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Introduction to Mobile Displays

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1.1 Introduction

Mobile displays have been undergoing tremendous advances in recent years, in terms of both technology and applications. In the past, the information that needed to be displayed on mobile devices was sufficiently low for the display not to limit the mobile device applications. For example, an early cellular phone only had a 1-line monochrome display consisting of $\sim 10^2$ pixels. However, as the mobile applications became richer, the displays also needed to evolve in order to keep pace with increased requirements. Displays with more than 10^5 pixels and up to 12 bits of color depth are common in today's mobile handsets. On the performance front, the mobile phone display is rapidly approaching the performance of a desktop monitor in terms of brightness, contrast, and color saturation, among other important display parameters. These changes are the results of rapid advances in technology for both wireless network infrastructure and mobile handsets, which are intertwined to provide a far-superior overall communication experience for the consumer. Another mobile application area that has witnessed significant improvements in the display characteristics is the mobile computer. The early notebook computers sported embedded displays of relatively modest attributes, whereas today the majority of laptops include a WXGA resolution (1280×800) screen with 18 bits-per-pixel color depth, and the state-of-the-art mobile computer boasts a high-definition screen (WUXGA,

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1920 × 1200) with 24 bits-per-pixel color depth. This rapid enhancement of the display is to match the increased richness of visual content offered by the modern mobile computer.

The term 'Mobile Display' has only recently appeared in technical literature. A quick scan through the back issues of major display technical publications, such as SID Digest of Technical Papers, International Display Workshop Proceedings, and International Display Research Conference Proceeding, reveals that the earliest session devoted to 'Mobile Display' was at the 2002 International Display Workshop held in Hiroshima, Japan [1]. In the past, terms such as mobile display, portable display, or handheld display, were often used interchangeably in the display field with little or no distinction. They were often invoked to refer just to low power display or small size display. Although power and size are important attributes in considering a mobile display, as will be discussed later, these are only a subset of display parameters of importance.

In this chapter, we will first take a look at the burgeoning applications that are driving the increasingly challenging requirements for the mobile display, in particular the ever-growing mobile phone and mobile computer applications, analyze the mobile environment and its impact on the display, and then review the advances in the display technologies in order to meet the stringent requirements imposed by the mobile environment and applications. We will also introduce and place in context subsequent chapters in the book.

1.2 Advances in Mobile Applications

Mobile communication and computing have seen drastic changes over the past decades. As average consumers, we have all witnessed and benefited from these changes. Let's start with a look at recent trends in mobile communication: smaller and thinner mobile phones with slick design, much longer battery life for prolonged talk time and standby time between charges, higher resolution and color display replacing the monochrome type, much better voice quality, and the wild popularity of text messages. All these advances are happening while the cost per minute is only a small fraction of what it was a decade ago. In 2007 the annual mobile phone production reached a new peak of more than 1 billion units and is projected to maintain double digit annual growth worldwide for the next several years, as shown in Figure 1.1, below, provided by DisplaySearch, a leading display market research firm. This is an astronomical number that few other electronic devices can ever compete with. Besides the mobile phone, which enjoys the largest share of the mobile communications market, other mobile devices have also seen significant growth. Notable among them are mobile personal computers, MP3 players, digital cameras, PDAs, GPS map readers, potable DVD players, electronic books, etc. The

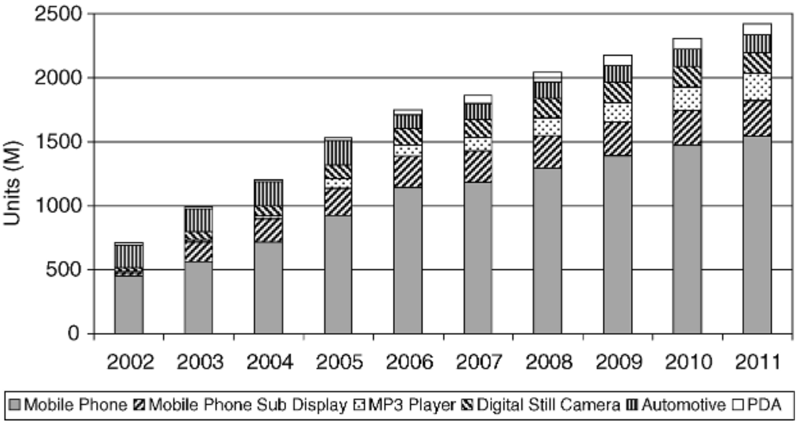

Figure 1.1 Mobile display growth (courtesy: DisplaySearch).

