



Multimedia Communication Systems I

Analog TV Systems: Migration from Monochrome to Color

Yao Wang Polytechnic University, Brooklyn, NY11201

Outline

- Overview of TV systems development
- Summary of monochrome TV systems
- Compatibility requirement for adding color
- Color coordinate: RGB to YIQ
- Multiplexing of luminance and chrominance components
- Color TV systems: NTSC, PAL, SECAM
- Color TV Receivers
- Terrestrial vs. Cable TV systems
- VCR
- Going to Digital

Overview of TV System Development

- Analog Black and White TV:
 - 1941 NTSC standard settled, first commercial broadcast in US
- Analog Color TV
 - 1950 first commercial color TV broadcast (CBS), incompatible with B/W systems
 - 1953 FCC approves RCA color TV system (compatible with B/W systems) (NTSC color)
- Cable TV, Satellite TV, VCR
 - Cable TV becoming popular in 70's
- Digital TV through small dish satellite (MPEG2 encoded)
 - mid 90's
- DVD (MPEG-2 encoded)
 - mid 90's
- Digital TV broadcasting: SD and HD (MPEG-2 encoded)
 - Selected programs on air since late 90's
 - All stations must broadcast in digital by 2006 (FCC requirement) See http://www.tvhistory.tv

Review of Monochrome TV Technologies

- Video representation by raster
 - Using interlaced scan to achieve a higher temporal resolution at the expense of vertical resolution
 - NTSC video: 30 frames/s, 525lines/frame, interlaced, 4.2 MHz
- TV broadcast
 - Multiplexing audio and video signals using frequency modulation
 - Multiplexing different TV channels using VSB
 - Tradeoffs between DSB, SSB, VSB
 - Total bandwidth of a NTSC TV signal: 6 MHz
- TV receivers
 - Tuning to a desired channel by demultiplexing (bandpass filtering) and demodulation
 - Display raster video using CRT

Challenges in Adding Color

- Backward compatibility Requirement by FCC
 - The broadcasted color TV signals should be such that old monochrome TV sets can extract the luminance and audio signals automatically
 - The color TV signal should still occupy 6 MHz bandwidth
 - Essentially requiring that the monochrome TV receivers automatically filter out the chrominance components
- How is this achieved?
 - Using Luminance+chrominance color coordinate (YIQ)
 - Modulate chrominance components to high end of the luminance spectrum, using QAM

Color Representation Revisited

- Trichromatic color mixing theory
 - Any color can be obtained by mixing three primary colors with a right proportion

 $C = \sum_{k=1,2,3} T_k C_k$, T_k : Tristimulus values

- Primary colors for illuminating sources:
 - Red, Green, Blue (RGB)
 - Color monitor works by exciting red, green, blue phosphors using separate electronic guns
- Primary colors for reflecting sources (also known as secondary colors):
 - Cyan, Magenta, Yellow (CMY)
 - Color printer works by using cyan, magenta, yellow and black (CMYK) dyes







Color Representation Models

- Specify the tristimulus values associated with the three primary colors
 - RGB
 - CMY
- Specify the luminance and chrominance
 - HSI (Hue, saturation, intensity)
 - YIQ (used in NTSC color TV)
 - YCbCr (used in digital color TV)
- Amplitude specification:
 - 8 bits for each color component, or 24 bits total for each pixel
 - Total of 16 million colors
 - A true RGB color display of size 1Kx1K requires a display buffer memory size of 3 MB

Color Transmission in TV: Why not using RGB directly?

- R,G,B components are correlated
 - Transmitting R,G,B components separately is redundant
 - More efficient use of bandwidth is desired
- RGB->YC1C2 transformation
 - Decorrelating: Y,C1,C2 are uncorrelated
 - C1 and C2 require lower bandwidth
 - Y (luminance) component can be received by B/W TV sets

NTSC YIQ Coordinate

- YIQ
 - Y: luminance
 - I: orange-to-cyan
 - Q: green-to-purple (human eye is less sensitive)
 - Q can be further bandlimited than I
 - Phase=Arctan(Q/I) = hue, Magnitude=sqrt (I^2+Q^2) = saturation
 - Hue is better retained than saturation
 - I and Q are rotated version of the color difference signal U=B-Y (Cb), V=R-Y (Cr)

I and Q on the color circle



Conversion between RGB and YIQ

• RGB -> YIQ

Y = 0.299 R + 0.587 G + 0.114 B I = 0.596 R - 0.275 G - 0.321 BQ = 0.212 R - 0.523 G + 0.311 B

• YIQ -> RGB

R = 1.0 Y + 0.956 I + 0.620 Q, G = 1.0 Y - 0.272 I - 0.647 Q,B = 1.0 Y - 1.108 I + 1.700 Q.



