REFLECTIONS, ECHOES, & MUSIC

Hervé Delétraz examines whether impedance matching in audio is myth or reality

I use audiophile cables in my system, and I have no doubt about the improvement in quality they bring to my hi-fi gear. As an electronic designer, however, I was always intrigued by the fact that the differences in sound between good and bad cables could not be measured, or even "scientifically" explained.

Low-capacitance and/or inductance cables are often claimed in advertisements to sound better. Special dielectrics and wire shapes, twisted pairs or thin, braided wires, Litz configurations, and so on—all are described as being better. But are they? I will try to provide some of the answers to that question in this article.

Because I've tried to keep my explanations as simple as possible, I apologize in advance to the skilled electronic guys who will find this article a bit simplistic. But as *Stereophile* reaches the worldwide audiophile community, I guess that others will find it a bit hard to understand. I'll be glad to personally answer their questions at deletraz@bluewin.ch.

Another thing: Because I live in Europe, I'm used to working with the metric system, aka MKSA (meter, kilo, second, ampere) notation. Therefore, the symbol used here for V(olt) is U, A(mpere) is I, W(att) is P. "U" is defined as a potential difference in volts, "I" as the current Intensity in amperes, and "P" as the electrical power in watts.

Transmission Lines

Matching impedances is de rigeur in radio-frequency electronics, but is very rare in components intended to handle audio frequencies. Manufacturers build their components with low output impedances for sources like CD players, tuners, preamplifiers and so on, high input impedances for preamplifiers and power amplifiers.

Definitions: Though most of us know about impedance, few really know what it means. **Impedance** (Z) is to an alternating current (AC) signal what **resistance** (R) is to a direct current (DC) signal. So, if $R = U_{DC}/I_{DC}$, $Z = U_{AC}/I_{AC}$. Both R and Z are measured in ohms (Ω). The

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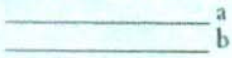
main difference between R and Z is that Z can vary with frequency—something you can see, for example, in a loudspeaker's impedance curve.

An *electrical* transmission line can be defined as being a device allowing an electrical signal to travel from point A to point B. In the hi-fi world, it simply means that a transmission line is, in fact, two or more wires that will let the audio signal pass from a source to a receptor.

Electrical transmission: Let's take the simplest electrical line—say, two copper wires, a and b, characterized by:



L = Total line length in meters, where L = La + Lb (m)
S = Section (area) of the copper wires used (m^2)
R = Total line resistance, where R equals Ra + Rb (Ω)

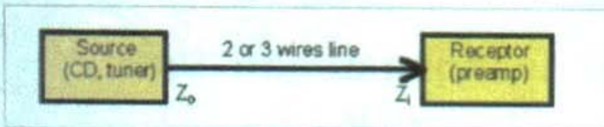


Fig.1 Typical audio-frequency electrical circuit, with $Z_i/Z_o \geq 10$.

For now, the parasitic capacitance and inductance are ignored. With a real circuit (fig.1), in order to minimize the perturbation effects of the line, it is usual to arrange that the impedances of the source and the receptor are as shown.

Almost all hi-fi systems use this arrangement: low output impedance, high input impedance. The minimum ratio for proper compatibility is 10 or higher, as stated above. Input and output impedances in tube machines are generally of higher value than those in transistor designs, meaning that a solid-state CD player output stage will easily drive a tubed preamp, but a tubed CD player's output could have some problem driving a professional, low-input-impedance solid-state amplifier. Nothing new there.

This impedance ratio of 10 is used worldwide for its design simplicity: no brainstorming problem when hooking our CD from Digital-Heaven to our Straight-Wire-Gain amplifier. Unfortunately, this simple impedance ratio doesn't take into account the properties of the interconnect cable.

Perturbations due to the Transmission Line: When hooking two hi-fi devices together, we generally don't know much about the characteristics of the cable we use. We may have been told that the cable is the best-sounding on Earth, that its insulation is made from very good dielectric material, that the wires are made from pure copper or silver, and that we paid a lot of bucks per foot for it. We are hardly ever told what the capacitance and inductance are per meter. After all, if the sound is good, who cares?

