

# High-Quality Low-Voltage Audio

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## LOW-VOLTAGE AUDIO PRODUCTS

We live in an interesting age full of mind-numbing technical advancements and funny contradictions. Contradictions like last Christmas where the two hottest *must-have* gifts were the Sony PlayStation 2 and Razor kick scooters.

It's ironic in this computer age with corporate predictors saying that low-voltage audio information appliances are the next big thing that a completely mechanical device consisting of a platform, a stick and two wheels was just as popular as one of the most sophisticated computers ever developed.

Another interesting contradiction is being able to obtain audio off the Internet from thousands of different sources, being able to store hours of full-bandwidth audio in a low-cost Web access device, with no moving parts, not much bigger than a package of gum, only to have it sound not much better than your best friend next door yelling at you through a tin can and waxed string.

Okay, it's not that bad. But it can be a lot better.

Let's look at the class of low-voltage audio devices called Information (or *Internet*, both are used interchangeably) appliances (IA)<sup>1</sup>, and let's define them as anything connected to the Internet other than a PC that includes audio. Things like

- Digital Audio Players (MP3)
- Web Phones (a.k.a. Smart Phones)
- Automotive & Home Jukeboxes
- Email devices with voice-actuation
- Digital Cameras and Camcorders
- PDA (Personal Digital Assistant)
- HPC (Handheld PCs or Pocket PCs)
- Internet Radio and Cinema
- Internet Game Consoles

And very soon, speech-recognition capability will be added to many of these.

As overpriced or unconvincing as some of these IAs are, successful technology is not far off. Along with everything else, achieving that success depends on good audio. It cannot be left behind. If you doubt this, try listening to a home theater system without surround sound and a subwoofer. Good audio predicts good success.

Yet the audio quality on most devices is inferior. Typical signal-to-noise ratios measure in the 60 to 70 dB range (re -20 dBFS), which is about 5-10 dB

worse noise than good portable CD players. They tend to suffer from non-flat frequency responses (bass and treble boost being the biggest offenders) with limited low frequency response (typically rolled off beginning at 60 Hz apparently to compensate for lousy headphones) and some high frequency responses stopping as low as 5 kHz. (Line outputs have better frequency response and noise level than headphone outputs.) Total harmonic distortion plus noise is not awful, usually below 0.1%. *None of this is MP3's fault*<sup>2</sup>.

Throughout all the early years, cassette machines sold their convenience over phonograph records and downplayed their inferior audio quality. But eventually market competition brought the audio quality level up to par, or even better than phonographs. It seems we are repeating history once again with inferior audio quality on IAs. Hopefully the demand for higher performance will accelerate the process.

But it's not going to be easy. Blesser & Pilkington<sup>3</sup> point out persuasively that consumers are more than willing to give up audio quality for convenience, portability and price. Their report uses the rapid growth in Internet audio as an example of the acceptance of low-quality audio by consumers willing to make the trade-off for something totally new (MP3 audio, for instance). In spite of what is claimed, there is no comparison between Internet audio and CD-quality, yet the success of MP3 is undeniable – overwhelming even. It is hard to find any examples that compare to this phenomenon. And it happened with audio quality that is “good enough.”

This lets us know in no uncertain terms that the consumer side of the audio business is running things, not the pro audio side. DVD-A, for example, is never going to impact the world the way that MP3 already has. While the committees fought and scrapped over bit-count and higher sampling rates, the MP3 folks were out changing the world. Lesson learned – but that doesn't mean we have to accept the quality. We can help make it better.

It is more than a little ironic that with many information appliances and other low-voltage audio products it is the *analog* parts and circuitry that are degrading the audio. As will be seen below, the latest audio converters are truly impressive. Based on the best delta-sigma technology, using extreme oversampling and advanced noise shaping, they leave little room for criticism.

Good audio requires good hardware. Important issues include interconnection, grounding, testing, noise, and selecting good parts. Too many designers think their job is done once they deliver the decoded data stream to the D/A converter on one end, or figure the A/D converter on the input end solves all their analog needs.

A complete step-by-step, nitty-gritty, smoke and mirrors design process for achieving high-quality low-voltage audio circuits lies outside the scope of this paper. However, the important issues are illuminated with tips, pointers and Internet Web addresses for obtaining additional information. If you have audio circuits to design, what follows should help.

### Interconnection

A full-featured information appliance usually contains several digital interfaces with digital audio capabilities. USB streaming controllers allow digital audio systems to connect bidirectionally to host systems via the USB port used in almost all PCs and Macs. In addition, many IAs support the S/PDIF digital interfacing standard used in DVD, CD and MD players. Likewise IEEE-1394 is emerging as the preferred digital interconnect for consumer electronics, computer peripherals, and professional audio/video networks. Digital Harmony offers digital audio applications for 1394, marketing their solution as the DHIVA (Digital Harmony interface for video and audio) transceiver<sup>4</sup>. With DHIVA, designers can quickly add a standards-compliant 1394 interface to their Internet information appliances.

Direct analog audio interfaces need careful attention to input and output stage design. Balanced, or differential, inputs and outputs are the best choice, offering noise immunity and greater dynamic range, but obviously not all of the real world agrees with the best choice. Designers must accommodate all sorts of unbalanced accessories and equipment – everything from stereo headphones to PCs. Treat unbalanced signals as floating or quasi-balanced sources by connecting the signal and the return/ground/shield as a balanced pair into a difference or instrumentation amplifier (e.g., hook the hot wire to pin 2 and the return wire to pin 3 of an XLR connector). Float the outputs and drive them differentially or balanced. Use a high-quality differential output line amplifier to drive the signal line and return leg. When interconnecting to other equipment use carefully proven wiring techniques<sup>5</sup>.

Interconnecting impedances must follow standard conventions of outputs low and inputs high. Keep output impedances in the 50-300 ohms range. If an output amplifier requires more than this to remain stable when driving capacitive loads (i.e., long lines) then get rid of it and get something better – something inherently more stable and designed to

drive long lines. Make line-level input impedances at least 10 k $\Omega$  and mic input impedances lower, but not less than 1 k $\Omega$ .

