"MATCHING" SIGNAL INTERCONNECTIONS OF PROFESSIONAL AUDIO COMPONENTS

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Suppose you have a bunch of line-level audio components — for example, mixer inputs and outputs, signal processor (equalizers, noise reduction systems, delays, etc), inputs and outputs, tape recorder inputs and outputs — and you need to interconnect them variously so that they all work correctly. Well, a circuit-theory expert, given a computer and some time, can hook anything to anything else, and make it work pretty well. But that's no help when you're setting up for a recording session and the producer says: "Hook that up, and I want it ready to go in five minutes!" So you would like to have your circuit designer come up with a system such that you can hook any line level unit to any other one, without having to think about circuit design.

You might answer: "Just match them together." The expression "matching" has become rather an audio buzz word, but what does it really mean? Let's start with a general definition of matching. Dictionary definitions that come closest to the usual audio meanings are: "To fit together or make suitable for fitting together"; and "To put in a set possessing equal or harmonizing attributes." So yes, matching properly *names* our requirement "to interconnect so they work right," but it does not say anything about *how* to do it.

In what way does the "interconnecting" affect "working right"? Well "works right" really means that the signal should not be changed (distorted) in the interconnection process: the signal received at the input of a component should be identical to the signal transmitted by the output of the preceding component. Two kinds of distortion are are likely to be introduced in the interconnection: first, the signal amplitude versus frequency at the "receiver" input could be different from that at the "transmitter" output; and second, the signal amplitude at the receiver input could be so small that it gets lost in the noise.

So our quest is to find an answer to the question: "How do we make an interconnection that has flat frequency response and does not reduce the dynamic range of the signal?"

Modelling a Transmission Line

So far we have mentioned inputs and outputs, but haven't said anything about a very important part of the interconnection: namely the *line* that connects one output to the next input. A generalized line is very complicated; a schematic of a generalized line is shown in Figure 1. This model consists of many series inductances and resistances (representing the distributed shunt capacitance and conductance of the line). You may be thinking that Figure 1 looks like a filter, not a line. And, in fact, it *is* a filter: it has a complicated frequency response, and even introduces losses at low frequencies. These losses and response depend not only on the line itself, but on the source and load impedances connected to the line. Thus, it would probably have a non-flat frequency response, and (because of the losses) could degrade the dynamic range of the signal.

Actually, this transmission line model must be used when the interconnecting line is more than about a tenth of a wavelength in that particular transmission medium for the highest frequency to be transmitted. For audio signals in "free space," which involve a 20-kHz bandwidth, one wavelength is 15 km, so the complicated model must be used for lines longer than roughly 1,500 yards. Thus, for telephone work this model is necessary and, in fact, telephone engineers developed the theory and practice of designing and using such lines starting around 1890(!). By the late Twenties they had codified it in textbooks on transmission networks, such as the 1929 book by Shea (Reference #1).

This transmission line has a characteristic impedance that is determined by the physical properties of the line — wire size and spacing, and insulation dielectric constant. The transmission line and filter theorists developed the simplifying concept of "image-impedance matching" of telephone lines (filters); briefly, at each interface (one output to the next input), the impedance was the same looking toward the source and toward the load. Since telephone "open-wire transmission lines" being used in those days had a characteristic impedance in the order of 600 ohms, all telephone equipment had an input and an output impedance of 600 ohms. The components were