At the other end are the professional audio people, who tend to believe that copper is copper and therefore buy the cheapest cables. "Silver cables? What a joke!"

Whatever a cable is made of, whether cheap copper or pure platinum, its parallel wires behave as a transmission line in which the signal travels step by step. In the line, the signal will then propagate from the input to the output. That kind of signal is called a **propagation wave**.

Fig.2 shows the equivalent circuit of a real transmission line (as opposed to the theoretical one shown earlier). In order to simplify the diagram, only one wire is drawn. (The return wire is represented by the ground path.) In a symmetrical line, the top half of the diagram would be mirrored for the cold signal or return half, but the principle remains the same.

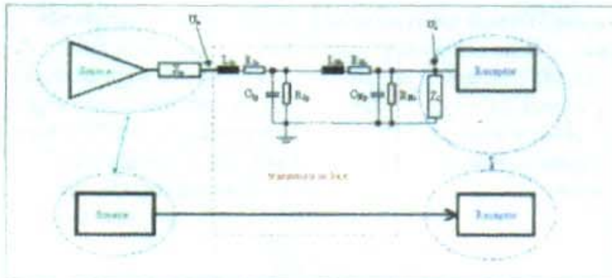


Fig.2 Equivalent circuit of a real transmission line.

You can easily see that a real transmission line is much more complex than the two-wires model. In order to better understand that the signal is propagating through the line as a wave, we also need to take into account the parasitic aspects of the line: the specific capacitance and the specific inductance.

This relative complexity partially explains why most cable manufacturers don't reveal too much about their products. In fact, *any* cable can be represented by fig.2:

First, let us consider that the cable is purely resistive. The parasitic capacitance and inductance can therefore be ignored, and it becomes easy to calculate the signal level at the input of the receptor:

$$U_i = U_o \frac{Z_i}{R_c + Z_o + Z_i} \quad [V]$$

With: U_o = Output source voltage without load
U_i = Input receptor voltage when the line is connected
R_c = Total series resistance of the cable (negligible for $L \leq 20m$.)

A quick computation shows that if Zi/Zo = 10, the attenuation factor is about 0.83dB, provided that the cable resistance itself is far lower than those of the source and receptor involved.

In this case, if we consider the two-wires model, the attenuation is constant throughout the entire audio frequency range and does not affect the frequency response.

A real transmission line is much more complex than the two-wires model.

Now take a look at the real, physical parameters of the transmission line—simply put, its **intrinsic impedance**.

Important note: Contrary to common belief, the frequency response does not *depend on the parasitic capacitance and/or parasitic inductance!*

It's well known in the audiophile community that high capacitance and/or high inductance of the cable *by itself* can severely affect the signal response. *Wrong!* In fact, one must think of a cable exactly as one thinks of the transmission line described in fig.2, where each portion of length is made of a partial series inductance Lxs, a partial series resistance Rxs, a partial parallel capacitance Cxp, and, finally, a partial parallel resistance Rxp, where the *x* varies from 1 to N for N parts composing the entire line.

In order to avoid mathematical complication not needed here, one can imagine that each portion of the line stores the energy before releasing it in the next portion. It's like a human chain extinguishing a fire by passing buckets of water from hand to hand — if everyone is careful, no drop of water is spilled. In fig.2, this ideal situation can be obtained by omitting resistors Rxs and Rxp.

Practically, however, losses due to imperfect materials lead to additional attenuation. But the **intrinsic** bandwidth of *any* cable is as high as several megahertz (MHz), a thousand times the best golden-eared audiophile's upper hearing limit.

So why explain all of the above if all cables can handle such high frequencies, and why care about the matching impedance, provided that Zi/Zo is greater than 10? The **intrinsic** bandwidth is the key thing here. As the cable behaves like a transmission line, it has practically unlimited bandwidth *only* when correctly matched in impedance.

Matching impedance is the only way to avoid echoes and data loss.

Before going further, a short detour into another well-known world could help.

A Brief Digital Detour

Digital Links: The confirmed audiophile knows that only true 75 ohm S/PDIF cables can offer good data transmission between a CD transport and its associated D/A converter. This 75 ohm figure is called the cable's **intrinsic impedance**.