### Grounding

Too often a connection between an unbalanced output and a balanced input produces hum and buzz. Consult the references<sup>6,7</sup> for detailed theory and application tips. If inputs and outputs are kept balanced, or fully differential, with all cable shields bonded to the chassis immediately at the point of entry or exit, few grounding noise problems occur.

However, we live in the real world where unbalanced interconnects are the norm and cable shields are too often grounded to the signal reference lines or at a distance too far from the input/output to be effective. As discussed below, this is another good reason to design your audio system fully differential. Fully differential lines are immune from ground-induced noises. It is with the conversion from differential to single-ended that problems begin.

It can get so severe that special jerry-rigged cable assemblies are proposed<sup>8</sup> to make interfacing different equipment easier. This suggested interconnecting cable allows the four possibilities of connecting the shield to be quickly tried: tied to both chassis; tied only to the sending end; tied only to the receiving end; tied to pin 1 of the receiving device.

### Testing & Documenting the Results

Judging from the lack of audio specifications on IA data sheets and sales literature, it is tempting to conclude that manufacturers do not print audio specs because they have never measured them. It is shocking, for instance, to overhear a conversation by a manufacturer of an information appliance with audio (in fact, audio is its only mission) and to hear him say, “What’s that?” when asked about Audio Precision measurements. But, to be fair, the lack of audio specs probably has more to do with the customers not asking for them than anything else.

From an audio quality standpoint, objectively comparing IA products is impossible without full specifications. Missing on most data sheets are basic audio specifications – SNR, THD+N, and frequency response – the basics. If found at all, the data is meaningless since test conditions are not stated. Audio specifications come with conditions. Tests are not performed in a vacuum with random parameters. They are conducted using rigorous procedures and the conditions must be stated along with the test results.

Many designers of Internet information appliances are new to audio and don’t know where to turn to learn about audio testing and how to state specifications. Here are some resources:

Basic analog audio tests are well covered by Metzler's fine book on fundamentals<sup>9</sup>. See RaneNote 145<sup>10</sup> for preferred testing conditions for specifying audio products.

Testing digital audio products is covered in Cabot's AES tutorial paper<sup>1</sup>. Fundamental concepts in analog and digital testing of audio equipment are reviewed, including tradeoffs inherent in the various approaches, the technologies used, and their limitations.

The unique requirements of testing all digital audio power amplifiers is covered in Neesgaard's application note<sup>12</sup>, available from Texas Instruments.

Accurate audio measurements are difficult and expensive. The test equipment necessary to perform all the common audio tests costs a minimum of \$10,000. And that price is for computer-controlled analog test equipment, if you step-up into the digital-based, dual domain stuff – double it. This is why virtually all purchasers of IAs must rely on the honesty and integrity of the manufacturers involved, and the accuracy and completeness of their data sheets and sales materials

### Noise

Low noise and low voltage don't like each other. Low voltage usually means portable, and portable always means low current to prolong battery life. You can design low noise and low voltage if you can be a current pig, but if you must have low noise, low voltage *and* low current – well, that's difficult. Everything works against you. The easiest way to make a really low noise op amp is to run as much current as possible through the front-end differential-pair until the silicon glows.

As unintuitive as it may be, a plain resistor, hooked up to nothing, generates noise and the larger the value the greater the noise. It is called *thermal noise* or *Johnson noise*<sup>13</sup>, and results from the motion of electron charge of the atoms making up the resistor. All that moving about is called thermal agitation (caused by heat – the hotter the resistor, the noisier). Therefore quiet designs should use small resistor values, but, alas, small resistor values draw large current, and there goes the battery life. Compromise must ensue. It is difficult to find the perfect balance between small resistor values for low noise and large resistor values for low current consumption. To make it even harder, with most analog circuits small resistor values mean correspondingly large capacitor values. Large capacitor values do not hurt the noise performance but they are physically large and cost more, so you must make a compromise between noise, space and cost (*analog design is like that*).

The choice of resistor values then becomes the deciding factor in selecting the right op amp for each application. Look at the resistor values; if they are

very small (like in a mic preamp) then the noise contributed by the op amp becomes critical. However, if the application is active filters, say, and the resistors surrounding the op amp are at least 10 k $\Omega$ , then the dominate noise factor becomes their thermal noise, not the op amp's noise. Understanding this simple fact allows you to use low-cost op amps for most of your needs.

Ultimately the performance gets down to how much voltage is available and how low is the noise floor: power supply and noise – the big two in designing quality audio for IAs.

### POWER SUPPLY DESIGN

Successful IA audio circuits begin with power supply design. Designing low-voltage audio circuits for portable and wireless information appliance products puts severe restrictions on quality. Sacrifices necessary to keep cost, size, and weight to a minimum often hurt audio quality.

Portable and wireless devices force audio designers to work with very small supply voltages, often just a single 1.5-volt cell. There is just one rule when designing quality audio circuits if you only have 1.5 volts to work with: *make more voltage*.

### Separate Audio Supply

No matter what the voltage, in order to achieve very high performance levels, audio circuitry must run from dedicated supplies. Obviously it does no good to select the lowest noise op amps if they are connected to a digitally corrupted power supply.

### Single-Supply Design

If the design cannot justify split-supply costs then you must design with a single supply. Since audio is an AC (alternating current) signal, its voltage swings positive and negative about some reference point. This reference point is normally ground (or common) for a bipolar or dual power supply, i.e., one with positive and negative voltages (e.g.  $\pm 15$  VDC). If you only have a single supply then you must create a reference point equal to one-half of the available supply. For example if you have a single 5 volt supply then you create a common reference point at 2.5 volts, which allows the audio to swing  $\pm 2.5$  volts (from the reference point up 2.5 volts to the +5 volt limit and down 2.5 volts to zero).

Splitting a single supply voltage is not difficult, nor expensive (although in some designs every extra op amp or resistor can mean trouble). Techniques exist ranging from a simple two-resistor voltage divider to more elaborate buffered op amp designs. Excellent application notes covering all aspects of this topic are available from Texas Instruments<sup>14</sup>, Linear Technology<sup>15</sup>, and Analog Devices<sup>16</sup>.

