The Effects Of Cable On Signal Quality

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System designs often require output amplifier stages of microphones and line-level devices to drive long lengths of cable with its associated capacitance. Most equipment works well in this application, but some equipment will allow significant signal degradation. The simple fact that measurable problems exist calls for more consideration of these factors by manufacturers. Until that happens, systems designers must pay more attention to output circuit specifications and performance.

Several years ago, I was asked to study the effects of different types of microphone cables on sound quality. I used time delay spectrometry (TDS) to measure microphone response with a variety of cable types and lengths. I fed a loudspeaker a TDS sweep via a power amplifier. Microphones were set up a short distance from the loudspeaker, and I measured the response with lengths of microphone cable varying between 5m and 150m. The receiving end of the mic cable was connected to a resistance typical of that found in modern mic pre-amplifiers (1,000Ω). Measurements were made with the input of the TEF analyzer bridging the microphone terminals (at the sending end of the line) and at the receiving end. I observed two important effects.

• *High-frequency peaking/ringing*. Some microphones exhibited a significant peaking of high-frequency response relative to their response with a short cable. This peaking was attributed to the capacitive loading of the microphones output stage by long (50m-150m) lengths of cable. I confirmed this assumption by substituting a fixed capacitance equivalent to the cable length and made all subsequent measurements with this fixed capacitance instead of the cable. (See Figure 1.) The degree of response peaking varies widely from one microphone type to another, amounting to more than +3dB at 15kHz in the worst case measured. No significant differences in frequency or phase response were observed from one cable type to another (except as related to capacitance per unit length) or from one end of the cable to another.

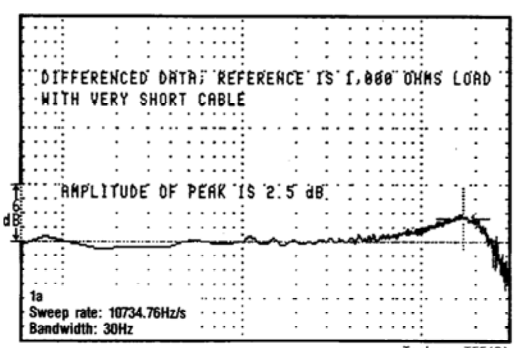
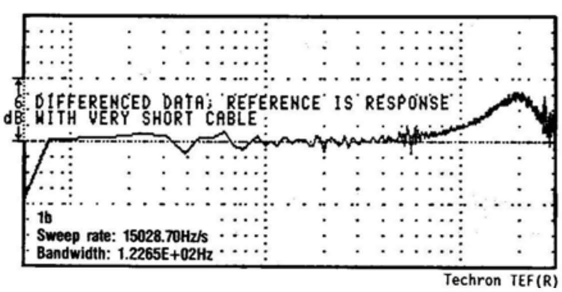


Figure 1A. Some microphones exhibited peaking of high-frequency response relative to their response with a short cable.



This peaking was attributed to the capacitive loading of the microphone's output stage by long lengths of cable. Figure IB (above) shows the same response with a fixed capacitance equivalent to the cable length.

• *Well-behaved* Most microphones exhibited some rolloff (typically -3dB at 30kHz) and resistive loss (typically 0.3dB) with cables of 1,000 feet or more. (See Figure 2.) The dynamic microphones measured primarily fell into the second category and tended to exhibit more rolloff than the condenser mics.

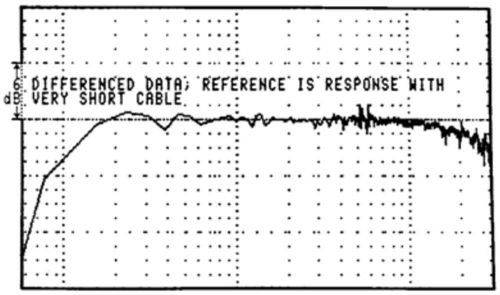


Figure 2. Most microphones exhibited some rolloff (typically -3dB at 30kHz) and resistive loss (typically 0.3dB) with cables of 1,000 feet or more. (Sweep rate: 15028. Hz/s; bandwidth, 122 Hz.)

Based on the microphone study, it seemed like a good idea to investigate the output stages of line-level audio devices. Once again, I used the TEF analyzer to drive the input terminals of the device under test and then measured the output. The device output was then connected to values of capacitance equivalent to cable lengths between 50m and 250m, with and without a 600Ω load resistance.