In the same manner, the networks used to link computers also need the use of specific cables with determined intrinsic impedance. In such a network, the source, the line, *and* the receptor work under the very same impedance. When care is not taken that those impedances are identical, parasitic echoes will smear the signal, introducing data errors.

Matching impedance is the only way to avoid echoes and data loss. Later, we will see how and why.

The Sound of Digital Cables: Anyone, audiophile or not, who uses different S/PDIF cables can hear differences among them. How is this possible? After all, ones and zeros are bits.

The main reason digital cables sound different is because they aren't always perfectly matched. Cables rated at 75Ω ±2Ω are tricky to manufacture, and can introduce jitter due to the echoes resulting from the mismatched impedances smearing the datastream. In the extreme case, these echoes can lead to misinterpretation — a "1" can be taken for a "0," and vice versa.

Digital Matching Impedance: Why match digital lines but not analog lines?

A good question. In the digital domain, the frequencies involved are in the MHz range, so even a very small echo leads to data smearing. In the analog domain, the frequency range is 500–1000 times lower, so the problem of echoes is very small. It is arguable whether or not the ear can detect such small anomalies?

Intrinsic Cable Impedance

Calculation According to Manufacturer Specifications: A cable's intrinsic impedance mostly depends on the cable's physical dimensions. This impedance is defined by the linear capacitance *and* the linear inductance, given in Farads per meter (F/m) and Henrys per meter (H/m), respectively.

Once again, I'll skip the mathematical demonstration and go directly to Formula 3, which gives a cable's intrinsic impedance:

$$Z_c = \sqrt{\frac{L_l}{C_l}} \qquad [\Omega]$$

Where:	Z_c = Intrinsic impedance of cable	[Ω]
	L_l = Linear inductance of cable	[H/m]
	C_l = Linear capacitance of cable	[F/m]

Unfortunately, It's not easy to get hold of a cable's linear parasitic values. Very few audio manufacturers give out that kind of information, simply because they are much less impressive than such words as "pure," "fast," "transparent," and so on.

High-frequency cables, like those used for TV or FM antenna feeds, clearly display their intrinsic impedance. Manufacturers even give the linear capacitance, sometimes indirectly as a cable's **propagation time** in nanoseconds per meter (ns/m).

The linear figures act directly on the propagation time. The more capacitive and/or inductive a cable is, the greater the propagation time is. As this propagation time can be seen to be a pure **delay**, you can now better grasp the fact that the cable's bandwidth does *not* depend on them.

For most cables, the propagation time is around 5ns/m, corresponding to a **propagation speed** of 2×10^8m/s, or two-thirds the speed of light.

The propagation speed is given by Formula 4:

$$V = \sqrt{\frac{1}{L_l C_l}} \qquad [m/s]$$

Where:	V = Speed of the propagation wave	(m/s)
	L_l = Linear inductance of cable	(H/m)
	C_l = Linear capacitance of cable	(F/m)

Calculation According to Physical Dimensions: Because the electrical data are often missing, one can use a different way to figure a cable's intrinsic impedance — by measuring its physical dimensions.

This method requires some care if one wants to obtain accurate results, but is very useful when one needs to know a cable's impedance. The advantage is that the intrinsic impedance does not depend on a cable's length; consequently, only a few measurements are needed.

A) Coaxial Cable:

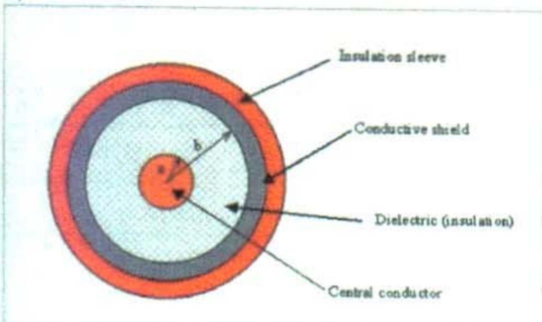


Fig.3 Coaxial cable construction.

$$Z_c = \frac{1}{2\Pi}\sqrt{\frac{\mu_0 \cdot \mu_r}{\varepsilon_0 \cdot \varepsilon_r}}\ 1\left(\frac{b}{a}\right)\ [\Omega]$$

With: Z_c = Intrinsic impedance of cable [Ω]
μ_0 = Inductance constant = 1.256 x 10^6 (A x s)/(V x m)
μ_r = Relative permittivity, here µr = 1
E_0 = Influence constant = 8.859 x 10^{12} (V x s)/(A x m)
E_r = Relative dielectric factor, here Er = 2 (PVC, plastic, Teflon)
a = Central conductor radius (m)
b = Internal shield radius (m)

It is possible to observe that the impedance is directly dependent on the b/a ratio. A small-diameter cable could have the same impedance as a thicker one, provided the central conductor is proportionally thinner, thus keeping the same b/a ratio.