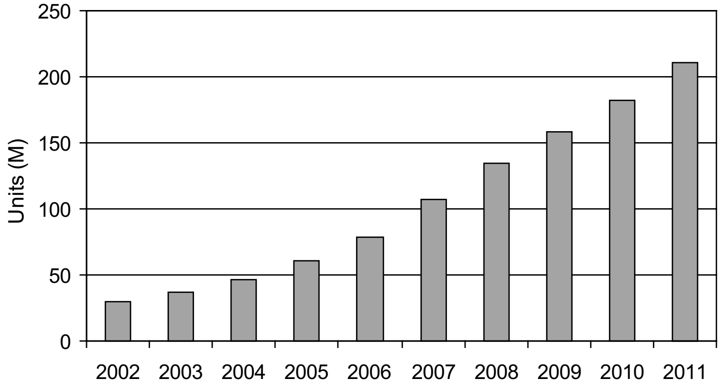

Figure 1.2 Annual notebook computer shipment data and forecast (courtesy: DisplaySearch).

mobile computer segment, in particular, has been witnessing a strong growth in recent years. The shipment of notebook computers exceeded the 100 million units mark in 2007, as shown in Figure 1.2, above, also provided by DisplaySearch. This is approximately five times the volume shipped in 2000. The mobile computer volume is forecast to continue to grow at about five times the rate of the desktop computer counterpart in the coming years. The notebook market share as percentage of the overall personal computer (PC) market is steadily increasing in all regions of the world, already accounting for more than half of the overall PC volume in mature markets. Sustained growth in notebook computers in recent years is fueled by a widespread consumer interest in getting high-bandwidth access to full Internet, anytime and anywhere, besides the computational power to drive PC applications with the levels of processor capabilities that were only common in desktop systems even a few years ago. Another new category of mobile computers is the emerging Ultra-Mobile PC (UMPC), or the consumer-focused variant termed as the Mobile Internet Device (MID), promising to pack the processing and internet capabilities of a full computer into attractive ultra-portable form factors. One of the key technological enablers for the rapid expansion in mobile computing has been the wide availability of color thin-film transistor active matrix liquid crystal displays (TFT AMLCD) [2], besides remarkable innovations in low-power processor, much improved electronic packaging technologies, and the arrival of lithium-Ion battery among many other electronics advancements.

Until recently, mobile computing was primarily for use in office, home, or similar environments that were not initially targeted for wireless communication applications. On the other hand, the technical landscape for mobile communication is more complex because both a wireless communication network and wireless communication device need to work together to deliver the rich experience that consumers demand. In fact, the introduction of the Intel Centrino mobile platforms in 2003 that integrated broad wireless network connectivity and interoperability into the notebook PCs spurred the subsequent rapid growth in the mobile computer market.

In the next section we will explain how the interplay at both the network and device levels laid the technology foundation for the rapid expansion in mobile communication applications and how these new applications drive the technological advancement in displays used in mobile devices.

Taking the evolution of the cellular network as an example, Figure 1.3, below, depicts the application expansion as the wireless network bandwidth increases. The initial wireless network was based on analog technology and only capable of providing voice calls due to its limited bandwidth. As we moved to the 2nd generation (2G) network, not only were large numbers of channel capability added to enable more users, but service quality in voice communication also significantly improved. However, non-voice services such as text messaging were not enabled until the cellular network was further upgraded to use packet data service network or 2.5 generation (2.5G) network, primarily due to the low bandwidth capability from the earlier networks. Nowadays the landscape of wireless communication is

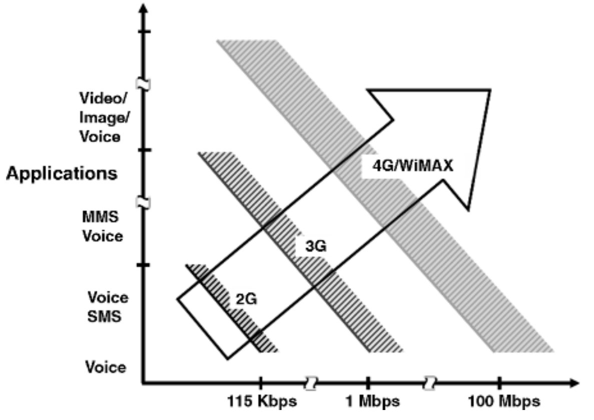

Figure 1.3 Applications enabled by increased network bandwidth.

much more complex than just a few years ago when cellular network had the monopoly for the most part, though cellular network is still dominant and hundreds of billions of dollars have been spent to move from 2G to 3rd generation (3G) network. In some parts of the world 3G network has already entered into service. The 3G network enables a bandwidth of 10–100 times of a 2G network, ranging from a few megabits per second (Mbps) to ~50 Mbps. In research labs around the world, next generation cellular networks beyond 3G have started to move away from the drawing board into limited field testing. On the other hand, among the developments that are occurring using non-cellular network with unlicensed spectrum band, WiMAX has a large coverage distance up to multiple miles and could provide more bandwidth than a 3G network. For a short range, the now ubiquitous Wi-Fi systems also provide high bandwidth in the range 10s of Mbps. These increased bandwidths are able to support data and image transmission in addition to voice transmission. In parallel, improvements in signal processing techniques, such as data compression and decompression, have allowed further optimization of the utility of the available bandwidth to enhance transmission quality.