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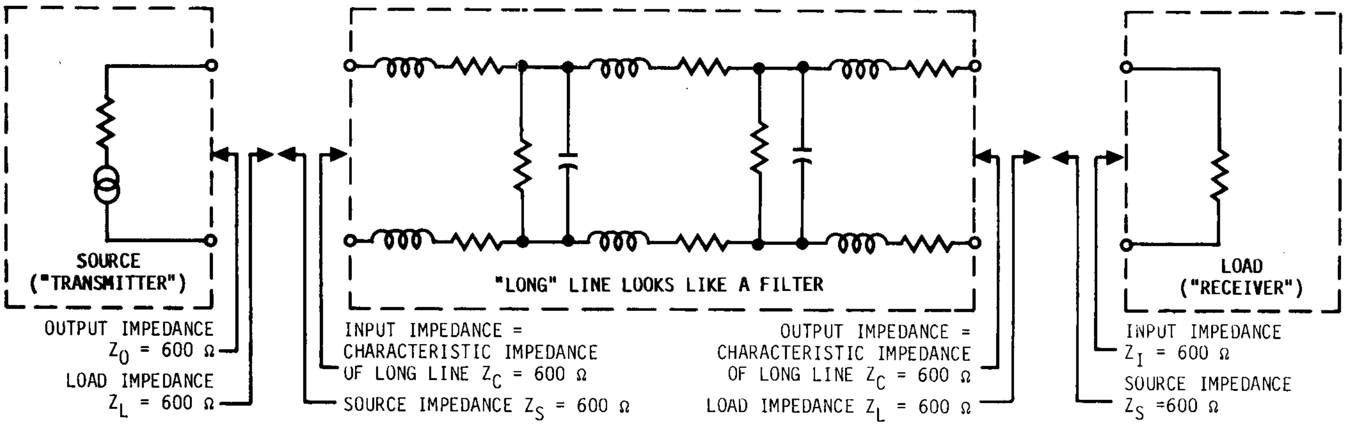

***Figure 1:** Schematic diagram of a long transmission line with a characteristic impedance shown as Zc=600 ohms, image-impedance matched to a source Zs=600 ohms, and a load of Zl=600 ohms. The lumped resistors, inductors and capacitors represent the distributed resistance, inductance and capacitance of the line, and constitute a filter whose response depends on the nature of the source and load impedances connected across it.*

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designed so that the system would have a flat frequency response and minimum loss when each source was connected to one load - no more and no less.

Most of the audio systems that we now consider to be professional audio — that is radio studios, motion-picture studios, sound-reinforcement systems, and sound-recording studios — were originally developed by telephone company engineers; based on the telephone theory, and often actually using the practical telephone equipment then available. After all, a telephone system has (at a given instant) one talker connected by one line to one listener, and that pretty well describes the original professional audio applications. In those systems there was often a telephone line between the microphone and the loudspeaker. "Audio perspective" experiments conducted in 1933 by the Bell Telephone Laboratories, for instance, were sent from Philadelphia to Washington, DC, by a carrier-system telephone line. Therefore, it is not surprising that these systems were assembled from 600-ohm, image impedance matched components, and that they performed their jobs very satisfactorily. Note that image-impedance matched systems work equally well with either telephone line interconnections or with the very short lines that are used within a studio. Consider also that active components (such as amplifiers) in those days were large and expensive, and were only used when absolutely necessary.

Contemporary Studio Practice

Now jump 50 years forward from 1930 to 1980. The telephone company and long lines are still there; they still have one source and one load; and they are still image-impedance matched with 600-ohm (or now often 150-ohm) sources and loads. Now, however, there are also large studio operations in sound recording, sound reinforcement, television and motion-picture facilities, wherein a very complex system of microphones, amplifiers, signal processors (equalizers, mixers, delay lines, noise reduction systems, etc), recorders, and loudspeaker systems are all used within a single studio. The result is that transmission lines are all short compared to a wavelength. Hence, a line can be modelled as shown in Figure 2; only a relatively small series resistance and shunt capacitance need be considered.

This line has no characteristic impedance to be image-impedance matched. But, on the other hand, the operating requirements are now quite different: sometimes a source — say a mixer output — is only connected to its output meter, and not to any other "receiver" (for instance, during preliminary setup and testing of a studio session). Conversely, sometimes that same source needs to be connected to several receivers, such as an equalizer input, one or more tape recorder inputs, and a monitor-speaker amplifier input. Thus, it would be convenient if receivers could be connected at will in a flexible way, in any number, without affecting the signal's level, frequency response, or dynamic range.