If only small power is involved, a very thin cable could be used with no degradation of performance.

B) Bifilar Cable:

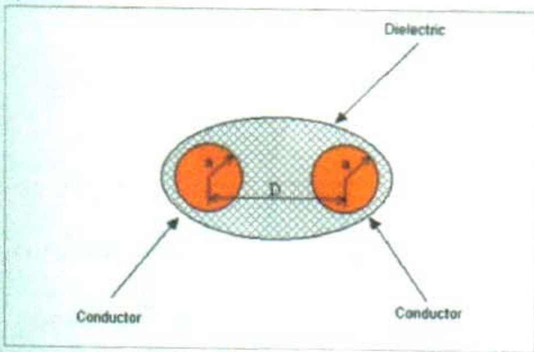


Fig.4 Bifilar (flat-twin) cable construction.

$$Z_c = \frac{1}{\Pi}\sqrt{\frac{\mu_0 \cdot \mu_r}{\varepsilon_0 \cdot \varepsilon_r}}\ 1\left(\frac{D}{a}\right)\ [\Omega]$$

With: Zc = Intrinsic impedance of cable [Ω]
µo = Inductance constant = 1.256 x 10^6 (A x s)/(V x m)
µr = Relative permittivity, here µr = 1
Eo = Influence constant = 8.859 x 10^{12} (V x s)/(A x m)
Er = Relative dielectric factor, here (Er = 2 (PVC, plastic, Teflon)
a = Conductor radius [m]
D = Distance between conductors [m]

Once again, you can see that the impedance depends on the physical distance between the conductors.

Intrinsic impedance of typical cables:

Coaxial cable RJ58	50	[Ω]
Coaxial cable RJ59 (S/PDIF datalink)	75	[Ω]
DNM speaker cable	288	[Ω]
Typical speaker cable (Monster)	117	[Ω]
OCOS (coaxial) speaker cable	60	[Ω]
Typical Klotz microphone cable	150	[Ω]

Important note: The theoretical lower limit for a bifilar cable is about 60 ohms, as that is the value reached when the two wires touch. A coaxial cable, however, can have an impedance as low as 0 ohm, provided its dielectric insulation is made of infinitely thin material. This limit, too, is theoretical.

True Impedance Matching of an Audio Line

Concept: We are here reaching the heart of this article. As described earlier, the term "true impedance matching" is in fact referring to the **power** impedance matching. Then we saw that the ratio between source and receptor is generally Zi/Zo ≥10. When applying the power-matching concept, the following principle is used:

$$Z_i = Z_o = Z_{cable}$$

Note: In using such a ratio, the signal attenuation will be 6dB, and not the 0.83dB in fig.1. This small caveat is the price to pay with this kind of linking. The solution is to turn up the volume slightly.

Propagation Wave Reflections: When the impedance is mismatched, a part of the outgoing signal from the source is reflected by the receptor.

In order to better show this phenomenon, we conducted all the following measurements using a 75 ohm coaxial cable 100m long. This cable had a propagation time of 5ns/m, or about 500ns for the signal to travel from the source to the receptor.

The reflection ratio of the generated propagation wave is given as follows:

$$\delta = \frac{Z_L - Z_c}{Z_L + Z_c}$$

Where: δ = Reflection coefficient (ratio)
Z_L = Receptor load impedance [Ω]

The source impedance is not taken into account because a source mismatch will act on the signal attenuation, not on the reflections themselves.

Formula 8 shows that even a slight deviation already generates reflections, or echoes; it will be of primary importance to keep the nominal values as tight as possible, in order to maintain the deviation within 1–3%. Furthermore, a symmetrical deviation leads to asymmetrical reflection ratios. Thus, +3% in the receptor impedance corresponds to +1.4% reflection, while –3% leads to –1.5% of reflection.

