Multichannel matrix surround decoders for two-eared listeners

David Griesinger
Lexicon 100 Beaver Street
Waltham, MA 02154

Abstract:

Although film matrix surround decoders are primarily four channel devices, with a single channel devoted to sound the sides and the rear, in practice there are almost always two or more surround speakers. These speakers are driven in parallel, with in some cases a delay modulation to “decorrelate” the single surround channel. There is substantial interference between the various loudspeakers, resulting in a listener dependent comb filtering and a non-spacious surround. Although designs for decoders with more than one rear channel exist, these suffer from low separation between the rear channels when the decoder inputs are decorrelated - during music or effects like applause. Current decoders also suffer from various defects such as pumping of the music during dialog. This paper discusses a mathematical design for a matrix encoder and decoder with radically different properties - maximum lateral separation during music, accurate placement of directionally encoded material, and constant music level in the presence of any directionally encoded effect. Matrix equations for both a 5 channel and a 7 channel decoder are presented, along with an active and a passive encoder for 5 channel films. Comparitive listening tests show that the decoder reproduces standard films with substantially improved surround, and the combination of the encoder and the decoder reproduces 5 channel discrete films with little subjective loss.

Introduction

While 5 discrete channel film reproduction is now in fashion, there is a large body of films available in two channel encoded surround. There is thus a market for a matrix decoder which can optimally convert an old film into the new format. There is also a market for a home processor which can play an easily available two channel film through five or more output channels in a way which closely matches a discrete mix. Is this possible? What are the properties of a 5 channel mix?

In a two channel mix the “surround” channel is used infrequently - primarily for an occasional rear directed effect. Most of the time in a two channel mix the surround output of the decoder is derived from the left-minus right component of the stereo main channels - a component which comes from decorrelated music or environmental effects recorded in stereo. In a discrete mix the rear channels are also mainly reproducing decorrelated sound - either the reverberation from the music channels or surround effects recorded in quad.

Sound effects steered rear are rare because they are highly noticeable - particularly when reproduced in mono through many loudspeakers. Even in a discrete mix it is very rare that a director would decide to place an important effect in one of the rear channels at the same time as an important sound is reproduced from the front. In fact, it is rare that sound effects should be heard from two different directions at the same time. Logic enhanced matrix surround - with the ability to reproduce a single encoded effect in an arbitrary direction - is in fact a good match to the human brain's ability to keep track of information of primary importance (foreground information). If logic surround could handle background sounds as well as it handles foreground effects there would be little need of five discrete channels.

The major advantage of having a five channel discrete system shows up when the rear channels are reproducing background. The two channels are decorrelated automatically - either by using two different reverberation channels, or by reproducing environmental effects in quad. Yet it is precisely in the reproduction of background that the conventional matrix decoder fails. The two or more rear channels are either mono, decorrelated artificially, or have low separation. Teile has found that the most revealing signal for the difference between matrix surround and discrete surround is the applause which follows a recorded concert. With matrix the applause is one dimensional, thin, and the timbre of it is highly dependent on listener position. With discrete rear channels the applause is enveloping, and the listening area is large.

The low separation of standard matrix is not necessiary - we have two channels coming in, and they are often entirely decorrelated. We simply have to reproduce them in a way which produces maximum envelopment.

In designing an improved encoder and decoder it is important to realize that the listeners have two ears, and that the listeners are facing forward. The perception of envelopment requires high lateral separation - envelopment need not be maximized for listeners facing sideways. It is possible to produce high lateral separation with a radically different matrix design. Such a decoder gives most of the advantages of discrete - namely high separation between all left and right output channels anytime there is no directionally encoded signal, and accurate placement of a directional effect when one is used. This paper presents the specification for such a decoder, and an encoder designed to make full use of it. The specification leads to a mathematical design which is easy to implement, compatable with standard films, and unique.

The decoder is designed to work both with a 5 channel encoder and the conventional 4 channel Dolby encoder. Additional circuitry can be included which increases the accuracy of the placement of sources in the rear by undoing the phase shifts which are a fundamental part of the standard film encoder. (see figure 1) A sound panned between left and surround in a four channel encoder has a phase shift of ~65 degrees between the two output channels, which makes it impossible to achieve full separation between the left rear and the right rear output channels of an uncompensated decoder. The decoder design can include an active phase compensation circuit for this shift. The design of a 5 channel encoder is also presented, which accurately encodes a 5 channel film. This encoder can also include active phase compensation, such that phase compensation in the decoder is unnecessary for full rear separation. This solution is cost effective, as a less expensive decoder can give good results, but there may be reason to keep the phase compensation in a high-end decoder, as it produces better results on pre-existing four channel films.

Design goals

The object of a matrix decoder is to convert signals which come in on two input channels into signals on 4, 5, 6, or 7 output channels. The output channels are intended to drive loudspeakers placed in different directions around a room. Through an encoding and decoding process sounds which are intended to come from only one direction are reproduced through the matrix in such a way as they appear to a listener to come from the intended direction. This description applies to any decoder. A film decoder has another exceedingly important requirement - there should be no sweet spot. A listener anywhere in the listening space should hear the identical performance. This requirement rules out solutions such as transaural or ambisonics. In practice the requirement of a large listening area has two consequences: First, that the sound effects should be reproduced as discretely as possible - if a sound is supposed to come from the left front, only the left front loudspeaker should reproduce it. Second, music and environmental effects should be spacious and enveloping regardless of listener position.

The outputs of any decoding matrix are simply linear combinations of the two inputs. In an active matrix the coefficients of the linear combinations - the matrix elements in the decoder - can be functions of time which vary non-linearly, but slowly compared to audible frequencies. In some decoders the matrix elements can be complex functions of frequency, as well as functions of time. It is the object of the decoder design to specify the behavior of these coefficients. The simplest matrix is the passive matrix, where all the multipliers are fixed. The most common passive matrix forms four outputs such that the left output is the left input times one, the center is the left input times .7 plus the right input times .7, the right output is the right input times one, and the rear output is the sum of the left input times .7 and the right input times minus .7. This matrix is 2x4, with 8 coefficients. (see figure 2)

Table 1: Passive surround decoding matrix

	Lin	Rin
L	1 (LL)	0 (LR)
R	0 (RL)	1 (RR)
C	.7 (CR)	.7 (CR)
S	.7 (SR)	-.7 (SR)

We give these matrix elements names: LL for the Left out Left in element, LR for the left out right in, RL for right out left in, RR for right out right in, etc.

The standard 4 channel encoder in figure 1 can also be described with a matrix, but this matrix is complex:

Table 2: Dolby Surround encoding matrix

	L in	R in	C in	S in
Lout	1	0	.7	.7j
Rout	0	1	.7	-.7j

The passive matrix decoder has the following properties:

1. Signals encoded with a standard encoder will be reproduced with equal loudness regardless of their reproduced direction.

2. When the input signal is a stereo signal with no specifically encoded direction - such as music that has been recorded so that the two inputs to the decoder have no correlation - all outputs have equal loudness.

3. When the input signal is a combination of a directionally encoded effect and decorrelated music there is no change in either the loudness or the apparent separation of the music as the directionally encoded effect moves.

The disadvantage of the passive matrix is that the separation of both the directional effect and the music is not optimal. For example:

1. A signal intended to come from the center is also reproduced in the left and right output channels. In fact, the level difference between the center output and the left output is only 3dB. This will be referred to in this paper as the separation between the left and the center channels.

2. In a passive surround decoder (and in Dolby Pro Logic active decoders) there is only one surround output, and yet in practice there are almost always two surround speakers, a rear left and a rear right. In Dolby Surround (and in theaters) these speakers are driven in parallel. There is no separation - 0dB - between these speakers. All reproduce only the difference between the two input channels. Music which in the original had violins on the left and cellos and basses on the right will be reproduced with all the instruments in all the rear speakers.

