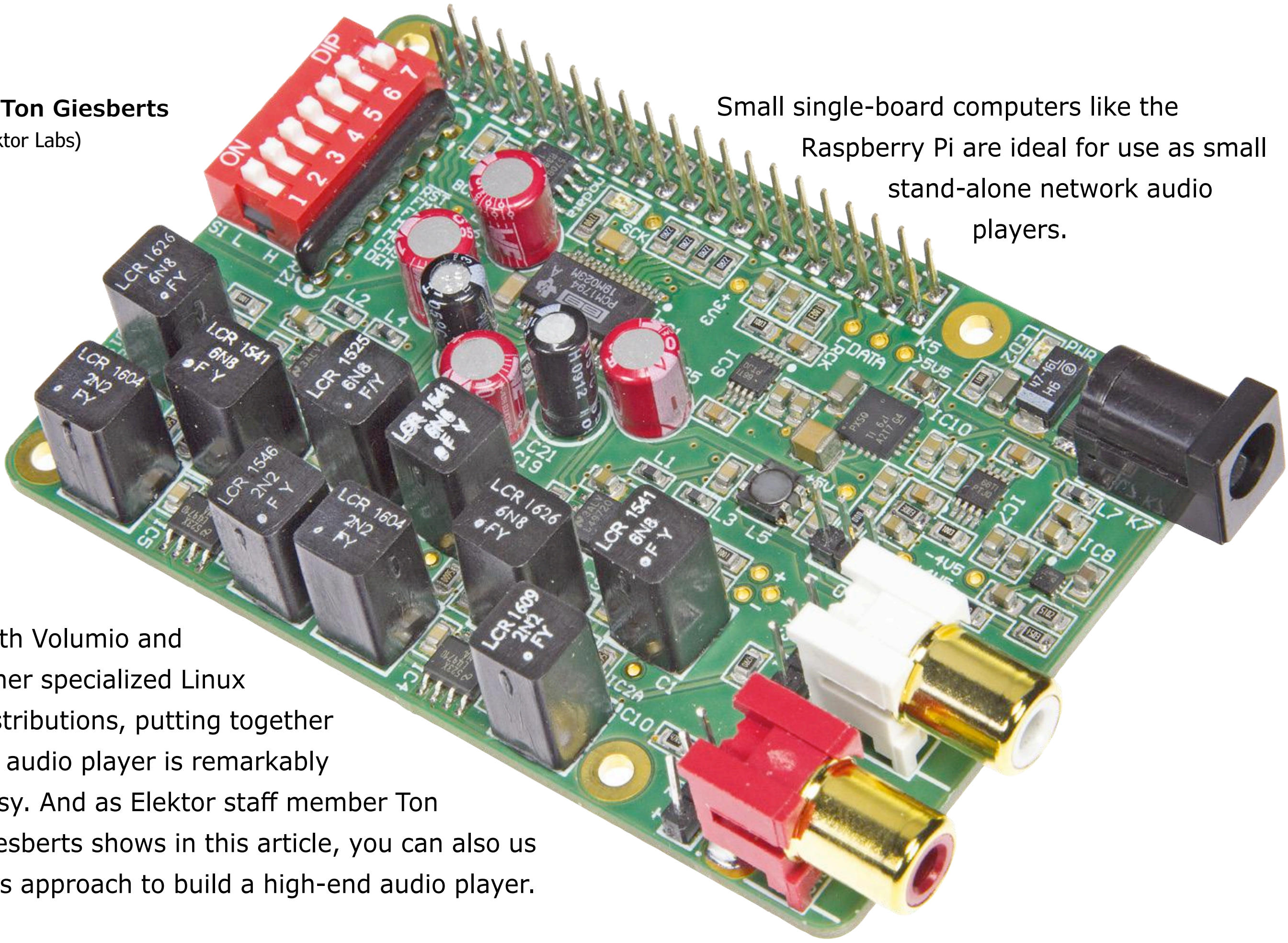
Audio DAC for Raspberry Pi

A network audio player with Volumio

By Ton Giesberts
(Elektor Labs)

Small single-board computers like the Raspberry Pi are ideal for use as small stand-alone network audio players.



With Volumio and other specialized Linux distributions, putting together an audio player is remarkably easy. And as Elektor staff member Ton Giesberts shows in this article, you can also us this approach to build a high-end audio player.

If you are looking for a small stand-alone network audio player, preferably with a touchscreen user interface, you don't have a lot of options. Usually you end up with a largish amplifier from one of the big brand names, with a corresponding price tag. And most of them do not have a touchscreen. If what you want is something compact and portable, these devices do not fit the profile.

That means your only real option is to make your own. Apps based on the Raspberry Pi are a good starting point, and DACs with fairly good specs are now available for the RPi platform. However, at Elektor we are not satisfied with "fairly good" – if we are going to develop a project for this, we might as well design a good high-end DAC for the RPi using components with top-notch specs.

