After recalling the aesthetic and psycho-acoustic factors that justify the introduction of quadraphony, the article explains the advantages of matrix systems which make it possible to transmit four audio signals over two channels only. A number of suitable configurations are then described, including, in particular, two C.B.S. developments, the so-called SQ and New Orleans matrices. The article then goes on to examine the compatibility of various matrices when the signals that they produce are heard on stereophonic or monophonic systems : the results obtained are summarised in tabular form. The author concludes by indicating how the SQ matrix may be used to produce pseudo-quadraphony from stereophonic recordings.

Quadraphony: Matrixing and compatibility

B.B. Bauer *

1. Introduction

During the past half-dozen years, several two-channel " matrix " quadraphonic systems have been introduced in various countries throughout the world by the C.B.S. and by others, and considerable information has been published about the theory and performance parameters of these various systems. A most important criterion, in addition to quadraphonic efficacy, is *compatibility*, or performance with the existing monophonic and stereophonic players and broadcasting transmission/reception apparatus. This article analyses the principal matrix systems from the point of view of compatibility. This analysis demonstrates that only the SQ system** is capable of *high-fidelity* compatible quadraphonic performance, thus providing full satisfaction to all listeners – quadraphonic, stereophonic, and monophonic – and even to those who prefer to use binaural earphones.

2. Compatibility and spatial high fidelity

The goal of high-fidelity recording and broadcasting is to convey a faithful replica of a musical programme to the listeners. Music, however, is a multi-dimensional experience involving both time and space and it requires more than one signal channel for faithful transmission and reproduction. Currently, quadraphonic sound is attracting the attention of the serious high-fidelity enthusiasts and technology is moving forward at lightning speed. A mass market for quadraphony is likely to develop in the near future and thus it is urgent that the engineer understands the compatibility issues of quadraphony so that he may be able to guide its future development to serve the needs of all listeners, whether quadraphonic, stereophonic or monophonic.

2.1. Ambiance and surround-sound options

The most frequently-heard classical-music programme is one in which a symphony orchestra or other musical group performs on a concert-hall stage. Here, quadraphony can play a most important role in contributing to spatial high fidelity. The front loudspeakers continue to carry the sounds of the stage as in stereo. The reverberant sounds are commonly applied to the back loudspeakers to reproduce the concert-hall ambiance. This type of recording is called ambiance quadraphony. It is evident that in this case an ideal " stereo-compatible " programme will allow the stereophonic listener to hear the front-channel sounds in precisely the same manner as with conventional stereo, allowing the reverberant sounds to be appropriately distributed between the two stereo channels.

Alternately, quadraphony opens a new opportunity for the home listener to participate, should he so desire, in *avant-garde* musical creations by the more daring producers and musicians – Gabrielli in the 14th century, who placed his performers on four balconies of St. Mark's Square in Venice ; Berlioz, who is his " Requiem " used five orchestras, an enormous choir, and batteries of percussion instruments sounding from various locations; Biggs playing antiphonal music on five organs in St. George Church in New York; Boulez who in some recording sessions at the Manhattan Center in New York places the orchestra in a circle around his podium ; Bernstein, who literally surrounds the audience with sound in performing his " Mass " ; and even jazz recitals where the performers surround the audience with sounds in a particularly intimate manner. All these " surround-sound " programmes are

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** SQ is a trademark of C.B.S. Inc.

reproduced in spatial high fidelity through the medium of SQ quadraphony. At the same time, they all sound as perfectly-normal stereophonic or monophonic programmes when recorded or transmitted in accordance with the principles of the SQ system.

3. Matrix versus discrete quadraphony

Some experimenters have assumed that only by providing four independent channels would one be able to produce satisfactory quadraphonic programmes. Unquestionably, given no limitations upon the availability of the electromagnetic spectrum or the area of recording medium or costs, it is simpler to use four discrete channels than to attempt the more-refined engineering task of transmitting a quadraphonic programme over two channels using matrix techniques. But a discrete quadraphonic system is far from compatible; as a matter of fact, its stereo compatibility is poor, This can be illustrated by the following example : let four signals, LF (left front), RF (right front), LB (left back), and RB (right back) appear in the corresponding channels of a quadraphonic array, then let this same programme be presented in the stereo mode by placing LF and LB [illegible] ie left stereo channel, and RF and RB in the right stereo channel. The result is not a satisfactory " fold "* of quad into stereo. It crowds the extremes of the stereo scene and leaves a " hole " in the middle.