## DC-DC Converters

If the hand you've been dealt contains only one AA cell battery then you must become a DC-DC converter designer at once. Luckily there is lots of help in this area. There's nothing you can do with a single AA battery except use it to create more voltage.

How *much* voltage depends on the product and the application. If you must create loud audio into big speakers, then life's going to be a lot harder than if you can get away with driving only headphones. Low efficiency loudspeakers and headphones are a big obstacle to pristine IA audio. Low efficiency means you need lots of power to drive high-quality speakers to loud levels. And lots of power means lots of voltage and current.

If it is your choice, then chose a pair of nice clean and quiet split supply voltages – as high as you can get them for loud results or if you are going to interconnect with the pro audio world. Most pro audio products use  $\pm 15$  VDC for their analog audio circuits.

While finding a single IC capable of converting 1.5 VDC to a nice clean and quiet  $\pm 15$  VDC is difficult<sup>17</sup> to impossible, several IC companies make converters that will pump up 1.5 volts to 12 volts, and from there you can split that into a useable  $\pm 6$  VDC. See for instance Analog Devices<sup>18</sup> or Linear Technology<sup>19,20</sup>.

See also Linear Tech's latest free design software for DC-DC converters, called *SwitcherCad III*<sup>21</sup>, although it doesn't help much for single cell converters. A better one is called *microPower SwitcherCad* (same webpage) but it hasn't been revised since 1996 so you should check with them for the latest devices. Search their site using "single cell" as key words.

Another free helpful DC-DC converter design program is available from National Semiconductor named *Switchers Made Simple*<sup>22</sup>, and take a look at the collaborative venture by National, Vishay, and Pioneer-Standard Electronics called *WebSIM*<sup>23</sup>, a free on-line tool to design, simulate and order prototype kits for power supplies. And not-for-free from ON Semiconductor is *Power 4-5-6* software for the design, simulation and analysis of power topologies. Free download demo of Release 7 available at <http://www.onsemi.com/pub/0,1684,smps,00.html>

## OP AMP SPECIFICATIONS IMPORTANT FOR AUDIO

Selecting op amps for audio is a lot easier than it was the first time I wrote about this topic in 1976<sup>24</sup>. This is primarily due to the quantity of audio specific

chips sold into the automotive and PC industries. Quantity is what IC companies understand. They live and die by quantity, and for the first two decades, audio was pretty much ignored as a product line. Back then selecting good audio op amps took some digging and required the designer to know quite a bit about audio's specific requirements. Things are different now. Audio-grade op amps are sold by the millions each day, and it makes selecting them a lot easier since most IC companies have a separate section in the selection guides for audio.

Here is a summary of the most important parameters (in no particular order):

- **Gain-Bandwidth Product**, or **GBW**, equal to at least 3 MHz. This gives plenty of open loop gain (>40 dB) for feedback circuits to still work well at 20 kHz. More is better as long as the *phase margin* does not get compromised. You want to see a solid phase margin of 60° at the unity gain BW crossing point.
- **Slew Rate**, or **SR**, equal to at least 1.5 V/ $\mu$ s. This value is necessary to prevent slew-limiting at 20 kHz with full output voltage. In a single-cell world you never have large voltage swings so you never need large slew rates, but it's nice to have some margin.
- **Noise**, or **Noise Density**: normally specified at 1 kHz, along with a graph showing wideband performance. Look for spot noise density at 1 kHz less than 15 nV/ $\sqrt{\text{Hz}}$  (approximately the noise of a 10-kohm resistor) for low gain circuits (like filters) and less than 4 nV/ $\sqrt{\text{Hz}}$  (noise of a 1-kohm resistor) for high gain circuits (like mic preamps). In addition to a low 1 kHz spot noise number, you want to see a low 1/f corner, i.e., you don't want the low-frequency noise to start rising dramatically until below 20 Hz.
- **Total Harmonic Distortion + Noise**, or **THD+N** This is not a spec to get overly concerned with. As long as the part stays out of whole numbers, you probably don't have to worry about any audible results. But in the interest of successful marketing, select parts with a THD+N less than 0.1% over the entire 20 Hz – 20 kHz audio range. Today it is very hard to find parts that don't shine in the THD department.

Low noise, high slew rates, wide bandwidths, and excellent linearity (low distortion) characterize high quality audio op amps. Other important specifications are application driven and include power supply voltage, current consumption, common-mode rejection, power supply rejection, input impedance and size. The *Audio Handbook*<sup>24</sup>, written in 1976, describes op amp audio requirements as follows: "The IC must process complex AC signals comprised

of frequencies ranging from 20 Hz to 20 kHz, whose amplitudes vary from a few hundred microvolts to several volts, with a transient nature characterized by steep, compound wave fronts separated by unknown periods of absolute silence. This must be done without adding distortion of any sort, either harmonic, amplitude, or phase; and it must be done noiselessly – in the sun, and in the snow – forever.” Nothing has changed.

## SELECTING LOW-VOLTAGE OP AMPS

Good audio requires good parts. Low-voltage information appliances make selecting the right audio ICs even more important – and more difficult. What follows are guidelines and pointers to high-quality audio ICs specifically designed for low voltage designs. (See appendix for summary tables.)

*[Editorial Note: There are too many world wide semiconductor companies to be all-inclusive regarding recommendations. Apologies are made to those left out. The author knows the ICs and companies spotlighted from direct experience. Omission of any company or specific products merely means the author was not aware of them. It is also recognized that many of the ICs mentioned will be outdated in 6 months, therefore if you are reading this after August, 2001 then check the manufacturer for the latest part replacing or improving the one shown.]*

### Single-Supply RRIO (Rail-to-Rail Input & Output)<sup>25</sup> Audio Op Amps

The marriage of analog and digital circuits created the need for RRIO op amps. Since digital circuits must run off low-voltage supplies (for speed and power reasons) the demand for analog chips to do the same was inevitable. A RRIO op amp is just what the name implies, one where the maximum input and output levels equal the available power supply voltage. Up to the introduction of RRIO op amps, both input and output levels were restricted to something less (sometimes *considerably less*) than the supply. See Hahn<sup>26</sup> for specific design detail.