The project at a glance

Digital to analog converter (DAC) ICs from Burr Brown (now part of Texas Instruments) have always been (and still are) about the best you can buy, and we have used them previously in various high-end DAC projects. For this project we opted for one of the top of the line devices from Burr Brown: the PCM1794A. This is a 24-bit DAC which can handle sampling rates up to 200 kHz and has an integrated 8× oversampling filter. This IC comes in a 28-pin SSOP package, and it has outstanding specs in all respects, including a dynamic range of 127 dB (2 V_{RMS}, stereo) to 132 dB (9 V_{RMS}, mono), a THD of 0.0004%, and differential current outputs (7.8 mA_{pp}). The PCM1794A accepts all known data formats: standard, left justified, and I^2S (which is important for our project). The digital portion of the IC operates at 3.3 V, but the digital inputs are also compatible with 5 V signals. For a complete overview of the specifications, see the device data sheet [1].

In order to convert the differential current outputs into single-ended voltages, we need a current to voltage converter for each channel, followed by a combined

filter and gain stage that converts the differential voltage output into a single-ended voltage output.
Based on this knowledge, we can draw the block diagram shown in **Figure 1**. From that we can derive the following shopping list: on the hardware side a Raspberry Pi 3 (version 2 is also usable) and the previously mentioned audio DAC, along with a Waveshare 3.5" touchscreen display for the Raspberry Pi to provide the user interface, and on the software side Raspbian for the RPi, Volumio or something similar (such as Mood Player), and the driver for the Waveshare display.

Power supply considerations

The digital to analog converter IC1 (see the detailed schematic diagram in **Figure 2**) needs two different supply voltages: +3.3 V for the digital portion and +5 V for the analog portion. In theory we could use the supply voltages available on the GPIO expansion connector of the Raspberry Pi board, but they are so noisy that there would be nothing left of our high-end aspirations. That means we have to provide an independent source of +3.3 V and +5 V. Of course, it would also be possible to power the Raspberry Pi from the DAC board, but that would have the same detrimental effect on the ultimate signal quality. A drawback of this totally separated approach is that we will need two AC adapters to power the overall device. To avoid the need for yet a third AC adapter to provide the negative supply voltage for the current to voltage converters and analog output filters, we use an on-board inverting voltage regulator to derive it from the +5 V rail.
If you take a closer look at the circuit diagram, you can see that the analog supply voltage is actually +5.2 V instead of +5 V. We intentionally chose this somewhat higher voltage, which is still within the safe range for the DAC IC, to ensure a maximum undistorted signal level of 1 V from the output filter. You often see an output voltage of 2 V, but for that you have to use rail-to-rail opamps or a higher supply voltage, and most rail-to-rail opamps cannot match the outstanding specifications of special high-end audio opamps.
We chose a TPS7A4700 ultra low-noise, low-dropout voltage regulator to provide the +5.2 V main supply voltage. It can supply a maximum current of 1 A with a voltage drop of just 307 mV. The output voltage can be set by grounding specific pins which are connected to internal resistors. Each pin has an associated voltage, and the output voltage is equal to the sum of the voltages of the individual pins. The minimum output voltage is the same as the reference voltage of 1.4 V. To obtain an output voltage of +5.2 V, we tie pins 6, 10 and 11 to ground, so the output voltage is given by the formula:

$$V_{out} = 1.4V + 3.2V + 0.4V + 0.2V = 5.2V$$

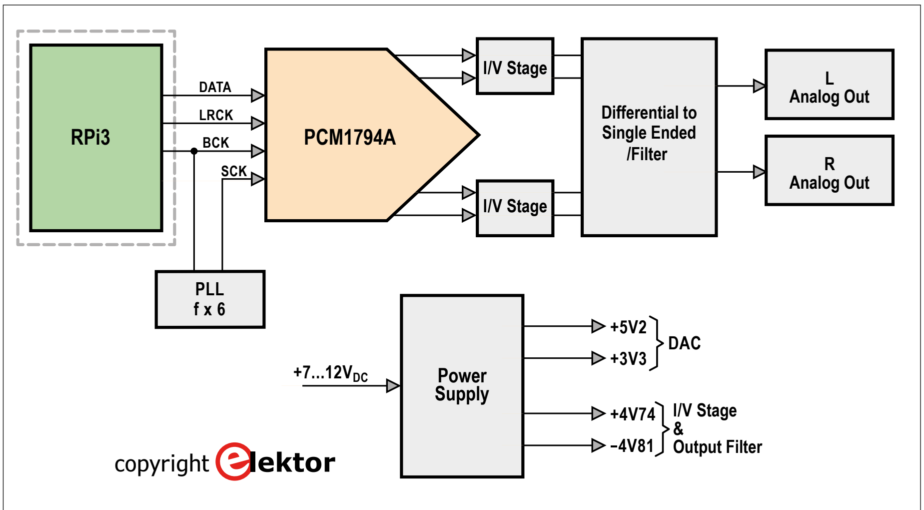


Figure 1. Block diagram of the audio DAC.