The impedance of high-end digital S/PDIF cables is generally 75Ω ±2 ohms, representing a tolerance of 2.7%, resulting in a reflection factor of around 1.35%.

In analog audio, the almost total mismatch of source and receptor impedances gives very high reflection ratios of close to 1, or 100% reflection! This is the worst case, but you and I listen to such mismatched systems every day with great pleasure. So what?

We will now examine what bad effects are induced by a mismatched line, using a high-quality, wide-bandwidth digital storage oscilloscope to examine the actual waveforms.

Perfect Matching: In fig.5, a 500ns pulse width is applied to the 75 ohm coaxial cable. Both source and receptor also have an impedance of 75 ohms.

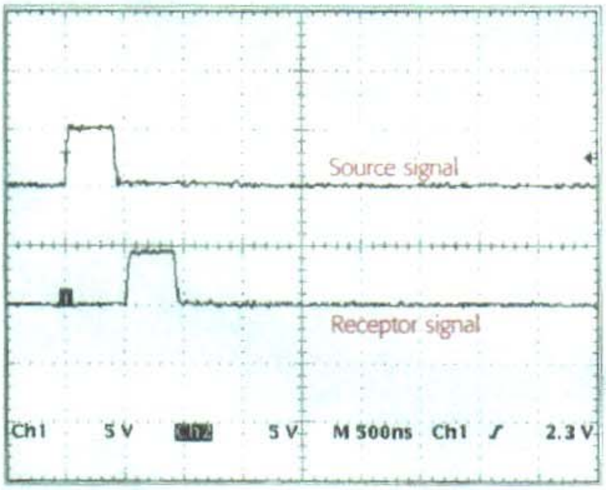


Fig.5 Transmission through 100m of 75 ohm coaxial cable. Out = 75Ω, In = 75Ω.

The signal at the receptor is exactly the same as the one from the source, except for the very slight attenuation due to the pure line resistance. No deformation here, even after 100m of travel.

The time delay of 500ns between source and receptor perfectly corresponds to the propagation time of 5ns/m times 100m.

The somewhat rough traces are artifacts of the oscilloscope input A/D converter and are not to be interpreted as noise or cable problems.

Source/Cable Matching Only: In fig.6 we can clearly see that when the receptor has a much higher impedance than required, the source signal is totally reflected by the receptor. The total delay of the echo to the source is 1µs, as expected, the signal having traveled forth and back — say, 200m at 5ns/m.

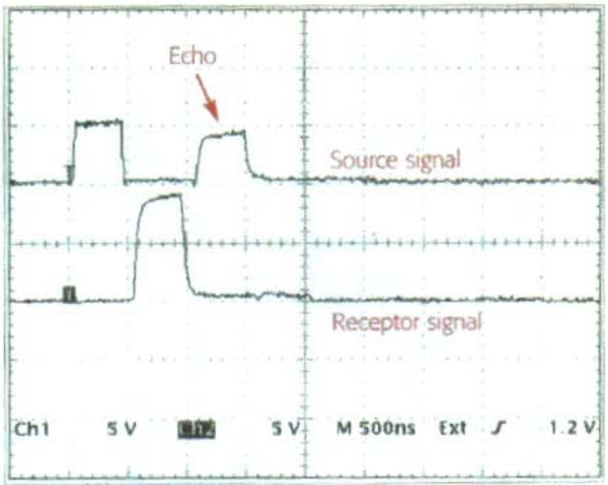


Fig.6 Transmission through 100m of 75 ohm coaxial cable. Out = 75Ω, In = 1MΩ.

There is now an amplified pulse arriving at the receptor and its shape is altered, with a slower risetime and a tilted plateau. If the cable is being used to transmit digital data, it should now be more than evident that the choice of cable will affect the resulting sound, given this degree of impedance mismatch.

Figs.5 and 6 show the two extreme cases. It is important to remember that even smaller echoes are echoes nonetheless, and that their perturbational nature will undoubtedly affect the signal.

