Coder/Decoder Units for RGB and NTSC Signals

By JOHN D. LOWRY

Appendix by PETER T. H. KWA

This paper contains a brief description of the RGB and the NTSC codecs used during the First SMPTE Component-Coded Demonstration of Digital Video. Each unit operates at the luminance/chrominance sampling ratio of 4:4:4 and is capable of running at any of three demonstration clock rates. Operating the above units in any tandem combination, as well as with a digital interface with units of the other Demonstration participants, yielded acceptable picture quality. In the Appendix the codec matrices between RGB, YUV, YIQ, and Y, R − Y, and B − Y of the digital interface are postulated. The relationship of Y, R − Y, and B − Y to the composite video signal is indicated. The numerical relationships described in this paper are independent of clock frequencies and luminance/chrominance sampling ratios.

The demonstration equipment comprises the RGB codec,* the NTSC encoder, and the NTSC decoder. Each unit is capable of operating at any of the demonstration frequencies or clock rates, i.e., at 12.08 MHz or 768 samples per (video) line (spl), at 13.59 MHz or 864 spl, and at 14.35 MHz or 912 spl. The luminance/chrominance sampling ratio in the Y, R − Y, B − Y digital interface is 4:4:4; the sampling structure is orthogonal. The analog low-pass filters at the input of the decoders and at the output of the encoders are loss-compensated, five-pole Cauer filters with three sections of group delay equalization. Their cutoff frequency is 5.5 MHz.

The RGB Codec

The RGB decoder converts analog RGB to digital Y, $R - Y$, and $B - Y$ signals; the RGB encoder converts digital Y, $R - Y$, and $B - Y$ signals to analog RGB. Both the RGB decoder and the RGB encoder are implemented twice in the hardware realization (see Figs. 1 and 2).

The RGB Decoder

After passing through low-pass filters, the analog RGB signals are digitized with a resolution of eight bits at the selected demonstration clock rate. These low-pass filtered RGB signals are fed to the digital matrix yielding Y, $R - Y$, and $B - Y$ signals. Scaling programmable read-only memories (PROMs) and adders are used to implement the following matrix equation:

$$\begin{pmatrix} Y - 16 \\ R - Y - 128 \\ B - Y - 128 \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.500 & -0.419 & -0.081 \\ -0.169 & -0.331 & 0.500 \end{pmatrix} \times \begin{pmatrix} R - 16 \\ G - 16 \\ B - 16 \end{pmatrix} \quad (1)$$

All three signal channels (Y, $R - Y$, and $B - Y$) have a bandwidth of 5.5 MHz. The clock generator, operating at the three demonstration clock rates, is locked to horizontal sync. The digital interface at the output of the RGB decoder is complete with the sync and clock signals.

The RGB Encoder

The Y, $R - Y$, and $B - Y$ signals from the digital interface are fed to the digital matrix yielding RGB. Again, scaling PROMs and adders are used to implement the following matrix equation:

$$\begin{pmatrix} R - 16 \\ G - 16 \\ B - 16 \end{pmatrix} = \begin{pmatrix} 1 & 1.402 & 0 \\ 1 & -0.714 & -0.344 \\ 1 & 0 & 1.772 \end{pmatrix} \times \begin{pmatrix} Y - 16 \\ R - Y - 128 \\ B - Y - 128 \end{pmatrix} \quad (2)$$

These digital RGB signals are converted to analog signals and passed

* *Codec* is a contraction for *coder and decoder*. Such a device combines circuitry for coding and decoding.

AUTHORS: Mr. Lowry is President of Digital Video Systems of Toronto, Ontario, Canada. Mr. Kwa is a member of the Design Engineering Department at Digital Video Systems, Toronto, Ontario, Canada.