Other voltages

The positive supply voltage for the analog output portion is set to +4.74 V, which is derived from the +5.2 V supply voltage by a TPS7A4901 ultra low-noise linear voltage regulator (IC7). The exact value of the output voltage is set by the voltage divider R28/R29:

$$V_{out} = \left(\frac{R28}{R29} + 1\right) \times 1.185V$$

For the +3.3 V supply voltage we use the same type of linear voltage regulator (IC9), with the output voltage set by the voltage divider R32/R33.
The negative supply voltage is provided by an LM27761 low-noise inverting voltage regulator (IC8). It uses switched capacitors to invert the input voltage, followed by a low-noise linear regulator which generates a stable output voltage from the inverted input voltage. This output voltage is set to −4.81 V by the voltage divider R30/R31:

$$V_{out} = -\left(\frac{R30}{R31} + 1\right) \times 1.22V$$

We intentionally chose these "odd" voltages for the output portion (instead of the more common ±4.5 V) to ensure an undistorted maximum output signal level of 1 V (0 dB).
The power connector (K7) is protected against reverse polarity by the Schottky diode D1. The voltage drop over this diode is just 0.3 V. The current

PROJECT INFORMATION

audio
network player
DAC
Raspberry Pi
touchscreen

entry level
➡ intermediate level
expert level

5 hours approx.

Raspberry Pi 2 or 3, computer with Putty (Windows) or Linux, two AC adapters

€110 / £95 / $120 approx.

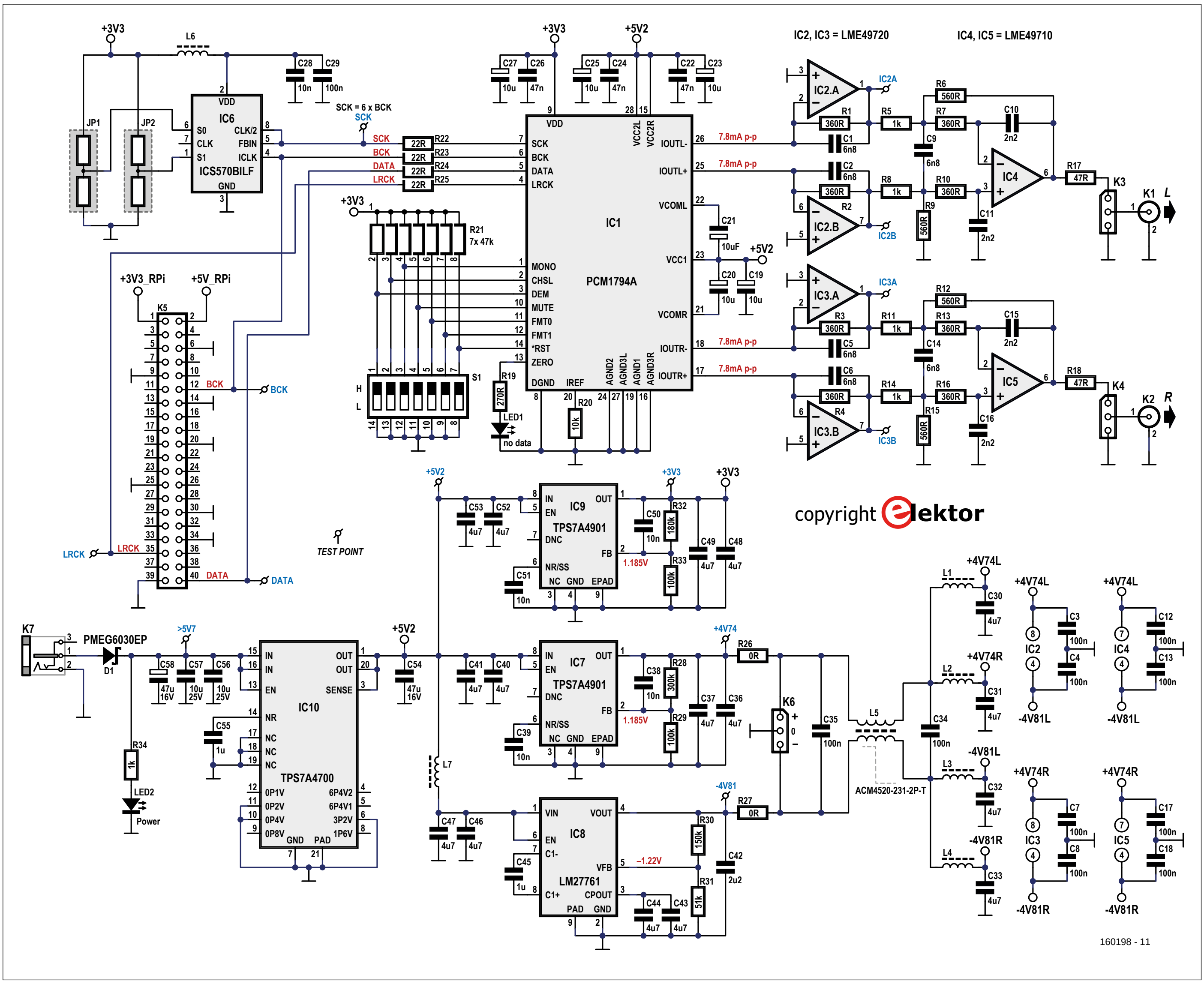


Figure 2. Detailed schematic diagram of the high-end DAC for the Raspberry Pi.

consumption of the audio DAC is listed in **Table 2**.