Color Image

Y image





Cr image (R-Y)

Cb image (B-Y)

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Color Image

Y image





I image (orange-cyan)

Q image (green-purple)

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Waveforms of Y, I, Q



Waveform of the Y, I, and Q components, from first 5 lines of a progressive frame of "mobilcal", 352x240/frame Notice the I and Q components have smaller dynamic range than Y, which is typical.

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Spectrum of Y, I, Q



Spectrum of Y, I, and Q components, computed from first two progressive frames of "mobilcal", 352x240/frame

Maximum possible frequency is 352x240x30/2=1.26 MHz.

Notice bandwidths of Y, I, Q components are approximately 0.8,0.2,0.15 MHz, respectively, if we consider 10³ as the cut-off magnitude.

Bandwidth of Chrominance Signals

- Theoretically, for the same sampling rate, the chromiance signal can have as high frequency as the luminance signal
- However, with real video signals, the chrominance component typically changes much slower than luminance
- Furthermore, the human eye is less sensitive to changes in chrominance than to changes in luminance
- The eye is more sensitive to the orange-cyan range (I) (the color of face!) than to green-purple range (Q)
- The above factors lead to
 - I: bandlimitted to 1.5 MHz
 - Q: bandlimitted to 0.5 MHz

Multiplexing of Luminance and Chrominance

- Position the bandlimited chrominance at the high end of the luminance spectrum, where the luminance is weak (above 3.5 MHz), but still sufficiently lower than the audio (at 4.5 MHz=286 f_{l})
- The actual position should be such that the harmonic peaks of chrominance spectrum interlace with those of the luminance

 $f_c = 455 f_l / 2$ (= 3.58 Hz for NTSC)

- The two chrominance components (I and Q) are multiplexed onto the same sub-carrier using QAM
 - The upper band of I is limited to 0.5 MHz to avoid interference with audio
- The resulting video signal including the baseband luminance signal plus the chrominance components modulated to f_c is called composite video

Spectrum Illustration



Multiplexing of Iuminance, chrominance and audio (Composite Video Spectrum)



Quadrature Amplitude Modulation (QAM)

 A method to modulate two signals onto the same carrier frequency, but with 90° phase shift



QAM modulator



QAM demodulator

QAM in more detail

Proof (in time domain) the demodulator can separate the signal on board! Discuss the sensitivity of the system to synchronization of the carrier signal.

Adding Color Bursts for Synchronization



For accurate regeneration of the color sub-carrier signal at the receiver, a color burst signal is added during the horizontal retrace period

Figure from From Grob, Basic Color Television Principles and Servicing, McGraw Hill, 1975 http://www.ee.washington.edu/conselec/CE/kuhn/ntsc/95x417.gif

Multiplexing of Luminance and Chrominance



DeMultiplexing of Luminance and Chrominance



Luminance/Chrominance Separation

- In low-end TV receivers, a low pass filter with cut-off frequency at 3MHz is typically used to separate the luminance and chrominance signal.
 - The high frequency part of the I component (2 to 3 Mhz) is still retained in the luminance signal.
 - The extracted chrominance components can contain significant luminance signal in a scene with very high frequency (luminance energy is not negligible near f_c)
 - These can lead to color bleeding artifacts
- For better quality, a comb filter can be used, which will filter out harmonic peaks correspond to chrominance signals.
- Show example of comb filter on board

What will a Monochrome TV see?

- The monochrome TV receiver uses a LPT with cut-off at 4.2 MHz, and thus will get the composite video (baseband luminance plus the I and Q signal modulated to f_c =3.58 MHz)
 - Because the modulated chrominance signal is at very high frequency (227.5 cycles per line), the eye smoothes it out mostly, but there can be artifacts
 - The LPF in Practical TV receivers have wide transition bands, and the response is already quite low at f_c .

Composite Video Viewed as a Monochrome Image w/o filtering

Original Y

Composite Signal as Y



On the right is what a B/W receiver will see if no filtering is applied to the baseband video signal

Recovered Y with Filtering

Original Y

Recovered Y



On the right is what a B/W receiver will see if a lowpass filter with cutoff frequency at about 0.75 MHz is applied to the baseband video signal. This is also the recovered Y component by a color receiver if the same filter is used to separate Y and QAM signal.

Y'(t) = conv(V(t), LPF(t))

Color TV Broadcasting and Receiving



Transmitter in More Details



Receiver in More Details



How Does the CRT Works?