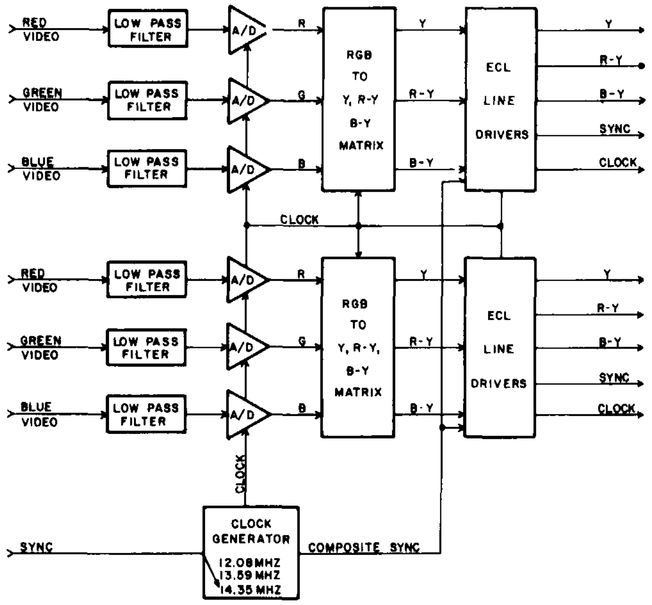

Figure 1. The RGB decoder accepts analog RGB and feeds the digital interface.

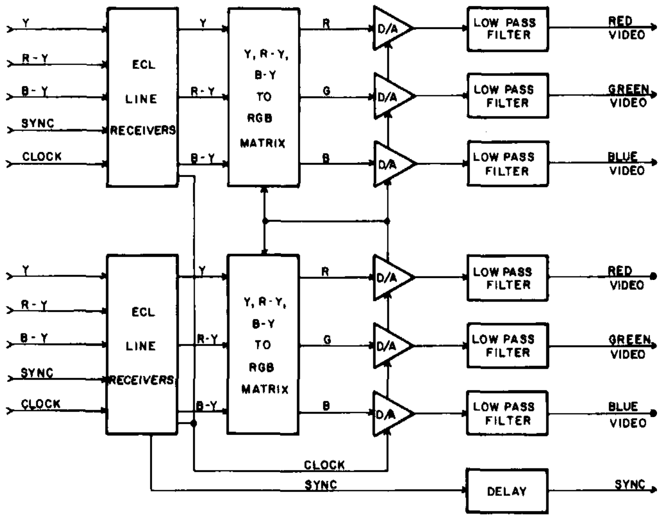

Figure 2. The RGB encoder accepts the data of the digital interface and converts it to analog RGB.

through low-pass filters to limit their bandwidth to 5.5 MHz. The sync signal is delayed to preserve the correct timing relationship with the RGB signals at the output of the system.

The NTSC Encoder

The NTSC encoder converts the Y, $R - Y$, and $B - Y$ signals of the digital interface to analog NTSC composite video (see Fig. 3). The low-pass filters in each signal channel are symmetrical FIR (finite impulse response) filters with twelve coefficients. The luminance filter has a Cauer characteristic with a cutoff frequency of 5.5 MHz. The color difference filters have a $\sin^2$ characteristic with a 6-dB cutoff frequency of 1.5 MHz. The color subcarrier is quadrature modulated along the R − Y and B − Y axis according to the equation

$$\text{Chroma} = 1.230\,(R - Y - 128)\cos w_{NTSC}t + 0.874\,(B - Y - 128)\sin w_{NTSC}t \quad (3)$$

PROMs are used to store two complete video lines of modulating sine waves. Multipliers and adders are used to implement the modulation arithmetic (Equation 3).

The clock generator is locked to the sync signal of the digital interface. It provides new sync, burst, and blanking signals, which are inserted immediately prior to the digital-to-analog converter. The output signal is passed through a low-pass filter to limit the bandwidth to 5.5 MHz.

The NTSC Decoder

The NTSC decoder converts the analog NTSC composite video signal to the Y, $R - Y$, and $B - Y$ signals of the digital interface (see Fig. 4). Whereas the NTSC encoder is a straightforward digital implementation of the standard analog encoding algorithm, the NTSC decoder utilizes more elaborate signal processing techniques, such as picture adaptive comb filtering and sample rate conversion.

After passing through a low-pass filter, the analog NTSC composite video is sampled on the $R - Y$ and $B - Y$ axis and digitized at four times the NTSC color subcarrier frequency (corresponding to 910 spl) with a resolution of eight bits. Separation of luminance and chrominance is performed by a picture adaptive comb filter, which employs up to three consecutive video lines for processing. The chrominance signal is passed through a symmetrical FIR bandpass filter with five coefficients. Since sampling is performed on the $R - Y$ and $B - Y$ axes, this bandpass filtered chrominance data stream contains the multiplexed baseband components $R - Y$ and $B - Y$.

