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► **To cite this version:**

Charbel Tannous. Display technology and the four screen saga. Master. Technologie des Médias, UBO Brest, France. 2016, pp.29. hal-04660061

HAL Id: hal-04660061

<https://hal.science/hal-04660061>

Submitted on 23 Jul 2024

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Display technology and the four screen saga

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(Dated: July 23, 2024)

Displaying information and ways to visualize or present it depend on their successful matching to the human visual system. Generally there are four types of screens: 1- Desktop Computer monitors, 2- Home TV, 3- Cinema, Large-displays, 4- Hand-held portable devices like laptops, smartphones, e-tablets, vehicular screens, e-books, wrist-watches and Head-mounted gears like Virtual-Reality goggles, helmets and headsets. Various existing technologies such as LCD, Plasma... used in these displays are described and compared with account of expectations pertaining to their future development.

PACS numbers: 61.30.-v, 84.47.+w, 78.60.Hk, 52.40.Db

Keywords: Liquid crystals, Cathode-ray tubes, Cathodo-luminescence, Electromagnetic radiation interaction with plasma,

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I. INTRODUCTION

The advantage of electronic displays is their appealing practical interactivity and tactile technology intuitive handling of information. Electronic displays have constantly improved from resolution, color palette, contrast, response time... points of view. As total number of pixels of display has increased with pixels getting smaller, faster, brighter, color shade subtler... quality and attractiveness of electronic text and graphics have surpassed that of a glossy fine printed page.

Electronic displays can be organized in four classes associated with a four screen saga corresponding to history of MPEG (Motion Picture Expert Group) digital standard [1] and organized according to:

1. MPEG-1: Desktop computer Monitor
2. MPEG-2: Home Television screen
3. MPEG-3: Cinema screen
4. MPEG-4: Hand-held device screen such as e-tablets, e-books and mobile phones

A few years later, the MPEG standard was modified by incorporating MPEG-3 into MPEG-2 and including storage media (CD, DVD and Blu-Ray), broadcast, digital networks and other devices such as e-books, e-tablets, Virtual Reality gears, wrist-watches and smartphones:

1. MPEG-1: Compact Disk (CD), desktop computer monitor and Single Definition (SD) Terrestrial TV
2. MPEG-2: DVD and High Definition (HD) Terrestrial TV
3. MPEG-4: Blu-Ray, Hand-held devices such as e-tablets, mobile phones and Head-mounted devices such as virtual reality goggles and helmets

These lectures are organized in four parts as follows:

1. General Display characteristics
2. Display technologies: LCD, Plasma, OLED, Quantum Dot and Digital Light Processing (DLP)
3. Television systems: Terrestrial Analog, Digital, Satellite and Stream
4. Display types: Desktop computer monitors and Large scale displays (Cinema and Wall), Hand-held and Augmented/Virtual-Reality displays and 3D displays

Note: Very large-scale displays such as domes and planetariums are not discussed in these lectures.

II. GENERAL DISPLAY CHARACTERISTICS

Key characteristics of an electronic display which are of greatest importance to a user are screen size, aspect ratio, information content (total number of pixels), resolution (pixel size), color (degree of saturation and number of levels of luminance or luma), brightness, contrast, dependence of image on viewing angle, and realistic quality of a moving picture.

Information content of an electronic display is described by the following:

- Moving picture formation time or temporal resolution, Aspect ratio or horizontal over vertical lengths
- Optimal viewing distance, Contrast, Interlaced or progressive scanning, Total of lines per frame or vertical resolution, Video bandwidth, MHz
- Frame (full image) or field (half-image) frequency (Hz) with Horizontal and vertical retrace time (resp. in milli-seconds (ms) and lines/field) or Line frequency (kHz) and Line time (ms)
- 3D technology

A. Temporal resolution

An electronic display should match temporal and spatial resolution of the human visual system as smoothly as possible and without straining or damaging it.

Smooth motion perception was historically pioneered by Cinema and electronic displays were designed along the same concepts while caring about eye strain when watching for a long time. In contrast, spatial resolution concepts originate historically from books, prints and photography.

Movies were developed with illusion of smooth motion using a set of still images per unit time. A scene had to be illuminated at high speed to prevent visible image unsteadiness or flicker. Generally, 16 images per second (16 Hz frame rate giving a time interval of 62.5 ms) is a minimum speed to provide a smooth motion illusion.

In fact, the exact minimum frame rate varies with brightness. For instance 40 Hz (25 ms) is acceptable in dimly lit scenes, while up to 80 Hz (12.5 ms) may be necessary for brightly lit scenes.

Early projectors were equipped with three blade shutter to make each frame displayed three times in order to minimize flicker and reduce eye strain. For instance a movie shot at 16 frames per second (fps) illuminated the screen 48 times per second.

Sound played a crucial role in rate determination of Cinema frame since image and sound had to be synchronized.

Ear temporal response spans an interval $\sim \mu s$ (internal inter-oral delay between right and left sides) to several ms (external inter-oral delay between right and left $\sim 660 \mu$ -seconds). Fusion time (flicker for eye and echo for ear) is about 40 ms for the eye and 35 ms for the ear.

In effect, after sound was introduced in silent movies, a projection speed of 24 fps (in Hz, equivalent to 41.6 ms) was adopted unanimously by image and sound engineers with a two blade shutter to produce 48 Hz illumination.

As display technology evolved, temporal resolution notion turned later into Fade Time and Screen Remanence since human eye is more sensitive to fade time than display time (cf. Response time section II H).

In fact, retinal adaptation to darkness is of paramount importance to understand how viewers perceive movies in cinema theaters or on a home TV.

This belongs to the area of sensory physiology whose fundamentally prominent aspect is remarkable eye adaptation to dim lights.

Data on eye dark adaptation show that on entering a dark environment after a stay in outside daylight, the eye begins at once to increase its sensitivity. This increase is, at first, slow; however after five minutes, it becomes quite fast, the eye acquiring a sensitivity several hundred times its initial value. After 30 minutes in dark, sensitivity still increases, nevertheless more slowly than previously. After 45 minutes or about an hour, a maximum value is reached.

The final sensitivity varies slightly with different people, however an eye fully adapted condition is easily 5,000 to 10,000 times more sensitive than at starting time.

It is believed that rate of adaptation is greatest at first, as displayed in Table 1 with sensitivity showing three parts: an initial slow phase, an intermediate rapid one, and a final phase ending into a maximum.

Time is given by formula $t = k \ln(I)$ with t in minutes I is light intensity and k is a constant measured between 0.01 and 0.02 by several researchers (see Table 1). Eye adaptation is triggered by retinal photochemical and physiological

Time (minutes)	Sensitivity	Intensity	ln(intensity)
0	38.7	25,840.0	4.41
2	99.7	10,030.0	4.00
5	398.7	2,506.0	3.40
8.5	1,065.0	934.6	2.97
12	3,420.0	292.4	2.47
20	16,870.0	59.9	1.78
31	30,780.0	32.5	1.51
39.5	45,270.0	22.1	1.34
45	54,080.0	18.5	1.27
72	54,080.0	18.5	1.27

Table 1: Early experimental data on Dark Adaptation of the eye. Adapted from Hecht [2]

adjustment as well as variation of pupil diameter. Thus it can finally handle luma levels over the $[10^{-6} \text{ cd/m}^2: 10^5$

cd/m^2 interval (cd is a candela [3]) with almost flat visual performance response between 100 cd/m^2 and $10,000 \text{ cd/m}^2$.

Adaptation time depends strongly on luma levels during process unfolding. Fig. 1 describes schematically dark

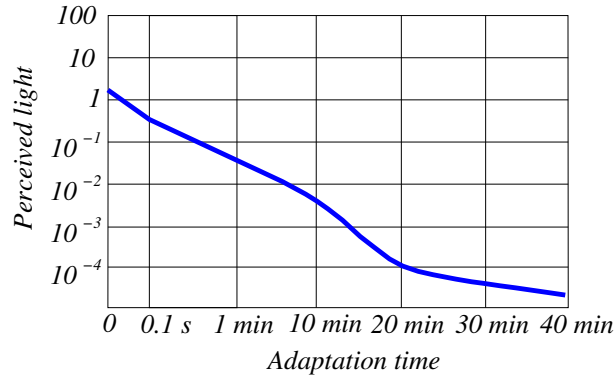


Fig.1: Time-dependent perceptual property of the eye. Dark adaptation in cd/m^2 is given versus time in minutes. Note that time scale at intervals [0: 0.1 second], [0.1 second: 1 min] are different from later intervals given in 10 minutes span.

adaptation process beginning at a 100 cd/m^2 luma. When luma varies up to a 10:1 ratio adaptation runs almost instantly without interrupting visual performance. Complete adaptation might take between 30 to 60 minutes. In sharp contrast, during light adaptation retinal sensitivity is reduced to a fifth of its original value to later on adjusting to a new surrounding light with the entire process lasting a few minutes.

B. Horizontal Resolution: dot, grain, spot and pixel

General spatial resolution concepts originate historically from printing (and scanning), and photography where the unit is dpi (dot per inch or dot per 2.54 cm) with dot referring to an ink droplet or silver halide grain size (in Black-White photography as illustrated by Table 2).

Plate or Film	Diameter (μm)
High-resolution film	0.048
Motion picture positive film	0.30
Positive type film	0.63
Fine grain roll film	0.79
Portrait film	0.88
High speed roll film	1.09

Table 2: Diameter of silver halide gains in emulsions used in Black-White Cinema and photography. Adapted from Ref. [4].

Modern granularity measurements are made with a micro-densitometer with a 48-micron diameter aperture. That allows measuring fluctuations in density, and root-mean-square (RMS) granularity. Since RMS numbers are very small, they are multiplied by 1000 to obtain an integer, typically between 5 and 50 as illustrated by Table 3)

In early electronic analog video displays (Cathode Ray Tubes), spot size was used to qualify resolution and later in digital displays, pixel (originating from picture element) notion and ppi (pixel per inch or pixel per 2.54 cm) were used to characterize horizontal resolution.

In $x - y$ plane, dots and spots are circularly shaped, a pixel is squarely shaped whereas a grain is randomly shaped. Perpendicularly to $x - y$ plane, a dot has an ellipsoidal profile akin to a liquid droplet whereas a spot has a Gaussian profile.

In printing technology, 100 dpi produces a very poor reproduction of text. At 200 dpi, undesired features are noticeable, but at 300 dpi and above, alphanumeric and other characters are well rendered. A 600-dpi laser printer can locate a dot position within $1/600$ of an inch ($42 \mu\text{m}$). There are laser printers with still higher resolutions such as 1200 dpi and 2400 dpi.

RMS Granularity Value	Granularity Classification
45, 50, 55	Very coarse
33, 36, 39, 42	Coarse
26, 28, 30	Moderately coarse
21, 22, 24	Medium
16, 17, 18, 19, 20	Fine
11, 12, 13, 14, 15	Very fine
6, 7, 8, 9, 10	Extremely fine
≤ 5	Micro fine

Table 3: Granularity of silver halide gains in emulsions used in photography. Adapted from Ref. [5].

Usually Color is obtained with either additive (transmissive) RGB (Red-Green-Blue primaries) system (in Electronic displays) or subtractive (reflective) CMY (Cyan-Magenta-Yellow or RGB complement) system (in printing, analog cinema films and photography). Persistence of vision allows color primaries to fuse into a single color. This means a dot, grain, spot or pixel contains three entities called sub-dot, sub-grain, sub-spot or sub-pixel corresponding to each of the RGB chromatic components.

C. Vertical Resolution: Lines and Modulation Transfer Function

Vertical resolution is given by the number of lines per unit length or inch. When a sample is observed by an optical microscope, its image is somehow degraded due to aberrations and diffraction phenomena, in addition to minute assembly and alignment errors in optics. In the image, bright highlights will not appear as bright as they do in sample and dark or shadowed areas will not be as black as those observed in sample. Contrast or modulation depth may be defined by:

$$M = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \quad (1)$$

where I_{max} is the maximum intensity displayed by a repeating structure and I_{min} is the minimum intensity found in the same sample. By convention, the modulation transfer function is normalized to unity at zero spatial frequency. Modulation is typically less in the image than in sample and there is often a slight phase displacement of image relative to sample. By comparing several samples having differing spatial frequencies, it can be determined that both image modulation and phase shifts will vary as a function of spatial frequency. By definition, the modulation transfer function (MTF) is described by:

$$MTF = \frac{M_O}{M_I}, \quad M_O = \left[\frac{I_{max} - I_{min}}{I_{max} + I_{min}} \right]_O, \quad M_I = \left[\frac{I_{max} - I_{min}}{I_{max} + I_{min}} \right]_I \quad (2)$$

where indices O, I mean Object and Image respectively. This quantity, as discussed above, is an expression of contrast alteration observed in the image of a sinusoidal object as a function of spatial frequency. In addition, there is a position or sinusoid phase shift that depends upon spatial frequency in both horizontal and vertical coordinates. A good example occurs in video microscopy where raster scan produces slightly different responses resulting in a variation between horizontal and vertical modulation transfer functions.