3. There is high separation between output directions which are opposite from each other in the encoder - that is the left and right main outputs have high separation, as do the center and the rear outputs.

It is possible to extend the design of the passive matrix to more than four channels. If we wish to have a rear left and a rear right speaker we can make them by using suitable matrix elements. Such matrix elements are not unique. However if we make the following conditions on the outputs there is a unique solution:

1. That the loudness of the music component of the signal be constant in all outputs

2. That there be high separation in opposite directions - that is an output channel intended to reproduce signals which are half-way between left and rear should produce no output from an input signal which is half-way between center and right.

Using these two design conditions, it is simple to design a 5 channel, 6 channel, or seven channel decoder. However the separation between adjacent channels becomes lower with each added channel - and it only started at 3dB.

For example, lets design a 5 channel passive decoder, assuming we have an encoder similar to the Dolby encoder, but with real coefficients. For this encoder, the output for a signal SIG which is intended to come from a direction ts (the angle as measured from the left side of the listener) is given by:

A simplified (real coefficient) surround encoder, acting on a signal SIG with an encoded angle of ti as measured from the left side:

Lout = SIG*cos(ti/2)
Rout = SIG*sin(ti/2)

If we use the same angle ts to describe the direction of the loudspeaker relative to the listener, the matrix for a 5 channel decoder becomes:

Matrix elements for a 5 channel passive decoder for outputs at angles ts(n):

	Lin	Rin
out(n)	cos(ts(n)/2)	sin(ts(n)/2)

The separation between channels in the rear is low. A signal applied to the encoder with ti = -22.5 will come out the left rear (ts=-22.5) decoder channel with a level of .85+.15=1, and out the right rear channel with a level of .35+.35=.71. The ratio is 3dB, as expected. Such separation may be barely sufficient to make having separate channels worthwhile, but it is less than satisfying, especially on music and applause.

Active Matrix Decoders

This situation can be improved with an active matrix. The object of an active matrix is to increase the separation between adjacent outputs. If we put aside the question of how does the matrix respond when there is no directionally encoded signal for a moment, we can make some design criteria for any active matrix when there is a strong directionally encode signal. These will be fulfilled with various degrees of success in a practical design:

1. When there is no decorrelated signal there should be a minimum output from channels not related to the ones involved in reproducing the directional signal. For example, a signal which should sound half way between right and center should produce no output in the left and rear channels. Likewise a signal intended for the center should produce no output on left and right.

2. The output from the decoder should have equal loudness as a directionally encoded input signal is moved through all directions. This means the total power from the outputs should be unity.

3. The loudness of the music component of an input signal should be constant in all output channels regardless of how the directional component of the input is moved, and regardless of the level differences between the music and the directional effect. This means the total power of the decorrelated component of the input in any one output channel should be constant as the matrix elements change.

4. The transition between the reproduction of the music component only, and the reproduction of a directional effect only, should be smooth and involve no shifts in apparent direction of the sound.

Dolby Pro-Logic, as currently implemented, modifies these requirements somewhat. This modification must be preserved in any decoder which intended to be accurate for film:

5. In a film decoder a signal intended to come from the left, center, or right output directions (or any direction in-between) should be boosted in level by 3dB relative to the level such a signal would have in a passive Dolby Surround matrix. Thus as the decoder makes the transition from a music only signal to a pure directionally encoded signal the level of signals in the front hemisphere should be slightly raised.

Requirement 5 makes it impossible to create a decoder which makes the music component constant as the directional component moves (requirement 3 above.) For example, the left output of a passive matrix is simply equal to the left input, (the LL matrix element is one and the LR matrix element is zero) but under conditions of a signal directionally encoded full left, requirement 5 says the LL matrix element should increase by 3dB. This will automatically raise the level of the left music component by 3dB, and there is nothing you can do about it. This slight pumping of the music in the direction of strong directional signals is not a problem however, because the directional sound will mask the pumping of the non directional sound. However if there is a strong signal in another channel - for example dialog in the center channel, it is important that the level of the music in the left and right channels be constant, even though their matrix elements must change to eliminate the dialog component. This can be achieved.

As an example, the standard Dolby ProLogic decoder keeps the music generally within 3dB of its proper level, except for the music in the surround channels during dialog, which exhibits a 5dB pumping (at least in some current designs.) Some early pre-Dolby decoders eliminated the left and right channels completely during dialog. These decoders have disappeared from the market.

The description so far applies to all active matrix decoders. However in most current active decoders there is an additional implicit design assumption:

6. In the absence of a directionally encoded signal the matrix should revert to the passive matrix described above, as implemented for the desired number of output channels.

This assumption appears at first glance reasonable - but it is neither necessary or desirable from the point of view of acoustic perception. The result is that music reproduced through a 5 channel conventional design has only minimal separation between the two rear channels, and the sound is poor both for music and environments such as applause.

New designs

The decoders presented here abandon assumption 6 and replace it with a requirement:

7. An optimal active decoder should have maximum lateral separation at all times, both during reproduction of music signals and for music signals in the presence of a directionally encoded effect.

It turns out that there is an enormous audible difference between a soundfield which has 4dB of lateral separation, and one which has more than 10dB. The THX decoder attempts to create some of this effect by "decorrelating" the two surround channels, but the subjective difference remains. It is the author's opinion that much of the difference between a discrete 5 channel film reproduction and a conventional matrix reproduction is due to the low lateral separation in standard matrix.

We have recognized the importance of this requirement for some time, and an earlier surround processor (and a patent) developed a method for creating a side output which had high separation when there was no steering, and no output when there was a directionally encoded signal in the front hemisphere. The matrix design for a signal steered to the rear hemisphere in the earlier decoder was developed heuristically and the separation between the rear outputs for steered material is not optimal. There is also more pumping with music than we wanted. For both reasons we decided to upgrade the design of this decoder.

It turns out it is possible to uniquely specify a decoder design which meets the requirements. For mathematical simplification we will design the decoder assuming the simplified (real) encoder described above. This encoder is simply a pan-pot with a phase inversion for the rear hemisphere. When steering from right to center to left a standard sine/cosine curve is used. In steering from right to surround to left the right output of the panpot is inverted. Such an encoder can be described easily by the steering angle, where L=cos(ts) and R=sin(ts). For rear steering, L=cos(ts) and R=-sin(ts). Full rear steering occurs when ts=45 degrees, and steering to left surround occurs when ts=22.5 degrees.

The new decoder is also designed to keep the lateral separation for music high even when there is a strong rear sound effect. Although the right rear has zero output to a steered signal as the steered signal goes from left to left side, from ts = 0 to 22.5 degrees, the music output is constant, and has minimum correlation with the music signal in the left rear. In the seven channel version decorrelation in the surround field is additionally increased by giving a time delay of about 15ms to the side channels, and about 25ms to the rear channels.

The difference between this decoder and a standard decoder is small in the front channels - the left, center, and right. These channels differ from standard only in their careful avoidance of pumping of the music during dialog. The major difference comes in the treatment of multiple rear outputs during music, and when there is a steered sound in the front. In the absence of a steered signal we want the left and right rear outputs to reproduce the left input and the right input respectively, and yet anytime there is a steered signal - dialog for example, these outputs should not reproduce it. The conventional four channel matrix is inherently immune to dialog leakage to the surround channel - as long as balance and azimuth are correctly set. This is not true of the new matrix. The matrix elements must change dynamically to remove the center componant of the rear outputs during dialog. To keep leakage acceptably low the decoder must be carefully designed, and balance and azimuth must also be accurate.