But, setting aside the question of compatibility of discrete systems, good engineering practice has always required that we find ways of combining the laws of physics with the characteristics of human perception to achieve a desired result with optimum economy. Well-known examples of this principle are the techniques adopted for cinematography and colour television.

In the SQ system, by taking into account the psychoacoustics of man, and noting that conventional stereophonic transmission utilizes the amplitude signal space and not the phase space between the two channels, it has become possible to devise a system to transmit and receive quadraphonic programmes over two-channel circuits or FM stereo transmitters with full compatibility for mono and stereo receivers.

Quadraphonic broadcasting using the SQ matrix s[illegible]m can be done via an FM stereo station simply by placing SQ records on the turntable; or in the case of live or discrete taped quadraphonic programme by passing the latter through an SQ encoder in the studio; a further programme source is available through quadraphonic synthesis of stereophonic records or programme using an SQ encoder, as described below. Furthermore, reception with stereophonic or monophonic receivers is not adversely affected by the SQ quadraphonic broadcasts.

4. Quadraphonic matrix encoding and decoding

In matrix quadraphony, we combine or encode four original corner input signals, LF, RF, LB and RB (and also derived signals like CF* contained in the corner signals) into two output signals, LT and RT**, using a matrix encoder, such that LT and RT contain the full power of the original signals and result in pleasing reproduction when played over a stereophonic loudspeaker system. Also, when LT and RT are summed to produce a monophonic signal, it is desired that all the essential musical values remain even if it is understood that the directional aspect is lost.

Furthermore, when LT and RT are processed through an inverse matrix called a decoder, four output signals should result which contain the essential musical values and directional aspect of the original input signals. Since decoding, in essence, is equivalent to solving two equations with four unknowns, it turns out that the decoded signals also contain transferred portions of the original signals from the adjacent or opposite channels. The presence of these transferred signals in a well-designed matrix decoder is not necessarily unpleasant, musically speaking, but it has been found optimal for effective quadraphonic reproduction to provide further processing of the decoded signals through an electronic enhancing circuit, called " electronic logic ", which emphasizes the original signals in the decoded channels and deemphasizes them in the channels in which they were not originally present.

The SQ system matrix and logic have been described elsewhere [1, 2, 3], and in this article we limit ourselves to the analysis of the stereophonic and monophonic compatibility of various types of encoders. However, the following caution is needed : any encoding parameters must be sufficiently distinctive to give the logic unequivocal directional information on which to work, otherwise false logic decisions might result.

For example, as one possible code it has been suggested to introduce a small amount of input signal from one channel to the other. In this approach, the LF signal might be coded by introducing, say, 10 % of LF in phase in the RT channel, and the LB signal might be coded by introducing 10 % of LB antiphase into the RT channel. A sensitive logic might then be able to differentiate between LF and LB. The fallacy of this approach is that if a phonograph pickup used to play the record exhibits only 20 dB channel separation, which is not untypical, this might result in the generation of a false code which will misplace the position of the LF or LB signals in the decoder output.

Thus, for reliable operation of a logic system, the greatest possible differentiation of the various directional signals has to be provided in the encoder consistent with the desired stereophonic and monophonic compatibility. This differentiation may be an amplitude or phase differentiation. The SQ code has been designed keeping the above considerations in mind.

* The stereo " fold " of SQ-encoded signals, described later, provides a far more pleasing and natural stereophonic reproduction.

* CF = centre front ; 0.71 CF is contained in each of LF and RF. Other derived signals sometimes used are CL = centre left, CR = centre right, and rarely, CB = centre back.

** LT = left total, RT = right total.

5. Encoding

There is obviously a large number of ways in which four signals can be coded into two. An early method of coding can be traced to Blumlein [4]. Another, purely arithmetical matrix was invented by Scheiber [5], whose quadraphonic demonstrations several years ago were instrumental in sparking the current interest in quadraphony. Our studies at the C.B.S. have shown that for compatible performance it is necessary to use complex matrix coefficients [6]. Two basic codes were discovered through these studies, which we called the SQ code and the New Orleans code [3]. After exhaustive tests and analyses of various recording and broadcasting problems, we decided to adopt the SQ code, because of its superior compatibility. Other investigators have preferred to use codes similar to the New Orleans code, and therefore we refer to it in a later section.