Master clock

In order to utilize the audio DAC, the operating system of the Raspberry Pi (Raspbian) has to be configured for a HiFiBerry DAC. Once that is done, the Inter-IC Sound (I²S) signals are available on the GPIO expansion connector. The official names of these signals are Continuous Serial Clock (SCK) or Bit Clock (BCLK/BCK), Word Select (WS) or Left/Right Clock (LRCLK/LRCK), and Serial Data (SD/SDATA).

For proper synchronization we also need a master clock, but that is not included in the original I²S specification. This signal is therefore not available on the expansion connector, so the DAC circuit has to generate it on its own. For this we added a frequency multiplier with an integrated PLL in the form of an ICS570BILF (IC6). This IC has a zero delay buffer to ensure that the rising edges of the input and output signals are perfectly aligned.

The multiplication factor can be set between 0.5 and 32 by two tri-state inputs (S0/S1). According to the date sheet, the output frequency range is 10 to 170 MHz. We chose a multiplication factor of 6 by leaving both S0 and S1 open, and we use the CLK/2 output, which is also connected to the feedback input. This configuration provides the best input range (2.5 to 12.5 MHz) with an output range of 15 to 75 MHz. You might think that with this arrangement it is not possible to handle signals with a sampling frequency of 32 kHz, but that is not true; it works perfectly.

A problem

We ran into a different problem when testing our prototype DAC. First we tried all sorts of 32-bit and 24-bit audio data with sampling frequencies from 32 to 192 kHz, all without any difficulties. However, when we tested the circuit with 16-bit audio data we did not see any output signal. To make a long story short, after a lot of sleuthing we discovered that although the PCM1794A supports 16-bit and 24-bit audio, that is not entirely true in I²S mode. The data sheet is not especially clear about this.

Does this mean that our player does not support 16-bit audio? That depends. Direct playback is not possible, but the Volumio version we use here (version 1.55) includes sampling frequency conversion capability with three different quality levels. With a bit of luck, this capability will also be implemented in the planned update to Volumio 2.

The D/A converter

The DAC device (IC1) has an integrated 8x digital oversampling filter and can handle sampling frequencies from 10 kHz to 200 kHz. The I²S signals are connected through four 22 Ω resistors (R22 to R25) to block RF noise, since the master clock runs at nearly 74 MHz with a sampling frequency of 192 kHz. The various hardware select lines (MONO, CHSL, DEM, MUTE, FMT0, FMT1 and RESET) are routed to a 7-pole DIP switch and a set of seven 47-kΩ pull-up resistors. This makes changing the settings very easy. The ZERO output on pin 13 drives LED1, which indicates that no audio data is present.

For supply voltage decoupling we use aluminum-polymer capacitors (C19, C23, C25, C27) due to their low equivalent series resistance (ESR) of 40 mΩ at 100 kHz. However, they have the disadvantage of a relatively high leakage current of 100 µA (max.). Since it is not clear whether this leakage current affects the internal input current, we added a pair of normal electrolytic capacitors

COMPONENT LIST

Resistors

Default: 1%, 0.125W, 0805
R1,R2,R3,R4,R7,R10,R13,R16 = 360Ω
R5,R8,R11,R14,R34 = 1kΩ
R6,R9,R12,R15 = 560Ω
R17,R18 = 47kΩ
R19 = 270Ω
R20 = 10kΩ
R21 = 47kΩ SIP 7-resistor array, 125mW, 2%
R22,R23,R24,R25 = 22Ω
R26,R27 = 0Ω
R28 = 300kΩ
R29,R33 = 100kΩ
R30 = 150kΩ
R31 = 51kΩ
R32 = 180kΩ

Capacitors

C1,C2,C5,C6,C9,C14 = 6.8nF, 63V, 1%, polystyrene, EXFS/HR 6800PF ±1%, LCR Components (alternative 5mm pitch or 0805)
C3,C4,C7,C8,C12,C13,C17,C18,C29,C34,C35 = 100nF, 50V, 10%, X7R, SMD 0805
C10,C11,C15,C16 = 2.2nF, 63V, 1%, polystyrene, EXFS/HR 2200PF ±1%, LCR Components (alternative 5mm pitch or 0805)
C19,C23,C25,C27 = 10µF, 35V, 0.04Ω, diam. 6.3mm max., pitch 2/2.5mm, 870055673001 (WCAP-PTHR series), Würth Elektronik
C20,C21 = 10µF, 63V, 1.06Ω, diam. 6.3mm max., pitch 2/2.5mm, UPM1J100MDD, Nichicon
C22,C24,C26 = 47nF, 50V, 10%, X7R, SMD 1206
C28 = 10nF, 50V, 10%, X7R, SMD 0603
C30,C31,C32,C33,C36,C37,C40,C41,C43,C44,C46,C47,C48,C49,C52,C53 = 4.7µF, 25V, 10%, X5R, SMD 0805
C38,C39,C50,C51 = 10nF, 50V, 10%, X7R, SMD 0805
C42 = 2.2µF, 10V, 10%, X7R, SMD 0805
C45,C55 = 1µF, 16V, 10%, X7R, SMD 0805
C54 = 47µF, 16V, 20%, X5R, SMD 1210
C56,C57 = 10µF, 25V, 10%, X5R, SMD 1206
C58 = 47µF, 16V, 10%, tantalum, SMD-C (2312), TR3C476K016C0350, Vishay