A perfect aberration-free optical system is termed diffraction limited, because the effects of light diffraction at the pupils limit the spatial frequency response and establish resolution limits.

When there are no significant aberrations present in an optical system, the modulation transfer function is related to diffraction pattern size, which is a function of the system numeric aperture ($[NA]$) [6] and wavelength of illumination. In quantitative terms, the modulation transfer function for an optical system with a uniformly illuminated circular aperture [7] can be expressed as:

$$MTF = 2(\phi - \cos \phi \sin \phi)/\pi, \quad \phi = \cos^{-1}(\lambda f_s/2[NA]) \quad (3)$$

In these expressions, f_s is the spatial frequency in line pairs per millimeter (lp/mm in printing) or cycle/mm (in photography), λ is illumination wavelength. At low spatial frequencies, image contrast is the highest, but falls to zero

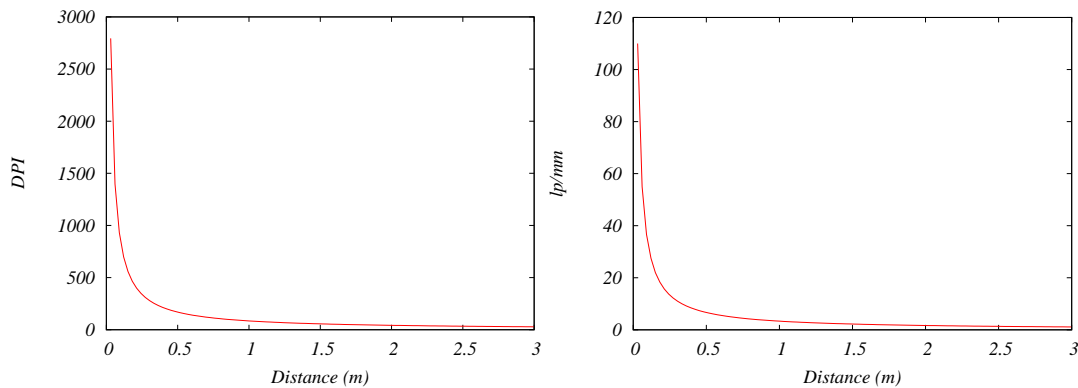


Fig.2: (Left) Required dpi versus distance between eye and object. Eye angular resolution is one minute of arc or 3×10^{-4} radian. At a distance d the total length covered is $3 \times 10^{-4} \cdot d$ and the associated dpi is $1 \text{ inch}/(3 \times 10^{-4} \cdot d)$. As a simple check, for reading at a distance of 25 cm, about 300 dpi are needed as observed in the graph. (Right) Required lp/mm (line pairs/mm) versus distance between eye and object with a conversion factor: $1 \text{ lp/mm} \sim 25.4 \text{ dpi}$.

as the spatial frequency is increased beyond a specific value. The cutoff f_c is the spatial frequency at which contrast reaches zero and can be expressed by $f_c = 2[NA]/\lambda$.

It is interesting to note that this expression reveals (in terms of spatial frequency) the fact that resolution increases with both $[NA]$ and shorter wavelengths. Resolution is reduced, in presence of noise as displayed in Fig. 3, to the intersection of the MTF curve with average noise level [8]. There are generally at least six factors that determine the

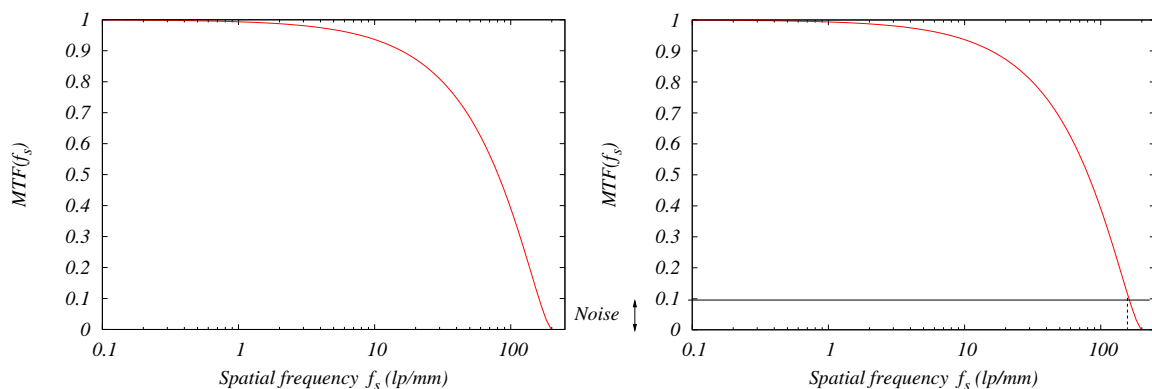


Fig.3: (left) Modulation Transfer Function as a function of spatial frequency f_s in line pairs per mm or lp/mm. In absence of noise, the cutoff spatial frequency is $f_c=200 \text{ lp/mm}$. (right) In presence of noise (about 0.1 in this example), there is reduction of resolution and f_c to $f_c \sim 160 \text{ lp/mm}$.

number of lines:

- Eye angular resolution, Viewing distance, Aspect ratio
- Scanning mode, Electronic constraints, Bandwidth limitations

As an example is NTSC (cf section IV) 4:3 aspect ratio, 525 line system. Setting viewing distance by "painter rule" dictating a $[3d_p - 4d_p]$ interval as the proper observation of any painting where d_p is the diagonal length of the painting.

Consider a display with Horizontal, Vertical lengths H, V with a diagonal $d_p = \sqrt{H^2 + V^2}$. A viewing distance $d = 4d_p = 4\sqrt{H^2 + V^2}$ gives the angular opening of observer eye:

$$\alpha = 2 \tan^{-1}[(V/2)/d] = 2 \tan^{-1}(V/2)/[4\sqrt{H^2 + V^2}] \quad (4)$$

Dividing by eye angular resolution (1 minute of arc $\sim 3 \times 10^{-4}$ radian), yields the minimum number of lines as: $\alpha/(3 \times 10^{-4}) \sim 500$.

D. Aspect ratio and Definitions: Single, High and Ultra-High

Aspect ratio is inherited from print paper size (8.5x11 or A4 format for instance) and photographs (4:3 format). Cinema theater technology is the main progress drive for aspect ratio triggered by its competition with Home TV and Home Cinema.

Various aspect ratio formats are given in Table 4 followed by description of definitions. Description of definitions:

Aspect ratio	Comments
1.33:1	Photography, 4:3 Analog TV
1.77:1	16:9, HDTV, 4K-UHD and 8K-UHD
1.85:1	35mm Academy Cinema
2.35:1	Scope format
2.39:1	Cinemascope, 4K-UHD
2.40:1	Anamorphic, Wide Screen
2.59:1	Cinerama

Table 4: Aspect ratio in Photography, Analog CRT TV, Cinema and High-Definition TV (HDTV) as well as 4K and 8K Ultra HD.

- Single Definition TV (SDTV) was developed with numerous variations found in different countries. The NTSC (National Television Systems Committee) system was developed first in North America, South America, and Japan. PAL (Phase Alternating Line) and SECAM (Séquentiel Couleur Avec Mémoire) are SDTV European standards (German and French respectively) that are similar to NTSC and were developed later; consequently only NTSC is described in this work. Afterwards HDTV (high-definition television system) was developed in North America as described further below and compared to SDTV in Table 5.

Television system parameters	NTSC	HDTV
Aspect ratio, horizontal/vertical	4/3	16/9
Total of lines per frame	525	1125
field frequency, Hz	60	60
Line frequency, kHz	15.75	33.75
Line time, ms	63.5	29.63
Video bandwidth, MHz	4.2	24.9
Viewing distance	7H	3H
Sound	Mono/Stereo	5.1 Dolby
Horizontal retrace time, ms	10	3.7
Vertical retrace, lines/field	21	45

Table 5: Television system parameters in the USA for single definition NTSC and HDTV. Note that 3H, 7H viewing distances based on frame height breaks away from the traditional $[3d_p - 4d_p]$ "painter rule". Adapted from Carlson [9].

- HDTV

The number of vertical and horizontal lines are doubled with respect to NTSC making the picture resolution four times greater. The aspect ratio is changed from 4/3 to 16/9. For example, with H equal to TV screen height and with a viewing distance of (7H) in the NTSC system, the viewing angle is approximately 10° . Whereas with HDTV, the same (3H) viewing distance yields a viewing angle of approximately 20° . HDTV has also adopted Dolby AC-3 surround sound system instead of NTSC stereo sound. This sound system has six channels: right, right surround, left, left surround, center, and low-frequency effects (LFE). The LFE channel has a 120 Hz bandwidth, providing 5.1 channels. The decimal notation .1 means that an LFE channel has a one tenth the bandwidth of any surround channel.

- UHD-TV

After HDTV, Ultra-High Definition TV (UHD-TV) is described with its peculiar specifications:

- 4K UHD-TV (2160p) has a resolution of 3840 x 2160 (8.3 Mega-pixels), 4 times HDTV 1080p pixels

- 8K UHD-TV (4320p) has a resolution of 7680 x 4320 (33.2 Mega-pixels), 16 times HDTV 1080p pixels HDTV. 8K UHD-TV format with 22.2 surround sound is known as Super Hi-Vision.
- In terms of CIE 1931 color space, Rec. 2020 [10] color space covers 75.8%, digital cinema initiative (DCI) covers 53.6%, Adobe RGB color space covers 52.1%, and Rec. 709 used in HDTV covers 35.9%. In addition, this format allows up to 120 fps.

Super Hi-Vision Image specifications:

- Number of pixels: 7680x4320, Aspect ratio: 16:9, Frame rate: 120 Hz progressive, Bit depth: 12-bit
- Viewing distance: 0.75 H, Viewing angle: 100°, Colorimetry standard: Rec. 2020 [10]

Super Hi-Vision Audio specifications:

- Audio system: 22.2 surround sound with 22 channels dispatched in three layers: Upper layer: 9 channels, Middle layer: 10 channels, Lower layer: 3 channels. The decimal notation .2 (similarly to 5.1) means two Low Frequency Effects (LFE) channels with a bandwidth about (1/10) of one pertaining to a surround channel.
- Sampling rate: 48/96 kHz and Bit depth: 16/20/24 bits

E. Vector Scanning and Analog Video Bandwidth

Humans perceive continuous motion if they are presented with a series of still images in rapid succession. Quality of perceived motion depends on presence of a blank or black image between successive still images. In a movie theater this is accomplished by a shutter that blocks light while the movie is being advanced to a next frame.

In order to reproduce a sequence of images electronically, physicists and engineers invented 3D Vector scanning based on the Cathode Ray Tube (CRT) involving an electronic beam sweeping a glass screen covered with phosphors emitting light by cathodo-luminescence when hit by electrons.

This process is very sophisticated in order to reproduce even a single frame. It entails applying an electric field with electrostatic plates and a magnetic field to direct the scanning electronic beam (cf. Fig. 4) across a funnel devoid of any particle that might interfere with the sweeping electrons. Scanning an image requires analog timing, synchronization, beam deflecting and counting circuits to control spot focusing, sweeping, blanking during its horizontal, vertical and diagonal returns (cf Fig. 5).

There are different analog counting circuits since they are designed for spot, line, fields (half-image) and frames (full image).

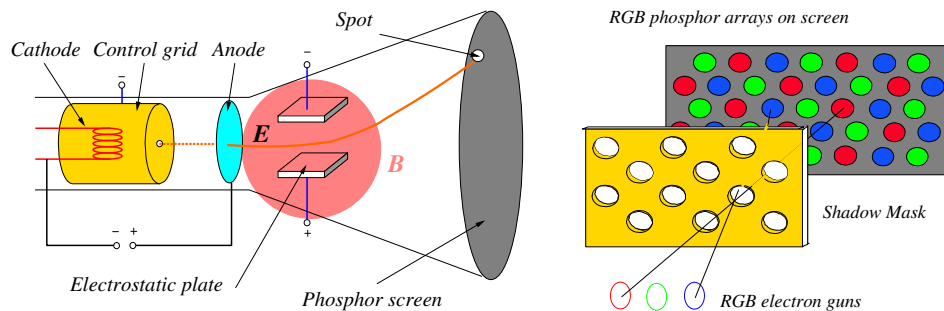


Fig.4: (Color on-line) (Left) Black and White CRT showing the electron gun, E field created by electrostatic plates, surrounded by magnetic induction field B to perform beam deflection and the phosphor screen. Partial vacuum inside a CRT is about $\lesssim 0.1\mu\text{Pascal}$ i.e. 10^{-12} atm. since 1 atm. is $\sim 10^5$ Pascals. (right) Part of a Color CRT showing three electron guns pointing through a shadow mask at their corresponding RGB phosphors.