In parallel with the network bandwidth explosion, in the past decade we have also witnessed vast enhancements in mobile terminal devices. In this regard, there has been a tremendous similarity between mobile communication and mobile computing at the device level. Much of the technological advancements discussed here are also applicable to the mobile computing devices. The early analog mobile phone had very limited process and memory that were only capable of handling voice communication. As we move to 2G and 3G handsets, there are several important technological developments at components and subsystem level. First of all, rapid progress has been made in miniaturization. This makes the much needed compact package readily available for designers. In addition to smaller components, interconnections among components are also much more condensed through varieties of high density interconnection technologies. The optimized usage of miniaturized active and passive components through design innovation has further driven the overall package volume down. Reduction of the power consumption of these devices has been another major advancement. These reflect the combined results from drastic improvements from base-band and other processors, power amplifier, and more efficient power-management chipsets. Memory devices have also seen major power reduction over the years in addition to its own size reduction. All these made it possible to integrate a much more powerful processor, high capacity memory chip, and other active and passive components into a compact package of a handheld device. Figure 1.4, below, depicts this general trend versus different generations of mobile devices. At the time of writing, a 3G handset can deploy as much as 256 MB memory with an equivalent processing power of an early mobile computer processor. Some handsets even have a hard drive in addition to flash memory. With all these advances, it may not be exaggerating to say that a modern mobile communication handset may be regarded as a PC in your palm.

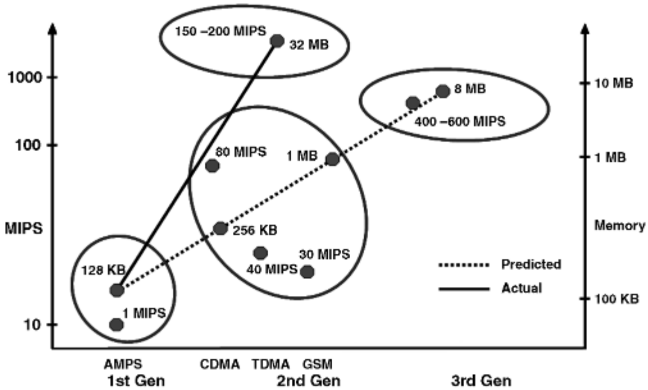

Figure 1.4 Processing power and memory trends for mobile communication devices.

These combined advances in network and handset provide the technological foundation for many new market applications far beyond simple voice communication. Nowadays, although voice communication is still the bread and butter for service providers, non-voice applications have become increasingly important to maintain existing customers and entice new ones. These applications take the forms of text messaging, multimedia messaging with images, mobile TV, and mobile on-line gaming, to name but a few. Another phenomenon that has expedited usage of images for communication was the introduction of cameras to handsets, which began around 2000, and which created a need for users to be able to send and receive pictures.

All these applications demand a much more advanced display on a mobile device than a traditional voice communication device. Just take the camera phone as an example: there is a huge disparity, several orders of magnitude in fact, between the resolutions of the camera and the display on a mobile phone. The first camera phone already had a camera resolution of VGA and now to have a few mega-pixels still-image camera on a phone is a norm. On the display side, VGA resolution display with 0.3 mega-pixels has just emerged recently from the trade-show floors and prototypes. A high quality photo taken with a mobile phone can not be fully rendered on its own display as a result. These new image and data centric applications targeted for mobile communication applications create a need for a new category of display – ‘mobile display’.

It’s important to realize that a new trend has been forming for the past few years, which is the convergence of mobile communication and mobile computing. In other words, the boundary between a mobile communication and mobile computing device has been increasingly blurring. This trend is accelerating due to the arrival of the so-called non-cellular wireless networks, most notably the now-ubiquitous Wi-Fi and the emerging WiMAX. We have seen the emergence of power and performance-optimized mobile computer platforms with high bandwidth wireless connectivity, ushering in the era of ‘personal Internet on the go’. The rapid evolution in the computational and communications capabilities of the modern mobile computers has also been accompanied by increased richness of the media processing and playback quality as well as the visual characteristics of the display embedded within the system.