The results this time were divided into three categories of responses, depending on the design:

• *High-frequency peaking/ringing*. A significant peaking of high-frequency response was measured in only one manufacturer's equipment, but it was quite serious. (See Figure 3A.) Capacitance equivalent to only 50m (150 feet) of cable produced a peak of 7dB at 20kHz and enough phase shift to raise questions about stability, such as, will it oscillate? Increasing the capacitance to an equivalent cable length of 200m (650 feet) reduced the peak slightly, to only 6dB and moved it down to 13kHz. (See Figure 3) A system using this device is going to have serious problems with sibilance and will sound pretty "spitty" with music.

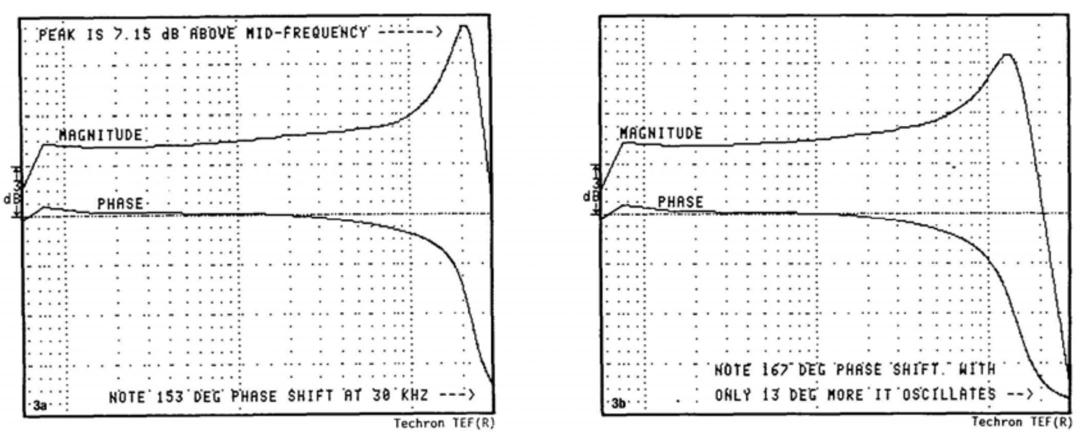


Figure 3. Peaking of high-frequency response was measured in only one manufacturer's equipment. Figure 3A shows peaking with a capacitance equivalent to 50m. Figure 3B shows peaking with an equivalent cable length of 200m. (Sweep rate: 7514 Hz/s: bandwidth: 87 Hz.)

• Well-behaved. A slight rolloff (typically -0.5dB at 20kHz) appeared with extremely long cables (2,000 feet or more) with most equipment that had output impedances of 100Ω or less. (See Figure 4.) This equipment had no measurable response variations with cables of 200 meters (650 feet) or less.

• *Excessive high-frequency rolloff.* A severe high-frequency rolloff appeared with equipment that used a 600Ω output stage — typically -3dB at 16kHz with 150m (500 feet) of cable and a high-impedance load. Adding a 600Ω load (at either end of the cable) raises the -3dB frequency to 32kHz (-1.5dB at 20kHz), but at the expense of 6dB of headroom. (See Figure 5.) Longer lengths of cable are proportionally worse. Any device that has an actual output impedance of 600Ω will have problems driving long lines. This is not the same as the unit's minimum recommended load impedance — nearly all pro equipment is specified for a 600Ω load, which indicates that it can supply enough current to drive the load.

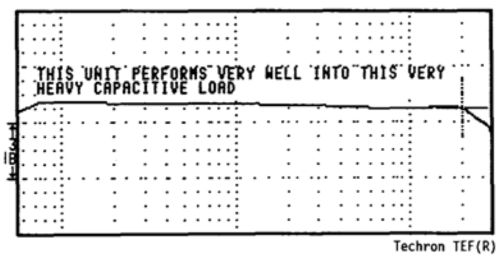


Figure 4. A slight rolloff appeared with long cables (2.000 feet or more) with most equipment that had output impedances of 100Ω or less. (Sweep rate: 7514 Hz/s; bandwidth: 87 Hz.)

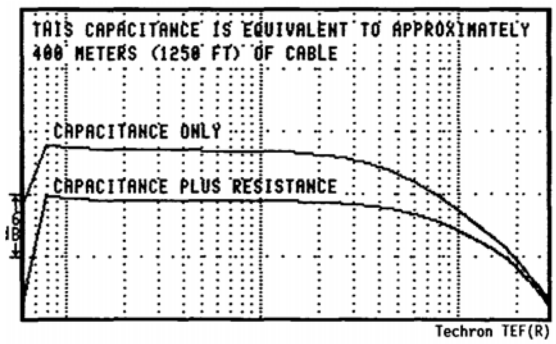


Figure 5. A severe high-frequency rolloff appeared with equipment that used a 600Ω output stage. Adding a 600Ω load (at either end of the cable) raises the -3dB frequency, but at the expense of 6dB of headroom. (Sweep rate: 7514 Hz/s; bandwidth: 87 Hz.)