Running an audio op amp off a single AA cell used to be a joke; today it is a reality. One incredible example is ON Semiconductor’s (formerly a division of Motorola) MC33501 called “SmartMOS”<sup>27</sup>. If you absolutely must run from one cell, this is a pretty good choice – and there aren’t many. Featuring a typical slew rate of 3 V/ $\mu$ s (min 1.8 V/ $\mu$ s), 10 kHz THD+N = 0.01% (although this degrades drastically for anything other than unity gain applications, e.g., it is 0.5% for a gain of x10), and a unity-gain-bandwidth of 3 MHz (min 2 MHz), this little guy is impressive, but its 1 kHz spot noise spec of 30 nV/ $\sqrt{\text{Hz}}$  (same as a 741 op amp), restricts its use to

low gain circuits with large resistors (around 100 k $\Omega$ ), otherwise it will degrade the S/N.

Once you increase your single 1.5-volt cell to something more useable, like 3-5 volts, then other audio-worthy single-supply RRIO ICs appear.

What looks like the low-noise low-voltage leader for the moment is Linear Technology’s LT1677<sup>28</sup> with a 1 kHz typical spot noise spec of 3.2 nV/ $\sqrt{\text{Hz}}$  (max of 4.5 nV/ $\sqrt{\text{Hz}}$ ). Combined with a 7.2 MHz gain-bandwidth product (min of 4.5 MHz), power supply range of a single +3 V to  $\pm 18$  V, typical slew rate of 2.5 V/ $\mu$ s (min of 1.7 V/ $\mu$ s), a low 1/f corner of 13 Hz (*the 1/f corner is where the noise density begins climbing with a 1/f amplitude characteristic*).

The only quibbling area is THD+N. The data sheet states it is (typically) 0.0006% -- very impressive, except that this is for unity gain, and a 10 V<sub>P-P</sub>, 1 kHz signal. The 1 kHz THD+N degrades to 0.04% for a 1 V<sub>P-P</sub> signal in a x100 gain application, and no information is given for 20 kHz THD+N under the same conditions (or for any other frequencies). The data sheet graphs indicate the THD+N has a knee around 2 kHz where it climbs rapidly. Nothing to be alarmed about, but it should be understood when measuring high frequency THD+N.

Analog Devices selections in this low voltage category include one standout: AD8517/AD8527<sup>29</sup> featuring operation at 1.8 volts, with 7 MHz gain-bandwidth, 7 V/ $\mu$ s slew rate, and 15 nV/ $\sqrt{\text{Hz}}$  (all numbers typical – no min/max given). THD+N is a respectable 0.03%, amazingly flat across the whole audio range (no 1/f corner shown down to 10 Hz, which probably says this is noise dominated and not distortion at all), with a smooth bump to 0.04% at 10 kHz and then back to 0.03% at 20 kHz. A couple of interesting things to note about this part’s THD+N behavior: the figures given above are for 1.8 volt operation, if this is increased to 3 volts, or greater, then the THD+N plunges to 0.001% (flat from 10 – 20 kHz). And there is this interesting comment on page 11: “*If an inverting configuration, the noise (note the comment is “noise” not “THD+N”) is 0.003% for all V<sub>SY</sub>.*” So the rule for this part – if you only have 1.8 volts – is to *always use it in inverting configurations*.

Moving up the power supply voltage ladder a bit, if you have succeeded in creating at least  $\pm 5$  volts to work with then you can use another ON Semiconductor part, the MC33078/MC33079 family of dual and quad op amps. With typical high gain-bandwidth product of 16 MHz (10 MHz min), slew rate of 7 V/ $\mu$ s (5 V/ $\mu$ s min), noise density of 4.5 nV/ $\sqrt{\text{Hz}}$  (1 kHz typ), and THD+N = 0.002% (typical, 20 Hz to 20 kHz, unity gain, and 1 V out – increasing to 0.01% for x10 gain and maximum output),

combined with low price, makes this is a very hard part to beat.

From Analog Devices there is the OP275<sup>30</sup>, a superb audio IC. Characterized with a 9 MHz (typ) gain-bandwidth product, minimum 15 V/ $\mu$ s slew rate, a flat noise spec of 6 nV/ $\sqrt{\text{Hz}}$  (typ) over the whole audio range, and a typical THD+N performance of less than 0.001% from 20 –10 kHz, only rising slightly to 0.002% at 20 kHz.

*[Word to the wise: do not use Analog Devices' SSM<sup>31</sup> line of ICs for new designs. Even though they are shown in their Single Supply Amplifier selection guide under Audio – do NOT use them for new designs. Over the past year, without warning, Analog Devices has discontinued three major SSM parts – all popular in the pro audio world, all outstanding achievers – the SSM 2017 Mic Preamp, SSM2110 RMS Converter, SSM2120 Dynamic Range Processor. The reason given is these are old parts done on smaller wafers that are not practical to manufacturer any longer. Based on this reasoning and these recent terminations, it is believed the entire SSM line will soon follow. Caveat emptor.]*

Texas Instruments (TI) offers some interesting candidates in the single-supply RRIO arena. Of particular use are the singles, duals and quads in each series. If you only have 3 volts, or less, take a look at the TLV2361/2362 series, TLV2460 series, and the TLV2780 series. If you have at least 5 volts, then check out the TLC070 series, TLC2201/2202 series, and the TLC2272/2274. Full data available at TI's website ([www.ti.com](http://www.ti.com) search by series number).

National Semiconductor's choice for single-supply RRIO audio grade is the LM6141/6144 family, operating from  $\pm 1.8$  VDC, but their noise spec of 16 nV/ $\sqrt{\text{Hz}}$  (1 kHz spot) restricts usage to low gain applications (unity gain filters, for instance). If you have at least  $\pm 5$  VDC, then you can use National's very fine LM833/837 series of audio op amps – long an audio staple. See data sheets at [www.national.com](http://www.national.com) searching by model number.