5.1. SQ encoding

In the SQ code, the front channels, LF and RF, are treated exactly and precisely as any stereophonic signal pair. This ensures that the front signals will be reproduced compatibly either quadraphonically, stereophonically, or monophonically, This quality of SQ is of enormous importance to the recording and broadcasting engineer, because the great majority of programmes are performed on a front stage.

The back channels of SQ are coded using phase-splitter circuits which change each of the applied signals into two identical signals at 90° phase angle with respect to each other, with their amplitudes reduced by a factor of 0.707 ; LB is applied with the leading signal in LT and lagging signal in RT, while RB is applied with the leading signal in RT and the lagging signal in LT.

It will be noted that if two signals at 90° are added vectorially and then squared, or if they are first squared and then simply added, the result in each case is the same; this demonstrates that in either the monophonic or the stereophonic mode the power of uncorrelated back channels remains unchanged which, again, is the essence of compatibility.

Any encoder that ensures that the above conditions are fulfilled can properly be classified as an SQ encoder [7]. Several circuits meet this requirement. Two SQ encoding circuits which are especially useful have been characterized as the *basic* and the *forward-oriented* encoders [2], respectively*. The basic SQ encoder conforms to the matrix equations :

$$\begin{aligned} LT &= LF + 0.71\, e^{-j90^\circ}\, LB + 0.71\, RB \\ RT &= RF - 0.71\, LB + 0.71\, e^{j90^\circ}\, RB \end{aligned} \qquad (1)$$

The forward-oriented encoder conforms to matrix equations :

$$\begin{aligned} LT &= LF + 0.71\, LB + 0.71\, e^{-j90^\circ}\, RB \\ RT &= RF + 0.71\, e^{-j90^\circ}\, LB + 0.71\, RB \end{aligned} \qquad (2)$$

* A "position encoder" which, using pan-pot controls, is able to encode signals from any direction ideally, is also available [2].

We note that any SQ encoder can be connected to the input terminals of an FM-multiplex transmitter and continue to meet in every way the FCC requirements for stereo channel separation in FM transmitters*. Any stereophonic signals connected to the LF and RF terminals remain fully isolated and precisely in phase, as demanded by FCC regulations. This is a prodigious advantage of the SQ system which no other matrix system is able to offer.

5.2. The New Orleans code and its derivatives

The C.B.S. New Orleans code (named after the city in Louisiana, U.S.A., in which it was invented) was an attempt to provide a matrix potentially capable of centre-back signals. As first published in the Belgian Patent No. 778,296, the New Orleans code can be defined by the following matrix equations :

$$\begin{aligned} LT &= 0.92\, LF + 0.38\, e^{j90^\circ}\, RF + 0.92\, LB \\ &\quad + 0.38\, e^{-j90^\circ}\, RB \\ RT &= 0.38\, e^{-j90^\circ}\, LF + 0.92\, RF + 0.38\, e^{j90^\circ}\, LB \\ &\quad + 0.92\, RB \end{aligned} \qquad (3)$$

This is the New Orleans code N°. I. The same patent describes another New Orleans code, which we have called No. II. It is defined by :

$$\begin{aligned} LT &= 0.92\, e^{-j22.5^\circ}\, LF + 0.38\, e^{j67.5^\circ}\, RF \\ &\quad + 0.92\, e^{-j22.5^\circ}\, LB + 0.38\, e^{-j112.5^\circ}\, RB \\ RT &= 0.38\, e^{j67.5^\circ}\, LF + 0.92\, e^{j22.5^\circ}\, RF \\ &\quad + 0.38\, e^{j112.5^\circ}\, LB + 0.92\, e^{j22.5^\circ}\, RB \end{aligned} \qquad (4)$$

It will be noted that both the above codes are characterized by the fact that each encoded signal contains four original signals, by the use of coefficients 0.92 and 0.38, and by 90° relationship between LF-RB and RF-LB in the encoded channels.