Cathode
Conductive coating
Anode

Phoepbor-coated screen
Electron beams
Shadow mask

http://www.howstuffworks.com/tv.htm

Matlab Simulation of Mux/Demux

- We will show the multiplexing/demultiplexing of YIQ process for a real sequence ('mobile calendar')
 - Original Y,I, Q frames
 - Converted Y,I, Q raster signals and their respective spectrums
 - QAM of I and Q: choice of f_c , waveform and spectrum
 - Multiplexing of Y and QAM(I+Q): waveform and spectrum
 - What will a B/W TV receiver see:
 - W/o filtering vs. with filtering
 - What will a color TV receiver see:
 - Original and recovered Y,I, Q
 - Original and recovered color image
 - Spectrum and waveforms

Spectrum of Y, I, Q



Spectrum of Y, I, and Q components, computed from first two progressive frames of "mobilcal", 352x240/frame Maximum possible frequency is 352x240x30/2=1.26 MHz.

Notice bandwidths of Y, I, Q components are 0.8,0.2,0.15 MHz, respectively, if we consider 10^3 as the cut-off magnitude.

QAM of I and Q: Waveform



Line rate f_1 =30*240; Luminance f_{max} =30*240*352/2*0.7=.89 MHz, The color subcarrier f_c =225* f_1 /2=0.81MHz. $M(t)=I(t)*cos(2\pi f_c t)+Q(t)*sin(2\pi f_c t)$

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QAM of I and Q: Spectrum



Spectrum of I, Q, and QAM multiplexed I+Q, fc=225*fl/2=0.81 MHz

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Composite Video: Waveform



Waveform of the Y signal Y(t) and the composite signal V(t)=Y(t)+M(t). 1 line

Composite Video: Spectrum



Blown-up View of Spectrum



Notice the harmonic peaks of Y and M interleaves near fc

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Composite Video Viewed as a Monochrome Image w/o filtering

Original Y

Composite Signal as Y



On the right is what a B/W receiver will see if no filtering is applied to the baseband video signal

Low-Pass Filter for Recovering Y



f_LPF=30*240/2*150=0.54MHz (chosen based on exp); fir_length=20; LPF=fir1(fir_length,f_LPF/(Fs/2)); Fs=sampling rate=30*240*352. In Matlab, frequency is normalized by Fs/2

Recovered Y with Filtering

Original Y

Recovered Y



On the right is what a B/W receiver will see if a lowpass filter with cutoff frequency at about 0.75 MHz is applied to the baseband video signal. This is also the recovered Y component by a color receiver if the same filter is used to separate Y and QAM signal.

Y'(t)=conv(V(t),LPF(t))

Y Waveform Comparison



Demux Y and QAM(I,Q)



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QAM Modulation and Demodulation

- Modulated signal:
 - $M(t) = I(t) \cos(2\pi f_c t) + Q(t) \sin(2\pi f_c t)$
- Demodulated signal:
 - $I'(t) = 2^{*}M(t)^{*}\cos(2\pi f_{c}t), Q'(t) = 2^{*}M(t)^{*}\sin(2\pi f_{c}t)$
 - I'(t) contains I(t) at baseband, as well as I(t) at $2f_c$ and Q(t) at $4f_c$
 - A LPF is required to extract I(t)



QAM modulator





Lowpass filter for Extracting QAM(I+Q)



f_LPF=0.2MHz; fir_length=20; LPF=fir1(fir_length,f_LPF/(Fs/2));

QAM Demodulation: Waveform



 $I'(t)=2^{*}M(t)^{*}\cos(2\pi f_{c}t)$

I''(t)=conv(I'(t),LPF(t))

QAM Demodultion: Spectrum







Recovered I





Recovered Q







Original color frame



Recovered color frame

History of Television: The Beginning

- Various experimental TV system and broadcasts existed since 1935 in US and Europe
 - 1936 Summer Olympic televised from Berlin
 - 1937 The coronation of King George VI and the Wimbledon tennis tournament televised in England
 - 1937 France install TV transmitter on Effiel tower
 - 18 Experimental Television Stations are operating in the United States by 1937
 - 1939, world fair at New York City, FDR becomes the first president to be televised
 - Sept. 1939, TV broadcast switched off due to imminent outbreak of WWII
- Standardization in US
 - FCC formed the NTSC in 1940, to decide on a TV standard (there are 23 experimental systems broadcasting in US)
 - March 1941: NTSC recommended the 30 fps (I), 525 line format
 - July 1941: NBC was the first commercially sponsored TV station using NTSC standard
 - Dec. 1941: Pearl Harbor
 From http://www.tvhistory.tv/1946-1949.htm