1.3 Mobile Environment and its Impact on the Display

What we define as a mobile display here is a display system that adequately performs in a mobile communication and computing environment. So to better understand what constitutes a mobile display, we need first to examine the mobile environment and its impact on the display performances and

Table 1.1 Summary of key environmental differences of display importance.

	Personal Mobile	Automotive	Office/Home
Illumination Range	huge	huge	minimum
Device Dimension	small	middle	large
Power	limited	better	unlimited
Relative Motion	non-stationary	in-between	stationary
Temperature Range	wide	wider	narrow
Viewer	1-2	a few	multiple
User Interface	difficult	difficult	easy

requirements, and how these environments differ as we move from a low mobility environment to a high mobility environment.

Table 1.1, above, provides a summary of the key mobile environmental considerations and compares the differences among the three main environmental conditions: personal mobile; automotive; and office/home. These considerations are primarily selected for their relevance in the context of visual communication. Personal mobile includes displays used in the mobile phone, laptop computer, or similar handheld devices. This category has the highest mobility environment. On the other end, office/home handles pretty much a steady situation. As one moves across the environment boundary or increases/decreases in the mobility, a large set of parameters unique to that environment also change accordingly. With increased mobility, the environment generally imposes a more restrictive and tougher requirement for a display. Among those listed in Table 1.1, we believe illumination range, power, handheld form factor, and a combination of these pose the most challenges for a mobile display. An ideal mobile display should render vivid color and be fully readable from pitch dark to direct sunlight, consume a tiny fraction of energy from a portable power source, and provide large image size and resolution similar to an office display, while still maintaining handheld form factor.

Human factors play a major role in how we see information on a display, since image quality is highly dependent on the viewing environment and context, more so for a display on a mobile device due to the widely varying viewing conditions. Related to this, Larimer details the major issues that impact the visibility of images reconstructed on a mobile display in Chapter 2. In the following section, we will discuss how environment impacts on display requirements and the related visual performance issues. As by far the largest market segment for mobile displays belongs to personal mobile communication terminals, we will mostly focus our discussion on the personal mobile communication display.

1.3.1 Illumination Considerations

The first major environmental difference between mobile and office/home environments is in ambient illumination. This difference has multiple aspects that include illumination level, illumination source, viewing angle with respect to illumination, and surroundings. Figure 1.5, below, illustrates measured surface luminance, measured using a white reflectance standard, at various locations where a typical consumer uses or desires to use a mobile device such as a mobile phone or a laptop computer [3]. Here we have used luminance instead of the conventional illuminance as the measure of display brightness, since for a mobile display, especially a reflective display, the perceived image is more influenced and related to the comparison with nearby surfaces. With the same illumination source at a fixed intensity, depending on the surface the display is being viewed on, one might perceive it differently. The mobile illumination range is extremely large and is in excess of six orders of magnitude from dark night to bright outdoor conditions. In order to further illustrate this condition and its impact on display we also plot out, at each location, the calculated nominal value of the display surface reflection. They are indicated by the short columns in Figure 1.5, below. Even in cloudy day conditions – the third data

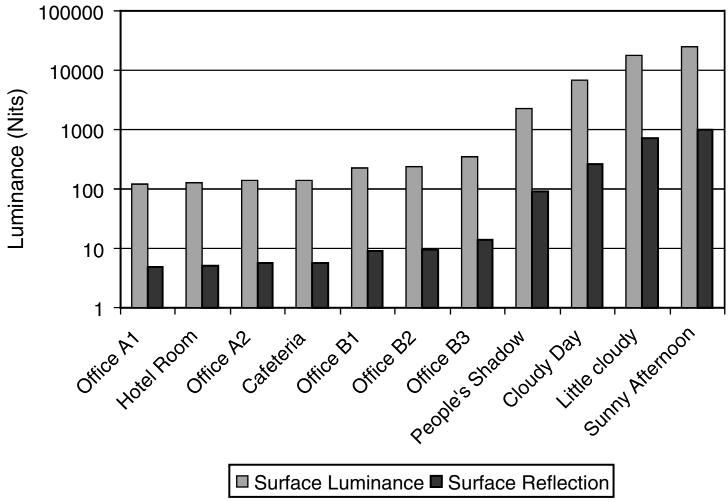

Figure 1.5 Surface luminance measured using a white reflectance standard and reflected. Luminance from the display at typical locations and conditions.

point from the right – there is significant surface reflection to cause substantial background luminance, enough to white out an intended image. For indoors, not only is the level of illumination much lower than outdoors, there is also little variation from location to location, in sharp contrast with outdoors. Finally, differently from an electronic book display, the mobile communication display mandates readability in low or zero ambient light condition. To that end, some form of auxiliary lighting is needed if the display in use is purely of reflective nature. This simple requirement can actually prevent certain display technologies, which otherwise could be very promising, from entering the mobile display market. For example, those displays that are purely targeting electronic book application need to find feasible lighting solutions before they become commercially viable for mobile communication and computing applications.