A number of experimenters working independently have proposed matrices similar to the New Orleans matrix, but in which the signal magnitudes have been altered and rotated to produce somewhat different matrix equations. None of these variants, in our opinion, has achieved significant improvement over the performance of the original New Orleans code. And while these various manipulations might have been justifiable in the expectation of superior decoding without the use of logic, promised by the variant proposers, most of these experimenters have now conceded that a logic system, or the like, must be added to their proposed matrix decoders to obtain adequate channel separation. In view of this, it would appear that compatibility remains the most cogent criterion for matrix selection.

* Based on a "proof of performance" test defined by a channel separation of 29.7 dB as being indicative of appropriate adjustment between the sum and difference channels.

Table 1. — Stereophonic and monophonic characteristics of quadraphonic matrices

System	Stereophonic								Monophonic		
	LF↔RF (dB)	Phase (deg.)	CF (dB**)	Phase (deg.)	LB↔RB (dB)	Phase (deg.)	CB (dB**)	Phase (deg.)	LB or RB (dB**)	CF (dB**)	CB (dB**)
Stereo	∞	*	0	0	*	*	*	*	*	3	*
SQ (Basic)	∞	*	0	0	0	90°	0	180°	0	3	—∞
SQ (Forward)	∞	*	0	0	0	90°	0***	0	0	3	3
New Orleans (I)	7.7	90°	0	45°	7.7	90°	0	45°	0	2.3	2.3
New Orleans (II)	7.7	45°	0	0	7.7	135°	0	90°	—4.8	1.3	— 1.7
QS (Original)	7.7	0	2.3	0	7.7	180°	2.3	180°	—7.7	3	—∞
QS (NQRC)	7.7	0	1.8	20°	7.7	180°	1.8	160°	—7.7	2.3	—13.0
QS (CCIR)	7.7	20°	1.8	0	7.7	160°	1.8	140°	—7.0	2.6	— 7.0
BMX	7.7	90°	1.8	70°	7.7	90°	1.8	70°	0	3.0	3.0
BBC (H)	8.8	75°	1.4	48°	8.8	140°	0	90°	—3.6	2.9	— 0.7

* Not applicable
** With respect to RF or LF
*** Decoded as CF

6. Matrix compatibility

We can now compare the compatible performance of the various matrices referred to in this article. The principal characteristics are shown in *Table 1.* True stereo and nine different matrix systems are listed in the first column. The second and third columns give the front-channel separation and phase angle of the crosstalk signal in the stereo mode. The fourth and fifth columns give the power level of the centre-front signal relative to a left-front signal and the phase difference between its left and right components. The sixth and seventh columns give the back-channel separation and phase angle. Finally, the eighth and ninth columns list the back-signal power and phase angle. The last three columns describe the monophonic characteristics – the strength of back-channel corner signals relative to the front-channel corner signals, and the levels of the centre-front and centre-back signals.

It is evident that of all the proposals, only the basic and forward-oriented SQ codes are exactly and precisely compatible with stereo and mono reproduction, except for the centre-back signal which is not transmitted with the basic SQ encoder in the monophonic mode. Despite the attention bestowed on the centre-back by some investigators, our experience of several years in producing quadraphonic records has convinced us that the centre-back position has negligible practical importance*.

* This fact is reinforced by the recent growth of the practice by quadraphonic listeners of placing the back loudspeakers at either side of the listener's location. With this arrangement any centre-back soloists would appear to be located overhead !

The New Orleans matrix No. I, which is among the best in its class, provides only 7.7 dB front-channel separation which is unacceptable for recording original stereo programmes, despite the fact that the phase shift of the crosstalk signal is 90° (this greatly improves psycho-acoustically what otherwise would have been a very poor front-channel separation). The centre-front signal is at 45° which, in our opinion, causes it to spread and shift excessively [8]. (This problem is remedied in the New Orleans matrix II, but here the *front-channel crosstalk* is at 45°, which generates excessive narrowing of the audible front-channel separation and results is an undesirable 4.8 dB drop in the back channels in the monophonic mode.)

