CABLES FOR DIGITAL AND ANALOGUE AUDIO

A short history of cable design

Telegraph signals combine elements of both analogue and digital electronics, and the first practical binary code electromagnetic telegraphs used two wires, connected broadly as we would wire an analogue audio circuit today. However during 1835-6, Carl Steinheil in Munich successfully showed that he could almost halve the landline costs by employing a single wire with ground return. Despite the vast distances of the terrestrial US telegraph systems (which were trans national by the 1860's), little was known about the electrical characteristics of these landlines, except for the importance of insulators. However, when undersea cables became involved, it was obvious that what we now know as 'bandwidth', was lacking.

Early cable designers failed to analyse this effect correctly. Famously, E.O.W. Whitehouse believed that with enough voltage, any cable could be successfully driven. This theory resulted in predictably nasty results on the first transatlantic cable.

By the 1890s, the choice of unbalanced landline operation was called into question for two major reasons. Firstly, unusual interference and landline characteristic changes on the long submarine cables, were guessed to be unknown effects of atmospheric electricity and the geomagnetic field. Interestingly, these mysterious effects motivated many of the early polar expeditions. Secondly, the emerging urban electric power distribution systems, along with traction (rail and tram) systems, all shared earth return circuits with the telegraphs and telephones. This led to the first proper use of twisted pairs, or for long distance telephones, four-wire circuits. Adding loading coils to these long circuits, formed a low-pass filter with peaking characteristics. This could flatten the electrical speech band response so that unamplified telephone calls could be made at distances up to 1000 km. By the 1920's, vacuum tube 'repeater' amplifiers enabled trans US calls to be made on these landline cables.

Analogue cables for high quality audio - best practice requirements

'Professional' audio uses twisted conductor two or four wire screened cables. The four conductor cables are used exactly as for two conductors using parallel connection of opposite pairs. The advantage of this four conductor 'star-quad' cable comes simply from the symmetrical electrical geometry that gives a better impedance balance between the two signal paths.

In either regime, each of the cable pairs can be seen as a fixed 'lumped' capacitance or inductance depending on the receiving load. Typical transmission line impedances are 30 to 70 ohms. As a result, the impedance (as 'seen' by the transmitting end) of two 10km open-ended cables, where the only difference between the two cables is the gauge size of the wires, if plotted against the signal frequency, will differ in the following way.

Since this produces a resistive characteristic, the two resulting curves will not start in the same place. However, as they get closer to the characteristic impedance, they get closer and closer together. If they have the same capacitance and inductance, they will eventually have the same value of impedance. Analogue audio cables are therefore normally driven from a low source impedance (50/100 ohms typically) with a high load impedance at the far end (10k ohm typically). There will be series copper losses and parallel dielectric loss. But signal losses across the baseband audio frequency range should certainly not exceed 1dB on a 100 metre run whatever the construction.

Balanced operation of transmission lines for high quality audio

Despite popular belief, a balanced signal is not necessary for noise rejection. As long as the two circuit impedances are balanced (including the cable), noise will couple equally into the two wires and be rejected by a differential amplifier, regardless of the signal that is present on them.

There are some benefits to driving the line fully differentially, though. The electromagnetic field around a differential line is ideally zero, which reduces crosstalk into adjacent cables. Also, for the same maximum signal level, the output from the differential drivers is twice as much, effectively improving the signal to noise ratio by 6dB.

Screening

Most audio cables are screened, and this keeps out the higher radio frequencies, and enables phantom power to be carried. However, telephone lines have always run over vast distances unscreened, and the BBC ran hundreds of metres of unscreened paper insulated cable successfully around Broadcasting House.

Because of the large dynamic signal range that can be expected on analogue audio cables, physical constructional characteristics such as balance, screening and noise induction (especially with flexing) become important. The different types of screening aim at different applications, and below is a list of the types normally met:

Serve or spiral shields can be made to be ultra-flexible. However, serve shields can open up when flexed, which compromises shield effectiveness. A spiral of wire obviously affects the inductance of the shield. Therefore spiral shields are rare in video and are usually used for audio only. There is a double spiral serve, also known as a 'Reussen' shield. This configurations 'shorts out' the inductive effect of a signal spiral, but the shield can still open up when flexed. The ultra-flexibility of these cables is a key.