How might this be done? Very simply, and in just the same way as the power company delivers constant voltage to your house, and you connect to it whatever you wish, limited only by the total current made available by the power company's installation. If each audio component output is low impedance (say, less than 50 ohms), and designed to work into loads of, say, 600 ohms or greater, and each input is high impedance (say, greater than 10 kilohms), and designed to work from impedances of zero to 300 ohms, then any number of loads from none to 16 can be connected.

Figure 3 diagrams these input and output impedances. The level change from no load to five minimum-impedance (10 kohm) loads, with a maximum-impedance (50 ohm) source, would be 0.2 dB; the maximum level change in the worst condition — 50 ohm source and 600 ohm load — will be 0.7 dB. With practical audio lines, the level loss due to the series resistance of the line, and the frequency response change due to its shunt capacitance, are both negligible.

An Ideal Solution?

Surely, you will say, we can't get a fully-flexible, ideal system for nothing. Of course not; amplifiers and any transformers used must be designed to work properly over the stated impedance range; and more amplifier gain is needed than for a 600-ohm, image-impedance matched system, but amplifiers these days are small and inexpensive.

And surely, you will also say, it can't be this easy or people would already be doing it this way. Ah, but they are! A tutorial review of this kind of system was published by Snow in 1953 (Reference #2) and 1957 (Reference #3). This system has been in use in Europe for many years, and it has recently been standardized by the International Electrotechnical Commission (Reference #4). The values given in Figure 3 are taken from that standard. The use of such a system in a new ABC TV studio is described by Hess in Reference #5.

But more: have you looked at the input and output specifications for a contemporary professional recorder, such as an Ampex ATR-100, MCI JH-110, or Scully

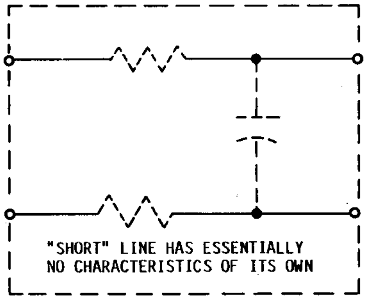

Figure 2: Schematic of a simple transmission line. The line has some series resistance and shunt capacitance as shown in dashed lines, but they are so small that they may be neglected. From an electrical design viewpoint, the line does not exist.

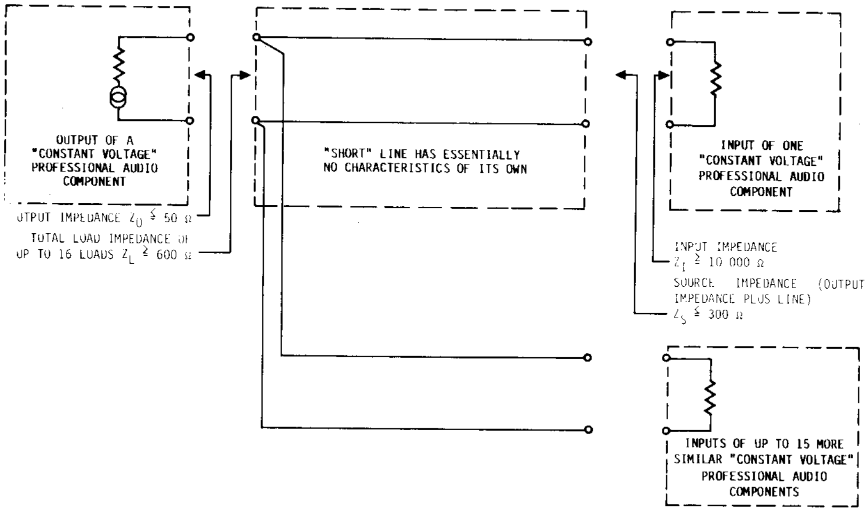

Figure 3: Requirements for source, output and load impedances for a "constant voltage distribution system", using the short line shown in Figure 2.

280B, or a noise reduction system such as a Dolby unit? *All* of these units meet the IEC constant-voltage distribution systems standard! In fact, you would be hard-put to find any stock commercial professional audio equipment that has an *actual* input or output impedance of 600 ohms.