Transmission lines Audio cables can act like transmission lines, but only when they are exceptionally long. To understand the concept of a transmission line, think of a length of electrical cable as a lot of tiny pieces of cable, all connected together, each having some series inductance and resistance, some parallel capacitance and some leakage resistance through its insulation. At high frequencies, the electrical signal's energy has to alternately charge and discharge the capacitance's electric field and the inductance's magnetic field. It takes time to do this, so it takes time for the signal to get from one end of a line to the other.

The distance the signal can travel in the time it takes a sine wave of a given frequency to go through one full cycle is its wavelength. Sound in air travels at about 1,130 feet per second, depending on the temperature. Radio waves travel in air and space at the speed of light — 186,000 miles per second. Electrical signals in transmission lines travel at some large fraction of the speed of light. This fraction (typically about two-thirds for common transmission lines) is called the velocity factor of the cable, or the velocity of propagation.

By studying how all of this works mathematically, electrical engineers learned long ago that if the signal frequency is low enough (or the line is short enough) and the length of the line is less than one-tenth of an electrical wavelength, don't worry —

the cable does not act enough like a transmission line. These short cables (short in terms of a wavelength) act like nothing more complicated than the sum of these parallel capacitances, series inductances and series resistances. When load impedances are high, the series inductance, like the series resistance, is too small to have significant effect.

Transmission line behavior is much more complicated. When lines get longer or frequencies get higher, the electrical signal can travel from one end of the cable to the other and be reflected back to the sending end, just like a sound wave bouncing off of a reflecting surface.

This kind of reflection happens if the transmission line is not terminated (loaded) with a resistance equal to its characteristic impedance, and is the reason video, RF, and high speed digital lines need to be terminated. A line with no termination (or a different value of termination) is called a mismatched line, and can smear the signal or even weaken it significantly when a reflected signal exactly cancels the forward one. A line with the proper termination passes the signal with no problems more severe than the lines simple resistive loss (which gets larger at radio frequencies, mostly because of skin effect).

The characteristic impedance of a cable depends on its wire size, the insulating material and the spacing between its conductors.[1] For modern audio cables, this is on the order of 60Ω. (A recent major cable manufacturer's catalog specifies nominal characteristic impedances of its audio snake cables as 50Ω for one type and 70Ω for another). [2]

The equation for calculating characteristic impedance is complex, and it isn't easy to determine what values to plug into the equation for a given cable. You can get a feel for this impedance intuitively, however, by comparing audio cables to some familiar cables of known impedance — RG58, RG-59 and 300Ω twin-lead, for example — and noting their relative conductor sizes and spacings. A 600 ohm cable that has conductors the same size as twin-lead (about #22) would need much wider conductor spacing than twin-lead would need. The electrical wavelength of a 20kHz signal in typical cable is nearly 10,000m (more than 6 miles). To start showing transmission-line effects, the cable would have to be at least 0.1-wavelength long, which, at 20kHz, is 1,000m (3,280 feet).

Significant harmonic energy is present in all live audio. Response problems up to 60kHz can cause measurable and audible distortion of the waveform when this ultrasonic energy is clipped or excites intermodulation, generating distortion products (including oscillation) inside the conventional (up to 20kHz) audio spectrum. [3] Minor transmission line effects will begin to appear at 60kHz with about 330m (1,100 feet) of cable.

Audio cable is available in three ranges of capacitance. Standard cable, including most flexible and snake cable, has about 30-34 pf per foot. Low-capacitance cable has about 20 pf per foot and is more expensive. Special cable constructions optimized to reduce noise pickup (star-quad and some double-shielded cables) have 46-56pF per foot. When you drive any of these cables unbalanced, the capacitance is approximately doubled. *[Ed note: Since this paper was written (1989), precision balanced cables have been introduced that are optimized for AES3 digital audio. These cables have much lower capacitance, typically 35-42 pF/m (12-13 pF/ft).]*

From the viewpoint of the cable and the load, the output impedance of the output stage driving it should be as low as possible. In a fine application note,[4] the late Deane Jensen showed that output stages need some isolation from the loads they drive, and he outlined methods of keeping that resistance as low as possible by using small wire-wound inductors. In a later application note, Jensen showed a 990 op-amp driving 2,000 feet of Belden 8451 as 50Ω cable via a 1:1 transformer.[5] His circuit adds 30Ω of fixed series resistance to the 40Ω loss resistance of the output transformer to provide the necessary isolation.