With at least  $\pm 2.25$  VDC available, consider Maxim's MAX4493/4494/4495<sup>32</sup> family of single, dual & quad op amps, featuring typical specifications of 3 MHz gain-bandwidth product, 3 V/ $\mu$ s slew rate, a noise spec of 8 nV/ $\sqrt{\text{Hz}}$  (typ) from 100Hz to 20 kHz, with a 1/f corner at 50 Hz, and a typical THD+N performance of less than 0.002% at 1 kHz.

Selecting the best op amp for your application involves many other parameters than those outlined above. There is always cost – some of these parts are pricey. Configuration is important – many of these are singles. Nowadays, with the proliferation of SMT (surface-mount technology) size has become an issue

– is it available in the package type your design and manufacturing constraints require? (The opposite side of that coin is can you get it leaded, or is it *only* available in SMT?)

Can you get the part you want, with the configuration you require, in the package you need, at the price you can afford? *That* is the difficulty ... oh, and then there is availability and second-sourcing.

## DIFFERENTIAL OR BALANCED AMPLIFIERS

Using differential or balanced amplifiers doubles your dynamic range. Operating in the same manner as a “bridged”<sup>33</sup> power amplifier, the two terms are used interchangeably and mean the same thing. Audio designers use the term “balanced” while their instrumentation colleagues use “differential.” Either way the signal exists between two equal impedance lines, instead of between one line and a ground. The amplifier drives the lines in a push-pull manner, simultaneously driving one positive and the other negative, consequently doubling the level. For example, if a normal single output amplifier drives its single output line positive to 1.0 volt, a differential amplifier would drive its positive line to 1.0 volt and its negative line to -1.0 volt yielding a net instantaneous voltage level of 2.0 volts. This doubling gives 6 dB more headroom – a very significant dynamic range increase.

Balanced techniques avoid grounding and return noise problems, lowers distortion since push-pull operation suppresses even-order harmonics, and minimizes electromagnetic interference (EMI).

Most high quality audio D/A converters have differential outputs – one of their tricks for better dynamic range and S/N specifications. Differential output D/As allow using bridging techniques for the analog audio outputs. Likewise, at the input end of things, analog audio input stages should be designed for balanced differential inputs, and use differential processing all the way to the A/D converter. This applies to all inputs: microphones, sensors, line-level stages, and so on.

Finding audio-grade ICs with balanced/differential inputs *or* outputs is easy (of course, all op amps have differential inputs but chips specialized as mic preamps & instrumentation amplifiers are of particular interest on the input side and balanced/differential line drivers on the output side; available from Analog Devices, TI/Burr-Brown, and others). But finding *fully* balanced/differential inputs *and* outputs is quite difficult. A fully differential amplifier is defined by Texas Instruments<sup>35</sup> as one with differential inputs and outputs, and whose differential structure rejects coupled noise at the input, at the output, and at the two power supply pins.

The parts exist, but they are designed for video and communications applications, not for audio. Therefore their use demands caution regarding specifications (e.g., some are not unity gain stable, and/or exhibit high noise performance due to the extreme bandwidths) and application (e.g., high frequency circuit layout design techniques are necessary to achieve the highest performance, as well as the use of surface-mount passive components for low lead inductance and small size allowing short runs).

Low voltage differential devices are available from a growing number of sources. Some recent parts to look over, if for no other reason than to get you thinking in this direction are available from Analog Devices (AD8138<sup>34</sup>) and of particular interest is a newcomer from Texas Instruments (THS4131<sup>35</sup>, also from TI is an excellent application note on new technology differential amplifiers<sup>36</sup>). What makes the THS4131 interesting is its unity-gain stability and the fact that the input noise is specified all the way down to 10 Hz (most high-speed amplifier data sheets only spec things down to 1 MHz) with an incredible 10 kHz spot noise of only 1.3 nV/ $\sqrt{\text{Hz}}$  (typ).

#### A/D AND D/A CONVERTERS FOR AUDIO

Very high quality audio data converters are available from AKM, Analog Devices, Burr-Brown (Texas Instruments), and Crystal (Cirrus Logic). Each seems to periodically leapfrog the other. At the time of this writing, the leading stereo (2-channel) A/D parts were the AKM AD5394<sup>37</sup> and Crystal's CD5396<sup>38</sup>. Leading stereo D/As include Crystal's CS43122<sup>39</sup>, AKM's AK4395<sup>40</sup>, Analog Devices' AD1853<sup>41</sup>, and TI/Burr-Brown's PCM1738<sup>42</sup>.

Due to the success of home cinema and surround-sound, and now with the introduction of DVD-Audio, the availability of high quality multichannel (at least 6-channel) D/As is increasing. Particularly interesting are Analog Devices' AD1833<sup>43</sup> and AKM's AK4355<sup>44</sup> offering six-channel volume control, wide dynamic range ( $\geq 106$  dB typ) and low THD+N ( $\leq 0.03\%$  typ). A new 8-channel part just released from TI/Burr-Brown is the PCM1608<sup>45</sup>, with 24-bit conversion, dynamic range of 105 dB typ (98 dB min) and max THD+N equal 0.008% (44.1 kHz sample rate; no frequency stated).

Codecs (coder-decoders) create a separate family of specialized converters interesting to information appliance designers (*Note: as used here the term "codec" refers only to that class of ICs that contain A/D and D/A converters; it does not mean the many devices used for data compression coding and decoding*). Usually containing at least two A/Ds and four D/As, what started out with telephone-audio quality has developed into something quite different.

High audio quality single-chip codecs include Analog Devices' AD1836 Multi-Channel 96 kHz Codec<sup>46</sup>, a high-performance, single-chip codec providing three *stereo* D/As and two *stereo* A/Ds (24-bit multibit delta-sigma) converters, 6-channel volume control, with 105 dB (typ) dynamic range and THD+N of only 0.003% (typ; no conditions given). And Texas Instruments' TLV320AIC27 audio-band codec features a stereo A/D and four D/A converter (18-bit delta-sigma) channels with an audio mixer for four stereo inputs, a phone, two microphones, and a PC-beep input. Performance claimed is signal-to-noise of 95 dB (typ) and THD+N equal 0.002% (typ; no conditions given). And it is designed to interface directly with TI's TMS320 DSP family discussed below.