Phase of the rear outputs

A standard Dolby surround installation has all the surround speakers wired in phase, and Dolby screening theaters are similarly equipped. However a 5 channel passive or active matrix has an inherent problem with the phase of the left rear and right rear outputs. We want a left side output to increase smoothly and in phase with the left front output as a signal is panned from left to left side, and we want the right side and front outputs to behave similarly. However if we reproduce a sound effect which is encoded to come from the rear (which means the right and left inputs to the decoder are out of phase), the left and right side outputs of the decoder will also be out of phase. Thus the two surround outputs will be out of phase during any full rear sound effect. Adding active matrix elements to improve separation will not affect this fundamental difficulty. When we listened to a prototype of the new decoder we decided this phase inversion was unacceptable - a rear steered sound, such as a plane flyby, became both thin and phasey in the rear. There was a pronounced difference between this thin sound and the sound of a standard decoder with only a single rear channel. We found we could correct the problem by adding a phase shifter to flip the sign of the right rear channels under full rear steering. This feature was included in the earlier decoder, and is retained in the new design. It is shown in the right side output of figure 3.

Implementation

Figure 3 shows a simplified block diagram of the new decoder. In designing a decoder one faces two basic problems. One is the determination of the intended direction of a sound, and the other is adjusting the matrix to put it there. In this paper we will only concern ourselves with the second problem. In the standard Dolby pro logic decoder the intended direction is determined by the log of the ratio of the amplitudes of the two inputs, (which we will refer to as l/r - or left over right) and the log of the ratio of their sum and difference (which we will refer to as c/s - or center over surround.) For this paper we will assume we know both of these values, and can express them in decibels. If c/s = l/r = 0dB, we can assume there is no directional effect - the inputs are decorrelated. When l/r~=0dB, and c/s is positive and high, we are seeing a center signal - probably dialog. Likewise if c/s is negative and high, we are seeing a surround signal. A signal where l/r ~=8dB and c/s is negative would be most likely a signal encoded to come from the left rear output. In a future logic system these steering values could even be sent over a sub channel of a digital system, and not derived from the phase of the incoming signals.

In designing the decoder one must first decide how you want the amplitude of the steered component of the input to change in each output as the input encoding angle varies. In the math below this function can be arbitrary. However, if we wish to satisfy requirement # 2 - that loudness be preserved as a signal pans between two outputs, there are some obvious choices for these level functions. For the front left, right and the center outputs the amplitude function is assumed to be the sine or cosine of twice the angle t. For example, as t varies from left, t=0, to center, t=45, the output amplitudes should be:

Left output = cos(2*t)
Center output = sin(2*t)
Right output = 0

As t goes from center to right, t=45 to t=90,

Left output = 0
Center output = cos(2*t-90)
Right output = sin(2*t-90)

This gives optimum placement of sources between left and center, and right and center. These functions also result in very simple solutions to the matrix problem. As we steer rear we have chosen some equally simple functions. In this case:

In designing the 5 channel version of the new decoder it was decided that a signal steered between left and left surround (t=0 to 22.5 degrees) should have no output in the right surround channel. The left surround channel should rise smoothly in output as t goes from 0 to 22.5 degrees (from left to left surround) and the output should follow the function sin(4t). As t goes from 22.5 degrees to 45 degrees the output should remain constant. (The matrix elements used to achieve this are not constant, but vary such that at full rear steering the matrix element for the right input into the left rear output goes to zero - thus giving maximum lateral separation even during strong steering.)

In the seven channel version, as t goes from 0 to 22.5 degrees the output in both the left side and the left rear outputs should be equal and smoothly rising (following the function sin(4t).) As t goes from 22.5 to 45 degrees the output in the left side goes down 6dB and the output in the left rear goes up 2dB, keeping the total loudness (the sum of the squares of each output) constant. The right side and rear output have no signal as t goes from 0 to 22.5. As t goes from 22.5 to 45 degrees the right rear output rises smoothly to the value of the left rear output, and the right side output rises smoothly to the value of the left side output.

As mentioned above, in the new decoder even when the steered signal is fully to the rear, the left rear and right rear outputs have maximum separation for music. In this case since the matrix element for the right input to the left rear output is zero, they have complete separation. Although the right rear has zero output to a steered signal as the steered signal goes from 0 to 22.5 degrees, the matrix elements used to achieve this signal cancellation are adjusted so the music output is constant, and has minimum correlation with the music signal in the left rear.

For a monaural signal which has been encoded by the simplified encoder such that the decoder inputs are L=cos(t) and R=+-sin(t), l/r and c/s are not independent. To find the steering angle we need only find the arctan of the left level divided by the right level, or if we define full left as t=0:

t = 90 - arctan(10^((l/r)/20)) degrees if l/r is in dB as defined above

However, since the two levels are compared in their magnitude only, to determine whether the steering is front or back we need to know the sign of c/s, which is positive for forward steering and negative for rear steering.

In the real world however the input signals to the decoder are NOT derived from a pan-pot, but from an encoding matrix which utilizes 90 degree phase shifts. In addition, there is almost always music present along with steered effects. In this case the value of l/r and c/s are not dependent. There are good reasons for using both to determine the matrix elements.

The following description divides the problem of specifying the matrix elements into four sections, depending on what quadrant an encoded signal occupies, i.e. left front, right front, left rear, and right rear. We will assume a 7 channel decoder, with left front, center, right front, left side, right side, left rear and right rear outputs. Two matrix elements must be specified for each output, and different matrix elements will be specified depending on the quadrant for the steering. We will describe only the left front front and left rear quadrants here. The matrix elements for the right quadrants can be found by reflection about the left-right axis.

In describing this decoder we will initially assume that there is NO boost of the front channels during front steering, as seen in the requirement 5 above for Dolby films. We will design the decoder for constant outputs on all channels under full steering, and add the correction later.

Left output as the input steers from left (t=0) to center (t=45)

The most important first point about the left output is that it should not have any signal when an input is steered toward center. Thus as ts varies from zero to 45 degrees the left output should decrease to zero. This decrease should depend on the magnitude of c/s, not the magnitude of l/r. Thus the angle ts should be determined from the c/s ratio.

If we make ts=0 full left, and c/s is in dB
ts = arctan(10^((c/s)/20)) -45 degrees

The left output is the matrix element LL times the left input, plus the matrix element LR times the right input. A fully steered signal through our simplified encoder results in a left input L = cos(ts), and a right input R = sin(ts) over this range. We want the level in the left output to smoothly decrease as t increases, following the function FL(ts), which in our example decoder is assumed to be FL(ts) = cos(2*ts). Thus we get the first equation:

left output = LL*cos(ts) + LR*sin(ts) = FL(ts).

Once again, the output to music is assumed to be constant. This means the sum of the squares of the matrix coefficients must be one:

LL^2 + LR^2 = 1

These equations - which are basically the same for all outputs, result in a quadratic equation for LR and LL, which has two solutions. In every case one solution is greatly preferred over the other.

LR = sin(ts)*FL(ts)+-cos(ts)*sqrt(1-FL(ts)^2)
LL = cos(ts)*FL(ts)-+sin(ts)*sqrt(1-FL(ts)^2)

When FL(ts) = cos(2t) and picking the best sign, this simplifies to:

LR = sin(ts)*cos(2ts) - cos(ts)*sin(2ts)
LL = cos(ts)*cos(2ts) + sin(ts)*sin(2ts)

mathematical identities simplify these further to:

LR = -sin(ts)
LL = cos(ts)

We see that in spite of the rather involved path, the result is quite simple - perhaps even obvious. See figure 4.

Right output as steering goes from left to center

The right output should be zero as the steering goes from left to center, and once again it should be the value of c/s which determines t.

output = RL*cos(ts) + RR*sin(ts) = 0

Once again the music should be constant, so

RL^2 + RR^2 = 1

These two equations determine RL and RR as a function of t. Since the right and left directions are completely symmetric, these two functions will also be used when steering from right to center, or center to right.