Other, more generalized applications are shown with a 10Ω output isolation resistor and wire-wound inductor in series with the primary of an optional output transformer. The first circuit would provide a 70Ω output impedance; the second would provide a 15Ω output without the transformer and 30 ohms with it. It seems likely that the output stage troubled with a strong peak above 10 kHz fails to provide sufficient isolation. Does this mean that output impedances lower than 70Ω are too low? No, not if they can drive all loads cleanly. Several units tested had output impedances in the range of 25Ω to 35Ω and outperformed any other units tested. In general, output impedance should be as low as possible consistent with good response, low distortion and stability (or no oscillation).

A microphone example Consider a 1,000 ohm load (a typical mic pre-amp) fed by a 150 ohm microphone and 1,000 feet of typical AWG #22 mic cable with a resistance of 16.5 ohms per leg and a capacitance of 0.034μF. This capacitance may not all come from a single run of cable or from the cable alone. (If a mic is split to drive a recording and/or stage monitor mixer, the capacitive load will be equal to the total length of all the parallel cables. If the input stage that is driven by the mic has some capacitance, or if a bypass capacitance was added to eliminate interference from an AM broadcast transmitter nearby, this capacitance will also add to the total.) The cable's total resistance of 33 ohms simply adds to the mic's source impedance of 150 ohms and forms a voltage divider with the 1,000 ohms load. The result is a resistive (flat with frequency) loss of 1,000/(183+ 1,000), or 1.46dB Only about 0.25dB of the resistive loss comes from the cable — if there were no cable loss, the resistive loss would be (1,000)/(150÷1,000), or 1.2 dB.

The capacitance forms a low-pass filter with the parallel combination of the 150Ω source and 1,000 load, having a -3dB frequency (f_{3dB}) of 1/(2πRC). The resistance for this circuit is (150x 1 ,000)/(150+ 1,000), or 130Ω, so f_{3dB} is 36kHz, and the mic's response will be down about 1.2dB at 20kHz. If the mic's output impedance were 100Ω, then f_{3dB} is 50kHz, the response will be only 0.6dB down at 20kHz, and the resistive component of the loss drops to 1dB. Figure 2 illustrates the effect of the cable capacitance on a well-behaved mic with an output impedance of 150Ω working into a load of 0.05μF.

A line-level example For line-level devices, the result changes because the impedances change, usually for the better. The modern audio output stages output impedance is 100Ω or lower, and input stages have input impedances of 10,000Ω or more. For the same 1,000-foot line, the resistive component of line-loss becomes 10,000/10,033, or 0.03dB. To find f_{3dB}: R is (10,000x100)/(10,100)=9.9kΩ and C is 0.034μF, so f_{3dB} is 47kHz, with a loss of 0.75dB at 20kHz. (See Figure 4.) Lowering the output impedance to 60Ω moves f3 up to 78kHz and reduces the loss at 20kHz to 0.25dB.

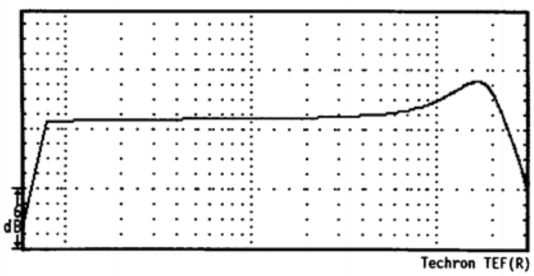
A 600 ohm example A 600Ω output stage doesn't work nearly as well. If the load is 10,000Ω, there is still no measurable resistive loss, but f_{3dB} happens to be another story. R is 10,000x 600/10,600=566Ω, C is still 0.034μF, and f_{3dB} becomes 8.27 kHz! If the 10,000Ω input impedance is changed to 600Ω, R becomes 300Ω and f_{3dB} is 15.6kHz. Better, but hardly an acceptable response, and the resistive termination loss is 6.25dB (Figure 5 illustrates this situation with a mic pre-amp and 400m (1,250 feet) of cable. Nearly all of the microphone tested would have driven the capacitive load three times better (with one-third the high-frequency loss) than the mic pre-amp. Because driving long lines is one of the major reasons for using a dedicated mic pre-amp, one has to wonder what the designer had in mind.