Total Mismatch: Same sourced signal, same 75 ohm cable, but both source and receptor with unmatched impedance. This is, in fact, **always the case with audio gear**. The chosen impedance values are similar to those found in today's audio gear, with a 150 ohm source feeding a 10k ohm receptor.

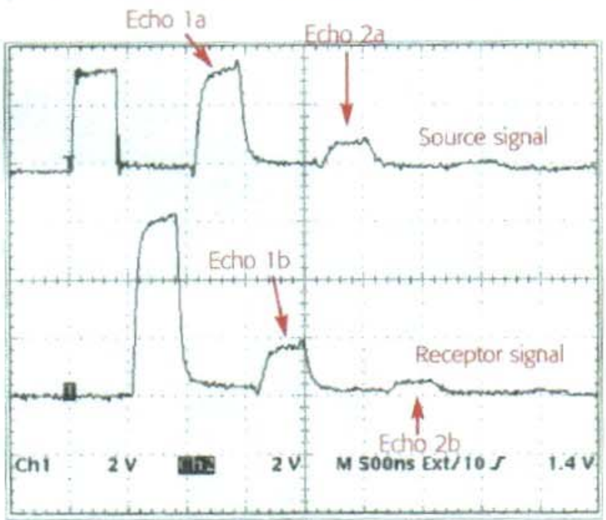


Fig.7 Transmission through 100m of 75 ohm coaxial cable. Out = 150Ω, In = 10kΩ.

Now many echoes become visible. Echo 1a is due to the 10kΩ receptor impedance, which itself induces echo 1b on the 150Ω source impedance, which generates echo 2a, and so on. These echoes are clearly visible here because the sourced signal is of very high frequency and small pulse width.

As we will see, these multiple echoes will also affect the signal at much lower frequencies, even if the result is often misinterpreted.

Perfectly Matched Audio Signal: In fig.8, an **audioband** signal is being sent through the cable. The rectangular shape is surely not very musical, but the 10kHz frequency is well in the audio range—even older people can hear it. The entire chain is matched; *ie*, the source, cable, and receptor all have

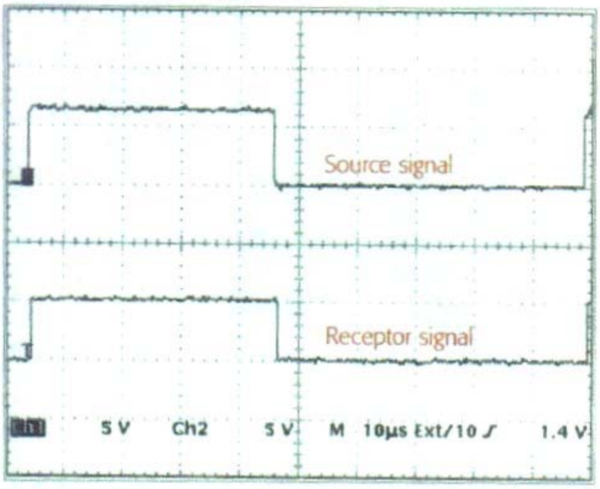


Fig.8 Transmission through 100m of 75 ohm coaxial cable. 10kHz fully matched signal.

the same impedance of 75 ohms.

The pulse width is much higher here, the signal period being 100µs, or 20 times higher than the signal's traveling time through the 100m cable.

There is nothing wrong to be seen in fig.8: The signal at the receptor perfectly mirrors the signal from the source.

Mismatched Audio Signal: Fig.9, too, shows source and receptor impedances close to those of real-world audio gear. Lower source and/or higher receptor impedances would be even worse. The choice of coaxial cable is not important; any cable used in such a mismatched arrangement would have the same behavior.