This large illumination range poses a huge challenge for any electronic display. Thus a mobile display, with limited power source to increase brightness of the device, needs special attention and a new set of solutions. In many cases, this may determine the viability of a display technology for its application in the mobile application space.

In addition to illuminance level or intensity, we also need to pay attention to other differences in illumination, again particularly between indoor and outdoor lightings. These differences include illumination pattern or profiles, spectrum distribution or color temperature of the light sources, and angle dependence between display and light source.

Figure 1.6 shows the measured surface luminance at a typical indoor lighting condition and how it compares with a typical point source illumination condition. The latter is very similar to outdoor conditions under bright sun. This data depicts that outdoor conditions can very closely resemble a point source illumination in a sunny day, while a typical indoor lighting is much more diffused in nature. Substantial illumination still remains when a display surface is turned away 90 degrees from its maximum which is directed toward the normal of the display. In other words, a display in the indoor conditions receives more portions of total ambient illumination at large angles than in the case of an outdoor illumination. This arises from multiple light sources and confined space in the indoor condition. Moreover, these multiple sources might have different characteristics in their spectrum distribution, irradiation profile, among other things. These considerations are particularly important when designing a reflective type display which, as will be discussed later, depends on effective

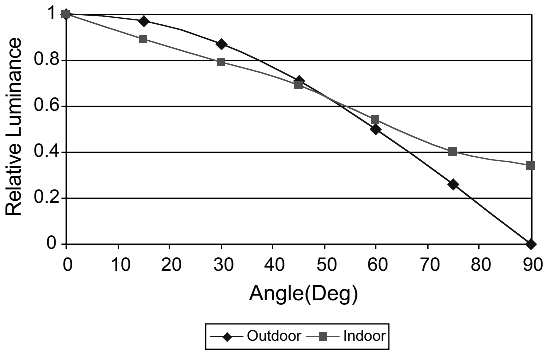

Figure 1.6 Relative illuminance as a function of the viewing angle in outdoor and indoor conditions.

collection and redistribution of ambient light. The source color temperature is another consideration, especially for color rendering and color fidelity.

1.3.2 System Power Considerations

Mobile devices are all battery operated and this imposes paramount limitation on power consumption for the display in use. Fundamentally different from non-communication types of handheld devices such as a pocket calculator or a Personal Digital Assistant (PDA), the communication device calls for a special power budget for the display. The reason resides in its intrinsic architectural complexity. Take the mobile communication device as an example; Figure 1.7 represents a simplified mobile communication terminal architecture diagram. There are multiple major high power components to share the energy provided by a battery. Among these, the base band processor, RF transceiver and associated components, and power amplifier for the RF transceiver are particularly high power consuming components.

When considering the power issue in this context, we ought to have in mind the total energy. It is the total energy capacity that limits power/energy budget for individual components like the display and the power amplifier. The Li^+ battery has become the only energy source for today's mobile devices. A battery is rated for its total energy capacity in mAh; a typical cell phone battery has a capacity in the range of 500–1500 mAh. One of the major attributes of a Li^+ battery is its suitability for high peak-power applications. Early displays on the mobile devices were all monochrome and reflective with

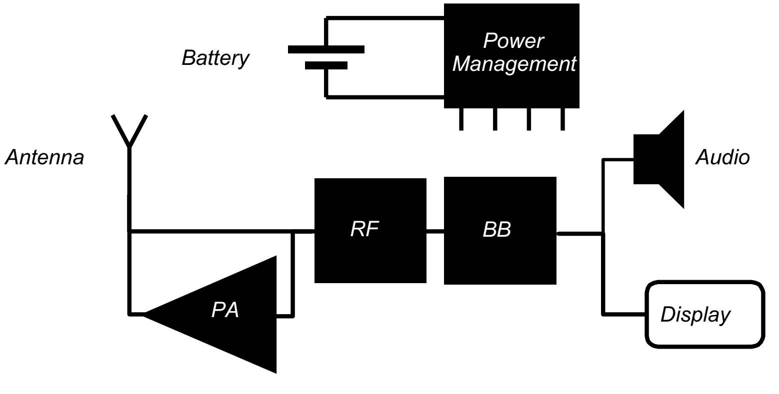

Figure 1.7 Simplified mobile communication terminal architecture diagram. PA: Power Amplifier, RF: Radio Frequency Components, BB: Baseband Processor.