600 ohm circuits 600Ω output and input impedances are an anachronism left over from vacuum tube and telephone days, and they have no place in modern audio. 600Ω became an audio standard when intercity telephone circuits were made of lines that had 600Ω characteristic impedance. Matching to this impedance was the right thing to do then — it minimized standing waves on the lines, eliminated ringing and reduced losses. The standard continued into vacuum-tube days because tubes and their output transformers needed to be terminated with their design impedance to minimize distortion and prevent ringing. Solid-state circuits do not need these loads to perform at their best; the 600Ω resistors use up headroom, increase distortion and degrade frequency response. Much has been written on the subject by me and by others.[6,7, 8, 9, 10]

Back to the real world This survey of modern professional microphones shows that although actual output impedances vary a bit from their published value (all of the microphones tested were rated by their manufacturer for 150Ω), and although their actual output impedances ranged between 90Ω and 600Ω, most were between 100Ω and 300Ω. In general, the output impedances of condenser and electret condenser mics tended to be about half that of dynamic mics.

When our survey looked at line output devices, it showed that although their actual output impedances range between 24Ω and 600Ω, most were between 30Ω and 100Ω. Of all the equipment measured, only one manufacturer that called its equipment "professional" used an output impedance higher than 150Ω, and even two-thirds of the hi-fi equipment tested had output impedances lower than 600Ω. This situation has improved significantly from 10 years ago, when many professional audiotape and videotape recorders had 600Ω output impedances and needed 600Ω loads just to keep their VU meters calibrated!

Transformer outputs A small mixer using inexpensive output transformers produced ringing (a rising high-frequency response) with capacitive loads. (See Figure 6A.) This ringing is nearly eliminated when a 600Ω load resistance is added. (See Figure 6B) Does this mean all transformer outputs should be terminated? No, only the under-designed ones. Does this mean manufacturers should use better transformers? Yes.



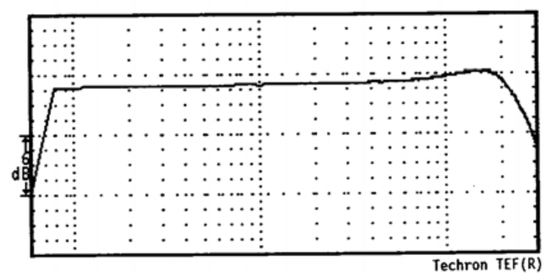


Figure 6. Equipment that uses inexpensive output transformers can produce ringing with capacitive loads, as shown by Figure 6A. This ringing is nearly eliminated when a 600 Ω load resistance is added, as shown by Figure 6B. (Sweep rate: 1977 Hz/s; bandwidth: 44 Hz.)

What about current? A capacitance of 0.05μF is only 160Ω at 20kHz, so this is not an easy load to drive, particularly at high signal levels. Output stages don't work hard until they supply significant amounts of current, and they don't supply much current working into a bridging (high-impedance) load. That's why removing the 600Ω load from a 50Ω output stage improves headroom by more than just the voltage divider ratio. Specifying an output stage for a 600Ω load means that it will supply that much current. But how many line-level output stages can drive a 160Ω load at +2OdBu? How many microphones can supply the current it takes to follow a voltage waveform from a closely miked trumpet, a sibilant vocal, or a cymbal crash working into this much capacitance? At mid-frequencies (below a few kilohertz), a mic may be able to handle peaks of +130dB SPL, but will it go into distortion when its output stage is asked to supply the current required to drive the low impedance of the capacitive load at these high frequencies?

A reasonable specification As users or systems designers, we would like all professional audio equipment to be able to drive a capacitive load of 0.05μF or less in parallel with a resistance of 600Ω or greater with minimal degradation in performance. Minimal degradation means that frequency response is +0, -0.5dB be- tween 20Hz and 20kHz, and +0, -1dB to 30kHz, which dictates that the output impedance needs to be less than 53Ω.

Are these necessary specifications? Yes, because cable has capacitance, and RF sometimes needs to be bypassed with capacitance. The 600Ω load capability allows many inputs to be driven in parallel by a single output stage without the use of distribution amplifiers and allows the use of simple resistive networks to combine multiple sources into a single input.

A number of other complex questions remain. For example, what are the waveshapes, and thus the transient voltage at high frequencies, under worst- case program conditions? How much derating of steady-state performance is reasonable for a mic or line amplifier if that device still must be able to follow these waveforms? Does an output stage really need to supply +20 dBu at 20kHz?

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