The QS matrix [9], which is similar to the New Orleans matrix except for variations in inter-phasor angles, has undergone considerable changes during the past year. The original QS produced a 7.7 dB front-channel crosstalk at 0° angle. In the monophonic mode. the back channels are attenuated by 7.7 dB with respect to the front channels which results in a 10.7 dB imbalance between musical sounds at centre-front and the back corners in a surround-sound performance. After several years' experience, the QS proponents have altered the matrix twice – the first time about a year ago for submission to the National Quadraphonic Radio Committee [10], and again more recently for submission to the C.C.I.R. [11]. These alterations have served to improve somewhat the monophonic transmission at the trivial CB position at the expense of CF phase integrity. but the corner-back channel signals, at – 7dB, remain seriously unbalanced for the monophonic listener.

The BMX matrix [12] is listed here because at one time it was thought that it would be offered by its sponsors as a quadraphonic matrix *per se*. It appears at present that this is not the case and the BMX seems to be destined for use as a baseband matrix for a proposed discrete quadraphonic broadcasting system. In the stereo mode, its performance is poorer than that of New Orleans matrix No. I because its centre-front signal phase is 70° as against 45° for the latter [8]. It is obvious that from the standpoint of stereophonic and monophonic compatibility, the SQ forward-oriented code is more suitable for the basebands of any compatible system than the BMX matrix.

And, lastly, we list here a B.B.C. offering [13] – the H ("hearing properties") matrix — which was originally intended to provide optimum quadraphonic reproduction without logic.

The B.B.C. H matrix has performance somewhat equal to the New Orleans I, except for its pronounced (– 3.6 dB) loss of back-channel power in monophonic reproduction and its centre-front phase shift of 48° which causes a perceptible spread and shift of the centre-front image [8], and thus proves to be unacceptable in high-fidelity recording practice. Its 8.8 dB front-channel separation contradicts normal stereophonic recording practice. Furthermore, the B.B.C. Research Laboratories' initial belief that logic enhancement for its matrix decoder was unnecessary has proven to be illusory, with a newly-developd B.B.C. logic system having been presented to the E.B.U. in the spring of 1976 [14]. Thus, the *raison d'être* for the B.B.C. matrix offering apparently has disappeared.

In summary, the SQ matrix is the only high fidelity, fully-compatible quadraphonic matrix thus far devised The alternate New Orleans matrix, the best in its class, and all its variants are less compatible because of relatively poor front-channel separation or phase-shifted centre-front signal or excessive loss of the back-corner signals in monophonic reproduction, or all three deficiencies combined. This, in our opinion, is too high a price to pay for a potential capability of favouring the inconsequential centre-back signal*

* During the past five years, the writer has encountered only two instances where mono-transmittable centre-back signals justifiably required centre-back placement on decoding: a) soloists placed at the centre of the choir in the back of a church (the choir itself could be conveniently "split" between the two back channels); and b) an automobile race in which the producer wished to "pan" the sounds around the quadraphonic perimeter. While these are unusual occurrences, it is now possible to accommodate them by using a back-signal "London Box" newly developed by the writer, in which a frequency splitting circuit applies 0.95 (cos 18°) of alternate octave bands of an audio signal to the left-back channel, and 0.31 (sin 18°) of the same octave bands antiphase to the right-back channel, following a similar procedure with the alternate set of octave bands connected to the right-back channel. Through the action of the logic circuit, the decoded centre-back signal appears to be sharply focussed between the two back channels in the quadraphonic mode, and it is heard precisely centered, albeit somewhat spread, in between the loudspeakers in the stereophonic mode. The monophonic transmission is reduced by 3.9 dB relative to the corner signals. In all other respects, the performance of the forward-oriented encoder remains unaltered.

7. Quadraphonic synthesis

One of the most important resources in quadraphonic broadcasting is the possibility of utilizing the immense libraries of stereophonic programmes available in FM stations by, in effect, re-encoding them for quadraphony. This is done simply with an SQ forward-oriented encoder, by connecting the left stereo channel to both the left-front and left-back terminals of the encoder, and the right stereo channel to the right-front and right-back terminals of the encoder. The amount of quadraphonic enhancement obtained in this manner can be adjusted by varying the relative signal levels into the front and the back channels. We consider here the generally recommended condition, that is the application of the stereo signals equally to the front and the back channels.