Wolfson Microelectronics Ltd. (Edinburgh, Scotland) offers a family of ICs that add digital audio capabilities to digital camcorders, digital still cameras, DVD players and other Internet appliances, including MP3 players, cell phones with MP3, and PDAs. These chips claim CD-quality audio not previously available in portable appliances. For example the WM8731<sup>47</sup>, a stereo codec (including a mic input *with bias voltage*) with integrated headphone amplifier, level control and programmable sample rates (*8 kHz to 96 kHz*), boasts signal-to-noise ratios of 97 dB for its A/D and 100 dB S/N for its D/A (*24-bit multibit delta-sigma*) converters, with a final headphone output THD level less than 0.1%, all for less than \$5.00 in only 1,000-piece quantities. And it is fully compliant with the Secure Data Management Interface (SDMI).

#### CLASS D POWER AMPLIFIERS

Linear audio power amplifiers, based on classic Class AB techniques, designed to run from low voltage are available from Maxim, National Semiconductor, Philips, Texas Instruments and others. Today these devices dominate, but new products are moving away from Class AB power chips to the more efficient Class D audio power amplifier ICs.

Information appliances require the highest efficiency in all component selection to prolong battery life and achieve high quality in small size. Class D audio power amplifiers satisfy this need. The switched output nature of Class D designs makes them the most efficient power amplifiers and a must for low-power, battery-constrained systems.

STMicroelectronics claims to have developed the world's first commercial audio amplifier IC to use Class D techniques<sup>48</sup>. Labeled TDA7480<sup>49</sup> and requiring at least  $\pm 10$  VDC to operate, it puts out 10W into 8 ohms at 10% THD. That THD figure may shock, but it is the standard test point for measuring maximum output power in the automotive industry, for which this part was developed. It has since sired a



family of parts that includes TDA7481 (mono 18W/8Ω), TDA7482 (mono 25W/8Ω) and the TDA7490 (stereo 25W/8Ω). Even though developed for automotive use, these parts are useful in IAs requiring higher power (that have the power supply to support them).

Today, Texas Instruments leads the pack with their unique “filterless”<sup>50</sup> designs designated the TPA200xD family<sup>51</sup>. TI claims that by eliminating the need for bulky LC output filters, the new amplifiers enable designers to reduce board space and lower overall system costs by 40 percent. Eliminating the output filter is restricted to short (less than 8 inches) speaker runs, a requirement easily met with information appliance audio devices.

Maxim offers a Class D stereo all-in-one part that allows operation as low as 2.7 volts called MAX4297<sup>52</sup>. An innovative feature allows logic-programmable PWM frequency selection between 125 kHz, 250 kHz, 500 kHz and 1 MHz, although at anything other than the 125 kHz rate, the THD+N climbs into whole numbers.

National Semiconductor’s first Class D chip is the LM4663<sup>53</sup>, featured in their popular BOOMER™ family of audio power amplifier ICs. National’s design differs from other Class D suppliers. They use a delta-sigma modulator instead of the usual pulse width modulator, claiming lower output noise and THD+N results. The LM4663 also includes a very handy separate stereo headphone amplifier.

LinFinity (a division of Microsemi) is already offering a second-generation Class D part, the LX1710/1711<sup>54</sup> AudioMAX™ controller IC, which requires an external MOSFET output bridge. This new design series replaces the original LX1720 part and is claimed to have better S/N, lower noise floor and reduced THD+N. Controller ICs are a mixed blessing. They are not as compact as the one-chip solutions but they allow using a higher voltage supply for the output bridge to produce more power.

From the UK, Zetex offers the ZXCD1000<sup>55</sup> Class D controller for use with a discrete MOSFET output stage. This is a stereo switching amplifier controller driver that comes with a reference design layout and custom magnetics from the company.

Other Class D chips are promised “soon” from Motorola (*Symphony* series) and Philips Semiconductors.

### MASSIVELY INTEGRATED SoCS

Moving way up the integration ladder from op amps and amplifiers to what is described today as massively integrated system-on-chip (SoC). These application-specific mixed signal ICs (combining analog and digital circuits) reveal some interesting new products that promise to up the audio quality on

information appliances and lower the demand for a real audio engineer. The latest in massive-scale integration leaves less and less for the audio engineer to do. Most – if not all – of the actual analog audio portion of the design is moving deeper into the silicon layer.

Already most information appliances consist of only three or four chips. The next generation will have just one chip. One chip that does the microprocessing, mass storage memory, all the DSP functions, power supply management, and all audio input and playback path functions. To this chip are connected the internet (hardwired or wireless), keypad, display, microphone, and loudspeaker or headphones. There is not much left for the audio engineer (see Blesser & Pilkington<sup>3</sup>) – which makes much of this paper irrelevant, and clarifies the last sentence of the opening section: “If you have audio circuits to design...”

Here is just a tiny sample of powerful single chips available today:

From Cirrus Logic/Crystal Semiconductor comes the CL-PS7500FE System-on-chip with CRT/LCD Controller, combined with their CS4333 Codec and CS8900A Ethernet Controller creating a powerful Internet information appliance<sup>56</sup>. It directly accepts audio inputs and directly drives audio outputs. While not a true one-chip solution it leads the way.

To see a preview of what tomorrow will bring, look at Cirrus Logic’s cooperative effort with LuxSonar ([www.luxsonar.com](http://www.luxsonar.com)), marketed as the CS98000 (nicknamed “98K”)<sup>57</sup> a processor that combines DVD decoding, a video input port for combining external video sources and a bus interface that can connect with hard drives. All this plus the audio capability to decode MP3, Dolby Digital and DTS surround-sound formats. Today this chip requires a lot of support chips (Codecs, A/Ds, D/As) but tomorrow will see many of these functions fully integrated.