Surprisingly the resulting equations for RL and RR are identical to LR and LL:

RL = -sin(ts)
RR = cos(ts)

Center output as you steer from left to center

The most important point about the center output is that it should smoothly decrease as steering moves either left or right - and this decrease should be controlled by the magnitude of l/r, NOT the magnitude of c/s. Strong steering in the left or right direction should cause the decrease. This will result in quite different values for the center left matrix element CL and the center right element CR, which will swap when steering switches from right to left. The l/r based steering angle will be called tl here. It is assumed to go from 0 at full left steering, to 45 when steering is full center, or when there is no steered signal. Note well tl decays to 45 degrees when the steered component is weak.

tl = 90 degrees - arctan(l/r).

Here the center output should increase smoothly as tl varies from 0 (full left) to 45. The function for this increase will be called FC(t) which is equal to sin(2*tl) in our decoder. By the above method,

center output = (CL*cos(tl) + CR*sin(tl)) = FC(tl) (=sin(2tl))

CL^2 + CR^2 = 1;

Once again CL and CR can be uniquely determined from these two equations.

CR = sin(tl)*sin(2tl)-+cos(tl)*cos(2tl)
CL = cos(tl)*sin(2tl)+-sin(tl)*cos(2tl)
the solution with the second sign is preferred. See figure 5.

Rear outputs during front steering

The matrix elements for the rear outputs during front steering are not as simple as the ones before. The problem is we want the left rear left (LRL) matrix element = 1 and the left rear right (LRR) matrix element to be zero when there is NO steering, and yet we want no directional output from this channel during either left or center steering. The solution to this problem is the key to making a decoder with high rear lateral separation.

To do this we must make the matrix depend both on the value of c/s and l/r. A solution for these coefficients can be found in reference 2, where the side left and right outputs are the "supplemental outputs". The solution derived there solves the problem of canceling the directional component at all angles in the left side output, but in the solution in (2) the music component of the output decreases by 3dB as the steering goes to full center. We can correct the coefficients of (2) to get the needed matrix elements. The correction factor is cos(ts)+sin(ts), where ts is an angle which is zero when c/s is one, and which increases to 45 degrees when c/s is large and positive. In the following equations the angles ts are derived from c/s, and tl are derived from l/r

ts = arctan(c/s) - 45 degrees.
tl = arctan(l/r) - 45 degrees.

Notice ts and tl vary oppositely for fully steered signals, that is ts is 45 degrees when tl is zero and vice versa. However as a steered signal fades down into an unsteered music signal, both ts and tl smoothly go to zero, regardless of the direction of the steered component. This is the terminology followed in (2). Note that tl here is different from the angle tl defined above for the center output.

from reference (2) column 6, line 65, adding the correction factor above

LSL = LRL = (cos(ts)+sin(ts))*(1 - gsl - 0.5*gc)
LSR = LRR = (cos(ts)+sin(ts))*(-0.5*gc-gl)

where from col 6 line 15,
gc = 2*(sin(ts)/(cos(ts)+sin(ts)) (note the misprint in reference (2))
gl = (cos(tl)-sin(tl))/cos(tl)

from col 7, line 9
gsl = gl*(1-sin(tl))/cos(tl)

After considerable manipulation, these equations reduce to

LSL = LRL = (cos(ts)+sin(ts))(sec(tl)-1)(sec(tl)-tan(tl) -sin(ts))
LSR = LRR = (cos(ts)+sin(ts))(tan(tl)-1)-sin(ts)

The right rear outputs when the input is steered between left and center can be found with the previous method. However the steering angle we must use is the one derived from c/s, or ts. This is because the right rear output if it reverts to the right input when there is no steering is inherently free of signal from the left input. We need only remove signals which are steered center.

Right rear and right side output as ts goes from 0 to 45 degrees front:

Right rear output = RRL*cos(ts) - RRR*sin(ts) = 0
and RRL^2 + RRR^2 = 1
as before, the solution is:
RRR = cos(ts) = RSR
RRL = -sin(ts) = RSL

These equations completely specify the matrix elements for front steering

Rear steering (c/s is negative) - Left, right, and center outputs

To determine how the front left and right outputs should behave during rear steering we must make a choice. Requirement #2 above would suggest that the output from the front left output should be zero when a signal is steered to the left side output. We could use the previous method to create matrix elements which would achieve this, where the left main output would decrease according to the function cos(4*tl) as a signal was panned from left to left side. However such a main output would not be compatible with a standard Dolby Prologic encoded film. For this reason we decided to make the front left and right outputs compatible with a Dolby Prologic decoder. In deciding for compatiblitiy we reduce the separation of a directionally encoded effect when it is steered to left side. Listening tests show the reduced separation to be not problematic, and perhaps even desirable. It does however make the 5 channel encode/ 7 channel decode of the Dolby AC3 trailer a bit less discrete.

In this case the left and right main outputs use the same matrix elements as they do for front steering, except that the absolute value of log c/s is used to determine the steering angle in the formulae, and the sign of the cross matrix element, (LFR and RFL) is switched.

The center output matrix elements are identical in front steering and rear steering. They depend only on angles determined from l/r, and do not depend on the sign of c/s.

Side and rear outputs, rear left steering, from t=0 to t=22.5 degrees

We want the side left and right outputs to have full separation when steering is low or zero. However, the signal on the left input must be removed from the left side and rear outputs when there is strong steering to the left. Thus the matrix elements for the left side and rear outputs must depend strongly on l/r in this quadrant. We will use the angle t in describing these matrix elements.

t = 90 - arctan(l/r) - as above for the center output
If l/r is in dB, then t = 90 degrees - arctan(10^((l/r)/20))

When there is strong steering (no music) the side and rear outputs have no output when t=0. As t rises to 22.5 degrees the output of the left side and left rear rises, following the curve sin(4*t). In the presence of music the loudness of music (as represented by the sum of the squares of the matrix elements) should be constant. If we let the left input L=cos(t) and the right input R=-sin(t), and the left side left coefficient be LSL, the left side right coefficient is LSR, the left rear left coefficient is LRL and the left rear right coefficient is LRR, then

LSL = LRL, LSR = LRR (the sides and rears have equal outputs)
The requirement that the amplitude during steering of the left side output should follow a particular function FS(t) (FS(t) = sin(4*t) in this case) translates into the following equation:

LSL(t)*cos(t) - LSR(t)*sin(t) = FS(t)

The requirement that the music be constant in level results in the following equation:

LSL(t)^2 + LSR(t)^2 = 1

These two equations can be solved for LSL(t) and LSR(t) as a function of FS(t), as before.

-LSR = sin(t)*FS(t)+-cos(t)*sqrt(1-FS(t)^2)
LSL = cos(t)*FS(t)-+sin(t)*sqrt(1-FS(t)^2)

In the current design FS(t) = sin(4t).

As before, simplifying and taking the first sign,

-LSR = sin(t)*sin(4t) + cos(t)*cos(4t)

LSL = cos(t)*sin(4t) - sin(t)*cos(4t)

these can be further reduced to:

LSR = -cos(3tl)
LSL= sin(3tl)

Notice that it is the value of left/right steering which is used to determine the dependence of the matrix elements. This separation of function is optimal when a signal has been encoded with a standard encoder. The presence of the 90 degree phase shift network makes the value of c/s unreliable as a predictor of the true steering, but the phase shift network has less effect on the value of l/r.

Left rear steering - t=0 to 22.5 degrees, right side and rear outputs

The right side and rear outputs are inherently free of the left input when there is full left steering. We must remove signals which are steered center or rear however. Thus we should use a steering angle derived from c/s to determine the matrix elements. The right side and right rear matrix elements are also equal to each other, and the two outputs are also equal to each other except for delay.

output = RSL*cos(ts) - RSR*sin(ts) = 0

RSL^2 + RSR^2 = 1

Once again these can be solved for RSL and RSR

RSL = sin(ts)
RSR = cos(ts)

Steering from 22.5 degrees to full rear

So far we have designed a decoder which meets all the requirements we set out at the start. Signals are removed from outputs where they do not belong, full separation is maintained when there is no steering, and the music has constant level in all outputs regardless of the steering. Unfortunately we cannot meet all of these requirements for the rear outputs. We cannot get the ideal decoder we desire unless we break one of our assumptions. The one to break is the assumption of equal music level as steering goes to full rear. The standard film decoder does not boost the level to the rear speaker, and thus a standard film decoder (assuming it is well designed) does not increase the music level as a sound effect moves to the rear. The standard decoder has little or no separation in the rear channels. We want the separation, and we can get it if we allow the music level to rise 3dB during strong rear steering. This is in practice more than acceptable. Some increase in level of music under these conditions is not audible - it may even be desirable.