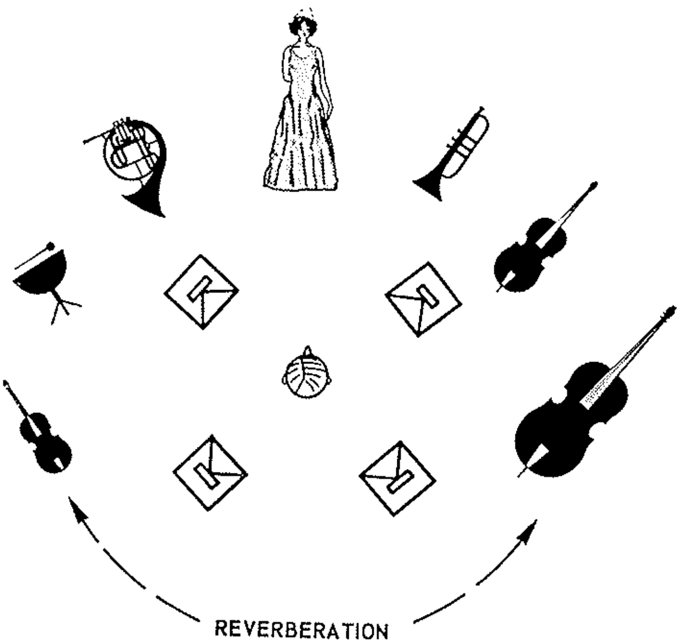

Fig. 1. — The effect perceived when SQ quadraphonic synthesis is applied to a stereophonic programme.

The connection described above obviously produces an SQ code which is equivalent to the generation of CL and CR signals. These are decoded at the corresponding CL and CR directions of the quadraphonic array. We will now consider the strength and position of the centre stereo signal, C, and the various power relationships which have a bearing on compatibility of the synthesized signal. Therefore, let the left stereo signal be L + 0.71 C, and the right one be R + 0.71 C.

Referring to the matrix equations for the forward-oriented encoder, and setting LF = LB = L + 0.71 C, and RF = RB = R + 0.71 C, we obtain

$$LT' = 1.71\ L + 0.71\ e^{-j90^\circ} R + (1.21 + 0.5\ e^{-j90^\circ})\ C$$

$$RT' = 1.71\ R + 0.71\ e^{-j90^\circ} L + (1.21 + 0.5\ e^{-j90^\circ})\ C$$

and normalizing to unity power for C in both channels :

$$LT'' = 0.92\ L + 0.38\ e^{-j90^\circ}\ R + 0.71\ e^{-j22.5^\circ}\ C \qquad (5)$$

$$RT'' = 0.92\ R + 0.38\ e^{-j90^\circ}\ L + 0.71\ e^{-j22.5^\circ}\ C$$

Therefore, the centre signal C has a total power of $0.71^2 + 0.71^2 = 1$, and its components are in phase ; and thus, C is decoded in centre front. The stereo image does not now appear between the front channels, but rather forms a semicircle around the quadraphonic array as shown in *Fig. 1*. The quadraphonic listener, in effect, is transported to the conductor's podium and senses a new and exciting perspective. The stereo listener hears a somewhat reduced stereo width because, while the crosstalk corresponding to the L and R signal in equation (5) is only 7.7 dB, this crosstalk is in quadrature, which means that it is less audible than if it were in phase. The centre signal remains at full strength and is centered, as with ordinary stereo. The monophonic listener continues to hear precisely what he has heard before enhancement. As far as he is concerned, no change has taken place.

There is another important consideration in connection with SQ quadraphonic synthesis. The sum and difference ratio of the synthesized LT'' and RT'' is the same as that which had existed before synthesis. This result is of tremendous importance. Stereo signals are transmitted via FM by modulating the audio baseband with the sum signal and the subcarrier channel with the difference signal. Let the conventional stereo signal contain one unit of power each of the L, C, and R signals. The sum signal is L + 1.41 C + R, and since these are incoherent unity signals, the total power is proportional to $1^2 + 1.41^2 + 1^2 = 4$. The difference signal is L — R and its total power is proportional to $1^2 + 1^2 = 2$. Thus, the ratio of sum/difference powers is also 2, corresponding to 3 dB. This means that normally the audio baseband of the transmitter carries twice as much power as the subcarrier.