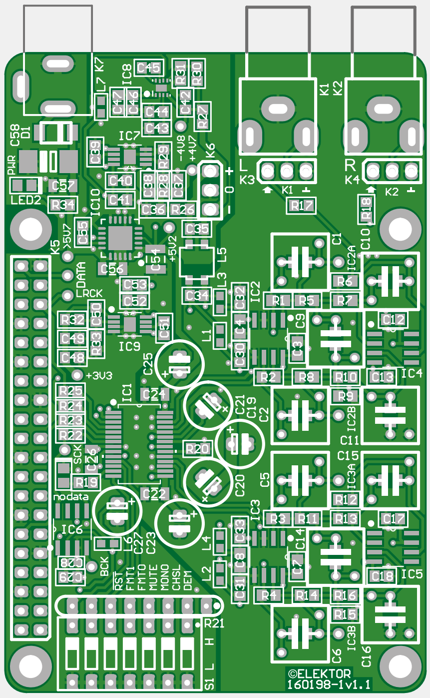


Figure 3. The component side of the PCB.

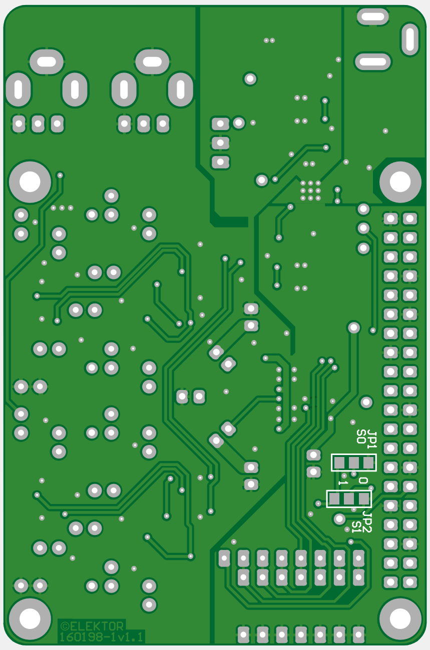


Figure 4. The bottom side of the PCB. Jumpers JP1 and JP2 can normally be omitted.

Inductors and Transformers

L1,L2,L3,L4,L6,L7 = 600Ω at 100MHz, 0.15Ω, 1.3A, SMD 0603, BLM18KG601SN1D, Murata
L5 = 2x0.05Ω, 230Ω at 100MHz, 2.6A, SMD, ACM4520-231-2P-T, TDK

Semiconductors

D1 = PMEG6030EP, 60V, 3A, SMD SOD-128
LED1,LED2 = green, low power, SMD 0805
IC1 = PCM1794ADB, SMD SSOP-28
IC2,IC3 = LME49720MA/NOPB, SMD SOIC-8
IC4,IC5 = LME49710MA, SMD SOIC-8
IC6 = ICS570BILF, SMD, SOIC-8
IC7,IC9 = TPS7A4901DGNT, SMD MSOP-8
IC8 = LM27761DSGT, SMD WSON-8
IC10 = TPS7A4700RGWT, SMD VQFN-20

Miscellaneous

K1 = RCA audio connector, white, PCB mount, right angle, gold plated, PJRAN1X1U02AUX, Switchcraft
K2 = RCA audio connector, red, PCB mount, right angle, gold plated, PJRAN1X1U03AUX, Switchcraft
K3,K4,K6 = 3-pin pinheader, vertical, 0.1” pitch
K3,K4 = jumper, 0.1” pitch
K5 = 40-pin GPIO stacking header, 2x20-way female, extra tall
K7 = DC power connector (jack), 3A, 1.95mm, Lumberg NEB 21 R
S1 = 7-position DIP switch
4x M2.5 17mm male/female threaded standoff
4x M2.5 14mm male/female threaded standoff
8x M2.5 nut
PCB 160198-1 v1.1