This is similar to the sophisticated Bipolar Junction Transistor invention before the simpler Field Effect Transistor. A CRT renders motion well because a phosphor emits light for a small fraction of frame time.

A BW (Black-White) CRT consists of an electron gun, electrostatic and magnetic fields to direct the electron beam, and a phosphor screen. When the electron beam strikes the screen, the targeted phosphor generates light (cf. Fig. 4).

A color CRT contains three electron guns, a shadow mask and a screen paved with an array of RGB phosphors (cf. Fig. 4). This process might be called 3D vector phosphor addressing akin to 3D vector line scanning.

The electron beam profile is Gaussian, implying that dot is brighter at center than at edge of screen. Dot brightness is controlled by electron beam intensity.

CRTs kept being manufactured for almost 100 years with higher brightness and contrast and with flatter tube faces, smaller size...

Flatter tube faces have required development of thicker faceplates, tapered electrostatic plates and shadow masks, leading to greater weight for a display of a given size. CRT contrast and brightness have been steadily improved by reducing phosphor reflectivity through reduction of display contrast, making display faceplate less light-absorbing [11, 12]. The faceplate should be efficient in absorbing light in order to reduce ambient light reflection from the phosphor screen.

CRT display technology has been inherently able to handle multiple display formats on a single device, since the number of scan lines is determined by drive waveforms that are applied to the display.

A CRT capable of vertical response in the GHz range (0.35×10^{-9} second risetime) by connecting directly to a signal source of interest [12].

Nevertheless, CRT technology suffers from several disadvantages:

1. Flicker: Flashing cathodo-luminescent light occurring on a screen creates flickering light. When flicker rate is fast enough, light from the picture is perceived as steady. Depending on duty cycle and brightness of light, 50 flashes per second are the minimum required for a steady light. Incidentally, this is the reason why 50 Hz was adopted for electricity mains and street lighting in many Metric System countries whereas 60 Hz was adopted by Imperial System countries like the USA and Great-Britain. A CRT is considered as flicker-free when its cathodo-luminescent light is between 72 and 75 Hz.
2. Kell factor: The ratio of perceived number of lines of resolution to the number of scan lines or pixels covering the same distance. The extended Kell Factor is a ratio between the number of lines perceived and the number of pixels or TV scan lines being used, at same distance, taking into account eventual degradation.
3. Monitor Bulkiness due to a large distance between the electron gun, electrostatic plates, magnetic circuits used for deflection and scanning and screen
4. Monitor Weight originating from the CRT glass and all the electronic control circuits.
5. Power consumption: Very large voltages (several tens of thousand Volts) are used for the electron gun, deflection yoke and beam scanning devices
6. Large currents produce Electromagnetic (EM) ionizing radiation around the CRT that is also sensitive to external EM produced by smartphone, Bluetooth, Wi-Fi... devices.

In 1930, Fritz Schröter a German Telefunken engineer imagined and patented the concept of breaking a single video frame into interlaced lines (cf. Fig. 5).

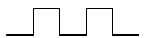
Interlaced scanning was introduced for two reasons at least: Combating flicker and reducing image display bandwidth.

In Progressive scanning, the entire image is refreshed every cycle (cf. Fig. 5).

In a progressive scan display at 60 Hz (or 120 Hz), the image is refreshed in its entirety 60 (or 120) times per second. Each scan displays every line in the image raster sequentially from top to bottom. In an interlaced scan, alternating rows of pixels are refreshed in each cycle and it takes two cycles to refresh every row of pixels in the display.

A progressive display produces a more stable and flicker-free picture, with smooth motion and a more realistic image. Improvement is especially noticeable with fast-moving images pertaining to TV or DVD media. In TV signal specifications, like 720p, 1080i or 1080p, the numeral indicates the number of horizontal lines, whereas i,p denote interlaced or progressive.

Calculating BW (Black-White) video bandwidth consists of considering a square pulse signal of the form

 depicting a white spot lasting a time τ followed by dark spot lasting for same time.

Inspection of the interlaced case of Fig. 5 allows to write: $(n_H n_V \tau + n_V \tau_H) n_F = 1$ second. n_H is the number of spots per line, n_V is the number of lines per field and τ_H is horizontal return time. n_F is the number of fields per second. Thus:

$$\tau = \frac{1}{n_H n_V} \left(\frac{1}{n_F} - n_V \tau_H \right), \quad B = \frac{n_H n_V / 2}{\left(\frac{1}{n_F} - n_V \tau_H \right)} \quad (5)$$

where $B = 1/2\tau$ is the BW video signal bandwidth.

Typically $\tau_H \sim 10 \mu\text{second}$, and $n_V = 525/2$, $n_H = 425$, $n_F = 60$, thus $B \sim n_H n_V n_F / 2$ which is about 3.34 MHz.

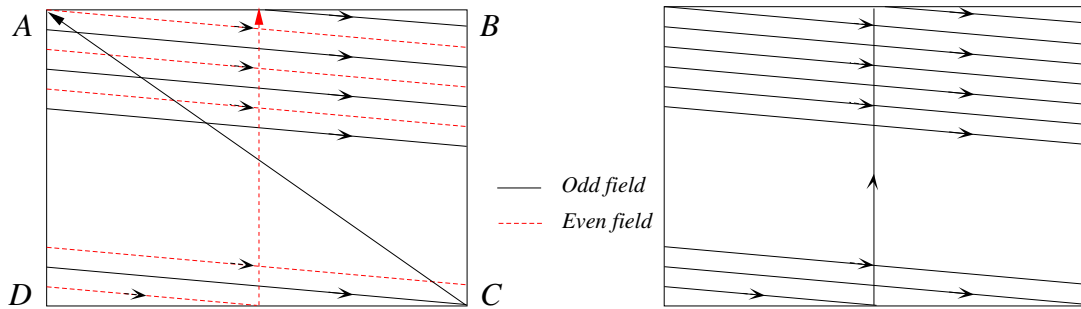


Fig.5: Interlaced versus progressive scanning. Scanning starts with the odd field to return diagonally from corner C to A in order to start even field scanning that finishes midway between corners D and C with a vertical return midway between corners A and B . Return blanked horizontal lines lasting a time τ_H are not shown in contrast to diagonal and vertical return lines.

Approximating $B \sim 4$ MHz makes it easy to compare to a speech signal with a bandwidth of 4 kHz, a thousand times smaller than BW video.

In progressive scan, bandwidth is twice the interlaced case since the number of lines is doubled with all other parameters being same.

F. Scalar scanning and Digital Video Bitrates

Performing bitrate calculation assumes a typical frame rate as well as image size, resolution, aspect ratio, color and noise. For instance computer animations with sharp images and static backgrounds can fit in a low bitrate without significant quality loss. Reducing bitrate of a video stream is based on exploiting redundancies in order to reduce data flow volume such as:

- Spatial: An image might have a fixed background or contain repeating patterns
- Temporal: Frames might evolve slowly such that it is possible to apply motion estimation algorithms to predict evolution
- Perceptual: Human visual system is more sensitive to BW than color so that it is possible to sub-sample color
- Entropic: Repetition might be present in a statistical fashion allowing to allocate less data to a highly repetitive pattern

As an example, H.264 codec (Coder-Decoder) treats intra-frame spatial redundancies in order to reduce bitrates whereas previous MPEG codecs dealt only with temporal inter-frame redundancies. In MPEG, a frame is decomposed into macroblocks consisting of a number of luma and chroma pixels (cf. Table 6) and monitoring data change between neighboring macroblocks in order to perform motion estimation. H.264 offers more flexibility than MPEG by decomposing a frame into sub-blocks (16×16 , 16×8 , 8×16 , 8×8 , 8×4 , 4×8 and 4×4) in order to perform efficiently intra-frame coding. H.264 performs other compression operations leading to a bitrate that is half of MPEG2 with same overall quality.

Estimation of video bitrate is based on several frame parameters such as:

- Image size:
- Digital Color sub-sampling management:
 YC_bC_r - General representation of a video signal containing one luma and two chroma components. For example, MPEG-2 is based on 4:2:0 YC_bC_r .
 4:4:4 - A video format for high-end studio recordings, where Y , C_b , and C_r are sampled equally.
 4:2:2 - A video format commonly used for studio recordings, where there is one C_b sample and one C_r sample for every two Y samples (1 pixel in a 1×2 grid). 2:1 horizontal down-sampling with no vertical down-sampling. Thus same number of samples are allocated to chroma and luma.
 4:2:0 - A video format used by DVD, where there is one C_b sample and one C_r sample for every four Y samples

Format Name	Frame Size	Frame Rate	MB/s
QCIF	176×144	29.97	2949.21
SIF	352×240	29.97	9830.70
CIF	352×288	29.97	11796.84
BT.601†	720×576	25	40500.00
HDTV†	1920×1035	30	232875.00

Table 6: Common image formats and number of macroblocks (MB) (16×16 pixel luma and 8×8 pixel for chroma components). †A vertical sub-sampling of chrominance (chroma) components by a factor of 2 is assumed. BT.601 is an ITU (International Telecommunication Union) video standard, with resolution and frame rate given by $720 \times 576 \times 30$. SIF is Source Input Format with 352×240 pixels when frame rate is 30p and 352×288 pixels when frame rate is 25p. CIF is Common Intermediate Format with a resolution of 352×288 . QCIF is Quarter Common Intermediate Format with a resolution of 176×144 . Note that a 29.97 frame rate is used instead of 30 in order to avoid sound interference caused by choice of color subcarrier.

(1 pixel in a 2×2 grid). 2:1 horizontal down-sampling and 2:1 vertical down-sampling. C_b and C_r are sampled on every other line, with one set of chroma samples for each two luma samples on a line. This amounts to a sub-sampling of chroma by a factor of two compared to luma (and by a factor of four for a single C_b or C_r component).

4:1:1 - Component digital video format with one C_b sample and one C_r sample for every four Y samples. 4:1 horizontal down-sampling with no vertical down-sampling. Chroma is sampled on every line, but only for every four luma pixels (1 pixel in a 1×4 grid). This amounts to a sub-sampling of chroma by a factor of two compared to luma (and by a factor of four for a single C_b or C_r component).

As an example, let us estimate the bitrate and total volume of an UHD movie to be stored on a Blu-Ray disk (BD) with the following characteristics compared to DVD:

Storage media name	BD25	BD50	DVD4	DVD9
Capacity	25 GBytes	50 GBytes	4.7 GBytes	9.4 GBytes
Data transfer speed	54.0 Mbps	54.0 Mbps	11.1 Mbps	11.1 Mbps
Laser wavelength	405 nm	405 nm	650 nm	650 nm
Laser spot diameter	480 nm	480 nm	$1.1 \mu\text{m}$	$1.1 \mu\text{m}$
Laser $[NA]^\dagger$	0.85	0.85	0.60	0.60
Pitch value	320 nm	320 nm	740 nm	740 nm
Smallest pit length	150 nm	150 nm	400 nm	400 nm
Pit width	130 nm	130 nm	320 nm	320 nm
Layers	single-layer	double-layer	single-layer	double-layer
Protective coating	0.1 mm	0.1 mm	0.6 mm	0.6 mm
Video compression	MPEG-2	MPEG-2	MPEG-2	MPEG-2
	MPEG-4/H.264	MPEG-4/H.264		

Table 7: Characteristics of Blu-Ray disks (BD) compared to those of DVD. bps is bits/second and Mbps is 10^6 bps. nm is nanometer. Pitch is the distance between neighboring tracks. Pit length is parallel to track whereas pit width is perpendicular to track. †Laser focusing over optical disks is provided by lens whose light concentrating property is given by $[NA]^2$ [6]. A Byte is an octet (8 bits).

Analog bandwidth is given by $n_H n_V n_F = 221$ MHz with n_H , the horizontal number of spots per line, n_V the number of lines per frame whereas n_F is the number of frames/second. In Blu-Ray 4K format, bitrate is given by: $r = 4096 \times 2160 \times 25 \times 30$ (pixels/frame) (frames/second) (bits/pixel).

Note: 4K UHD-TV frame format is 3840×2160 that is slightly different from the Blu-Ray 4096×2160 format. According to Nyquist theorem [9], equivalent bandwidth is half-bitrate or $B = r/2$. Thus $B = 3.3$ GHz amounting to 15 times the analog bandwidth of 221 MHz. Each chroma component C_R, C_B has same bandwidth value. This implies that C_R, C_B possess individually 1.65 GHz bandwidth giving a total bandwidth of 6.6 GHz.