Final Birth of TV era: After WWII, 1946-49

- Production of TV sets begin after WWII in US
- Sales of monochrome TV sets explode in US during 1948-49
- 1946: CBS gave the FCC a demonstration of their mechanical color system.
- RCA flooded the market with black & white sets to slow the potential launch of CBS color



1946 7" RCA 621TS, \$226



1946 10" RCA Model 630TS, \$352

From http://www.tvhistory.tv/1946-1949.htm

Migration to Color

- Interests in developing color TV in late 40's lead to a FCC hearing on color TV: 1949-1950
 - Three competing methods: CBS, RCA, CTI
 - The CBS field sequential system: Use 72 frames/second (144 fields/s), with R,G,B frames interleaving
 - CBS system had the best quality, but was incompatible with B/W
 - FCC approved the CBS color TV system in 1950
 - This standard did not survive primarily because its lack of compatibility
- Development of a compatible standard by NTSC and a consortium of corporations from the television industry
 - Based on the RCA's earlier dot sequential system
 - But with many other improvements by RCA and others
 - A new standard was approved in Dec. 1953, which is still in use today
 - The first coast-to-coast colorcast carried the live images of Rose parade on 1/1/1954

See http://www.novia.net/~ereitan

First Coast-to-Coast Colorcast!



Rose parade on 1/1/1954

From http://www.novia.net/~ereitan/rose_parade.html

Color Television Development Elsewhere

- US was the first in having commercial color TV broadcasting
- Other countries improved upon the basic NTSC color system in developing their own standards
 - Main problem with NTSC: phase shift of the color sub-carrier can lead to hue shift.
 - SECAM (France)
 - PAL (Germany and UK)
 - Regular Color TV broadcast started in Europe in 1967

Analog Color TV Systems

Parameters	NTSC	PAL	SECAM
Field Rate (Hz)	59.95 (60)	50	50
Line Number/Frame	525	625	625
Line Rate (Line/s)	15,750	15,625	15,625
Color Coordinate	YIQ	YUV	YDbDr
Luminance Bandwidth (MHz)	4.2	5.0/5.5	6.0
Chrominance Bandwidth (MHz)	1.5(I)/0.5(Q)	1.3(U,V)	1.0 (U,V)
Color Subcarrier (MHz)	3.58	4.43	4.25(Db),4.41(Dr)
Color Modulation	QAM	QAM	FM
Audio Subcarrier	4.5	5.5/6.0	6.5
Total Bandwidth (MHz)	6.0	7.0/8.0	8.0

Which country use which system?



From http://www.stjarnhimlen.se/tv/tv.html#worldwide_0

Many Pathways of the TV Signals

- How does the TV signal get to you
 - Over the air ("terrestrial TV") (Majority of households in earlier days)
 - Over co-axial cable (Majority of the households nowadays)
 - From satellite using huge antennas (to cable operators, which then relay the signal via cables)
 - From satellite using small antennas (direct broadcasting television, using digital technology, started after mid 90's)

Cable TV

- Initial motivation:
 - To allow households far away from TV stations to view TV
- Added advantage than over-the-air
 - Much higher bandwidth, less interference than terrestrial reception, better quality
- Principle
 - Use microwave towers to receive terrestrial broadcast TV from distant TV stations.
 - Use coaxial cable to deliver from microwave tower to custom houses
 - To avoid interference from terrestrial TV signals, use a different spectrum allocation
 - 88-174Mhz for channels 1-13, 216- for channels 14-
 - In order to avoid un-paid viewing, the signal are scrambled and a set-up box is need to decode a chosen station.
 - Initial system operated at 200 MHz (33 channels), now up to 550 MHz (91 channels)

New Development at the Cable Front

- Cable to fiber
 - Change from coaxial cable to fiber
 - Increased bandwidth and very low attenuation of signal (need less amplifiers)
 - Enable other services: cable modem, etc.
- Analog to digital
 - With MPEG-2 compression, a 6MHz band can carry 10 TV channels
 - 550 MHz can carry nearly 1000 channels
- From scrambling to encryption
 - Analog scrambling lead to a jagged, jumbled set of video images, which is partially viewable
 - Digital encryption: make the signal completely useless without proper decryption key

VCR (Video Cassette Recorder)

- Development of VCR is an important step in TV history
 - Allows people to control what they want to see
 - 1969: Sony created first inexpensive VCR
 - 1976: VHS tape format standardized and dominated the market
 - 1985: first Blockbuster store opened

How are audio and video recorded on tape?