5 channel decoder, rear outputs

We have been finding matrix elements to the rear based on a steering angle t derived from the l/r level ratio. As we move from t=22.5 to t=45 this ratio decreases to one, while the log of the ratio of center to surround (c/s) becomes large (and negative). However, consider what happens when you have a directional signal at t=22.5 degrees, and mix it with non-directional music. As the music becomes stronger than the directional signal both l/r and c/s decrease to a dB value of zero. We need to distinguish in our matrix elements between the l/r ratio decreasing to a log value of zero because a strong directional signal is going to the rear, and the case when a directional signal of constant angle is fading down into the music. The best solution is to make the matrix elements relax to high separation when l/r goes to zero, while keeping the music level constant.

The resulting matrix elements are easy to derive:
let t = 90 degrees - arctan(10^(l/r/20)). Note t = 45 when l/r (in dB) is zero
LRL = cos(45 degrees - t) for t going from 22.5 to 45 degrees

LRR = -sin(45 degrees -t)

These matrix elements keep the music level constant, but they cause the output of a steered signal to decrease by 3dB when the signal goes to the rear. To see this, find the left rear output by multiplying LRL by cos(t) and LRR by -sin(t):

Left rear output = cos(t)*cos(45-t) + sin(t)*sin(45-t)

When t=45 degrees this is equal to cos(45), which is not equal to one! Note that these matrix elements are based only on l/r. We can fix this problem by adding a dependency on c/s. The solution is to boost the value of LRL proportional to the increase in the log of the c/s ratio. We can solve for the value of the boost needed to keep the rear output level constant, using values of t going from 22.5 to 45. With an additional numerical step we can find the boost as a function of the c/s ratio. The results are presented as a table:

LSL = cos(45-t) + RBOOST(log c/s) where t is calculated from l/r
LSR = -sin(45-t)

RBOOST:

c/s in dB	RBOOST
-32	.41
-23	.29
-18	.19
-15	.12
-13	.06
-11	.03
-9	.01
-8	0

Right rear outputs when the signal is steered left and rear from t=22.5 to 45

The right rear output should smoothly rise under these conditions to the value of the left rear output. The solution is similar to the left channel:

RRR = cos(45-t) + RBOOST(log c/s)
RRL = sin(45-t)

Seven channel decoder - left channel, rear steering from 22.5 to 45

The seven channel decoder starts with the matrix elements for the 5 channel decoder, and adds an additional term based on the value of c/s. This function decreases the value of the left side matrix element during full rear steering, while boosting the value of the left rear left element. (In a particular embodiment it may be desirable to boost the left rear right element. In our test decoder boosting LRL further than 1.41 was not possible. Adding the boost to LRR instead reduces separation a little at full rear steering, but this seems not to be audible.)

Thus we define a rear side boost function which starts at a value of zero for tsc=22.5 and rises to a max of .5 when ts=45, where tsc is the angle as determined from the value of c/s.
tsc = 90 - arctan(s/c)

RSBOOST = 0.5 * sin(2*(tcs-22.5))

LSL = cos(45-t) + RBOOST(tsc) - RSBOOST(tsc)

RSR = cos(45-t) + RBOOST(tsc) - RSBOOST(tsc)

LSR = -sin(45-t)

RSL = sin(45-t)

Left Rear output

LRL = cos(45-t) + RBOOST(tsc) + RSBOOST(tsc)/2
RRR = cos(45-t) + RBOOST(tsc) + RSBOOST(tsc)/2

LSR = -sin(45-t)
RSL = sin(45-t)

Figure 6 shows two of the rear matrix elements, figure 7 shows RBOOST, and figure 8 shows RSBOOST.

Film decoder with directional boosts to the front channels

As mentioned before there is a film standard which wants the levels to be boosted by 3dB in all front directions. The decoder presented here can be modified to perform in this way by adding a term to the matrix elements based on the appropriate steering direction. For example, during left steering the left front left matrix element should be increased by a boost function depending on l/r
tlr = 90 - arctan(l/r)
trl = 90 - arctan(r/l)

LFL = cos(tsc) + LFBOOST(tlr)

Likewise, when the steering is right,

RFR = cos(tsc) + LFBOOST(trl)

Both matrix elements are boosted for the center channel during center steering.

CL = sin(tlr) + LFBOOST(tsc)/1.41
CR = cos(tlr) + LFBOOST(tsc)/1.41

These equations completely specify an ideal film decoder.

Decoder with center channel absent

When the center channel is missing - which can happen if a consumer does not provide a center speaker - the Dolby specification suggests that the center channel output be added to the left and right front outputs with a gain decrease of 3dB in each channel. Doing this insures that dialog will be heard at the proper level, but it reduces the separation in the left and right when there is no steering. For example, when there is no steering the center output is 0.71*L + 0.71R. Adding this to left and right gives

Left output = L + 0.7*(0.7*L+0.7*R) = 1.5*L + .5*R
Right output = R + 0.7*(0.7*L+0.7*R) = 1.5*R + .5*L

Separation = .5/1.5 = 9.5dB

It would be better to not have this loss of separation in the left and right front channels. This can be done by modifying the left and right matrix elements when you have center steering: For all steering in the front hemisphere, where tsc is the angle derived from c/s,

LFL = 1 + LFBOOST(tsc)
RFR = 1 + LFBOOST(tsc)

LFR = RFL = 0

These matrix elements do not remove the dialog from the left and right channels, and also keep it the proper loudness in the room. There is no loss of separation at any time as long as the steering is in the front hemisphere.

Encoders

Real world encoders are not as simple as the panpot used to design the decoder. However, by choosing carefully how to detect the input steering angle the problems with a standard 4 channel encoder can be largely avoided. We found the phase shift networks in the standard encoder affect primarily the center/rear directional signal, leaving the right/left signal largely unaffected. By using the right/left signal primarily we found even a standard film made with a 4 channel encoder will decode with a substantial amount of directional steering in the rear hemisphere. Although a standard encoder will not work with a 5 channel discrete film it is possible with two 90 degree phase shift networks to design a 5 channel encoder which will work very well with the new decoder. Such an encoder (in a simple form) uses a standard 4 channel encoder. In the new design left rear input is connected to a 90 degree frequency independent phase shift network and then equally to the left and rear inputs of the standard encoder. The right rear input is connected to a minus 90 degree network, and then to the right input and rear input of the standard encoder.

This encoder has the property that a signal on any of the discrete inputs results in an encoded signal which will reproduce correctly on the new decoder. A signal which is in phase in the two surround inputs will produce a fully rear steered output, and a signal which is out of phase in the two surround inputs will produce an unsteered signal. Figure 9 shows a block diagram of an active version of this encoder. The attenuator values are not quite identical to the values suggested by the standard encoder. They have been adjusted so that in the passive mode of the encoder if a signal is applied to only the LS input, the value of l/r seen by the decoder is 8dB, indicating a left side steered signal.