Let us apply these results to evaluate the volume of an UHD (4K) movie of duration 1H and 30 minutes considering

a typical compression rate of 200.

Volume is given by $V = r\tau$ with τ the total movie duration. Thus $V = 6.6 \times 10^9 \times 90 \times 60/200 = 178 \times 10^9$ bits or 22.27 GBytes (after division by 8 since 1 Byte=8 bits). A Blu-Ray disk such as BD25 (that stores about 25 GBytes) is sufficient to store 22.27 GBytes with its ancillary data.

Requirements pertaining to Cinema, Video, video post-production and different media (DVD, Satellite, Internet...) are displayed in Table 8.

Video Format	Resolution	Sub-sampled Color	Frame Rate (Hz)	Bitrate (Mbps)
HDTV Terrestrial, Cable, Satellite, MPEG2, 20-45 Mbps				
SMPTE-296M	1280x720	4:2:0	24p/30p/60p	265/332/664
SMPTE-295M	1920x1080	4:2:0	24p/30p/60i	597/746/746
Video production, MPEG2, 15-50 Mbps				
BT.601	720x480/576	4:4:4	60i/50i	249
BT.601	720x480/576	4:2:2	60i/50i	166
High quality video distribution (DVD, SDTV), MPEG2, 4-10 Mbps				
BT.601	720x480/576	4:2:0	60i/50i	124
Intermediate quality video distribution, MPEG1, 1.5 Mbps				
SIF	352x240/288	4:2:0	30p/25p	30
Video conferencing over Internet, H.261/H.263, 128-384 kbps				
CIF	352x288	4:2:0	30p	37
Video telephony over wired/wireless modem, H.263, 20-64 kbps				
QCIF	176x144	4:2:0	30p	9.1

Table 8: Digital Video Formats. i is for interleaved, p is for progressive. SMPTE is Society for Motion Picture and Television Engineering. SDTV is single definition TV. bps is bits/second, kbps is 10^3 bps and Mbps is 10^6 bps . Adapted from Kim *et al.* [13])

G. Brightness and Contrast

The desirable brightness and contrast of a display depend on its internal light output as well as externally ambient light level. In typical office or home lighting, a brightness of 150-250 cd/m^2 is adequate and is achieved by most displays. For viewing in darkened conditions (such as watching television or movies), black state darkness of the display is important and a lot of work and research had to address this issue in CRT and Plasma emissive technologies as well as in non-emissive technology like LCD that needs backlighting.

There are three definitions of contrast: Conventional, Ambient and Dynamic.

- Conventional contrast is defined as the ratio of white to black luma. For example, when watching some movie on a home display, black luma greater than 0.1-0.2 cd/m^2 can deteriorate the perceived quality of dark images. Given a display with typically a bright luma of about 500 cd/m^2 and a contrast ratio of 1,000:1, means that the black luma is 0.5 cd/m^2 , which is not sufficiently dark to represent a vivid black image.
- Ambient contrast ratio is white state luma to black state luma ratio under ambient lighting conditions.
- Dynamic contrast is valid for backlit systems (like LCD) since it involves localized dimming of the display using an image-synchronized backlight system. By reducing and increasing brightness of the backlight unit in dark and bright areas of the image, respectively, image quality and the apparent contrast ratio can be much improved. By dimming backlight in dark areas, dynamic contrast ratios of 150,000:1 and 1,000,000:1 can be achieved with backlight technologies, respectively. However, local dimming can introduce artifacts such as poor quality of gray levels in either dark or bright state. In particular, a sizable difference in black level between dimmed and non-dimmed areas might be perceptible.

H. Response time

In flat-panel displays, pixel response time to some state change is of paramount importance.

For a BW display it is a rise-and-fade response. Response time is the interval it takes a pixel to change state from B→W and W→B. Thus it represents pixel ability to change from 10% "on" to 90% "on" and then back from 10% "off" to 90% "off" again. Originally, this was a standard way of reporting response times of TV and computer monitors, and is normally indicated as a $T_r - T_f$ (Rise time-Fade time) feature.

This specification is reported with either rise and fade response separate times or the total response by adding both figures. It should be noted however that if reported as an overall time, a good portion of figure represents the fall response time since it is generally substantially longer.

Response time started evolving with technology from milli to μ -second and is expected to reach nano-second values (cf. Table 21).

III. DISPLAY TECHNOLOGIES

There are essentially two types of technologies: Flat-Panel (FP) or Projection-Based (PB) and three types of displays:

1. FP non-emissive transmissive displays requiring backlighting like LCD
2. FP emissive displays like Plasma, Organic LED, Quantum dot
3. PB display with transmissive LCD panels or reflective Digital Micro-mirror Devices

A. Liquid Crystal Displays (LCD)

LCD are non-emissive flat-panel displays that need backlighting consisting of Cold Cathode Fluorescent Lamps (CCFL) or Light-Emitting Diodes (LED) that consume about 30% less than CCFL.

Twisted nematic Liquid Crystal (TNLC) is the most widely used technology in LCD to achieve panel light change. TNLC exploit the birefringence effect (polarization rotation) of the LC layer directly to control light polarization and panel transmittance. However, since LC layer birefringence varies with viewing direction, image distortion occurs in off-axis observation. This degradation of off-axis image quality is generally considered as the weakest point of LCD technology, and has been addressed by the development of Thin Film Transistor (TFT) technology that allows fine control of TNLC rod orientation. Generally, TNLC offers good brightness and response time performance leading to its wide adoption.

An LCD panel is such that an LC layer is injected between a TFT substrate and a color filter (CF) substrate (cf. Fig. 6). Two orthogonally aligned polarizers are attached to panel outer faces. LC molecules are aligned by surface anchoring to alignment layers formed on the inner surfaces of both substrates by rubbing in one direction resulting in a preferred alignment of LC molecules.

Rubbing directions of both substrates are perpendicular to each other as shown in Fig. 6, resulting in an LC layer with a 90°twisted structure in absence of an electric field. The twisted LC structure rotates polarization of light traveling through the cell, aligning polarization with that of the front polarizer and allowing light to pass (bright state). Increasing an electric field \mathbf{E} applied between pixel and common electrodes (cf. Fig. 6), TNLC rods align along \mathbf{E} , reducing LC layer birefringence and resulting into a gray or dark pixel state.

Compared to PDPs or CRT displays, LCDs have better contrast ratios under ambient conditions because, unlike CRTs and Plasma Display Panels (PDP), the LCD does not use phosphor, which emits light when excited by incident particles. To further improve the ambient contrast ratio for LCDs, suitable surface treatments for reducing reflections on the surface of the polarizer are used. In terms of color performance, the standard Red-Green-Blue (sRGB) color space known as "true color" in display systems [10], and most LCD monitors and televisions cover sRGB [13] color space, which corresponds to 71% of the NTSC standard. Other standards such as the Adobe and xvYCC color spaces [10], cover approximately 100% of the NTSC color space used by several brands of LCD monitors and televisions.

Energy consumption is such than 60% of total power consumption for a laptop LCD display and more than 80% of that for an LCD monitor or television is attributable to backlight.

Backlight-dimming technology, originally developed to enhance the dynamic contrast ratio, also reduces power consumption. The backlight luma in this case is varied according to the maximum gray level of the displayed image. For example, if the image maximum gray level is half the full white level, backlight luma is dimmed to 50% of full

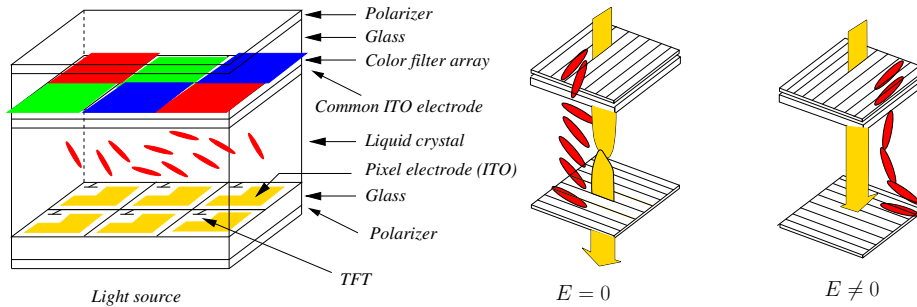


Fig.6: (left) TFT LCD panel. The panel is backlit by fluorescent tubes, LED arrays in the case of FP display or a Projector in Cinema. (right) TNLC rods (in red) with light (in yellow) traveling between cross polarized plates. In absence of electric field $\mathbf{E} = 0$, light polarization rotates following freely twisting TNLC rods to finally emerge out of the cross polarized system yielding a bright display. Presence of an electric field \mathbf{E} freezes TNLC rod twisting and light is blocked by the cross polarized plates resulting in a dark display. Adapted from Scientific American [14] and Lee [15].

Contrast ratio	Year			
	2003	2006	2008	2009
Conventional	1,000:1	2,000:1	5,000:1	8,000:1
Ambient*	600	1,250	1,600	1,800
Dynamic	5,000:1	10,000:1	50,000:1	150,000:1

Table 9: Improvement in measured contrast ratios for 2009 technology LCD television panels. *Under 200 lumens/m² luma source. A lumen is a photometric unit of luminous flux equivalent to watt in Radiometry. Adapted from Kim *et al.* [13])

luma by reducing the electric current supplied to the light sources, and image data are modified to effectively double panel transmittance in order to achieve same luma as the original image.

To further increase energy efficiency, the panel can be divided into segments, and each segment luma can be controlled independently. The average power saving for these dimming technologies can reach about 30% to 50%, respectively. As a result, use of LED backlighting is important not only for improving image quality but also for substantially reducing power consumption.

B. Organic LED (OLED) displays

In late 1980s, some organic conjugated polymers with a molecular weight greater than 10,000 were found to be electroluminescent [15].

Spectral emission bandwidth [15] of organic molecules is usually around 50-70 nm at half-height amplitude. Color gamut can be made larger by sharpening the emission peak. Very high luminous efficiencies have been achieved with these OLEDs, roughly on the order of 10-40 lm/W in the green. Operating voltages are low, on the order of 3-10 V, because the organic emissive layer is very thin, on the order of 50-200 nm. OLED Color displays are very bright (they can be $> 50,000$ cd/m²), have long lifetimes (longer than 10,000 hours), have wide viewing angles (greater than 160°), and fast response time (less than 1 μ -second).

Organic light-emitting diodes (OLEDs) can be fabricated on top of silicon wafers. An OLED material is self-emissive i.e. produces light directly, with no additional light source needed.

OLED have better color accuracy than LCD with higher saturation and their colors span a large gamut.

C. Plasma displays

A Plasma is an ionized medium containing free ions and electrons. A plasma display panel (PDP) is made of array of cells (cf. Fig. 7) that make a Solid State version of CCFL. Thus a PDP can be considered an integrated array of CCFL. CCFL are known as cold sources as opposed to thermal (Black-Body like) or incandescent sources (like

Tungsten bulbs). They need a special circuit called a ballast to stabilize current and accelerate electrons in order to make them collide inelastically with a gas mixture of heavy atoms (typically Mercury, Terbium and Argon) producing radiation.

A PDP can also be considered as a flattened CRT since it uses phosphors like CRT. Nevertheless, CRT phosphors glow when hit by electrons whereas in a PDP, phosphors glow when hit by UV radiation emitted by a plasma discharge [16]. Moreover, a CRT does not contain any specific gas whereas in a PDP, there is a gas mixture of Helium, Neon and Xenon emitting UV radiation when excited by a high voltage (cf. Fig. 7).

A PDP cell consists of two glass plates fabricated with a set of parallel metallic film ribbons. The plates are set perpendicularly to each other like a matrix and enclose cells filled with a gas mixture that emits UV radiation to excite phosphors turning the PDP into an emissive device (cf. Fig. 7).