limited resolution, and as a result, the energy impact on the mobile device was small. As we move through from early analog devices to today's digital devices in the form of 2G and 3G mobile terminals, we see a reversal in energy considerations for the display power budget. This reversal in power demand is the result of several factors. From the source side, the commercial release of Li^+ batteries provided a large jump in the power density and peak power handling capability compared to the early battery technologies. The past decade has seen a steady increase in the power density from the Li^+ battery, however, this improvement is limited to a few per cent annually. Without a breakthrough in new energy source materials or chemistry, we would not expect a major leap in the power density. Moreover, as explained earlier, rapid miniaturization has drastically reduced the dimensions of all major components to enable much thinner design and slick form factors for mobile devices. This puts pressure on device designers to use a smaller battery in order to maintain the required form factor. These trends have limited the available energy on the source side. Meanwhile, on the demand side, the opposite situation applies. Increased wireless bandwidth enables more applications and mobile communication devices to become more complex with more processing power and more memory needed to be able to handle these added applications. Many of the new components are power hungry and are not depicted in Figure 1.7. The wide adaptation of cameras in cell phones is just one of many examples of added components. Along with the camera, it creates a need for a large amount of digital storage and processing, both of which need a power budget out of the total energy capacity. In addition, other new functionalities for example, near-range communication links such as Bluetooth, GPS, and others require multiple radio frequency components. All these compete for the fixed amount of available energy. With these new applications, a monochrome low-resolution display is replaced by a high-resolution color display that needs more power to operate. Even with a reflective liquid crystal display, which is by far the most power efficient, at least an order of magnitude increase in power consumption has been required compared with early displays. To further compound this energy shortage problem, average use duration for mobile devices has been steadily increasing as well, due to these new applications and functionalities. People use their phone for calling, playing games, sending/receiving messages, playing music as a MP3 player, and more. The combined effect of more power consumption from added hardware and extended usage has caused the rate of power consumption to outpace the limited improvement in battery power density. As a result, device designers are increasingly forced to impose a much more restricted power budget on the display subsystem.

Figure 1.8 shows a generic energy model depicting the relationship of display energy consumption as a function of the display resolution for different display technologies. In the model, we used representative data for the battery and for display power consumption. A battery capacity of 10,000 Joule is assumed. Power consumption data of different types of displays are based on popular LCDs and taken from published data from Society for Information Display publications [4]. We assume eight hours on-time for the display and this is also the time duration between two successive chargings of the battery of the device. Armed with this information, Figure 1.7 plots the energy consumption by the

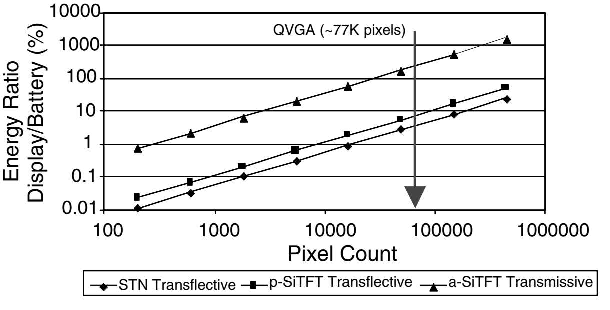

Figure 1.8 Ratio of the energy consumption of the display alone over the total battery capacity as a function of the display resolution. Assumptions: battery capacity = 10,000 J, display on-time = 8 hours.

display as a percentage of the total battery capacity versus display resolution [3]. This model yields many insights into the power management considerations when choosing a display technology for a mobile device.

At very low resolution, as was the case for early displays, power consumption was not a cause for concern regardless of the display technology in use. The very first mobile phone had a one-line electroluminescent display which was known for its high power consumption due to its emissive nature. As we move to higher resolution, say 170 × 120 pixels, and color which, in most liquid crystal displays, has three times more pixel count than a monochrome counterpart, a transmissive type display could easily exceed 10% of the total energy budget. As will be discussed in Section 1.3.3 the Resolution Considerations section, we see display resolution increasing to QVGA (320 × 240) and beyond. With such resolution, to maintain a manageable power budget for the display, we are left with only reflective or transflective options if a liquid crystal display is used. The high power consumption of a transmissive display is primarily due to the backlight. With rapid advancement in solid state lighting, we expect transmissive display power to continue to decline. With certain phone form factor design or clever use of case manipulation, moderate power drain from a transmissive LCD is expected in the future.