Braid shields are formed by spinning wires or groups of wires around a core. and braiding is the most expensive single step of cable manufacturing. Single braid coverage of up to 95% can be realized. Double braid coverage can be up to 98% coverage. Since braids always have 'holes' where the wires cross, 100% coverage is not possible with braid. Braid shields are most effective at frequencies from 1,000Hz to 50MHz. For these frequencies, the low resistance of a braid gives good coverage. Below 1,000Hz there is no standard braid material which is effective. The wavelengths are so long, and the low frequency energy so pronounced, that the only effective shielding is solid steel conduit. And, even at 60Hz, steel conduit gives only 27dB of noise reduction! At frequencies above 50MHz, braid becomes 'wavelength dependant' where the holes look larger and larger as the wavelength gets smaller and smaller. The effective coverage of a braid gets worse and worse, especially compared to a foil shield, which has no holes.

French braid shields are a combination of serve and braid. A French braid consists of two serves braided along one axis. This gives cables excellent flexibility and excellent RF performance. This may be partly because the braiding 'shorts out' the inductive effect of serve shields and 'shorts out' the RF noise too. Maximum coverage of a French braid is 98%.

Foil shields are the easiest and cheapest to apply and they actually consist of two layers, a metal layer and a polyester substrate. Since foil shields lack the mass and low resistance of a braid shields, the exhibit poor to average low-frequency performance. However, after 50MHz, foil shields have excellent high frequency coverage. Since foil is a continuous sheet of metal, coverage can be 100%.

Combination shields consist of foil and braid combined. Occasionally there can be more than one layer of each. Because of this, combination shields are the most expensive of all. But they also give the best broadband coverage, since it contains a braid for low frequencies and a foil for high frequencies.

The difference between broadcast coax cables, which often contain foil and braid in digital applications, and CATV/broadband cable is that CATV cables use low coverage braid (sometimes as low as 40%). The reason is that these cables only operate above 50MHz. At those frequencies, braid shields are ineffective and it is actually the foil shield that is doing all the noise reduction. The braid shield is there just to give the connector something to connect to.

Conductors and dielectric

For any practical cable, the performance at all frequencies will improve with increased size, up to the point at which the core (or core to screen) width spacing becomes a significant fraction of the signal wavelength. Inside any screening braid, the ideal dielectric would consist of a vacuum, but practically the need to insulate and accurately space both the inner and outer conductors demands a dielectric material with tough physical and electrical characteristics. Air spacing or gas foaming will improve the electrical characteristics of any solid polymer at the cost of crush resistance, but accurate spacing of the conductors then becomes quite difficult.

For the most demanding applications expanded PTFE is currently the best dielectric, effectively reducing the size of any cable of fixed electrical performance by 20 to 30%, according to a specialist manufacturer of cables using this material, Gore. It is however difficult and hence expensive to produce.

On the conductor side, Gore exploit the 'skin effect' frequency dependent reduction of cable performance, by silver plating a resistive core, thus reducing low frequency performance to flatten the overall frequency response. They call this technology 'Eye-opener+', presumably from the digital electrical signal eye-diagram improvement produced. The value of these new techniques, and the associated cost, is however only worthwhile as very high digital data rates (e.g. video on coax) are approached.

Summing up therefore:

Analogue audio cables ideally require...

Good impedance balance - for noise rejection on balanced circuits. Essentially a question of preserving the physical symmetry of the cable throughout manufacture, installation, and use.

Low capacitance - 150 pF/m for short runs under 30 metres, down to 40pF/m for runs over 300 metres or where ultimate performance is desired (c/f digital cables).

Low resistance - 0.4mm diameter centre conductor for short runs under 30 metres where ruggedness is not an issue, but 0.65mm or more for runs over 300 metres or where ruggedness is essential.

Low crosstalk between pairs - Foil shields for RF protection, braid shields for low self-noise and protection 1kHz to 50MHz.

Good Physical performance -

- Flexibility, including good maintenance of electrical performance after much flexing in use.
- Low Self-noise generation. Audio noise can be produced as a side effect of physical deformation of a cable. This physical deformation leads to electrical deformation, particularly in capacitance and balance, hence resulting in signal modification, or conversion of phantom power voltage to audio frequency noise.

Digital cables - best practice requirements

Digital audio cables actually deal with a narrower bandwidth spread (less octaves) of signal frequency signals than for analogue audio. AES/EBU digital audio covers roughly the frequency range from 1.5 to 6MHz at a 48kHz sampling frequency, with a small amount of energy down to 100kHz. Because of the high frequencies, however, we can only treat the cable performance in the same way as analogue up to lengths of 5 metres or so. Cable lengths over 15 metres will start to show different source impedances depending on the length and the frequency presented, unless driven at the physically controlled characteristic impedance of the cable. This is simply the transmission line effect coming into play.