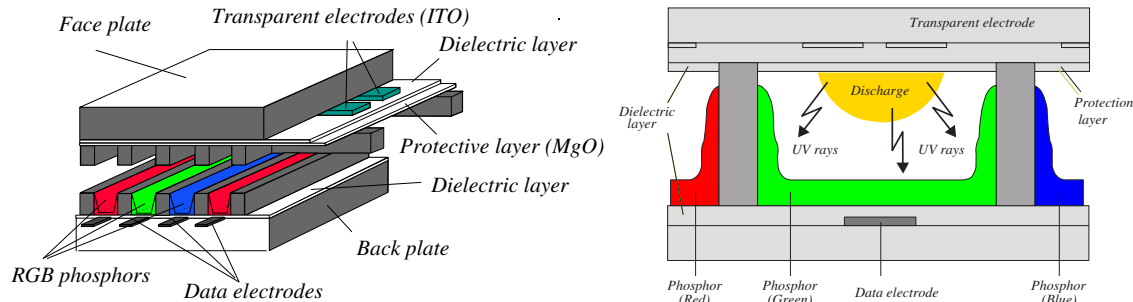


Fig.7: A PDP part (left) and an RGB cell (right) that behaves like a solid state version of RGB fluorescent tubes. ITO is Indium Tin Oxide that makes transparent electrodes. MgO is a protecting layer from the plasma discharge. Adapted from NEC [17]

Electrodes are sandwiched between the glass plates, on both cell sides. The address electrodes are located behind the cells and when sufficiently large voltages are applied simultaneously at their crossing (cf. Fig. 7).

By scanning sequentially, one row at a time, and repeating the process at least 60 times per second, one can trick the eye into perceiving a steady image. The image is nonetheless dim because a given pixel cannot glow more for a long enough time.

A brighter image is obtained by employing alternating current. Its inventors, H. Gene Slottow and Donald L. Bitzer of the University of Illinois [18], found that an AC (alternating current) would produce an inherent memory effect because a cell that has just fired will briefly retain some charge on its insulated electrodes.

Pixels fire each time the voltage reverses, emitting light for a longer time interval, nevertheless with current inexpensive semiconductor memory, a PDP has brightness and reliability.

Moreover, Super Real Gamma system provides an optimal number of sub-fields for each scene enabling Panasonic PDP to produce 1,024 shade levels in highly detailed dark scenes.

Table 10 summarizes specifications of the first 60 inch PDP set fabricated in 1999:

Diagonal Length	60 inches
Brightness	450 cd/m ²
Color Temperature	10,000 K
Contrast Ratio	≥ 500:1
Aspect Ratio	16:9
No. of Pixels	1366 x 768
Pixel Pitch	0.972 x 0.972 mm
Viewing Area	1328 x 747 mm
No. of Colors	16.7 Million
No. of Gray Levels	256
Viewing Angle	160°
Set Thickness	133 mm

Table 10: First 60 inch PDP set developed by PlasmaCo [19] in 1999. The PDP front protective glass incorporates a Deep Black Filter that suppresses light transmittance and reduces the amount of external light reflected. This provides the industry highest level of contrast when viewed in bright surroundings.

D. Quantum dot displays

Quantum dots can be viewed as artificial man-made atoms. In fact, their sizes range between 2 to 10 nanometers in diameter, which is equivalent to about 50 atoms.

Their technology is proper to high dynamic range (HDR) displays enabling them to be very bright.

In LCD displays they eliminate need for White LED backlights and color filters. Instead of using existing White LEDs (which have yellow phosphors) that produce a broad light spectrum that makes it hard to efficiently produce saturated colors,

The color light that a quantum dot emits is directly related to its size; smaller dots appear blue, larger ones more red. Quantum Dots directly convert light from Blue LED into highly saturated narrow-band primary colors for LCD.

TV manufacturers are keen to adopt quantum dots since they allow them to produce displays with much higher peak brightness. This opens up some interesting possibilities, such as enabling support for high dynamic range (HDR) displays.

HDR technology means displays with larger color gamuts and a serious increase in video quality as well as other visual parameters. Specifically, level of detail improves substantially with a greater number of colors available.

This improvement brought by HDR technology in color production, implies standards better than both sRGB and Rec.709 [20], that cover only 80% of the color available in the P3 color space provided by HDR [21].

None of this would be possible, on an LCD TV at least, without quantum dots.

While there are plenty of complexities to integrate quantum dots into screens, a big trouble facing any observer would be light bleed issue.

Overcoming this hurdle is crucial as to whether quantum dot will be someday incorporated into smartphones, e-tablets...

E. Digital Light Processing

Digital cinema requires discharge arc lamps such as Xenon or high power LED supported by three projection technologies:

1. Transmission through Liquid crystal (LC) frames
2. Reflection by Digital Micro-mirror Devices (DMD) and Digital Light Processing (DLP)
3. Transmission through Liquid Crystal on Silicon (LCoS) frames

3D Cinema requires two well-synchronized projectors (for left and right eyes) implying many technical and financial problems for the Cinema industry. Thus, Texas Instruments [22] was asked by the Cinema industry to develop a solution for projecting 3D pictures with a single projector.

Texas Instruments (TI) is the inventor of DLP [22] Cinema, implemented by nearly 90% of digital theater screens worldwide. TI DLP technology provides the Digital Micromirror Device (DMD), a high speed, efficient MEMS (Micro-Electro-Mechanical System) light steering device that can work with many sources of light (lamp, LED or laser) including visible, infrared and ultraviolet. Each DMD contains up to 8.8 million individually controlled micro-mirrors (each typically $16\ \mu\text{m} \times 16\ \mu\text{m}$) sitting on top of a fast SRAM memory. The mirrors are capable of switching on and off more than 1000 times per second to provide gray shades and color.

DLP is more efficient than transmissive LCD technology that requires polarized light. It has a light efficiency of greater than 60% stemming from the reflective character, making DLP systems more efficient than LCD projection displays.

LCD technology is polarization-dependent. This means that 50% of lamp light is lost since it is filtered out by a polarizer. Other light is blocked by transistors, gate, and source lines in the LCD cell. In addition to these light losses, LC material itself absorbs a portion of light. The result is that only a small amount of incident light is transmitted through the LCD panel and onto screen [22].

DMD technology is also fast enough to support higher frame rates demanded by 3D Cinema requiring interleaving two 24 fps streams (for left and right eyes), and to replicate the interleaved stream by a factor of two, resulting in 96 fps total frame rate.

When White light hits a DMD, shades of gray are obtained from angular tilts of DMD pixel elements and color is obtained with a color wheel in home cinema projectors. In theaters White light is split into RGB primaries with filters to be reflected by three DMD providing shades of each RGB primary resulting in up to 35 trillion (35×10^{12})

colors.

Table 11 summarizes the different available display technologies.

Technology	LCD Monitor	LCD Home TV	OLED	DMD-DLP	PDP	e-book
Power Consumption (W)	28-75	60-300	400 mW	100-200	300-660	0-1.5
Resolution (pixels)	1024x768- 1600x1200	640x480- 1920x1080	521x218 (dots)	1280x720 - 1920x1080	852x480- 1366x768	800x600, 170 pixels per inch
colors	16.2-16.7 million	16.7million- 3.2 billion	16.7 million	16 million	16.7 million - 3.62 billion	grayscale
Brightness (cd/m ²)	250-300	350-500	120	400-800	700-1000	
Contrast	350:1-800:1	350:1-3000:1	100:1	1000:1 - 2500:1	1000:1- 4000:1	10:1
Response Time	4-25 ms	8-30 ms	5 μ -second	no data	11-13 ms	300 ms
Viewing Angle ($^{\circ}$)	140/120- 178/178	160/140- 170/170	170	160	160	> 70 $^{\circ}$ \forall direction
Dot Pitch (mm)	.264-.297	.24-.75	0.172	0.4	1.02-1.55	0.164

Table 11: Year 2005 display technology status. *Field Emission Displays are not included. Adapted from Lytica [23].

IV. TELEVISION SYSTEMS

A. Analog terrestrial broadcast systems

Broadcasting a video signal entails transmitting a moving image over a variable distance and this is done by modulating a high frequency carrier $\cos(2\pi f_c t)$ by the video signal $x(t)$ where f_c is the carrier frequency. The modulated signal is written as: $y(t) = A(t) \cos(2\pi f_i(t)t + \phi(t))$ where f_i is an instantaneous time-dependent frequency and $\phi(t)$ is an instantaneous time-dependent phase.

- In Amplitude Modulation (AM), $A(t)$ is proportional to $x(t)$.
- In Frequency Modulation (FM), $A(t) = A_c$ is constant, the instantaneous $f_i(t) = f_c + \mu_f x(t)$ and $\phi(t) = 2\pi f_c t + 2\pi \mu_f \int_0^t d\tau x(\tau)$ yield $y(t) = A_c \cos(2\pi f_c t + 2\pi \mu_f \int_0^t d\tau x(\tau))$ where μ_f is the FM counterpart of the modulation index.
- In Phase Modulation (PM), $A(t) = A_c$ is constant, the instantaneous frequency $f_i(t) = f_c + \frac{\mu_p}{2\pi} \frac{dx(t)}{dt}$ and instantaneous phase $\phi(t) = 2\pi f_c t + \mu_p x(t)$ yield $y(t) = A_c \cos(2\pi f_c t + \mu_p x(t))$ where μ_p is the PM counterpart of the modulation index.

In BW TV, the modulated signal becomes: $y(t) = x(t)A_v \cos(2\pi f_c t + \phi(t))$, that is equivalent to a frequency shift by carrier frequency f_c as shown in Fig. 8. This leads to doubling video signal bandwidth from B in baseband to $2B$ with a Lower Side Band (LSB) and an Upper Side Band (USB) around carrier frequency f_c .

- BW Television:
In BW Television the modulated signal $y(t)$ is written as:

$$y(t) = A_v(1 + \mu x(t)) \cos(2\pi f_c t) \quad (6)$$

where $0 < \mu < 1$ is the modulation index and $x(t)$ is the BW or luma (luma) signal.

AM doubles the baseband width of BW TV signal from 4 MHz to 8 MHz yielding an upper (above f_c) and lower sideband (below f_c) as shown in Fig. 8. Thus an additional operation is required such as a 2 MHz filtering reduction of the lower sideband (LSB) resulting in a VSB (Vestigial Side Band) (cf. Table 13) with an overall bandwidth shrinking from 8 MHz to 6 MHz.

Thus it is required to generate single-sideband AM since LSB filtering requires transformation of individual sidebands. This operation is done by a quadrature filter [9] that shifts the phase of positive frequency components

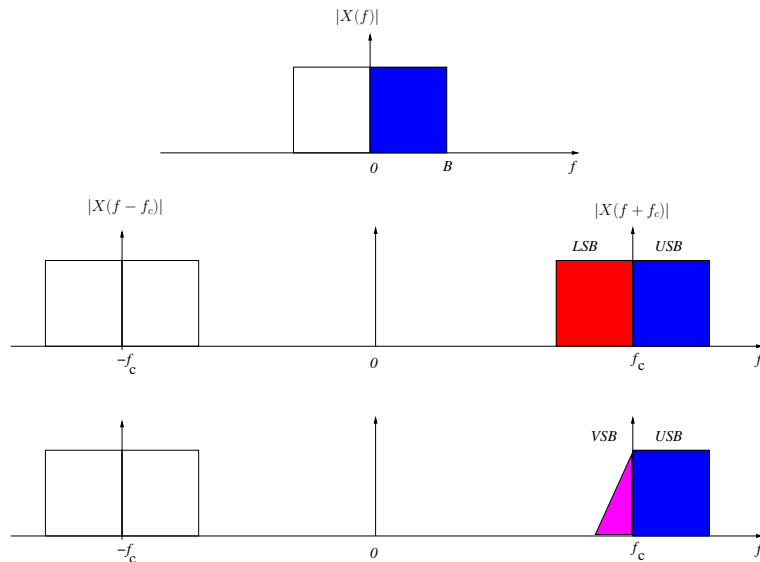


Fig.8: (Color on-line) (Upper) Baseband video signal with bandwidth B . (Middle) Modulation amounts to frequency shift by carrier frequency f_c leading to doubling signal bandwidth from B to $2B$ with a Lower Side Band (LSB) and an Upper Side Band (USB). (Lower) Modulated signal with LSB replaced through filtering by VSB carrying its half-bandwidth $B/2$.

of a signal by -90° and negative frequency components by $+90^\circ$. Since a $\pm 90^\circ$ phase shift is equivalent to multiplying by $e^{\pm 90^\circ} = \pm j$, where $j = \sqrt{-1}$ is the unit complex number, the transfer function can be written in terms of the signum function $sgn(f)$ given by:

$$sgn(f) = 1, \quad f > 0; \quad sgn(f) = 0, \quad f = 0; \quad sgn(f) = -1, \quad f < 0 \quad (7)$$

The quadrature filter [9]. transfer function is given by:

$$H_Q(f) = -j sgn(f) = -j, \quad f > 0; \quad \text{and} \quad H_Q(f) = -j sgn(f) = +j, \quad f < 0 \quad (8)$$

The corresponding impulse response $h_Q(t) = \frac{1}{\pi t}$ and the output response of the quadrature filter is $y(t) = x(t) * h_Q(t)$ where $x(t)$ is the input.