In mobile computers, the display subsystem poses a significant power consumption issue as well. Figure 1.9 shows the breakdown of average power consumption of a typical main-stream notebook computer by each major component. A mainstream notebook computer includes a 14.1″–15.4″ diagonal size transmissive LCD panel of WXGA resolution, which consumes as much as 30–50% of the overall system average power depending on the brightness setting, thereby significantly limiting the battery life. The largest power consuming component within the notebook LCD panel is the backlight. For example, the backlight of a typical notebook LCD panel accounts for as much as ~80% of the total panel power consumption at 200 cd/m^2 brightness, and ~67% at 60 cd/m^2 brightness, while the rest of the display power consumption is due to the panel electronics. This has prompted the development of system-level display power and performance optimization techniques integrated in the notebook graphics chipsets, such as dynamic backlight modulation and image enhancement, dynamic content and power-policy dependent display refresh rate management, etc., besides the more traditional approaches to achieve display module-level power reduction by incorporating higher-efficiency optical components [5].

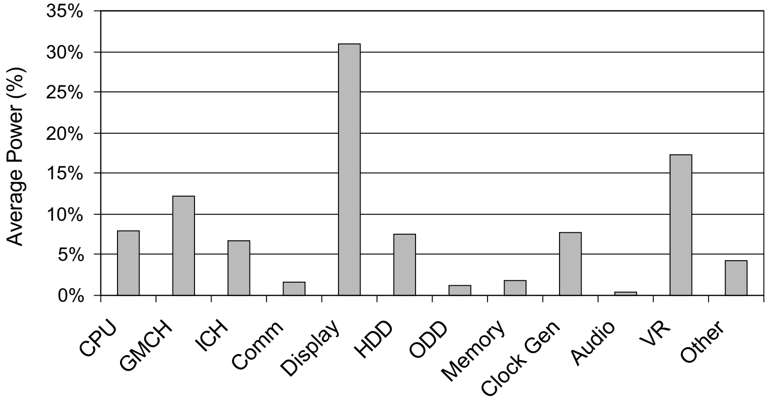

Figure 1.9 Average power consumption breakdown for a typical lightweight notebook. Computer consisting of a 14.1″ WXGA display. CPU: Central Processing Unit, GMCH: Graphics and Memory Control Hub, ICH: Input and Output Control Hub, Comm: Communication Components, HDD: Hard Disk Drive, ODD: Optical Disk Drive, VR: Voltage Regulators.

1.3.3 Display Resolution Considerations

The data shown in Figure 1.8 raise an important display resolution issue for mobile device as resolution significantly impacts the display power consumption. In this section, we will discuss another aspect of resolution of mobile displays, namely, the resolution limitation imposed by the intrinsically small display dimension of a handheld display. It is well known that the human vision system has finite angular resolution. Typically, one arc minute resolution is assumed. The accommodation limit of our vision system is about 25 cm while the comfortable reading distance is around 40–50 cm. These conditions impose a pixel density limit on an electronic display. For a small mobile display, the situation is far different from a desktop monitor in terms of reaching the resolution limit of the human eye.

Let's illustrate this with an example of a 3.5 square inch display, which by mobile display standards is a fairly large display. We can easily calculate that the eye resolution limit corresponds to 0.16 mega pixels at 40 cm distance or 0.40 mega pixels at the accommodation limit. Since most displays on mobile handsets are smaller than this, these pixel counts are already at the higher end of what can be resolved. Also, these numbers of pixels are what we can effectively resolve under ideal lighting conditions. As discussed earlier, the mobile lighting environment is far from ideal, and we expect an average user to start to reach the eye resolution limit at lower pixel counts than those stated above. Now looking at the display side, at half VGA resolution, a display already has 0.20 mega pixels. This indicates that we are already pushing eye resolution to its limits with this large a display on a mobile device. One can do the same calculation for the case of a desktop monitor to show that the reverse is true. A 16″ diagonal display requires more than 5 mega pixels to reach the eye resolution limits. An ultra high resolution display (e.g. WUXGA at 1920×1200) only offers slightly more than 2 mega pixels. Thus, for a desktop monitor, there is a long way to go before reaching the eye resolution limit. The single factor that makes this difference is the large display size disparity between a mobile display and a desktop monitor. So a further increase in the pixel resolution of a mobile display will bring no actual visual benefit while creating substantial power constraints on the power budget.

The technological advances in mobile display technology during the past decade have been primarily focused on addressing the first two constraints imposed by the mobile environment associated with high personal mobility: the huge illumination range and limited power availability with ever increasing power demand. Rapid progress on both fronts has been achieved and nowadays display performance on mobile devices has met end-user expectations for supporting applications with some exceptions. With the accomplishments on these fronts and a flood of new applications that call for high information content, i.e. more resolution, a shift in research effort towards addressing the resolution considerations has been observed in the last few years.