In the passive mode there is a phase shift between the A and B outputs which prevents complete separation in the decoder outputs. For this reason we designed an active version of the encoder. In the active encoder there is a log ratio detector similar to the ones in figure 3 to detect the ratio of LS and RS. This ratio is used to derive two new steering angles, tls and trs. When the absolute value of ls/rs is less than 3dB tls and trs are zero. If ls/rs is > 3dB, then tls smoothly rises to the value of 90 degrees while trs stays zero. If ls/rs is < 3dB, then trs smoothly rises to the value of 90 degrees while tls stays zero. The result of the active change is to make the encoding of a signal uniquely steered to the LS or RS terminal real - while preserving the value of l/r in the decoder of 8dB. This will result in complete separation between the LS and RS outputs of the decoder.

Phase compensation for the decoder

It is possible for the decoder to detect when a signal has been panned half way between left or right and surround with a conventional 4 channel encoder, or with the passive version of the 5 channel encoder above. It is then possible to correct the phase of the input signals. A circuit for this purpose has been designed for our decoder, although the commercial version does not include it. This circuit allows high separation between the left and right side and rear outputs of the decoder even when the film has been encoded with a standard 4 channel encoder. A high end version of the decoder might include such a circuit.

Listening results

We have been able to compare the sound of this decoder with other decoders on the market, and the results are quite gratifying. The difference in envelopment and openness and listening area during any part of a film which contains music or environmental effects is quite pronounced. We have made a number of observations. One of the most important is that using four independent rear channels is quite an improvement over using just two. This is particularly noticeable in a music section of a film or when playing a music recording. The difference between using just the side (dipole) speakers and using sides and rears is quite dramatic. Much of the improvement disappears if the side and rear speakers are driven in parallel. The additional delay supplied by the decoder appears to be essential to the effect, and the differentiation between the sides and the rears in the matrix is also useful. The seven channel improvement is sufficiently powerful that we are including a matrix circuit in our AC3 decoder to differentiate the rear channels from the side channels.

In our commercial decoder it is possible to roll off the treble content of the side and rear channels, and this was found to be a big improvement, particularly with music. Music recordings played through this system have a very large listening area. The orchestra is firmly frontal, but the sound is highly enveloping. With a film containing a strong directional surround - such as the vortex sequences in “Lawnmower Man” the seven channel version was very successful in flipping the room around, and the five channel version was still better than any other decoder we tried - including one with separate left and right rear channel outputs.

The difference in a two channel recording of some applause after a recorded concert was spectacular. The new decoder made you feel you were fully immersed in the audience, with different people clapping all around you. Other decoders gave a thin and often phasey surround.

Encoding and decoding a discrete 5 channel film was also gratifying. Although some highly directional effects were lost, the overall impression of the decoded version was very good. Without a direct A/B comparison it was not obvious that the result was encoded. It was found that the best results with 5 channel encoding and decoding were obtained when no additional filtering was used in the encoder and the decoder. The Dolby B circuit and the low pass filters in the surround channels of the decoder were switched off. The encoder give here could be modified to put a Dolby B encoder in the surround channels, which would be advised in a commercial application. The Dolby AC3 test disk includes two sections with rotating noise. The passive encoder and our new decoder were very successful in reproducing these sections. The right surround signal was quite convincingly reproduced to the right side of the listener, the left surround was on the left, and the full rear surround was strongly to the rear, with little apparent leakage to the sides. The active encoder should further sharpen the performance for left side or right side steering.

The listening tests suggested several improvements to both the encoder and the decoder which hopefully can be included in future designs.

Conclusions

We have shown a mathematical method for designing matrix surround decoders with high lateral separation. The separation is particularly good during music or other decorrelated input material. A simple passive matrix encoder for 5 channel films is also presented, which can encode a discrete film down to two channels with little loss. An active version of the same encoder improves the separation between the rear channels during directionally encoded effects, allowing three discrete rear directions.

References

1. Mandel - US Patent # 5,046,098
2. Griesinger - US Patent # 5,136,650

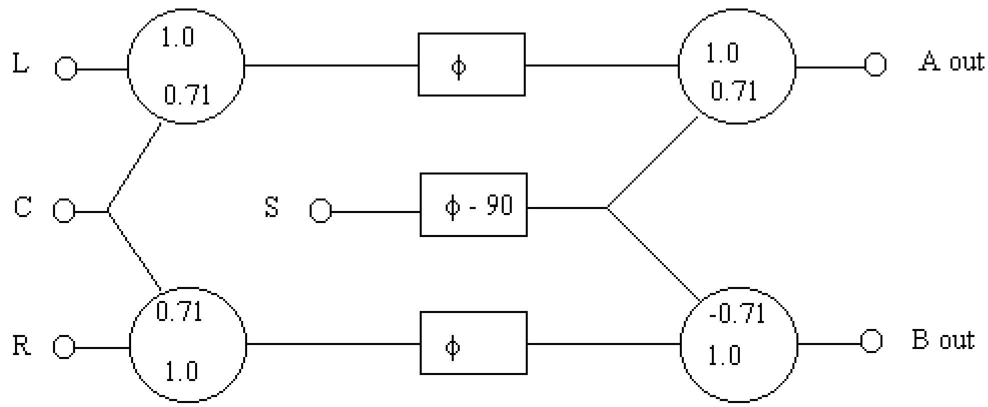

Figure 1: A simplified (no surround channel filtering) version of a standard four channel film encoder. Note the inclusion of phase shift networks to create a 90 degree phase difference between the surround channel and the other channels.

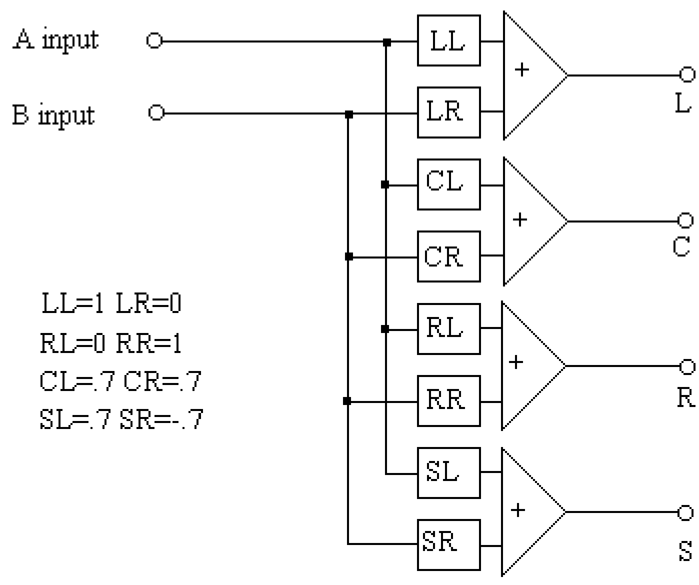

Figure 2: Dolby surround decoding drawn as a matrix. Each output is a linear combination of the two input channels, with fixed matrix elements.