Impressive is Texas Instruments’ TMS320DA250<sup>58</sup>, claimed to be the industry’s most highly integrated single-chip DSP+codec solution for portable digital audio systems. Based on TI’s very successful low-power TMS320C5 DSP core found on many information appliances already (e.g., Sony’s Network Walkman™, JVC’s e-CyberCam, and Digital 5’s Internet Jukebox platform), the DA250, as it is called, considerably ups the ante.

Once everything is on one chip, all that’s left is to eliminate the D/A converters and use the digital audio bit stream to directly drive the power amplifiers.



## ALL DIGITAL AUDIO POWER AMPLIFIERS

The next big thing in integrated audio power amplifiers is digital input. Traditional Class D power amplifiers have analog inputs. The analog signal is converted into *pulse width modulation* (PWM) which drives an H-bridge (so called because the loudspeaker is connected bridge-style between two complementary MOSFET pairs, the whole thing forming the letter-H). Normal digital data is called *pulse code modulation* (PCM). With PCM each sample is represented by a word made up of ones and zeros, as the value changes from sample to sample the number of ones and zeros change. With PWM, the width of the pulse changes from sample to sample.

Successfully changing PCM into PWM has been a long quest, and is the technique behind digital input power amplifiers, which some people used to call “power DACS,” since that is just what they do – convert digital data into analog power output. *(Techniques other than strict PWM exist, but for clarity purposes all approaches are generalized here as PCM-PWM.)*

Converting PCM into some useable form of PWM turns out to be quite a can of problems and its success has taken a lot longer than anyone thought. Serious study began with Dr. Mark Sandler’s landmark paper delivered at the AES Convention in 1984<sup>59</sup> based on his PhD research. Dr. Sandler became a professor in the EE department at King’s College London, where he and his students have delivered over a dozen papers on the subject. Joining his research was the Technical University of Denmark (DTU) who targeted this technical area for intensive research with great results. At least three DTU students turned their university research into successful products.

The first was Lars Risbo who completed his PhD in 1994, went on to publish an important AES paper<sup>60</sup>, and then teamed up with classmate Niels Anderskov to found Toccata Technology (acquired by Texas Instruments in 2000). Along the way they created the TACT Millennium<sup>61</sup>, billed as the world’s first true digital audio power amplifier, which debuted to rave reviews at the January 1998 Winter Consumer Electronics Show.

Meanwhile, another DTU student, Karsten Nielsen, completed his PhD in 1998, while working for Bang & Olufsen (B&O) along the way. He presented several papers at various AES conventions and had one published in the AES Journal<sup>62</sup>. Upon leaving the university he joined B&O as Technology Director and now heads up their digital power amplifier division producing the ICEpower<sup>®63</sup> modules.

These were not the only successful researchers, but their contributions were significant. The result of their efforts, combined with that of many other individuals, is that today we are seeing the first

generation of true digital audio power amplifier integrated circuits.

With Texas Instruments’ acquisition of Toccata Technology (Niels Anderskov is now TI’s director of digital audio development), their first offering is the TDAA (True Digital Audio Amplification) chip set<sup>64</sup> consisting of the TAS5000 plus two TAS5100s. The TAS5000 is a PCM-PWM modulator that directly handles S/PDIF and USB data streams, converting 16- to 24-bit data, sampled at 44.1 kHz to 96 kHz. The TAS5100 is an outboard power MOSFET H-bridge. Scheduled for release in 2001 is a similar part to the TAS5000 with a 1394 interface.

Cirrus Logic’s entry into the PCM-PWM technological arena is based partly on proprietary technology purchased from B&W Loudspeakers (resulting from Peter Craven’s extensive collaboration with them in the late ‘80s resulting in patents relating to high-resolution D/A conversion and PWM power amplifiers<sup>65</sup>). They are readying the CS44L10 Class D amplifier<sup>66</sup> for introduction in mid-2001.

Apogee Technology Inc. (not affiliated with Apogee Electronics or Apogee Sound) is already marketing their patented DDX (Direct Digital Amplification) series, consisting of a DDX2000 PCM-PWM processor and a DDX2060 output stage<sup>67</sup>.

Three suppliers already offer true digital audio power amplifier technology. Based on their success others will follow quickly. We have yet to hear from Analog Devices, Motorola, National Semiconductor, NEC, Sony or European IC houses, although it is reasonable to expect to hear that B&O has licensed their ICEpower<sup>®</sup> technology to someone for integration and use with low voltage products – Philips perhaps?

And all these technologies are available as core intellectual property for directly integrating into system-on-chip solutions, completing the all-digital audio world.

## THE END

And so we reach the end. Audio in a 1.5 volt world ends up as one chip with the audio deeply embedded in the silicon sand. The key to pristine audio in any digital-based product (and what audio product isn’t nowadays?) is to keep the audio signal in a digital format from the source to the loudspeaker. Hardware and software solutions exist already to do it all.

Everything is here. Front-end A/Ds using powerful delta-sigma conversion technology producing 24-bit digital audio data streams with at least 120 dB dynamic range. This will be integrated with enough programmable DSP power to handle all audio formats such as MP3, Dolby Digital, DTS, Advanced Audio Coding, MPEG-4 and all the evolving new

ones, along with algorithms for 3D surround sound and all forms of equalization (tone controls, graphic, parametric, band-limiting, sweetening, loudspeaker compensation, etc.), as well as all types of dynamic response functions (compression, expansion, gating). Headphones and loudspeakers will be driven directly from built-in true digital power amplifiers, and it will be done clickless and noise-free, with distortion products buried in the noise floor. Complete with interconnectivity hardware supporting S/PDIF, USB, IEEE-1394, and developing new ones. Operating from a single AA cell, lasting at least one day with continuous play.

Like it or not, the all digital audio world is here to stay.