Cable resonances

Apart from frequency dependent losses, once any cable length exceeds several wavelengths at the signal frequency, cables have the potential of exhibiting resonances due to small cyclic physical variations, rather than the bulk transmission line reflected signal resonances caused by poor electrical terminations. A digital signal actually consists of an analogue square wave with a truncated harmonic spectrum. The most important harmonics are the third and fifth harmonics of the signal fundamental, and these are the ones that are most vulnerable to distortion caused by cable resonance. Apart from cable construction cyclic variations, another often worse source of resonance can be produced during installation by neat cable tying at regular lengths.

The significance of cable impedance

The best unbalanced coaxial cable impedances to use in high-power, high-voltage, and low-attenuation applications were experimentally determined in 1929 at Bell Laboratories to be 30, 60, and 77 ohms respectively, and this can be shown mathematically. In the case of balanced cables, these figures translate to 60, 120 and 150 ohms respectively, but higher impedances in screened cables than 110 ohms are rarely seen, as physically the centre conductors become rather delicate and so prone to breakage or electrical unbalance due to strain. In contrast, unscreened flat twin 300 ohm cable was widely used for radio frequency uses until quite recently. It was however used mainly outside for antenna feeder supported by posts, and is quite unwieldy in complex installations because of the need to support it in an electrically balanced manner alongside any other cables. The ideal requirements for analogue cables point to fairly low impedances below 50 ohms, but the analogue performance of a 110 ohm cable is still very good.

High frequency skin effects and conductor design

As the frequency of currents carried on the cable conductors increases, the generated AC magnetic field progressively pushes the slow moving carrier electrons towards the surface of the conductor. The table below gives some idea of the effect on practical wire sizes. This effect produces the fundamental frequency dependent loss of the cable. For this reason, solid centre conductors are therefore normally used for digital cables, although in the case of balanced pair cables carrying AES/EBU digital signal, the excess losses produced by stranded conductors is marginal.

Frequency	Skin depth mm	Inner diameter mm	Percentage of conductor used
20kHz	0.46	0.6	100
20kHz	0.46	2.0	46
4.2MHz	0.32	0.6	100
25MHz	0.13	0.6	44
750MHz	0.024	0.6	8

AES/EBU Digital audio twisted-pair cable requires...

Specific impedance 110 ohms - May vary between 88 and 132 and an excellent analogue/digital compromise would be produced using 100 ohms.

Low capacitance - Below 60 pF/m (most AES pairs are 40 pF/m)

Low resistance - Gauge size becomes the major factor due to skin effect. 0.4mm to 0.65mm is most common. 0.65mm can go about 10% farther.

Moderate crosstalk requirements - Only 30dB required (even UTP cables can meet this).

Maximum cable losses - AES/EBU specifications allow for 12dB cable attenuation at 6MHz, compared to the loss at 0.1MHz. This enables a typical run of 300 metres of PVC insulated stranded core cable or even unshielded Cat 5 cable to be easily compensated for.

- Frequency dependent cable losses increase as the square root of the frequency, so a system using 192kHz (4 x 48kHz) sampling will in theory only go half as far on any cable as the basic 48k signal.
- Using signal recovery techniques (similar to those used in digital video), the ultimate cable length would be limited by the crosstalk to signal ratio, not just by attenuation.

Towards an optimum combined cable design for Digital (AES/EBU) and Analogue Audio – D’n’A

Cable characteristic AES/EBU audio cable	Balanced professional Dual function cable compromise analogue audio cable	Balanced digital
Transmission line impedance +- 20%	Not necessary limits 100 ohms	110 ohms
Acceptable losses across band 20dB at 64fs, is the stereo sample frequency)	1dB at 20kHz on a 100m cable run? No problem	Up to (Where fs audio
Degree of balance specification not necessary HF radio sensitive areas	Highly desirable for interference No reason why star-quad for rejection, star quad an example. digital should not work	High except in
Dielectric material materials give few benefits cable lengths	Chosen for cost and maintenance Chose mainly for physical performance. of cable geometry Maybe beware plasticiser migration	Exotic for normal
Inner conductors hold impedance	Chosen for flexibility and Use thinner 100/110 ohm inners low noise generation	Chosen to
Screen important	Cost sensitive specification Specify for analogue performance	Not
High resistance screening layer Undesirable because of conduction losses	Reduces flexing noise Don’t use	 skin

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