Let us calculate the same power relationships for the SQ-synthesized signals (from equation 5). The sum signal is,

$$\begin{aligned} LT'' + RT'' &= (0.92 + 0.38^{-j90^\circ})\ L \\ &\quad + (0.92 - 0.38\ e^{-j90^\circ})\ R \\ &\quad + 1.41\ e^{-j22.5^\circ}\ C \\ &= (L + R - 1.41\ C)\ e^{-j22.5^\circ} \qquad (6) \end{aligned}$$

and the difference signal,

$$\begin{aligned} LT'' - RT'' &= (0.92 - 0.38\ e^{-j90^\circ})\ L \\ &\quad - (0.92 - 0.38\ e^{-j90^\circ})\ R \\ &= (L - R)\ e^{-j22.5^\circ} \qquad (6) \end{aligned}$$

Thus, the respective magnitudes of the sum and difference signals for the stereo and the SQ-synthesized programmes are identical. The transmitter power and the listener coverage remain the same for all listeners – quadraphonic, stereophonic, monophonic – as they were prior to the synthesis operation. Moreover, the same relationships remain regardless of the degree of SQ enhancement.

- SQ is the only known matrix system in which enhancement is carried out in such a benign manner. For example, consider what happens when enhancement is performed in the QS mode. The recommended procedure is to subtract a fraction (0.41) R from the L-stereo channel, and a fraction (0.41) L from the R-stereo channel [15], albeit in practice this operation is performed by connecting the stereo signals to the LB and RB channels of the QS encoder and reversing the right-back input terminals. Thus, the QS-enhanced signals become,

$$\begin{aligned} LT'' &= (L + 0.71\ C) - 0.41\ (R + 0.71\ C) \\ &= L + 0.41\ C - 0.41\ R \end{aligned}$$

and (7)

$$\begin{aligned} RT'' &= (R + 0.71\ C) - 0.41\ (L + 0.71\ C) \\ &= R + 0.41\ C - 0.41\ L \end{aligned}$$

Assuming, as before, that each of the original stereo signals (L, R and C) has unity power, the total stereo power for L in the enchanced signal is $1^2 + 0.41^2 = 1.17$; for R it also is $1^2 + 0.41^2 = 1.17$; but for C it is $2 \times 0.41^2 = 0.34$. This means that in the QS-synthesized programme the relative power of C is diminished by 10 log 0.34/1.17 = — 5.4 dB relative to L and R. Because of the resulting imbalance, the quality of the programme is noticeably altered for the stereo listener.

Another problem of QS enhancing arises in the FM transmitter, in which the sum signal is modulated on the baseband, and the difference signal on the subcarrier. From equation (7), the sum signal is,

$$\begin{aligned} LT''' + RT''' &= 0.59\ L + 0.59\ R + 0.82\ C \\ &= 0.59\ (L + R + 1.41\ C) \qquad (8) \end{aligned}$$

and the difference signal is,

$$\begin{aligned} LT''' - RT''' &= 1.41\ L - 1.41\ R \\ &= 1.41\ (L - R) \qquad (8) \end{aligned}$$

It is seen that the sum signal which reaches the monophonic listener is now diminished by a factor of 0.59^2 or to 0.35 of its former power, while the difference signal carried on the subcarrier is increased by a factor of 1.41^2, or to twice its former power. The power balance of the transmitter is completely altered, and the signal-to-noise ratio at the receiver is likely to be diminished, especially for distant listeners*.

* The above analysis is based on 20 log (0.41/1) = —7.7 dB inverse crosstalk enhancement. Some QS encoders have an internal stepped switch for adjusting the crosstalk, thus reducing the afore-mentioned effects as well as the degree of enhancement.

8. Conclusion

In this article we have demonstrated that quadraphony is essential to high fidelity, but that in achieving it the engineer has to be careful to preserve the high fidelity values presently available to the stereophonic and monophonic listeners. Matrix quadraphony is the approach most likely to achieve this objective. Considering the practical priorities of the recording arts, it is shown that of the large number of possible matrices, SQ is the most compatible because of its ideal front-channel separation, its front-channel phase integrity, and its ability to transmit all corner signals equally in the monophonic mode. Another C.B.S. matrix, the so-called New Orleans matrix, has been commercialized, but numerous variants of it that have been proposed by other investigators have reached varying stages of development. It has been shown that the New Orleans matrix and all its variants fall short of the performance of the SQ matrix because, although in some cases they are able to transmit the relatively trivial centre-back signals more effectively than the SQ matrix*, in all cases they are deficient in one or more of the important capabilities of : (a) maintaining front-channel stereo separation, (b) phase integrity of the centre-front signals, or (c) reception of the back-corner signals without loss in the monophonic mode.