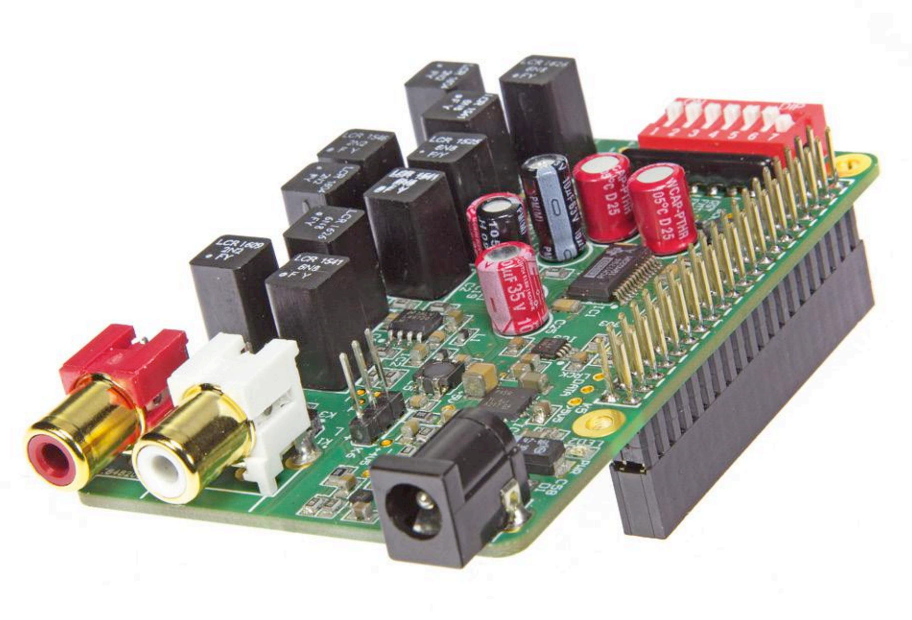


Figure 5. The GPIO connector is mounted on the bottom side.

Table 1: S1 settings		
S1-1	L	De-emphasis disabled for 44.1 kHz
S1-2	L	Digital filter with steep falling edge
S1-3	L	Mono off
S1-4	L	Mono off
S1-5, S1-6	L	I²S mode
S1-7	H	Reset off

Table 2: Current consumption at different sampling frequencies	
Sampling frequency	**Current consumption (K7)**
No data	120 mA
32 kHz	127.5 mA
44.1 kHz	131.7 mA
48 kHz	133 mA
96 kHz	149.5 mA
192 kHz	182.1 mA
(Measured with 8 V lab power supply; both outputs terminated with 10 kΩ)	

Table 3: Distortion				
THD+N				
Sampling frequency		48 kHz	96 kHz	192 kHz
1 kHz	BW = 22 kHz	0.0008%	0.0009%	0.0013%
	BW = 80 kHz	0.0028%	0.0012%	0.0014%
7 kHz	BW = 22 kHz	0.00095%	0.0011%	0.0013%
	BW = 80 kHz	0.003%	0.0014%	0.0016%
IMD				
50 Hz:7 kHz = 4:1		0.0014%	0.002%	0.0036%

(ESR 1.06 Ω at 100 kHz, leakage current 4 µA). If you want to experiment with different capacitor types, there is plenty of room on the PCB.

Output filter

Although the sampling artifacts are largely suppressed by the 8x digital oversampling filter, there are still undesirable high frequency components present in the output signal of the DAC. We use a reconstruction filter to suppress these components. The filter in question is a third-order Butterworth filter, and the current to voltage converters (IC2/IC3) are part of this filter. The corner frequency is 64.5 kHz. With a sampling frequency of 44.1 kHz, the 8x frequency component at 352.8 kHz is attenuated by more than 40 dB, and with a sampling frequency of 192 kHz the attenuation is more than 80 dB. The chosen corner frequency is a compromise between adequate attenuation at low sampling frequencies and the audio bandwidth of the output signal at higher sampling frequencies. Here the filter bandwidth is more than three times the normal audible range.

The DAC IC has differential current outputs, which allows an external filter to be used. To convert the output current into a single-ended voltage, we need a current to voltage converter, which in this case is built around the dual opamps of IC2 and IC3. The differential output voltages of IC2A/IC2B or IC3A/IC3B are fed to IC4 or IC5, respectively, which convert them into single-ended voltages. They are also configured as second-order filter stages. In combination with the current to voltage converters, the overall filter characteristic is equivalent to a third-order Butterworth filter.

On the PCB the single-ended output signals are available on connectors K1 and K2 via headers K3 and K4. Jumpers allow the signals from K3 and K4 to be fed directly to K1 and K2. It is also possible to connect a stereo potentiometer to the headers to provide a simple volume control.

The DAC IC does not have integrated volume control capability. Although it is possible to use Volumio for software volume control, that comes at the expense of the resolution and therefore affects the sound quality. For us that is out of the question. We therefore decided to add hardware volume control in the form of a separate board, which also allows the volume to be adjusted under remote control. The volume control board will be described in the next issue of *Elektor*.

As a final detail, the balanced analog supply voltages for the filter and current to voltage stages are decoupled from the digital supply voltage by a common-mode choke and four RF chokes (for each channel individually).

The board

For the DAC board we only need a single external supply voltage in the range of 7 to 8 V, since the Raspberry Pi board has its own 5 V supply. An external supply voltage of 9 to 12 V is possible, but not recommended due to the higher power dissipation in IC10.