*Portions of this paper appeared previously as "Audio in a 1.5 Volt World," published in The Proceedings of the AES 18<sup>th</sup> International Conference: Audio for Information Appliances, Burlingame, CA., pp. 52-65, March 16-18, 2001, Audio Engineering Society.*

## Appendix A. Low-Voltage Audio Op Amp Selection Charts-1

[Compiled March, 2001— Consult Manufacturer for Latest or Replacement]

### Audio-Quality Op Amps Power Supply = +1 VDC

Mfgr P/N	GBW	Slew Rate	Noise 1 kHz	THD 20-20kHz
<b>ON</b> <b>MC33501</b> <b>(Single)</b>	<b>3 MHz</b>	<b>2.5 V/μs</b>	<b>30 nV/ √Hz</b>	<b>&lt;0.02%</b>

Rane Corporation

### Audio-Quality Op Amps Power Supply = +2 VDC

Mfgr P/N	GBW	Slew Rate	Noise 1 kHz	THD 20-20kHz
<b>AD</b> <b>AD8517</b> <b>(Single)</b>	<b>7 MHz</b>	<b>7 V/μs</b>	<b>15 nV/ √Hz</b>	<b>&lt;0.03%</b>
<b>TI</b> <b>TLV2780</b> <b>(Family)</b>	<b>8 MHz</b>	<b>2.8 V/μs</b>	<b>18 nV/ √Hz</b>	<b>&lt;0.06%</b>

Rane Corporation

### Audio-Quality Op Amps Power Supply = +3 VDC

Mfgr P/N	GBW	Slew Rate	Noise 1 kHz	THD 20-20kHz
<b>LTC</b> <b>LT1677</b> <b>(Single)</b>	<b>7.2 MHz</b>	<b>2.5 V/μs</b>	<b>3.2 nV/ √Hz</b>	<b>0.005%</b>
<b>TI</b> <b>TLV2460</b> <b>(Family)</b>	<b>5.2 MHz</b>	<b>1.6 V/μs</b>	<b>11 nV/ √Hz</b>	<b>0.006%</b>

Rane Corporation

## Appendix A. Low-Voltage Audio Op Amp Selection Charts-2

[Compiled March, 2001— Consult Manufacturer for Latest or Replacement]

### Audio-Quality Op Amps Power Supply = +5 VDC

Mfgr P/N	GBW	Slew Rate	Noise 1 kHz	THD 20-20kHz
<b>NSC LM6142 (Dual) LM6144 (Quad)</b>	<b>17 MHz</b>	<b>25 V/<math>\mu</math>s (function of level)</b>	<b>16 nV/ <math>\sqrt{\text{Hz}}</math></b>	<b>&lt;0.003%</b>

Rane Corporation

### Audio-Quality Op Amps Power Supply = $\pm 5$ VDC

Mfgr P/N	GBW	Slew Rate	Noise 1 kHz	THD 20-20kHz
<b>ON MC33078 (Dual) MC33079 (Quad)</b>	<b>16 MHz</b>	<b>7 V/<math>\mu</math>s</b>	<b>4.5 nV/ <math>\sqrt{\text{Hz}}</math></b>	<b>&lt;0.002%</b>

Rane Corporation

### Audio A/Ds: Stereo (2-Ch) ?-S 24-Bit

MFGR P/N	Sample Rate	Dynamic Range	SINAD (THD+N) <sup>-1</sup>
<b>AKM AK5394</b>	<b>192 kHz</b>	<b>123 dB</b>	<b>105 dB</b>
<b>Cirrus/ Crystal CS5396</b>	<b>96 kHz</b>	<b>120 dB</b>	<b>105 dB</b>

Rane Corporation

## Appendix A. Low-Voltage Audio Op Amp Selection Charts-3

[Compiled March, 2001— Consult Manufacturer for Latest or Replacement]

### Audio D/As: Stereo (2-Ch) ?-S 24-Bit

MFGR P/N	Sample Rate	Dynamic Range	SINAD (THD+N) <sup>-1</sup>
<b>Cirrus CS43122</b>	<b>192 kHz</b>	<b>117/192k 122/48k</b>	<b>100/192k 102/48k</b>
<b>AKM AK4395</b>	<b>192 kHz</b>	<b>120/44.1k ?/192k</b>	<b>100/44.1k 97/192k</b>
<b>AD AD1853</b>	<b>192 kHz</b>	<b>119/48k M 116/48k S</b>	<b>107/48k M 104/48k S</b>
<b>TI/B-B PCM1738</b>	<b>192 kHz</b>	<b>117 dB</b>	<b>108 dB/44 98/192k</b>

Rane Corporation

### Multichannel Audio D/As ?-S 24-Bit

MFGR P/N	No. of Chs	Sample Rate	Dynamic Range	SINAD (THD+N) <sup>-1</sup>
<b>AD AD1833</b>	<b>6-Ch</b>	<b>96kHz/6 192kHz/2</b>	<b>108 dB/44 ?/96/192</b>	<b>95 dB/44 ?/96/192</b>
<b>AKM AK4356</b>	<b>6-Ch</b>	<b>96kHz/6 192kHz/2</b>	<b>112 dB/44 105 dB/96 ? /192kHz</b>	<b>94 dB/44 92 dB/96 ?/192kHz</b>
<b>TI/B-B PCM1608</b>	<b>8-Ch</b>	<b>96kHz/8 192kHz/4</b>	<b>100 dB/44 99 dB/96 98 dB/192</b>	<b>90 dB/44 86 dB/96 84 dB/192</b>

Rane Corporation

### Audio Codecs ?-S 24-Bit

MFGR P/N	A/Ds D/As	Sample Rate	Dynamic Range	SINAD (THD+N) <sup>-1</sup>
<b>AD AD1836</b>	<b>4 A/Ds</b>	<b>48 kHz 96 kHz</b>	<b>105 dB ?</b>	<b>90dB ?</b>
	<b>6 D/As</b>	<b>48 kHz 96 kHz</b>	<b>108 dB ?</b>	<b>90dB ?</b>
<b>AKM AK4527</b>	<b>2 A/Ds</b>	<b>44.1 kHz 96 kHz</b>	<b>102 dB 102 dB</b>	<b>92 dB 83 dB</b>
	<b>6 D/As</b>	<b>44.1 kHz 96 kHz</b>	<b>106 dB 106 dB</b>	<b>90 dB 88 dB</b>

Rane Corporation

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