* On rare occasions where a centre-back signal must be transmitted and decoded via SQ, this is also possible by adding a back-signal processing " London Box ", as already explained.

The SQ matrix-with-logic system is uniquely adaptable to the production of stereo-compatible ambiance or surround-sound programmes. Quadraphonic synthesis from stereophonic records is another task for which the SQ matrix can be used in an effective and benign manner. It is shown that SQ synthesis does not result in significant degradation of signal fidelity to either the stereophonic or monophonic listener, while synthesis attempted by means of some other matrices may result in severe alteration in the FM transmitter's signal strength and balance for the stereophonic and the monophonic listeners.

We conclude that, of all the proposed matrix systems, only SQ meets the requirements of quadraphony, spatial high fidelity, and compatibility.

BIBLIOGRAPHICAL REFERENCES

[1] Bauer, B.B., Gravereaux, D.W. and Gust, A.J. : *A compatible stereo-quadraphonic (SQ) record system.* Journal of the Audio Engineering Society, Vol. 19, No. 8, September 1971, pp. 638-646.

[2] Bauer, B.B., Budelman, G.A. and Gravereaux, D.W. : *Recording techniques for SQ matrix quadraphonic discs.* Journal of the Audio Engineering Society, Vol. 21, No. 1, Jan./Feb. 1973, pp. 19-26.

[3] Bauer, B.B., Allen, R.G., Budelman, G.A. and Gravereaux, D.W. : *Quadraphonic matrix perspective — Advances in SQ encoding and decoding technology.* Journal of the Audio Engineering Society, Vol. 21, No. 5, June 1973, pp. 342-350.

[4] Blumlein, A.D. : *Improvements in and related to sound-transmission, sound-recording and sound-reproducing systems.* British Patent 394,325, 14th December, 1931.

[5] Scheiber, P. : *Four channels and compatibility.* Journal of the Audio Engineering Society, Vol. 19, No. 4, April 1971, pp. 267-279.

[6] Bauer, B.B. : *Directional ambiguity of quadraphonic matrices.* Letter to the Editor, Journal of the Audio Engineering Society, Vol. 19, No. 4, April 1971, pp. 315-316.

[7] White, J.V. : *Synthesis of 4-2-4 matrix recording systems.* Journal of the Audio Engineering Society, Vol. 24, No. 4, May 1976, pp. 250-257.

[8] Matsudaira, T.K. and Fukami, T. : *Phase differences and sound image localization.* Journal of the Audio Engineering Society, Vol. 21, No. 10, December 1973, pp. 792-797.

[9] Ito, R. : *Proposed universal encoding standards for compatible four-channel matrixing.* Journal of the Audio Engineering Society, Vol. 20, No. 3, April 1972, pp. 167-173.

[10] *Report of the National Quadraphonic Radio Committee to the Federal Communications Commission. November 1975.* Published by the Electronic Industry Association.

[11] *Four channel broadcasting via two transmission channels.* C.C.I.R. document 10/54 (USA), 1974-1978.

[12] Cooper, D.H. and Shiga, T. : *Discrete-matrix multichannel stereo.* Journal of the Audio Engineering Society, Vol. 20, No. 5, June 1972, pp. 346-360.

[13] Crompton, T.W.J. : *The subjective performance of various quadraphonic matrix systems.* B.B.C. Research Department Report No. 1974/29.

[14] *Report of the 7th meeting of Working Party S (Stereophonic broadcasting and multiple-modulation systems).* E.B.U. document Com. T. (S) 177-E, 10th March 1976.

[15] Ito, R., Takahashi, S. and Hitano, K. : *QS quadraphonic synthesizer ; what it does and how it does it.* Pre-print from a Paper of the Audio Engineering Society 49th Convention, September 1974.