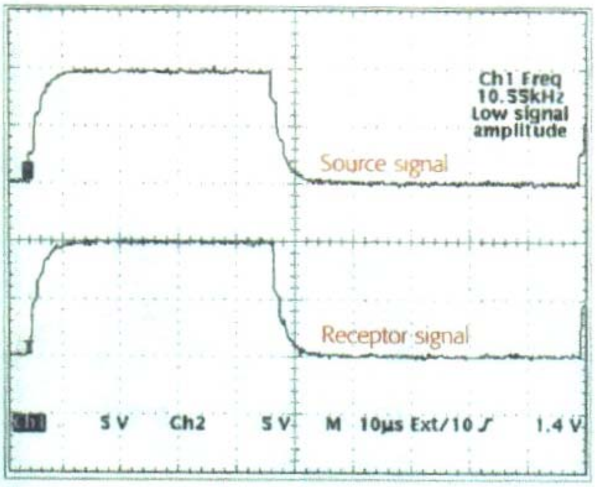


Fig.9 Transmission through 100m of 75 ohm coaxial cable. 10kHz, Z_o = 250Ω, Z_i = 10kΩ

Surprise, surprise—high-frequency attenuation, as revealed by the longer risetime of the pulse's leading edge. As manufacturers and audiophiles have being saying for decades, it's the parasitic capacitance that acts as a low-pass filter. When using 100m of cable, you'll be lucky if the result is not worse!

What's the point of writing an article that explains what everybody already knows? Well, what if fig.9's resolution wasn't high enough? What if the rounded shape of the signal was due, not to reduced bandwidth but to multiple echoes? You might find this hard to believe, but take a look at fig.10.

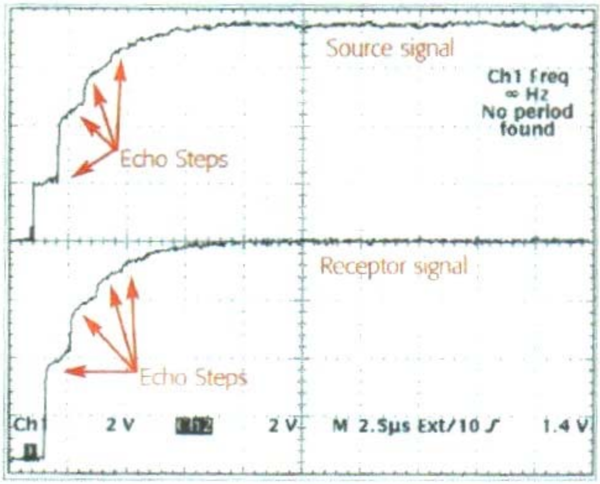


Fig.10 Detail of fig.9.

See? I was surprised myself. What we take as being due to high-frequency attenuation is, in fact, the superimposition of multiple echoes spaced apart by 500ns, which corresponds to the propagation time of the cable. As each echo is delayed by the propagation time, they add together, forming steps exactly like the discrete echoes seen in fig.7.

Fig.10 clearly shows that the signal will be modified when links are not perfectly matched. *Such mismatching represents 99.99% of the audio gear in the world, including high-end systems.* In other words, *your* system.

It's true that, if the cable is only 1m long instead of 100m, the problem will be divided by 100. Divided, yes; eliminated, no.

Can the ear detect the difference between matched and mismatched audio lines? I'm tempted to say "yes," but I have not conducted serious comparative listening tests. The measurements were conducted only a few months ago (February 2001), and the results were so surprising and interesting that I couldn't wait to share them with you.

Practical Considerations

Matching Lines at Home: We just saw that matching impedances *does* improve a system's measured performance. Does it contribute to better clarity in sound? The big question is whether the average audiophile can easily adapt her/his audio system to directly benefit from matched impedances.

System Disparities: Every manufacturer imposes his own standards, so it's not easy to match an existing system to the cables used without seriously modifying components and thus voiding their warranties. Furthermore, most audiophiles are not familiar with electronic tweaking.

A smart solution is to add an active box at the source and a passive one at the receptor end. The problem is finding a system transparent enough—one that won't degrade the sound more than the matching action would improve it.

This matching option is different from that offered by those cable manufacturers who include black boxes with their flagship cables. The boxes, all passive, don't take into account the real impedance of the components, because they can't "know" which components you will link together.

At the other end, a few high-end manufacturers offer such matched linking as an option, but this is very rare.

Matching Modules: These modules, inexpensive by high-end standards, adjust the source and receptor impedances to that of the cable used. Any skilled DIYer will be able to build them. The only critical component with respect to sound quality is the active module, but some ICs are now of high-end quality.