The top and bottom PCB layouts for the DAC board are shown in **Figure 3** and **Figure 4**. The board has the same dimensions as the Raspberry Pi. The power connector and the two signal outputs are on the same end of the board, with the seven-pole DIP switch S1 on the opposite end (adjacent to the WiFi antenna on the RPi 3 board). The 40-pin GPIO stacking header K5 is mounted on the bottom of the board, as can be seen from the photos of the assembled board. The pins of connectors K1–K4, K6 and K7 protruding on the bottom of the board must be trimmed as short as possible to avoid shorting on the metal shells of the Ethernet and USB connectors on the Raspberry Pi board. It is probably a good idea to place a bit of insulation between the two boards. In our prototype we used M2.5 metal male/female threaded standoffs with a length of 17 mm (0.675”) to attach the DAC board to the Raspberry Pi. The solder pads for the capacitors in the filter stages are laid out to allow three different types of capacitor to be mounted for C1, C2, C5, C6, C9–C11, and C14–C16. SMD 0805 components can be used here, but it is also possible to mount conventional through-hole capacitors with a lead pitch of 5 mm. For best results, we recommend using 1% polystyrene capacitors.

Pin 1 of each IC is marked with a small white dot, but with IC7 this is difficult to see due to capacitor C38. There was not enough room to put the numbers of the 0805 resistors and the 0805 and 1206 capacitors next to the components concerned, so we put them inside the component outlines. That means they are hidden on the board. If you assemble the board manually using a hot-air soldering iron or a reflow oven, it’s a good idea to use an enlarged copy of the component layout to help you put all the components in the right place. With many of the 0805 components, replacement is difficult or virtually impossible after the conventional through-hole components have been soldered in place. The latter should therefore be kept for last.

Jumpers JP1 and JP2 are located on the bottom of the PCB. They can normally be left open (SCK = 6 × BCK). The audio output connectors (Cinch/RCA connectors) are Switchcraft components with two terminals closer together than in the standard 10 mm version. This means