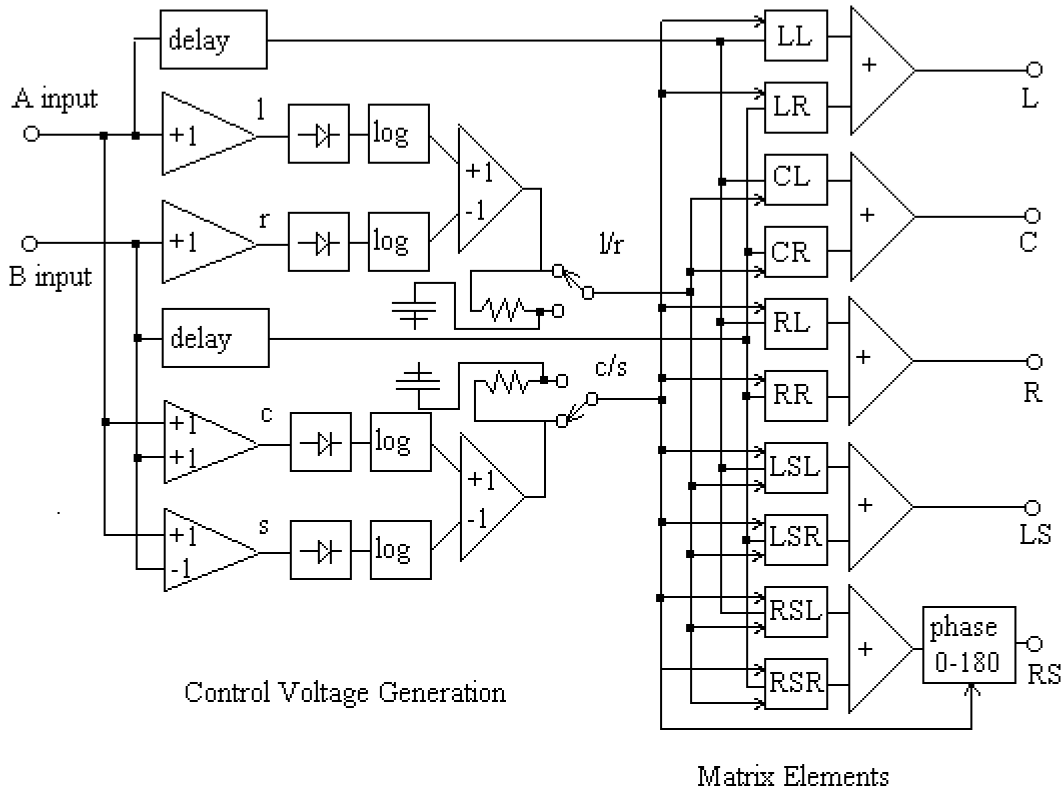

Figure 3: Simplified block diagram of a five channel film decoder. The seven channel version is similar, but with two more rear summing channels. The matrix elements are functions of the control voltages l/r and c/s.

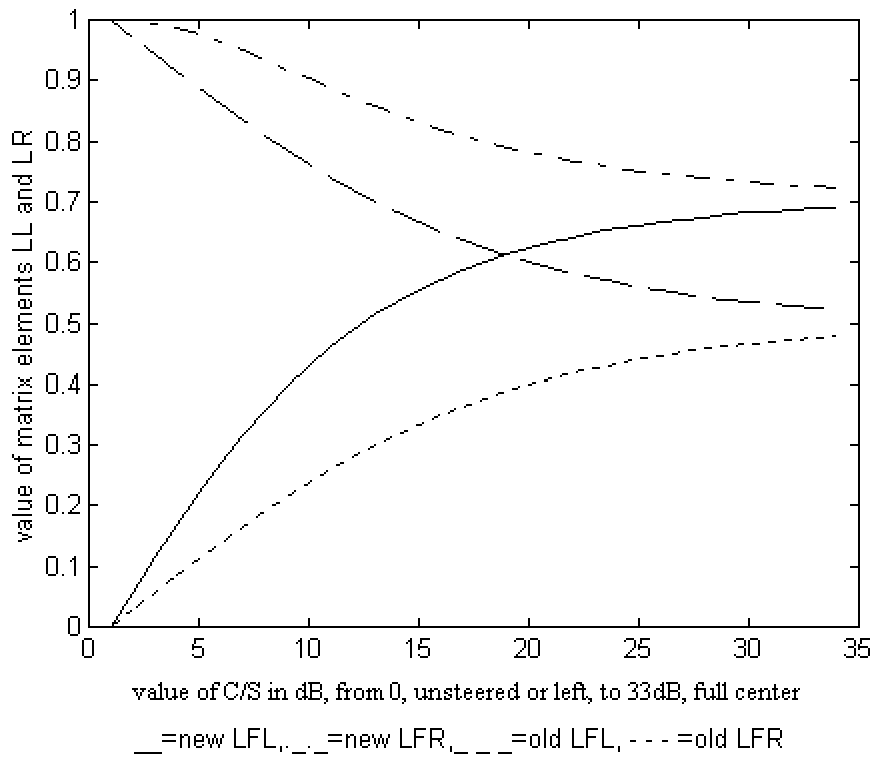

Figure 4: Left front matrix elements for the new and old decoders. The new curves give less pumping with music. ____ = LR - new _-_- = LL - new __ __ = LL - old, - - - = LR -old

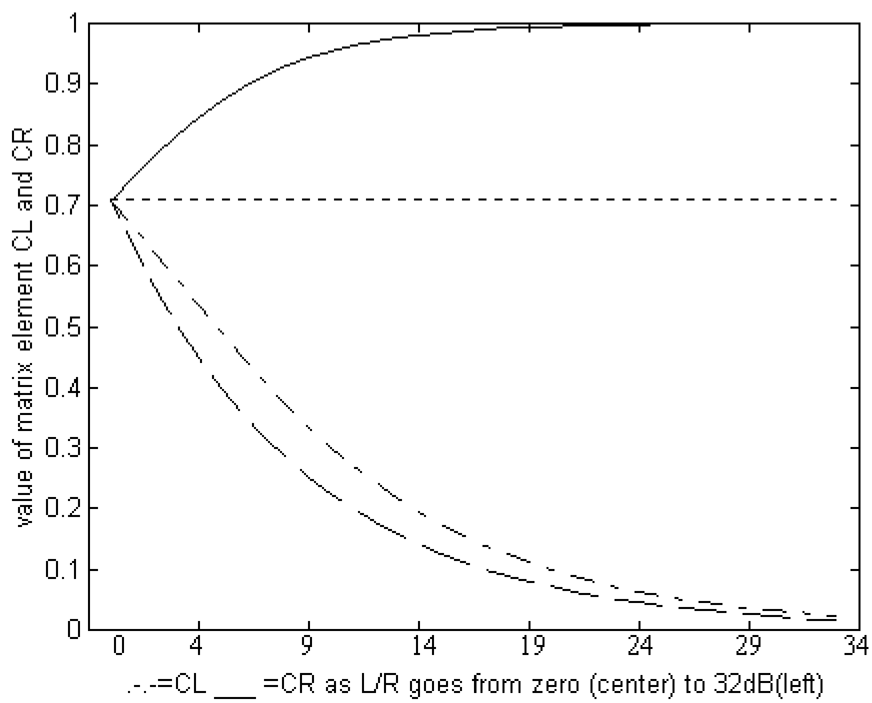

Figure 5: Graph of CL and CR in two different surround decoders. ____ = CL in the new decoder, _-_-_- = CR in the new decoder, - - - - = CL in the old decoder __ __ = CR in the old decoder

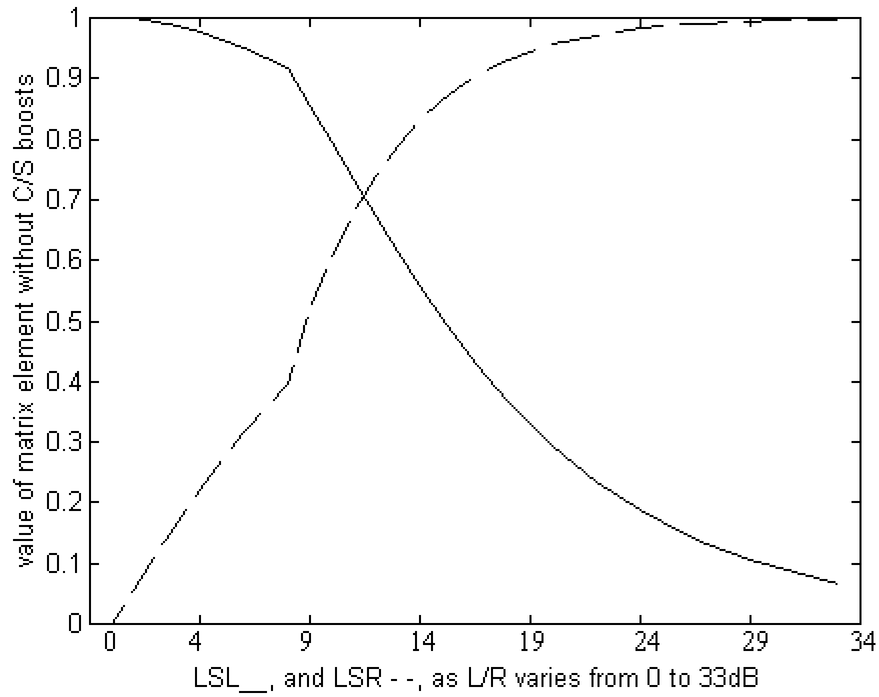

Figure 6: Rear matrix elements as material is steered from left to rear. Note that l/r = 33dB is equivalent to full left, and l/r goes to zero as steering goes to full rear. Note the break in the curves at l/r = 8dB, which corresponds to left rear.