The Hilbert transform performs the required quadrature filter operation and is given by [9]:

$$y(t) \equiv \hat{x}(t) = x(t) * h_Q(t) = \frac{1}{\pi} \int_{-\infty}^{+\infty} d\tau \frac{x(\tau)}{t - \tau} \quad (9)$$

In the frequency domain, the Fourier transform of $\hat{x}(t)$ is $\hat{X}(f) = -j sgn(f)X(f)$ where $X(f)$ is $x(t)$ Fourier Transform.

A short summary of Hilbert transforms is given in Table 12.

$x(t)$	$\hat{x}(t)$
$\delta(t)$	$\frac{1}{\pi t}$
$\cos(t)$	$\sin(t)$
$1/(1+t^2)$	$t/(1+t^2)$
e^{jt}	$-je^{jt}$
$rect(t)$	$\frac{1}{\pi} \ln[(2t+1)/(2t-1)]$

Table 12: Some typical Hilbert transforms [9].

The different resulting modulations based on sideband operations through Hilbert transform is given in Table 13.

Modulation type	$I(t)$	$Q(t)$	Comments
AM	$1+\mu x(t)$	0	$x(t)$ is luma signal
DSB	$x(t)$	0	$x(t)$ is luma signal
SSB			
Upper SB	$\frac{1}{2}x(t)$	$\frac{1}{2}\hat{x}(t)$	$\hat{x}(t)$ is luma signal
Lower SB	$\frac{1}{2}x(t)$	$-\frac{1}{2}\hat{x}(t)$	Hilbert Transform (HT)
VSB			
Lower SB	$\frac{1}{2}x(t)$	$\frac{1}{2}\hat{x}^*(t)$	$\hat{x}^*(t)$ is filtered†
Upper SB	$\frac{1}{2}x(t)$	$-\frac{1}{2}\hat{x}^*(t)$	luma signal HT†

Table 13: Modulation techniques for BW TV. μ is AM modulation index. HT is Hilbert Transform. SB is sideband. DSB is Double SB with a modulated signal given by $y(t) = x(t) \cos(2\pi f_c t)$. VSB is Vestigial SB. †Filter transfer function is given by $H_F(f) = -j[H(f + f_c) - H(f - f_c)]$ where $H(f)$ is the VSB sideband shaping filter operating over 2 MHz and f_c the carrier frequency. $j = \sqrt{-1}$. Adapted from Carlson [9].

- Color Television

The three primary color signals can be uniquely represented by luma component inherited from BW TV and chroma represented by two CIE color components (x_c, y_c) [24] that are color coordinates of the CIE diagram shown in Fig.9. In order to economize bandwidth, luma is sent by AM carrier as in BW TV and color components are sent by QAM in a sub-carrier whose bandwidth is comprised inside the luma bandwidth.

Thus, in order to deal with more than one carrier $\cos(2\pi f_c t)$, it is possible to phase shift it by $\pi/2$ (called a quadrature shift) and thus employ two different signals to modulate two carriers.

This is Quadrature Amplitude Modulation (QAM) that is used in Color TV to transform a CIE color signal $I(t), Q(t)$ (cf. Fig.9) such to modulate a carrier $\cos(2\pi f_c t)$ by $I(t)$, and its phase shifted version by $Q(t)$ in order to obtain a modulated signal: $y(t) = I(t) \cos(2\pi f_c t) + Q(t) \sin(2\pi f_c t)$.

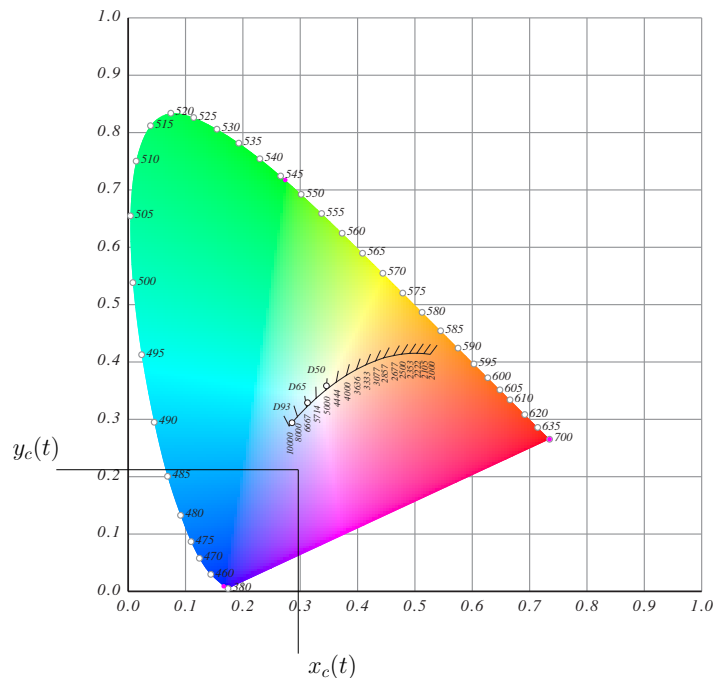


Fig.9: (Color on-line) CIE color diagram showing a time dependent color signal

$I(t) \equiv x_c(t) - x_W, Q(t) \equiv y_c(t) - y_W$ where $x_c(t), y_c(t)$ are time dependent CIE color coordinates drawn from the CIE color diagram and x_W, y_W are the coordinates of the White point. $I(t), Q(t)$ modulate respectively a carrier $\cos(2\pi f_c t)$ and its quadrature $\sin(2\pi f_c t)$ to make a QAM signal $y(t) = I(t) \cos(2\pi f_c t) + Q(t) \sin(2\pi f_c t)$. Adapted from Hoffmann [24]

The resulting modulation NTSC band consists of a VSB band for luma (main carrier), QAM band (subcarrier) and FM band for stereo sound as shown in Fig. 10.

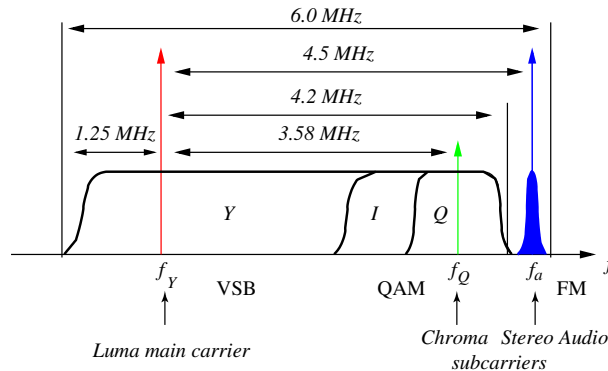


Fig.10: (Color on-line) NTSC frequency organization for luma, chroma and stereo sound with the different carriers, sub-carriers, respective bandwidths and modulations.

B. Digital terrestrial broadcast systems

Digital coding and modulation brought tremendous advances for telecommunications, video and TV systems by efficient combating of signal fading and image ghosting problems due to multipath propagation that plagued analog systems for a long time [9].

Broadcasting a digital video signal (consisting of a series of 0 and 1) entails transmitting it over a variable distance through modulation (called Shift Keying) of a high frequency carrier $A_c \cos(2\pi f_c t + \phi_c)$. While in analog communications, a single modulated signal $y(t)$ is sufficient, in the digital case, two signals $y_1(t), y_2(t)$ are modulated by bit 1 or 0 respectively. Consequently, in single bit transmission, the following possibilities are:

- In Amplitude Shift Keying (ASK), $A_c = \sqrt{\frac{2}{T_b}}$ for bit 1, or $A_c = 0$ for bit 0 where T_b is bit duration. This implies that the modulated signal $y_1(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t)$ for bit 1 and $y_2(t) = 0$ for bit 0. E_b is the transmitted signal energy per bit.
- In Frequency Shift Keying (FSK), $f_c = f_1$ for bit 1, or $f_c = f_2$ for bit 0 implying that the modulated signal $y_1(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_1 t)$ for bit 1 and $y_2(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_2 t)$ for bit 0.
- In Phase Shift Keying (PSK), $\phi_c = 0$ for bit 1, or $\phi_c = \pi$ for bit 0 implying that the modulated signal $y_1(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t)$ for bit 1 and $y_2(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t + \pi)$ for bit 0.

Symbol transmission goes beyond single bit by packing a series of bits into symbols of a given length such as dibits: 00,01,10,11 or tribits: 000,001,010,011, 100,101,110,111...

As an example QPSK (Quadrature PSK) allocates phase ϕ_c to 0 for symbol 00, π for symbol 01, $\pi/2$ for symbol 10 and finally $-\pi/2$ for symbol 11 implying four modulated signals $y_1(t), y_2(t), y_3(t), y_4(t)$ for each symbol.

QAM (Quadrature Amplitude Modulation) allows to modulate amplitude A_c and phase ϕ_c of the high frequency carrier $A_c \cos(2\pi f_c t + \phi_c)$ as $y(t) = I(t) \cos(2\pi f_c t) + Q(t) \sin(2\pi f_c t)$ where $I(t), Q(t)$ are given by symbol coordinates as shown in Fig. 11. Digital Video Broadcasting has two modulation methods: 8,16 VSB (Digital version of Analog VSB) or OFDM (Orthogonal Frequency Division Multiplexing described in Section 17).

8-VSB transmission

In HDTV, data is transformed into packets [9] that is an ensemble of bits. The packetized data is scrambled to remove any undesirable discrete frequency components, and is channel encoded. During channel coding, data is encoded with check or parity symbols to enable error correction at the receiver. The symbols are interleaved to minimize the effects of burst-type errors where noise in the channel can cause successive symbols to be corrupted. The encoded data is combined with synchronization signals and is then 8-VSB modulated. 8-VSB is a VSB technique where an 8-level baseband code is VSB modulated onto a given carrier frequency.

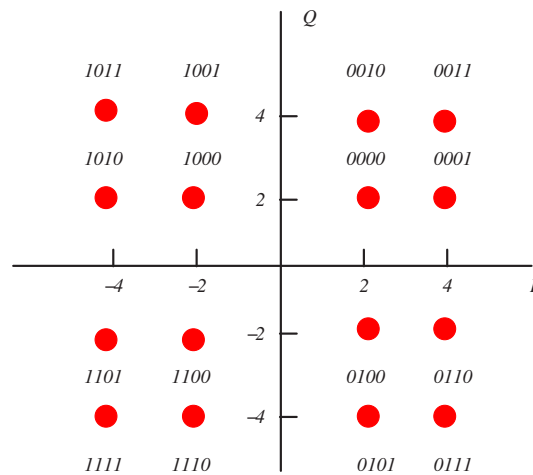


Fig.11: 16 QAM constellation showing 16 symbols each containing 4 bits that modulate a high frequency carrier $A_c \cos(2\pi f_c t + \phi_c)$ with f_c fixed. There are 16 modulated signals $y_i(t) = I_i(t) \cos(2\pi f_c t) + Q_i(t) \sin(2\pi f_c t)$, $i = 1, 2, \dots, 16$ with each $(I_i(t), Q_i(t))$ symbol coordinate corresponding to a 4 bit combination: 0000,0001,...

When optimal digitized, the 24.9 MHz composite video signal has a bitrate of 1 Gbps, whereas an NTSC 6-MHz television channel can transmit only 20 Mbps. Therefore a compression ratio of more than 50:1 is required. The raw video signal obtained by the scanning process contains significant temporal and spatial redundancies that are reduced by compression algorithms. During transmission of each frame, only those parts in the scene that move or change are actually transmitted.

Modulation format	Application
PSK	Cable TV modems
QPSK	Satellite, CDMA, DVB-S, Cable TV modems
8, 16 VSB	North American digital TV, Broadcast, Cable
8 PSK	Satellite, aircraft, pilots for monitoring video systems
16 QAM	Microwave digital radio, modems, DVB-C, DVB-T
32 QAM	Terrestrial microwave, DVB-T
64 QAM	DVB-C, modems, broadband set top boxes
256 QAM	Modems, DVB-C (Europe), Digital Video (US)

Table 14: Digital modulation applications circa 1997. Cable is abbreviated Coaxial Cable. DVB-T is Digital Video Broadcast-Terrestrial. DVB-C is Digital Video Broadcast-Cable. DVB-S is Digital Video Broadcast-Satellite. Adapted from Ref. [25].

Modulation method	Bandwidth
ASK	1 bit/second/Hz
PSK	1 bit/second/Hz
QPSK	2 bits/second/Hz
8 PSK	3 bits/second/Hz
16 QAM	4 bits/second/Hz
32 QAM	5 bits/second/Hz
64 QAM	6 bits/second/Hz
256 QAM	8 bits/second/Hz

Table 15: Digital modulation applications. ASK is Amplitude Shift Keying with 1 bit coding yielding 1 or 0 amplitude, whereas PSK is Phase Shift Keying yielding 0, π phase corresponding to 0,1 bit value respectively. Adapted from Ref. [25].