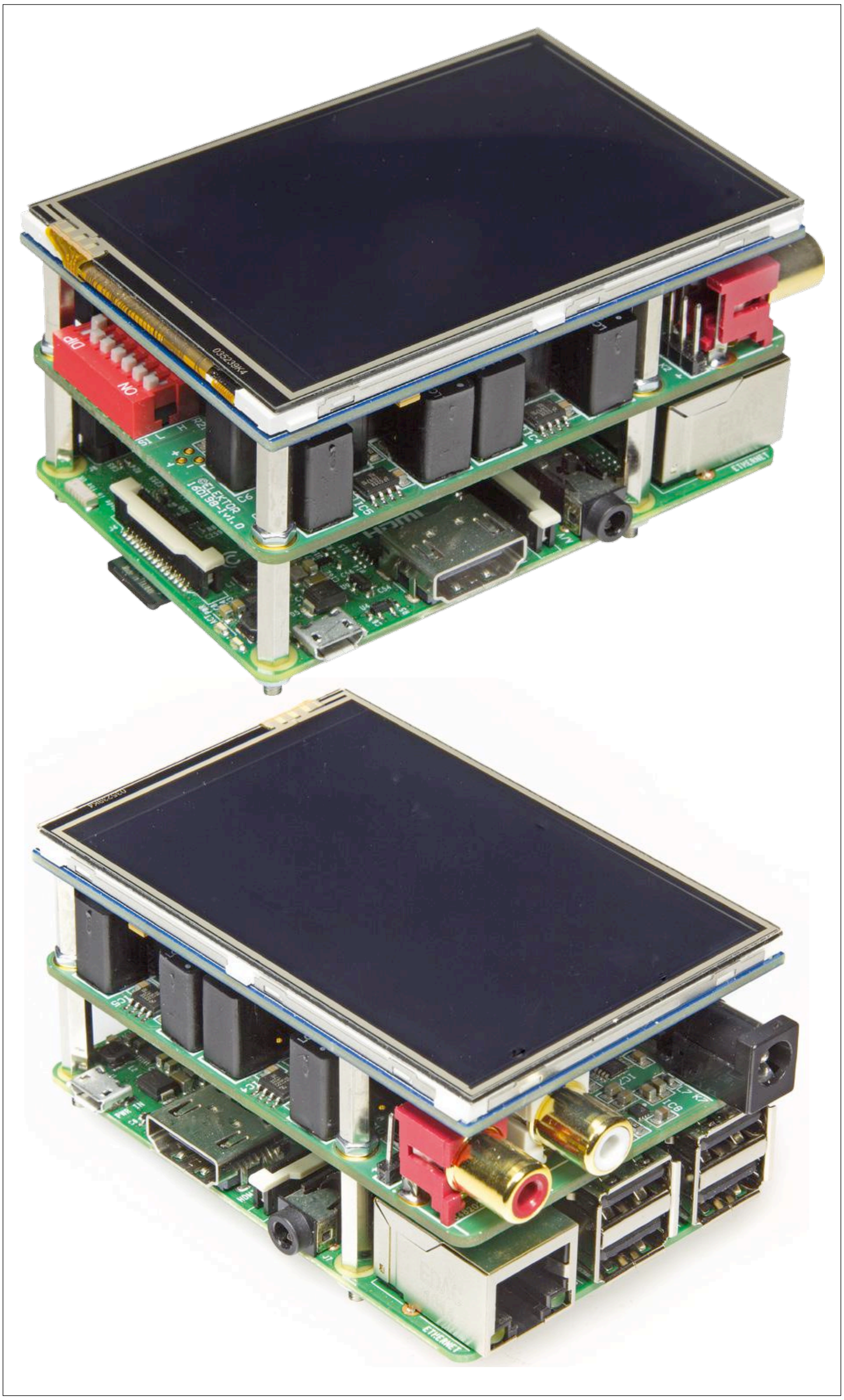


Figure 6: The complete network audio player.

that if you want to use a different type, it probably will not fit.
The Waveshare 3.5 inch touchscreen display for the Raspberry Pi must be mounted 16 mm (0.625”) above the DAC board. For this we used four metal male/female threaded standoffs with a length of 14 mm (0.55”) together with an M2.5 nut under each standoff for the extra distance. This means you should not press the connector down as far as possible. In case of doubt, it is better to use a second stacking header and mount the display a bit higher. The distance between the 26-pin connector of the display and the DAC board is about 2 mm.
Figures 5 and 6 show what the complete network audio player looks like.

Measurements

It goes without saying that we subjected our audio DAC to extensive testing. The key results are summarized in **Tables 2 and 3**. All measurements were made with the S1 settings listed in **Table 1**.
The current consumption increases at higher sampling frequencies, as can be seen from **Table 2**.
The measured figures for total harmonic distortion plus noise (THD+N) and intermodulation distortion (IMD) are listed in **Table 3**.
Several plots made with our Audio Precision analyzer are also available on the Elektor Labs page for this project [2]. ◀

(160198-I)

Volumio

Volumio is a free open source Linux distribution specifically tailored to music playback. Volumio runs on a wide variety of devices, including small inexpensive computers such as the Raspberry Pi. After you install Volumio, the device turns onto a headless audiophile music player. Here “headless” means that you have to use another device, such as a smartphone, computer or tablet, to operate the audio player.
For that you can use the Volumio user interface, which is a web app that runs on any device with a browser and makes playing music files easy and intuitive. The web app and Volumio communicate with each other over the local area network. On the Elektor Labs page for this project [2] we provide detailed instructions for installing Volumio on your Raspberry Pi (please note that we used version 1.55) so that you can **also** use the touch screen for this purpose. ×
Figure 7 shows the Volumio user interface on the display (left) and on a PC monitor (right).

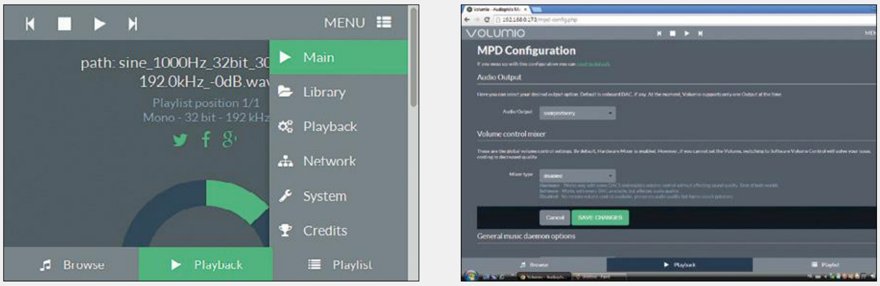
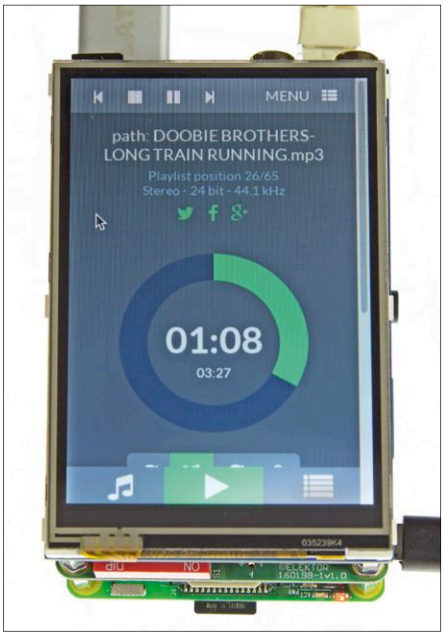


Figure 7. Volumio can be operated using the touchscreen (left) or a PC (right).



FROM THE STORE

→ **160198-1:**
Bare PCB

→ **160198-91:**
Assembled module with touchscreen; headers included separately (to be soldered by user))

→ **SKU 17631:**
Raspberry Pi 3 (model B)

Web links

[1] PCM1794A data sheet: www.ti.com/general/docs/lit/getliterature.tsp?genericPartNumber=pcm1794a&fileType=pdf

[2] Elektor Labs project page: www.elektormagazine.com/labs/audio-dac-for-rpi-networked-audio-player-using-volumio