output of an existing amplifer, and the parallel resistor to ensure the correct DC offset is applied to the AudioMoth input, allows a wide range of other amplifiers and signal sources to be used with AudioMoth. Here we describe two custom amplifiers: one to boost low-frequency signals and one to allow the connection of geophones. Both amplifiers were developed as part of a projected funded by a WILDLABS Awards 2024 to explore technologies to improve the detection and monitoring of forest elephants.

3.1 Low-Frequency Amplifier

In some applications, it is desirable to improve the low-frequency sensitivity of AudioMoth to better record sounds such as infrasonic elephant rumbles. The circuit shown in Figure 15 uses the Maxim MAX4466 to provide a low-frequency amplifier for a Primo EM419N electret microphone. The 1 uF capacitor in parallel with the microphone creates a low-pass filter that suppresses high-frequency sounds. The amplifier sits between the microphone and the AudioMoth and provides additional gain at low frequency (see Figure 13).

Figure 11 shows the rumble of a elephant at a wildlife park in the UK recorded during tests in the summer of 2024. Note the very low fundamental frequency of less than 20 Hz and the multiple harmonics. The drop-off in sensitivity below 10 Hz is also clearly visible.

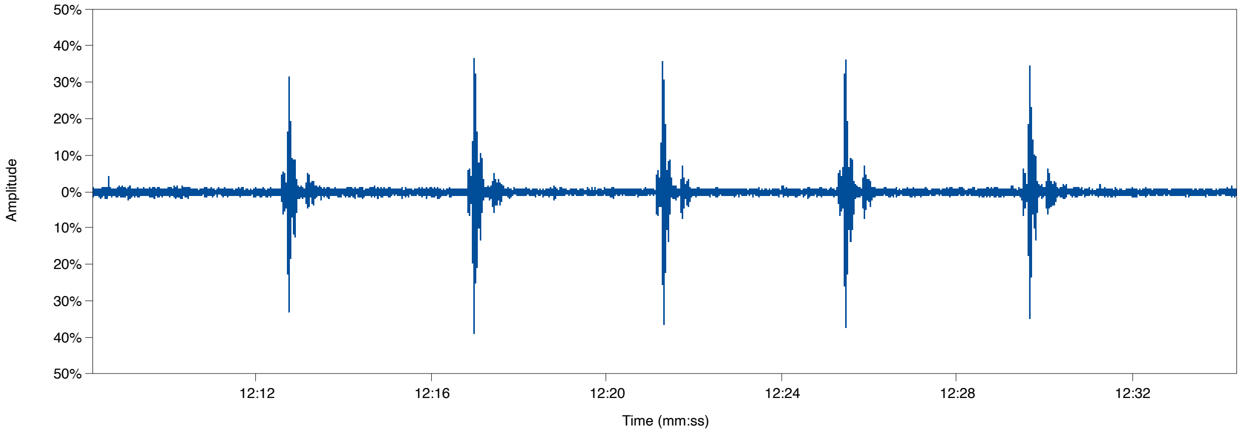

Figure 14: *Example geophone recording of a bowling ball dropped five times from a height of 2 m when 50 m from the geophone.*

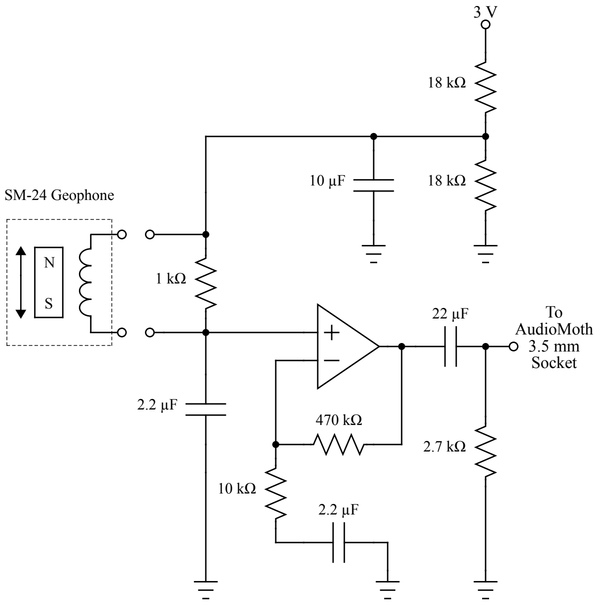

Figure 15: *Geophone amplifier circuit.*

Figure 16: *Custom piezoelectric sensor containing a 50 mm piezoelectric transducer and a custom JFET buffer amplifier (left) and a SM-24 geophone in a commercial housing with a soil spike (right).*

3.2 Geophone Amplifier

A similar circuit can be used to connect other signal sources such as geophones (see Figure 16). Here we use a common SM-24 geophone that incorporates a permanent magnet moving inside a coil. Placing a 1 kΩ resistor in parallel with the output of the geophone generates a small voltage signal which is then amplified using the same Maxim MAX4466 amplifier as used in the low-frequency amplifier. A 2.2 uF capacitor placed in parallel with the signal is used to suppress high-frequency signals (see Figure 15). The circuit has the same gain profile as that of the low-frequency amplifier shown in Figure 13 but with a higher peak gain of 34.

Figure 14 shows an example geophone recording created by dropping a bowling ball from a height of 2 m five times at a distance of 50 m from the geophone. The initial impulse, and the bounce of the bowling ball, are very strong signals.

3.3 Powering External Amplifiers

Both of the amplifiers described above use a regulated 3 V supply for the Maxim MAX446 integrated circuit and to generate an appropriate DC offset on the positive input of the amplifier. It is possible to automatically switch this supply on and off by detecting the AudioMoth microphone bias current. This current is

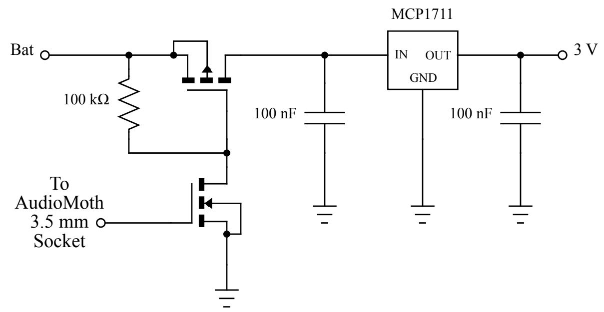

Figure 17: *Circuit to provide a regulated 3 V supply to external amplifiers when AudioMoth is recording.*

enabled under firmware control when an external microphone is plugged into the 3.5 mm jack and when the AudioMoth is making a recording. When enabled, the voltage at the AudioMoth input across the 2.7 kΩ resistor, goes from 0 V to approximately 1.5 V. This voltage will switch a MOSFET with a sufficiently low gate threshold voltage.

Figure 17 shows an n-channel and a p-channel MOSFET (in this case a Onsemi FDC6420C dual MOSFET integrated circuit) used to sense the presence of the AudioMoth microphone bias current. The circuit connects the battery to the voltage regulator when the microphone bias voltage is detected. The same dual MOSFET circuit can be used to switch the battery supply for an external hydrophone amplifier. The battery voltage being switched is isolated from the AudioMoth input by the high impedance of the MOSFET gate.

4 Discussion

Despite being designed for electret microphones, the AudioMoth 3.5 mm socket can support a wide range of other amplifiers and signal sources with appropriate interfacing. In this application note, we have described a custom JFET amplifier, a low-frequency amplifier for electret microphones, and a geophone amplifier. The same approach can be used to interface any sensor that generates an analog voltage output.