DVB System	Modulation	Band (GHz)	Signal Bandwidth (MHz)	Bitrate (Mbps)
Satellite TV	16-QAM	0.23-0.47 or 0.95-2.05	5.9-7.9	18.9-25.2
	32-QAM	0.23-0.47 or 0.95-2.05	4.7-8.0	18.9-31.9
	64-QAM	0.23-0.47 or 0.95-2.05	3.9-8.0	18.9-38.1
Cable TV (1)	16-QAM		2.0-7.9	7.0-27.3
	32-QAM		2.0-8.0	8.7-34.6
	64-QAM		2.0-7.9	10.4-41.3
Terrestrial TV (2)	OFDM (QPSK)	0.3-3.0	7.6	5.0-10.6
	OFDM (16-QAM)	0.3-3.0	7.6	10.0-21.1
	OFDM (64-QAM)	0.3-3.0	7.6	14.4-31.7

Table 16: Typical DVB Transmission System Parameters. (1) Frequency band is chosen by Coaxial Cable TV operators, (2) There is a variety of OFDM called COFDM (Coded OFDM) with hierarchical coding. Adapted from Ref. [26].

OFDM transmission

In presence of multipath interference, the delay of the echo is often longer than the symbol duration of the main signal. This results in a high level of interference. Echoes can be treated by making the symbol duration longer. In turn, this would lead to more required bandwidth. However, a tradeoff between bandwidth and symbol duration is possible. A method of achieving a larger symbol duration within the same bandwidth is to demultiplex a distinct symbol into several sub-symbols. Next, the sub-symbols are modulated in parallel onto different carriers. The total bandwidth (sum of all carrier frequencies) remains the same. Hence, the sub-symbol duration is increased. Next, the modulated sub-symbols are added, after which the newly obtained data stream can be transmitted.

OFDM is a multicarrier transmission technology that is currently being used in digital audio broadcasting (DAB). Typically, all adjacent carrier frequencies are orthogonally polarized. OFDM transmission system is able to operate in a 2K mode with a maximum of 1,705 carriers per OFDM symbol or 8K mode with a maximum of 6,817 carriers per OFDM symbol. The symbol duration in the latter is longer.

OFDM signals are organized in a frame structure. Each frame consists of 68 OFDM symbols. Four frames together constitute a super-frame. As each symbol in its turn is modulated on a number of carriers, a matrix is obtained. The distinct elements of the matrix are referred to as cells. DVB has specified 1,512 active carriers for the 2K mode. In 8K mode the number of active carriers is 6,048. The rest of the carriers information content is reference data (i.e., scattered pilot cells, continual pilot cells, and transmission parameter signaling (TPS) carriers (cf. Table 17)). Identification is established by using pilot cells, frame synchronization, frequency and time synchronizations, channel

Parameter	2K Mode	8K Mode
Maximum carriers	1,705	6,817
Active carriers	1,512	6,048
Scattered pilot cells	131	524
Continual pilot cells	45	177
TPS carriers	17	68

Table 17: OFDM Frame Structure. TPS are transmission parameter signaling carriers. Adapted from Ref. [26].

estimation as well as transmission mode. Pilot cells are transmitted with larger power, as e.g. in QPSK, amplitude is doubled. TPS carriers contain information concerning channel coding and modulation type.

C. Satellite TV

Digital video broadcasting by satellites use geostationary emitters at a distance about 40,000 kms that grants perfect synchronized rotation with Earth.

Frequency Range (GHz)	Restriction
2.52-2.655	c
11.7-12.2	1, 3 only
12.2-12.5	1, 2 only
12.5-12.7	2, 3c only
12.7-12.75	3c only
21.4-22	1, 3 only
40.5-42.5	
84-86	

Table 18: Frequency Allocations to Broadcasting Satellite Services related to Television (Downlink). c = community reception only; 1 = (Region 1): Europe, Africa, former USSR, and Mongolia; 2 = (Region 2): North and South America and Greenland; 3 = (Region 3): Asia (except former USSR and Mongolia), Australia, and Southwest Pacific. Adapted from Ref. [26].

D. Streaming video

Streaming is based on UDP (User Datagram Protocol) and not TCP (Transport Control Protocol) [27]. A datagram is an Internet Protocol (IP) packet that begins with a header followed by data (or payload) area. A datagram in IP (version 4), can contain as little as a single Byte (8 bits) of data or at most 64 KBytes, including header. In most datagrams, a header is much smaller than payload. A header represents overhead, because its size is fixed. Thus sending large datagrams results in more data bytes transmitted per unit of time (i.e., higher throughput).

UDP [27] is described by:

- UDP is a transport protocol that can distinguish among multiple application programs running on a given computer.
- The interface that UDP supplies to applications follows a connectionless paradigm.
- An application that uses UDP sends and receives individual messages.
- UDP offers applications the same best-effort delivery semantics as IP (Internet Protocol) [27].
- UDP allows an application to send to many other applications, receive from many other applications, or communicate with exactly one other.
- UDP provides a means of identifying application programs that does not depend on identifiers used by the local operating system.

The most important characteristic of UDP, its best-effort semantics, arises because UDP uses IP for transmission. In fact, UDP is sometimes characterized as a thin protocol layer that provides applications with the ability to send and receive IP datagrams.

UDP uses a connectionless communication paradigm, which means that an application using UDP does not need to pre-establish communication before sending data, nor does the application need to inform the network when finished. Instead, an application can generate and send data at any time. Moreover, UDP allows an application to delay an arbitrarily long time between the transmission of two messages. UDP does not maintain state, and does not use control messages; communication consists only of the data messages themselves. In particular, if a pair of applications stop sending data, no other packets are exchanged. As a result, UDP has extremely low overhead.

To summarize [27]:

- UDP is connectionless, which means that an application can send data at any time and UDP does not transmit any packets other than the packets that carry user data.

- UDP offers application programs a message-oriented interface. Each time an application requests that UDP send a block of data, UDP places the data in a single message for transmission. With UDP, each message that some application sends is transported across the Internet and delivered to the receiver.
- The message-oriented interface has several important consequences for developers. Applications that use UDP can depend on the protocol to preserve data boundaries, i.e. each message UDP delivers to a receiving application will be exactly the same as transmitted by the sender. Moreover, each UDP message must fit into a single IP datagram. Thus, the IP datagram size forms an absolute limit to a UDP message size.

V. DISPLAY DEVICES

A. Desktop computer monitors

While TV displays target image quality, computer monitors have the task of reproducing sharply printing characters like books. Thus the minimal 300 dpi quality explained in section I is transposed into 300 ppi.

Currently most computer (desktop and laptop) monitors are LCD in various applications such as CAD, graphic arts, and publishing.

Significantly, high-resolution displays can make practical use of existing amorphous silicon technology to produce novel products. Amorphous silicon technology is practical because of its extendability. Metal wires distributing electrical signals over the display must be deposited with low-resistance aluminum or copper. Color filters should be fabricated with higher tolerance in order to overlay sub-pixels of higher-resolution device, accurately.

A WQXGA (cf. Table 19) display requires data rates of almost 1 GByte/s between the frame buffer and the display when the display is refreshed at 60 Hz [28]. Four SXGA display adapters are used to render this display, and the display is split into four virtual displays for rendering purposes. Such parallel approaches significantly reduce the operating frequency required [28].

Monitor Size	Format name	Resolution	Mega-pixel	Aspect Ratio	Pixel per Inch	Pitch (mm)
15.0 in.	XGA	1024x768	0.79	1.33	85	0.298
17.0 in.	SXGA	1280x1024	1.31	1.25	96	0.263
19.0 in.	SXGA	1280x1024	1.31	1.25	86	0.294
20.0 in.	UXGA	1600x1200	1.92	1.33	100	0.254
16.0 in.	WXGA	1366x768	1.05	1.78	98	0.259
17.0 in.	WXGA+	1440x900	1.30	1.60	100	0.254
19.0 in.	WXGA+	1440x900	1.30	1.60	89	0.284
19.0 in.	WSXGA+	1680x1050	1.76	1.60	104	0.244
20.0 in.	WXGA+	1440x900	1.30	1.60	85	0.299
20.0 in.	WSXGA-	1600x900	1.44	1.78	92	0.277
20.0 in.	WSXGA+	1680x1050	1.76	1.60	99	0.256
22.0 in.	WXGA+	1440x900	1.30	1.60	77	0.329
22.0 in.	WSXGA+	1680x1050	1.76	1.60	90	0.282
24.0 in.	WUXGA	1920x1200	2.30	1.60	94	0.269
26.0 in.	WUXGA	1920x1200	2.30	1.60	87	0.292
30.0 in.	WQXGA	2560x1600	4.10	1.60	101	0.252

Table 19: Desktop computer Monitor Display formats and pixel information. Upper part is for Non-Widescreen (<1.50 Aspect Ratio) whereas lower part is for Widescreen (>1.50 Aspect Ratio) monitors with format name starting by W. Comparing with HDTV 1,920x1,080 format resulting in 2.07 Million pixels. GA is Graphics Array.

C, E, V, X, SX, UX and QX are respectively: Computer, Electronic, Video, Extended, Super-Extended, Ultra-Extended and Quad-Extended. For instance: WQXGA is also called QSXGA with 2560x2048 pixels, that is four (quad) times the total number of pixels of the SXGA standard (1280x1024). 1 in. is 2.54 cm. Adapted from Muller [28].

B. Large-area displays: Cinema and Wall

There are two possibilities for a large area coverage:

- Projection as in Cinema theaters, on wall and facade [29] of large buildings, Malls Cathedrals.... Facade animations are based on a 2D to 3D transformation of images and offer to citizens an alternate view of some familiar structure...
- Tiling (splitting the full wall area into smaller ones) as explained further below

1. Digital Cinema Screen

In digital cinema, the screen is required to be non-specular and equally reflective over the entire visible spectrum. The screen is required to have variable black masking, adjustable to tightly frame the projected image. This is required to minimally include 1.85:1 or 2.39:1 image formats.

All image parameters pertaining to screen are required to be measured from the center of the normal seating area in a theater. Nominal (reference) parameters and tolerances for review rooms and theaters are summarized in Table 20.

- Pixel Structure
For a theater, the sampling structure of a displayed image is required to be compliant with image and aspect ratio specifications of DCI standard [20].
- Peak White Luma
Using a white field test pattern [20], adjust peak white luma, as measured at screen center, to 48 cd/m², with measurement made at a reference viewing position.
- Luma Uniformity
Using the white field test pattern [20], align the lamp house to minimize luma fall-off from center to corners. The measured luma of the corners and sides in a (3x3) grid should be at least 75% of the center, as measured from a reference viewing position.
- Calibration White Point and Color uniformity
Using the white field test pattern [20], measure the white point chroma coordinates of the screen center with a spectro-radiometer [20].
- Sequential Contrast
The sequential contrast ratio is computed by dividing the white luma (of a peak white field) by the black luma (of a black field). The nominal (reference) value is required to have a minimum sequential contrast of 2000:1. Tolerances for mastering and display are shown in Table 20.

2. Large walls

In order to achieve tiling a moving image on a wall, multiple zoomed-in camera [29] views of feature points projected on the display wall are collected. These detailed views help determine with great precision the feature point positions in the camera coordinate system. Significant overlap is employed so that the camera views to calculate transformations that map one view coordinate system to its neighboring views. These camera views and transformations form the vertices and edges of a special geometrical operation called homography. A projective linear transformation is known as a collineation or projectivity. In the case of projective plane, it is called a homography [30] or plane projectivity. In computer vision, homography plays an important role because any two images of the same planar surface are related by a homography. It is used for camera calibration, image rectification...

A tree representing the homography [30] is used to warp and merge all camera views into a mosaic view. However, valuable feature correspondence information is lost in forming the tree, resulting in increased error in the feature point estimation and ultimately lower alignment accuracy of the display wall [29]. To address this problem, an optimization algorithm that recaptures all of the tree homography information is developed. First, a tree branching is selected to minimize the path length between any pair of adjacent camera views. Next, a minimization algorithm is used to iteratively refine the homography associated with each edge in the tree by traversing all paths between the two sets of camera views separated by an edge. The process runs until the feature point location is defined below a given threshold.