Are these IEC-standard systems matched or not? Unfortunately many people in audio think that "matched" can only mean image-impedance matched and, of course, the IEC standard constant-voltage distribution system is not image-impedance matched. But, in the general sense of "suitable for fitting together," the IEC system most certainly *is* "matched."

In Summary:

1) Although image-impedance matched connections work on long or short lines, they are only *necessary* when working with long lines, such as the telephone-company lines. If you *need* image-impedance matching, then remember that hardly any US-made professional audio equipment has an actual 150 ohm or 600 ohm input or output impedance.

2) For interconnections with short lines, such as those within studios, constant-voltage matched connections give much greater flexibility of interconnection than image-impedance matched connections.

3) Constant-voltage matched connections are not only the IEC standard, but are also the *actual* standard for a large portion of the present-day US-made professional audio equipment. Even equipment that does not conform exactly to the IEC standard is usually much closer to the constant-voltage distribution system standard than to image-impedance matching. □ □ □

REFERENCES

1. T.E. Shea, *Transmission Networks and Wave Filters;* Princeton; D. Van Nostrand Co, 1929.

2. W.B. Snow, *Audio-Frequency Input Circuits; Journal of the Audio Engineering Society;* Volume 1, pages 87 to 94 (January 1953).

3. W.B. Snow, *Impedance — Matched or Optimum?; Journal of the Audio Engineering Society;* Volume 5, pages 66 to 70 (April 1957).

4. IEC Standard: *Publication 268-15, Sound System Equipment, Part 15: Preferred Matching Values for the Interconnection of Sound System Components;* International Electrotechnical Commission, Geneva, 1978: Section 2, Number 7 ; "Connections " (cables); and Chapter II "Broadcast and Comparable Professional Use"; Section 4, "Preferred Matching Values."

5. R.L. Hess, *Voltage Transmission for Audio Systems; Audio Engineering Society Convention Preprint #1708* (October 1980 - probably to be published in the AES Journal).

What About Microphone and Loudspeaker Interconnections?

I'm glad you asked, because they are "constant-voltage matched," too! But the reasons are different.

In microphone systems a very important consideration is obtaining the maximum ratio of the desired signal output to the noise generated by the microphone and the following amplifier. Early Western Electric microphone input systems loaded the microphone with 50 ohms. By the late Thirties, engineers had discovered that a 3 dB gain in dynamic range could be obtained by operating a microphone *not* into an equal-impedance load, but rather into an open circuit. RCA microphones and microphone pre-amplifiers starting in the mid-Thirties were designed in this manner, and essentially all microphones and mike pre-amps since then have used this "constant-voltage matched" principle. (Snow gives the details of the theory in Reference #2.) The IEC Standard for interconnecting professional microphones (Reference #4) calls for a microphone source impedance of 200 ohms or less, and a microphone amplifier input impedance of 1 kohm or more. Essentially all microphones and microphone amplifiers in use today meet these requirements.

In loudspeaker systems other factors are important: we want the maximum power output from the amplifier with minimum distortion; and we want the amplifier output impedance to "damp" the loudspeaker. Both of these goals are served by making the amplifier output impedance small compared to the loudspeaker input impedance — therefore you will find that all commercially available loudspeaker driving amplifiers and loudspeakers are "constant-voltage matched."

Amplifier output impedances are typically less than 0.4 ohms, and loudspeaker input impedances typically 4 ohms or more.

The "damping factor" value given for loudspeaker amplifiers is the ratio of loudspeaker impedance to amplifier output impedance. Typical damping factors are in the range of 30 to 100, verifying that the systems are constant-voltage matched.

Thus, the constant-voltage matched system is used in microphone systems, in line-level systems around a studio, and in loudspeaker systems. So where will you find "image-impedance matched" systems? In three places:

1] where the interconnecting line is long.

2] where the system was designed and installed prior to about 1960 or 1970, and

3] in audio articles and text books in which the authors have not recognized either the operational needs in modern systems, or the fact that hardly any modern audio equipment is image-impedance matched.

Old ingrained ideas die very hard!