The data buffer immediately prior to the interpolator low-pass filters is required to provide for the expansion from 910 to 912 spl. The data buffer immediately following the interpolator low-pass filters is required to provide for the reduction of samples from 910 to 864 or 768 spl. The interpolator low-pass filters are time-variable FIR filters. In each clock cycle, 1 set out of 128 sets of coefficients is effective. Each set comprises 12, generally nonsymmetrical, coefficients. This algorithm achieves interpolation with a resolution of 1 nsec on the time axis. The cutoff frequency is 5.5 MHz in the luminance channel and 1.5 MHz in the color difference channels. The maximum ripple is less than 0.5 dB throughout the passband.

The method of decoding with multiple output data rates was chosen based on the ready availability of picture-adaptive comb filter hardware which operates at 14.318 MHz. The interpolation filters added a high order of hardware complexity, in part due to the three demonstration sample rates. Decoding NTSC at 14.318 MHz and interpolation to the single line-locked frequency of 13.5 MHz reduces the complexity of the interpolator by a high order.

The practicality of picture adaptive techniques for comb filtering at rates asynchronous to the subcarrier still requires further study.

The synchronous input clock generator operating at four times the NTSC color subcarrier frequency ($4f_{sc}$) is locked to the incoming color burst. The asynchronous output clock generator operating at the three demonstration clock rates is locked to horizontal sync.

Conclusion

All units described in this paper performed in a satisfactory manner, except for the NTSC decoder. Owing to severe time constraints, this decoder could not be completed by the time of the demonstrations; further work with it, however, has proven the viability of the proposed approach to NTSC decoding. Digital interfacing with units of the other participants of the Demonstration yielded acceptable picture quality.

Appendix

Codec Matrices in Component-Coded Digital Video

The Y, $R - Y$, and $B - Y$ signals in the digital interface, the RGB signals, the PAL signals (YUV), and the NTSC signals (YIQ) are three-dimensional information cubes present in color television, mathematically described as three-dimensional vectors. The objective of this appendix is to establish those numerical relationships between the above vectors, which are independent of clock frequencies and luminance/chrominance sampling ratios. Spectral considerations are not treated here.

Binary Formats and Implications

The positive binary format for the luminance signal in the digital interface is applied to the RGB signals:

Y, R, G, and B

Dynamic range from 16 to 240
[Black = 16]

The color difference signals $R - Y$ and $B - Y$ in the digital interface have the following offset binary format:

$R - Y$ and $B - Y$

Dynamic range from 16 to 240
[Black = 128]

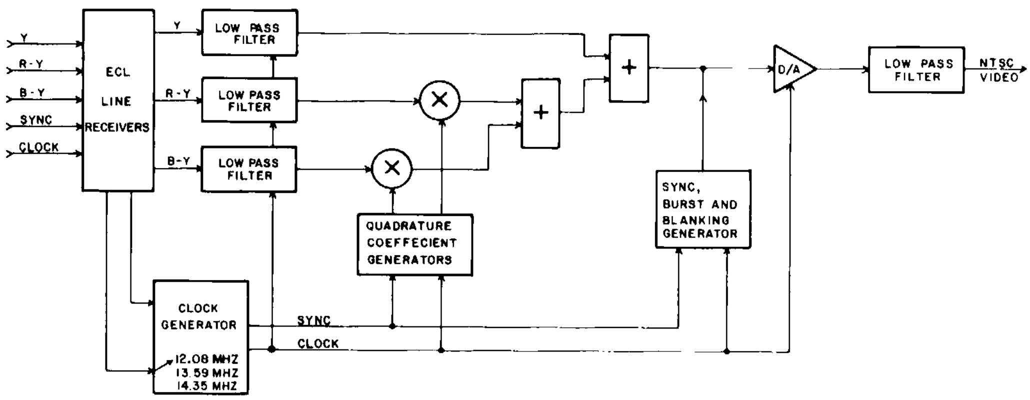

Figure 3. The NTSC encoder accepts the data of the digital interface and converts it to analog NTSC.