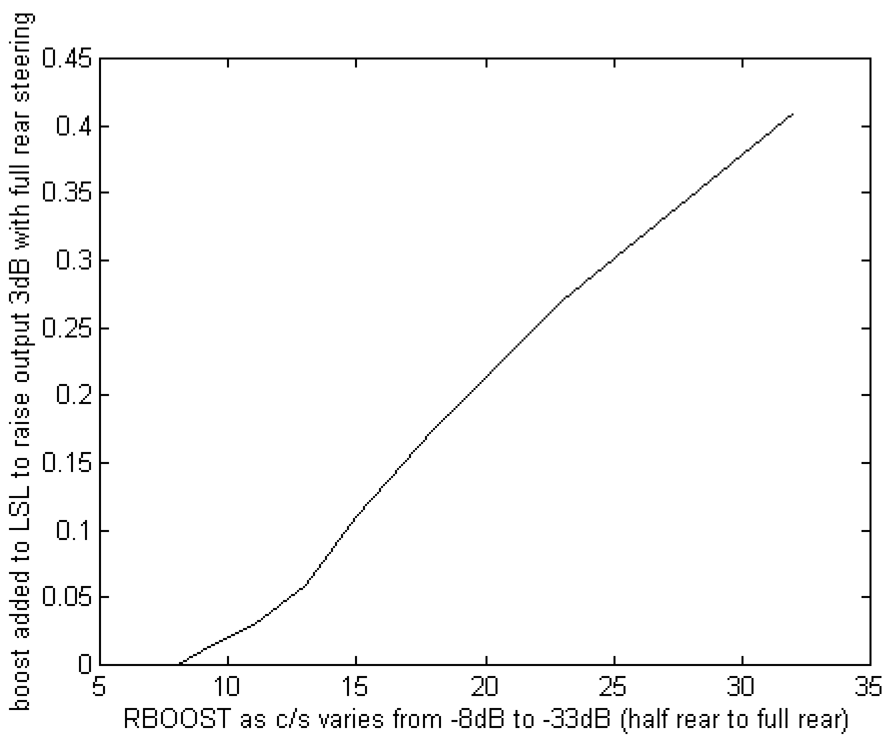

Figure 7: RBOOST as steering goes from half rear to full rear.

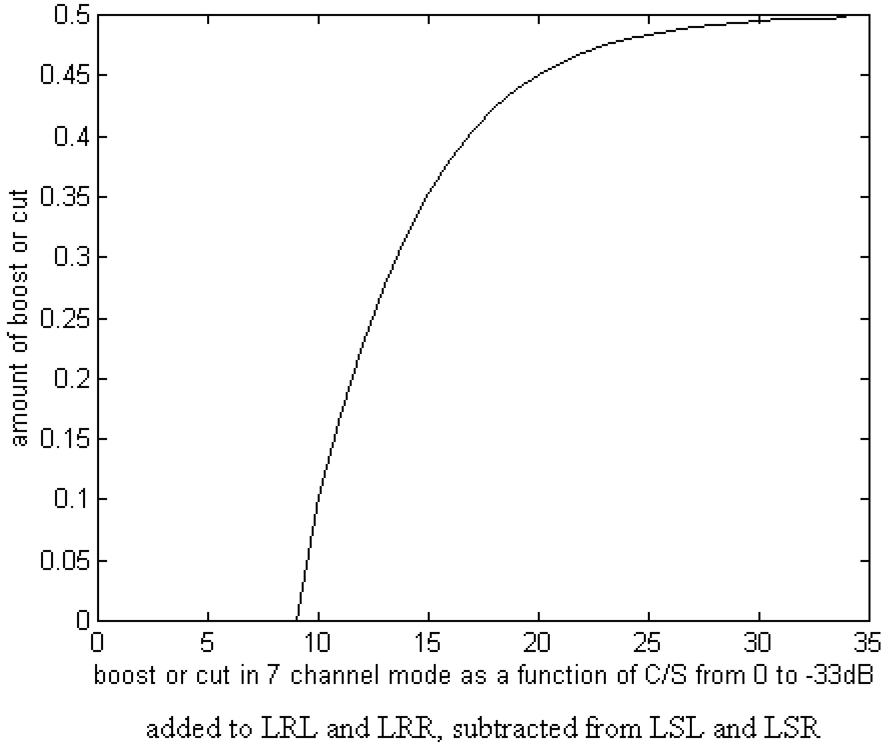

Figure 8: RSBOOST - added to LRL and LRR and subtracted from LSL and LSR to differentiate these outputs during full rear steering

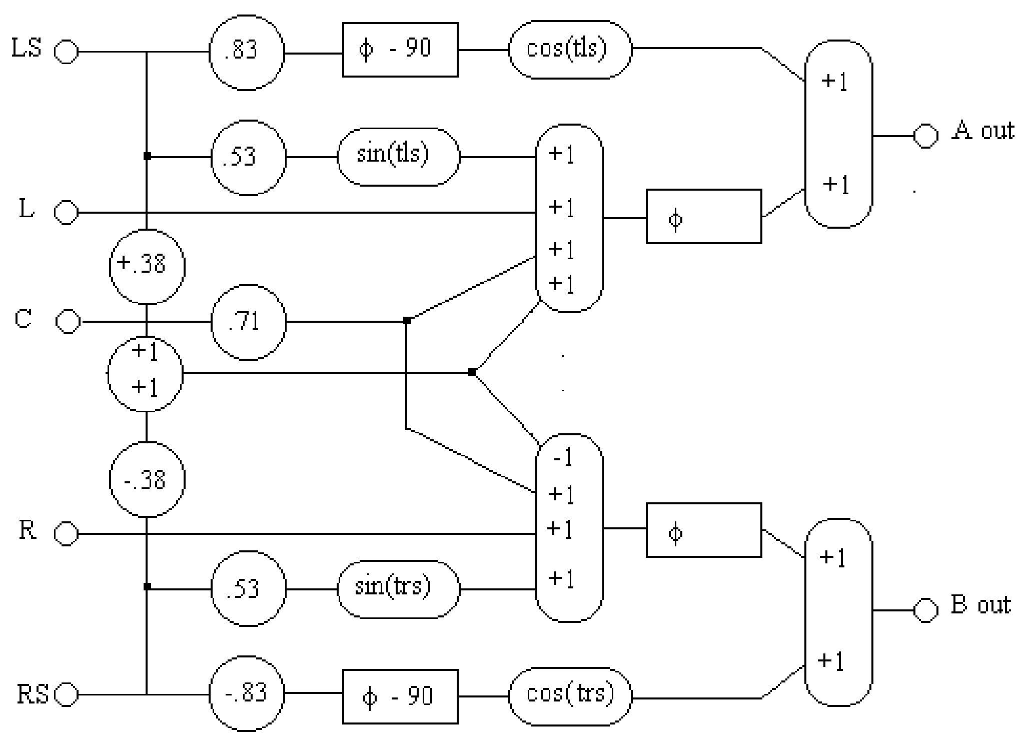

Figure 9: Block diagram of an active 5 channel film encoder. The passive encoder results when trs=tls=0. This encoder behaves almost identically to a standard 4 channel encoder when the two surround channels are driven in phase.