To handle the high speed of video data, the video raster waveforms are stored in two dimensional fashion (helical scan), while the audio is stored in one dimension (linear scan)

Tape direction



http://repairfaq.cis.upenn.edu/sam/icets/vcr.htm



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Direction of head rotation

http://electronics.howstuffworks.com/vcr2.htm

VHS VCR

- Recording: Y and QAM (I+Q) are demultiplexed, bandlimited and remultiplexed (using different carriers) and stored
- Playback: demultiplexed and multiplexed back into a composite video compatible to NTSC TV, and modulated to a carrier frequency before sending to a TV receiver (through "composite video" cable)
- The Y signal has a bandwidth of 3.0 MHz instead of 4.2 MHz as in broadcast video
 - Effective line resolution: 240 lines/frame
 - Effective line resolution of broadcast TV: ~330
 - (480*0.7=336)
- Audio is recorded linearly using a separate head, in analog format
- VHS-C, 8 mm tapes all have similar bandwidth and resolution, but differ in tape sizes

Multiplexing of Y and C: "Color Under"

- Magnetic tape losses and distortions tend to occur at high frequencies
- To avoid color distortion
 - Y is moved upward to 3.5 MHz using FM
 - C is moved downward to 600 KHz
- For more details on modulation in VCR, see
 - Grob, B., and C. E. Herndon. *Basic Television and Video Systems*. 6th ed. New York: McGraw Hill, 1999.

Modulation of Y Using FM

•changes in amplitude of the signal are converted into changes in frequency

•the peak white signal is at 4.8 MHz

•the peak black is at 3.5 MHz.

•the positive sideband is largely cut-off due to channel limitations and only the negative sideband is used.



http://www.ee.washington.edu/conselec/CE/kuhn/vcr/vcr.htm

R. Brenner and G. Capelo, VCR Troubleshooting and Repair, 2nd. ed., SAMS, 1991, pg. 109

Multiplexing of Y and C in VCR



S-VHS VCR

- Better tapes are used which can retain more high frequency
- Y and C are stored separately at higher quality (wider bandwidth for Y)
- Y and C are sent to TV separately (through "S-video" cable) (S=separated Y/C)
 - Cross color between these signals is largely decreased!
- Audio is recorded digitally in stereo (Hi-Fi)
- Total bandwidth ~5MHz, quality better than broadcast TV with good reception
- Effective line resolution: 400
- Hi 8 is similar to S-VHS in bandwidth/resolution

Bandwidth Comparison



http://repairfaq.cis.upenn.edu/sam/icets/vcr.htm

Video Terminology

- Component video
 - Three color components stored/transmitted separately
 - Use either RGB or YIQ (YUV) coordinate
 - New digital video format (YCrCb)
 - Betacam (professional tape recorder) use this format
- Composite video
 - Convert RGB to YIQ (YUV)
 - Multiplexing YIQ into a single signal
 - Used in most consumer analog video devices
- S-video
 - Y and C (QAM of I and Q) are stored separately
 - Used in high end consumer video devices
- High end monitors can take input from all three

What you should know

- Why does NTSC color system uses the YIQ representation instead of the RGB?
- How to convert between RGB and YIQ coordinates?
- How are the I and Q components multiplexed onto the Y components? What are the factors that determine the color subcarrier frequency?
- How does the color TV receiver demultiplexes Y, I, and Q components?
- How can a monochrome TV extracts a monochrome video signal from a broadcasted color video signal?
- What are the three types of analog color TV systems, how do they differ in terms of video format and modulation methods
- Difference between component/composite/S-video

References

- Y. Wang, J. Ostermann, Y. Q. Zhang, *Video Processing and Communications,* Prentice Hall, 2002. chapter 1.
- B. P. Lathi, Modern digital and analog communication systems, 3rd ed. Oxford Press, 1998. Chap. 4.
- Whitaker J. C. and K. B. Benson. ed. *Standard Handbook of Video and Television Engineering.* 3rd ed. New York: McGraw-Hill, 2000.
- Grob, B., and C. E. Herndon. *Basic Television and Video Systems*. 6th ed. New York: McGraw Hill, 1999.
- A. M. Noll, Principles of modern communications technology, Chaps. 9-12
- K.J. Kuhn, Conventional analog television: an introduction, <u>http://www.ee.washington.edu/conselec/CE/kuhn/ntsc/95x4.htm</u>
- History of early color television: http://www.novia.net/~ereitan/
- History of television, <u>http://www.tvhistory.tv/</u>
- P. Schlyter, Analog TV broadcast systems, <u>http://www.stjarnhimlen.se/tv/tv.html</u>
- http://www.ee.washington.edu/conselec/CE/kuhn/vcr/vcr.htm