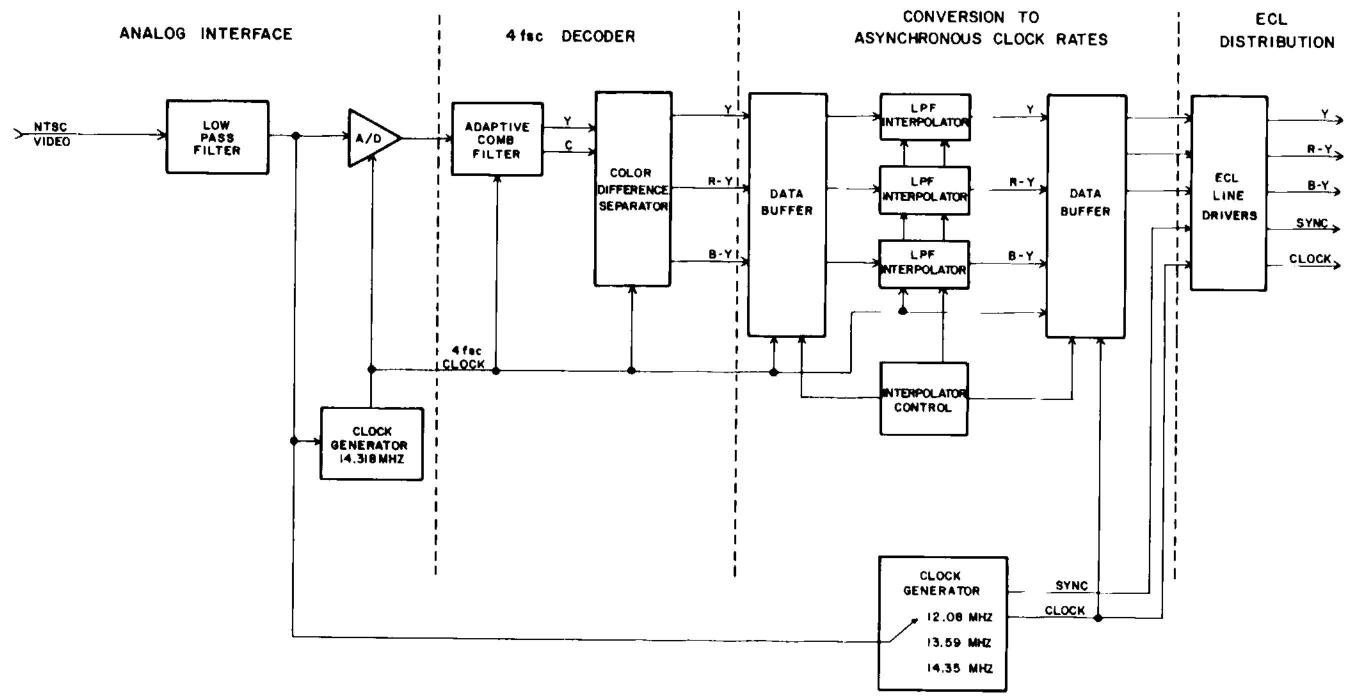

Figure 4. The NTSC decoder accepts analog NTSC and feeds the digital interface.

Taking the pertinent offsets into the algebraic notation, the well-known constant luminance principle now reads:

$$Y - 16 = 0.299\,(R - 16) + 0.587 \times (G - 16) + 0.114\,(B - 16) \quad \text{(A1)}$$

The algebraic differences red minus luminance ($R - Y$) and blue minus luminance ($B - Y$) do not satisfy the offset binary format needed for $R - Y$ and $B - Y$ in the digital interface. This is achieved by properly scaling and offsetting the above algebraic differences:

$$R - Y - 128 = \frac{0.500}{0.701}\,[(R - 16) - (Y - 16)] \quad \text{(A2)}$$

$$= 0.500\,(R - 16) - 0.419\,(G - 16) - 0.081\,(B - 16) \quad \text{(A3)}$$

$$B - Y - 128 = \frac{0.500}{0.886}\,[(B - 16) - (Y - 16)] \quad \text{(A4)}$$

$$= -0.169\,(R - 16) - 0.331\,(G - 16) + 0.500\,(B - 16) \quad \text{(A5)}$$

Equations A1, A3, and A5 are linear and are concisely written with the notation of matrix algebra in the next section.

The RGB Codec

The RGB codec describes the matrixing between the Y, $R - Y$, and $B - Y$ and the RGB vectors. Rewriting the pertinent equations given alone, we obtain the following matrix equation for decoding RGB to Y, $R - Y$, $B - Y$:

$$\begin{pmatrix} Y - 16 \\ R - Y - 128 \\ B - Y - 128 \end{pmatrix} = \begin{pmatrix} 0.299 & 0.587 & 0.114 \\ 0.500 & -0.419 & -0.081 \\ -0.169 & -0.331 & 0.500 \end{pmatrix} \times \begin{pmatrix} R - 16 \\ G - 16 \\ B - 16 \end{pmatrix} \quad \text{(A6)}$$

We obtain the encoding procedure (for encoding Y, $R - Y$, and $B - Y$ to RGB) by inverting the above matrix equation (A6).