Image Parameters	Nominal (Projected Image)	Tolerances (Review Rooms)	Tolerances (Theaters)
Pixel Count	2048 x 1080 or 4096 x 2160	N/A	N/A
Calibrated White Luma	48 cd/m ²	±2.4 cd/m ²	±10.2 cd/m ²
Calibrated White Chroma center	x=.3140, y=.3510	±.002 x, y	±.006 x, y
Sequential Contrast	2000:1 minimum	1500:1 minimum	1200:1 minimum
Intra-frame Contrast	150:1 minimum	100:1 minimum	100:1 minimum
Transfer Function	Gamma=2.6	± 2% per component	± 5% per component
Color Gamut	Minimum Color Gamut enclosed by white point, black point and Red: x=0.680, y=0.320, Y=10.1 Green: x=0.265, y=0.690, Y=34.6 Blue: x=0.150, y=0.060, Y=3.31	(same)	(same)

Table 20: Some DCI reference image parameters and tolerances. Adapted from DCI [20].

C. Hand-held displays, Head-mounted and virtual-reality displays

Small portable devices such as laptops, e-tablets, smartphones... present special requirements for displays, since power and allowable thickness are limited.

The earliest hand-held displays, that appeared in wrist-watches and calculators, were seven-segment LC displays. In mobile devices, an important issue is power efficiency and improvement of battery life since a display can take as much as 50% of total power. In head-mounted virtual-reality applications, displaying images separately to each eye at close distance demand special requirements such as display weight, viewing distance, angle of view... For instance, the diameter of a typical exit pupil used to design head-mounted displays is 6 to 8 mm [11]. For eye relief, or distance from user eye to lens that images the display, typical values are 25 to 35 mm. The diagonal field of view ranges from 24 to 40°, with a pixel angular resolution of 24 to 40 pixels/°, well below the visual acuity limit of the eye, which is one minute of arc [11].

In head-mounted displays, each eye looks into a separate display connected to a distinct rendering engine producing two views of the scene.

In these systems the viewer is immersed in an interactive 3D space generated by a computer graphic chip. The viewer can move within that space and interact with objects or other users. When some objects within the 3D space are close to viewer, the human visual system detects the scene binocular disparity (i.e. difference between right and left scene views) and finally the human visual system fuses both images into a 3D view.

Although these systems can generate sensation of 3D within the human visual system, they do so without using all perceptual capabilities that humans muster in real environments.

D. 3D displays

Most perceptual tools that humans employ to visualize the World 3D structure are available in 2D projections. That is how one can make sense of photographs and images on a TV screen, at cinema, or on a computer monitor. Some tools [31] are occlusion (one object partially hiding another), perspective (distant object apparent size is different from real), comparison with familiar objects (real-world sizes of many objects are well known inducing prejudice), atmospheric haze (remote objects look fuzzy)...

Four issues are missing from 2D media [31]:

- Stereo parallax: seeing a different image with each eye,
- Movement parallax: seeing different images when moving our heads,
- Accommodation: eye lenses focusing on an object of interest,
- Convergence: both eyes converging on the object of interest.

All 3D display technologies (stereoscopic displays) provide at least stereo parallax. Auto-stereoscopic displays provide a 3D image without the viewer needing to wear any special viewing gear.

Polarized glasses or Headsets

These 3D displays require the viewer to wear special glasses present two different images in the same display plane. The glasses select which of the two images is visible to each of the viewer eyes. Pertinent technologies include:

- A standard color display combined with colored glasses;
- Two standard displays, made coplanar by a half-silvered mirror, combined with polarized glasses;
- Two projectors, projecting onto a polarity-preserving screen, combined with polarized glasses; and
- Two double-frame rate display combined with shuttered glasses.

Early stereoscopic cinema employed a method in which the right part of a composite image, usually red in color, is superposed on the left part with a contrast color in order to produce a 3D effect when the viewer looks through colored filter glasses, with a risk of suffering from headache during prolonged use.

Shutter glasses, notably those produced by Stereographics, are used for scientific applications. Polaroid glasses are the usual norm for stereoscopic cinema, however equipment and expertise required to operate thoroughly stereoscopic cinema lead to a higher cost than conventional cinema.

An alternative to glasses is to mount two small displays in a headset allowing a single view for each eye.

Auto-stereoscopic displays

Auto-stereoscopic displays [31] provide 3D perception without need for special glasses or a headset. Drawing upon three basic technologies, developers can make two different types of auto-stereoscopic displays: a two-view, head-tracked display for single-viewer systems or a multiview display that supports multiple viewers.

All these technologies provide stereo parallax and convergence. When combined with head-tracking, they can provide movement parallax for a single viewer.

Multiview and head-tracked auto-stereoscopic displays [31] combine effects of both stereo parallax and movement parallax to give 3D without glasses. When an observer looks at a scene in real world, he sees a different image with each eye and different images again when he moves his head.

Head-tracked displays only two views to appropriate slots, tracking the viewer head with each eye always seeing the correct view. If the image-generation process takes the head position into account, it can simulate movement parallax effects. Otherwise, a head-tracked display provides stereo parallax.

Display Technology	LCD	OLED	μ -LED
Emission Mechanism	Backlight	Self-emissive	Self-emissive
Contrast ratio	5000 : 1	∞	∞
Response time	ms	μ -second	ns
Operating temperature	-40 to 100 °C	-30 to 85 °C	-100 to 120 °C
Power consumption	High	Medium	Low
View angle	Low	Medium	High

Table 21: Comparison of LCD, OLED and Micro-LED technologies. ms and ns are milli-second and nano-second respectively. Adapted from Liu *et al.* [32]).

VI. PERSPECTIVES

LCD and LED electronic displays are playing a vital role in opening up novel types of information devices (such as screens for cars, trains, airplanes...) and enlarging traditional display device functions.

Micro-light-emitting diodes (μ -LEDs) have excellent properties in terms of brightness, lifetime, resolution and efficiency. Their attractiveness is proven e.g. by Sony who introduced in 2012 its first 55 inch μ -LED HDTV panel with 1920 x 1080 resolution.

Display type	Car screen	Home TV	e-tablet
Panel size (inch)	6 - 12	32 - 100	150 - 220
Pixels per inch	150 - 250	40 - 80	20 - 30
Chip size (μm)	50 - 100	50 - 80	80 - 100
Display type	Augmented Reality	Wrist-Watch	Mobile
Panel size (inch)	0.5 - 1	1 - 1.5	4-6
Pixels per inch	450 - 2000	200 - 300	300 - 800
Chip size (μm)	1-5	10 - 30	30 - 50

Table 22: Requirements for micro-LED displays in various cases. Car screens provide GPS, maps and traffic information to drivers. Adapted from Liu *et al.* [32].

μ -LED development is based on established solid-state techniques with more advanced fabrication processes at a higher resolution than those of regular LED. Ordinary blue and green LED are typically based on InGaN semiconductors, whereas red LED use AlGaInP semiconductors.

To conclude, micro-LED technology is not the only promising perspective since technological developments might eventually provide fabrication of 3D holographic displays.

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- [1] J. Watkinson, *The MPEG Handbook MPEG-1, MPEG-2, MPEG-4* Focal Press, An imprint of Butterworth-Heinemann Linacre House, Jordan Hill, Oxford OX2 8DP 225 Wildwood Avenue, Woburn, MA 01801-2041 A division of Reed Educational and Professional Publishing Ltd (2001).
- [2] S. Hecht, *The dark adaptation of the human eye*, The Journal of General Physiology, 499 (1920).
- [3] A candela (cd) is a photometric unit of luminous intensity given in lumens/steradian equivalent to watts/steradian of Radiometry. A lumen is a photometric unit of luminous flux equivalent to watts in Radiometry.
- [4] I. Reiser, Chapter 18 in *Diagnostic Radiology Physics: A Handbook for Teachers and Students* Edited by D.R. Dance, S. Christofides, A.D.A. Maidment, I.D. McLean and K.H. Ng, IAEA Vienna (2014).
- [5] The essential reference guide for filmmakers, KODAK Educational Products, Code: H-845 CAT No. 145 6144, Eastman Kodak Company (2007).
- [6] A measure of an optical device ability to concentrate light is given by $[NA]^2$ where $[NA]$ is its numeric aperture as described by E. Hecht, *Optics*, Fourth Edition, Pearson Education-Addison-Wesley, San Francisco (2002).
- [7] G.D. Boreman, Chapter 4: *Transfer Function Techniques*, in *Handbook of Optics*, Volume 1, Third edition, edited by M. Bass, SPIE and McGraw-Hill (New-York, 2010).
- [8] W. H. Press, W. T. Vetterling, S. A. Teukolsky and B. P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing* Third Edition, Cambridge University Press, New-York (2007).
- [9] A. B. Carlson and P. B. Crilly *Communication systems: An Introduction to Signals and Noise in Electrical Communication*, 5th Edition, McGraw-Hill, New York (2010).
- [10] J. Froehlich, S. Grandinetti, B. Eberhardt, S. Walter, A. Schilling, and H. Brendel, *Creating Cinematic Wide Gamut HDR-Video for the Evaluation of Tone Mapping Operators and HDR-Displays*, Proc. of IS&T/SPIE Electronic Imaging, (2014). See also J. Froehlich, A. Schilling and B. Eberhardt *Gamut Mapping for Digital Cinema*, SMPTE Motion Imaging J. (2014).
- [11] R.L. Wisnieff and J.J. Ritsko *Electronic displays for information technology*, IBM J. Res. Dev. **44**, 409, (2000).
- [12] Tektronix Document 068-0313-00, *Cathode Ray Tubes: Getting Down to Basics*, (1989).
- [13] K. H. Kim and J. K. Song, *Technical evolution of liquid crystal displays*, NPG Asia Mat. 1(1) 29 (2009).
- [14] S. W. Depp and W. E Howard, *Flat-panel displays*, Scientific American, March (1993).
- [15] H.C Lee, *Introduction to color imaging science*, Cambridge University Press (2005)
- [16] A discharge occurs when an excited atom returns to its ground state by emitting radiation or photons. One way for an atom to be excited or energized to higher than its ground state and thereby become able to radiate is by a collision with another particle. A high voltage applied to the atomic gas triggers collisions (leading to excitation) and in 1 μ -second average time, the atom gives off energy by emitting photons. See A. Beiser, *Concepts of Modern Physics*, Sixth Edition, McGraw-Hill, New York (2003).
- [17] NEC White paper *Plasma Displays*, NEC Technologies, Visual Systems Division (1998).
- [18] L. F. Weber, *History of the Plasma Display Panel*, IEEE Trans. on Plasma Science, **34**, 268, (2006).
- [19] Plasmaco, Inc. is a subsidiary of Matsushita Electric Industrial Co., Ltd. based in Highland, New York (USA).
- [20] DCI Digital Cinema System Specification v.1.2 (2008)
- [21] G. Kennel, *Color and Mastering for Digital Cinema* Focal Press and Elsevier (2007).
- [22] L. A. Yoder, *An Introduction to the Digital Light Processing (DLP) Technology*, Texas Instruments (1996). See also L.J. Hornbeck, *Deformable-Mirror Spatial Light Modulators, Spatial Light Modulators and Applications III*, SPIE Critical

Reviews, Vol. 1150, 86 (1989).

- [23] J. Gurski and L. M. Quach *Lytica White Paper: Display Technology Overview* Lytica Inc. (2005).
- [24] G. Hoffmann, *CIE Color Space*, Web document ciegraph17052004.pdf from University of Emden
URL: <http://docs-hoffmann.de>
- [25] *Digital Modulation in Communications Systems: An Introduction*, Hewlett-Packard Application Note 1298 (1997).
- [26] R. de Bruin and J.M. Smits, *Digital Video Broadcasting: Technology, Standards, and Regulations*, Artech House Publishers (2003).
- [27] D. E. Comer, *Computer Networks and Internets*, Fifth Edition, Pearson Education, Inc. Upper Saddle River, New Jersey (2009).
- [28] S. Mueller, *Repairing and Upgrading PCs*, 20th Edition, Pearson Education (2012).
- [29] G Wallace, O J. Anshus, P Bi, H Chen, Y Chen, D Clark, P Cook, A Finkelstein, T Funkhouser, A Gupta, M Hibbs, K Li, Z Liu, R Samanta, R Sukthankar, and O Troyanskaya, *Tools and Applications for Large-Scale Display Walls* IEEE Computer Graphics and Applications, Published by the IEEE Computer Society (2005)
- [30] D. S. Goodman, *General Principles of Geometrical Optics*, Chapter 1 in *Handbook of Optics*, Volume 1, Third edition, edited by M. Bass, SPIE and McGraw-Hill (New-York, 2010).
- [31] N. A. Dodgson, *Autostereoscopic 3D Displays* Published by IEEE Computer Society, 31 (August 2005).
- [32] Z. Liu, C.H Lin, B.R. Hyun, C.W. Sher, Z. Lv, B. Luo, F. Jiang, T. Wu, C.H. Ho, H.C. Kuo and J.H. He, *Micro-light-emitting diodes with quantum dots in display technology*, Light: Science & Applications (Nature), 9:83 Official journal of the CIOMP 2047-7538 (2020)