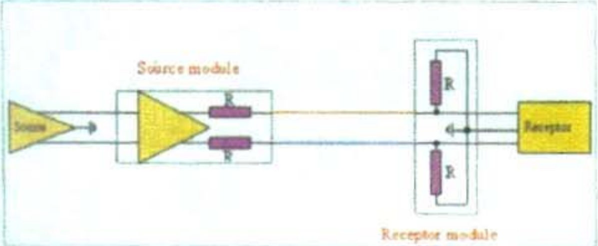


Fig.11 Impedance matching modules.

Fig.11 shows a symmetrical (balanced) matching module. For single-ended (SE) operation, only half the components need be used; *eg*, only one matching resistor R at both ends.

The source module is basically an op-amp, or a very-high-speed discrete buffer, with the desired matched series output impedance. The receptor module is much simpler, using only two resistors—or even one, for SE operation—of the same value than those used in the source module, connected to the signal ground path.

Both modules should be sited as close as possible (100mm, 4", or less) to the components. The great thing then is that the line between them can be as long as needed, with virtually no signal degradation.

The four resistors R (or two for SE operation) all have the same value as the cable. For example, if we use Klotz microphone cable, which has an intrinsic impedance of 150 ohms, all resistors should also be 150Ω.

If a cable of unknown impedance is used, we can calculate the impedance using Formula 5 or 6.

Subjective Thoughts

Audiophiles view the subject of cable sound differently from mass consumers and even from most of the pro audio community. For the latter, wires are wires, no matter what kind of cable they use. For the audiophile, cables are considered components in themselves.

Who is right? Maybe both. I'm not saying that *any* cable can be used to interconnect hi-fi components. I use silver cables in my system and find that they sound pretty good. However, as in most systems, my links are not matched. Not yet.

When you use mismatched links, it becomes obvious that every cable will have its own sound signature. I believe that if perfect matching is performed, the cables will tend to have reduced influence when it comes to affecting the system's sound quality. I strongly recommend that curious tweakers experiment with impedance matching. The first steps can be taken at very low cost—perhaps this could be another tweak to be discussed in J-10's "Fine Tunes" column? Provided you own a CD player or other source with a known impedance of 50 ohms or less, you can try this little experiment, which doesn't involve modifying your components:

- Calculate your cable impedance with Formula 5 or 6.
- Add a complementary series resistor at the output of your CD player.
- Terminate the cable at the preamplifier with a parallel resistor between the signal wire and ground.
- Listen for differences.

A Practical Example: Your CD player has an output impedance of 30 ohms. After calculation, you find that the intrinsic impedance of your interconnect is 250 ohms. By inserting a series 220 ohm resistor directly at the output of the CD player—or, even better, inside the interconnect's RCA jack—you get a source impedance of 250 ohms.

At the other end of the cable, put a 250 ohm resistor between the signal wire (central pin of an RCA jack) and the ground. Provided the preamp's input impedance is high, this gives you a receptor impedance of 250 ohms.

Do this again for the other channel.

This trick works only if your player's output can drive a low load impedance without a significant increase of total harmonic distortion (THD). With solid-state output, this trick is nondestructive, provided the output impedance of the player is less than 100 ohms. In practical use, even a short at the player's output will not destroy anything, the output circuits being designed to handle such bad treatment. For tube output, forget it. A matching module will be needed.

It is 100% guaranteed that the sound will dramatically change. But was the change for the better or the worse? Let me know. If you lose dynamics or bass, it is only because your player's output can't handle such a load—you'll need a matching module.

If you're not sure about how to do this trick, your questions are welcome.

Conclusion

As you all know, every high-end product tries to offer the best sound by modifying the audio signal as little as possible. This is very difficult to do using active components, and some degradation cannot be avoided. In the cable, where the signal is "only" passing through, it would be too bad not to try to eliminate a known source of signal degradation.

As we saw above, a mismatched link leads to a smeared signal response, however small the amount of the smearing, the signal is still distorted. Echoes are a physical fact, even if they are very small. Canceling them by matching the transmission line is cheap and easy to do; the result can be both measured and heard.

It is still a bit early to claim that matching the impedances of cables and interconnects will make 2 cents/meter cables sound as good as $1000/m ones. But I'm convinced that $1000/m cables *do* sound better when matched in impedance with the source and the receptor.

Why wait any longer?

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