$$\begin{pmatrix} R - 16 \\ G - 16 \\ B - 16 \end{pmatrix} = \begin{pmatrix} 1 & 1.402 & 0 \\ 1 & -0.714 & -0.344 \\ 1 & 0 & 1.772 \end{pmatrix} \times \begin{pmatrix} Y - 16 \\ R - Y - 128 \\ B - Y - 128 \end{pmatrix} \quad \text{(A7)}$$

The PAL Codec

The PAL codec describes the matrixing between the Y, $R - Y$, and $B - Y$ and YUV vectors. The luminance signal Y is identical in both vectors. The well-known scaling equations for the color difference signals now read

$$U = 0.493\,[(B - 16) - (Y - 16)] \quad \text{(A8)}$$

$$\pm V = \pm 0.877\,[(R - 16) - (Y - 16)] \quad \text{(A9)}$$

With the relationships found in the matrix equation A7, we obtain the following matrix equation for encoding $R - Y$ and $B - Y$ to UV:

$$\begin{pmatrix} U \\ \pm V \end{pmatrix} = \begin{pmatrix} 0 & 0.874 \\ \pm 1.230 & 0 \end{pmatrix} \times \begin{pmatrix} R - Y - 128 \\ B - Y - 128 \end{pmatrix} \quad \text{(A10)}$$

Inverting the above matrix equation A10 yields the following matrix equation for decoding UV to $R - Y$ and $B - Y$.

$$\begin{pmatrix} R - Y - 128 \\ B - Y - 128 \end{pmatrix} = \begin{pmatrix} 0 & \pm 0.813 \\ 1.144 & 0 \end{pmatrix} \begin{pmatrix} U \\ \pm V \end{pmatrix} \quad \text{(A11)}$$

The NTSC Codec

The NTSC codec describes the matrixing between the Y, $R - Y$, and $B - Y$ and the YIQ vectors. Again, the luminance signal Y is identical in both vectors. The rotating matrix equation for the color difference signals now reads

$$\begin{pmatrix} I \\ Q \end{pmatrix} = \begin{pmatrix} -\sin 33° & \cos 33° \\ \cos 33° & \sin 33° \end{pmatrix} \begin{pmatrix} U \\ V \end{pmatrix} \quad \text{(A12)}$$

With the encoding matrix A10 we now obtain the following matrix equation for encoding $R - Y$ and $B - Y$ to IQ:

$$\begin{pmatrix} I \\ Q \end{pmatrix} = \begin{pmatrix} 1.031 & -0.476 \\ 0.670 & 0.733 \end{pmatrix} \begin{pmatrix} R - Y - 128 \\ B - Y - 128 \end{pmatrix} \quad \text{(A13)}$$

Inverting the above matrix equation A13 yields the following matrix equation for decoding IQ to $R - Y$ and $B - Y$:

$$\begin{pmatrix} R - Y - 128 \\ B - Y - 128 \end{pmatrix} = \begin{pmatrix} 0.682 & 0.443 \\ -0.623 & 0.959 \end{pmatrix} \begin{pmatrix} I \\ Q \end{pmatrix} \quad \text{(A14)}$$

The Composite Video Signals for PAL and NTSC

The analytical expressions for the composite video signals are

$$\text{PAL} = Y + U \sin wt \pm V \cos wt \quad \text{(A15)}$$

$$\text{NTSC} = Y + I \cos (wt + 33°) + Q \sin (wt + 33°) \quad \text{(A16)}$$

With the encoding matrices A10 and A13, the composite video signals can be expressed in terms of the Y, $R - Y$, and $B - Y$ signals of the digital interface. Spectral consideration are to be separated from codec matrixing.

Summary

The RGB vector, the YUV vector, and the YIQ vector are related to the Y, R − Y, B − Y vector with the RGB, PAL, and NTSC codec matrices respectively. The relationships between the Y, R − Y, B − Y vector and the PAL and NTSC composite video signals are indicated.

Acknowledgment. The authors wish to acknowledge the contributions of Ben Tsai, Tom Ostoma, Peter Lowe, and Bob Kaye Design Engineers at DVS who took part in the writing of this paper.

Invitation to Opryland

The next (16th) SMPTE Television Conference is scheduled for February 5–6, 1982 at the Opryland Hotel in Nashville, Tenn. Readers are invited to make plans to attend—see future issues of the *SMPTE Journal* or contact SMPTE headquarters for further information.