1.4 Current Mobile Display Technologies

1.4.1 Overview

The dominant technology for mobile displays is currently the color TFT AMLCD. In addition to many other benefits that the LCD provides, its inherent ability to adopt reflective, transflective, and transmissive device configurations, as described in the next section, makes it uniquely suitable for mobile applications. The liquid crystal layer in a LCD, in conjunction with the polarizers, serves as an optical shutter to modulate the light intensity created from a separate light source. Liquid crystals respond to very low voltages, a few volts in most cases, and require sub-micro Ampère current to switch, thus enabling very low power devices, consuming a fraction of a micro-watt per pixel. A liquid crystal device can be illuminated from either the front or the back to form an image.

Mobile displays started to migrate to color versions early 2000 and the adoption rate has been accelerating ever since. By 2002–2003, color displays overtook their monochrome counterpart to become the overwhelming majority display choice. These days nearly all mobile devices are shipped with color displays. Color performance in terms of saturation has made major strides at the same time. The early color displays had rather limited color saturation – color gamuts below 20% of the NTSC color space were common. With the technological progress discussed throughout this book along with the wide adoption of AMLCD displays, the norm is currently well over 40% of NTSC.

Although the early versions of color mobile displays used passive matrix super-twisted nematic (STN) liquid crystal displays due to their low power and low cost, their performance lagged behind that of active matrix liquid crystal displays using direct drive liquid crystal effects such as twisted nematic (TN), particularly in terms of video and color performance. With new applications increasingly calling for higher display performance, major improvements have been made in power consumption, electrical connection and mechanical packaging, as well as in the visual performance of active matrix devices.

There are two active matrix technologies available in the market today, based on amorphous silicon (a-Si) and poly-crystalline silicon (p-Si) backplanes. The a-Si based thin-film transistor (TFT) was the first active matrix technology introduced to mobile displays and it provided better video and color performance than STN. The p-Si technology was introduced to provide increased resolution, a thinner package, simple connection to display drivers, and improvement in luminance. These benefits from p-Si are, by and large, due to the much higher electron mobility of p-Si over a-Si.

More recently, even higher performance active-matrix backplane technologies have been introduced, targeting single crystal silicon performance for high level integration. All these are driven by unique mobile display requirements: high compactness, high mechanical integrity, and high visual performance. Higher cost has been an issue for the active matrix, especially for the p-Si version. As the cost differential between a passive matrix and active matrix has diminished in recent years, the better performance provided by TFTs has become very attractive and the active matrix is going mainstream. With the active matrix replacing the passive matrix, the mobile entertainment era is finally here, enabling exciting new applications such as mobile TV, mobile on-line gaming, just to name two. Chapters 3 and 4 provide detailed discussion on important advances and trends related to color AMLCDs devices.

1.4.2 Operational Modes of LCDs

As mentioned earlier, one of the major advantages of LCDs are their flexibility in the way they manipulate light. An LCD can employ three distinct operating methods to utilize light, namely reflective, transflective, and transmissive modes (see Figure 1.10, below). As the backlight module often accounts for over half of the total power consumption for a typical transmissive liquid crystal display used in a mobile device, the reflective design is used when maximum power savings are required. It uses only ambient light to provide illumination for the display. This approach was popular for early displays when only simple segmented and monochrome displays were required. As it has no

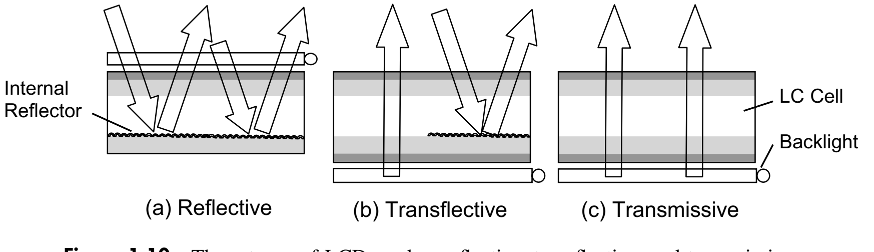

Figure 1.10 Three types of LCD modes: reflective, transflective, and transmissive.

backlight, its cost is also reduced. However, as visual applications become more complex with new network and mobile device capabilities, these new application trends drove the introduction of color displays for mobile terminals. The requirement for color brought performance issues with reflective designs. As all mature LCD technologies use a direct drive effect, such as the twisted nematic mode, with an active matrix backplane, or a multiplexed passive matrix drive for super-twisted nematic liquid crystal configurations, in which a polarization effect from the liquid crystal layer is employed to control the intensity, only one polarization state of ambient light can be utilized to form the image. To achieve color, a spatial color filter is added as the most reliable technique to synthesize color. The color filter is highly absorbing with an insertion loss for unpolarised light in excess of 60%. The combined loss from polarizer and color filter results in a very dim display under most lighting conditions except good outdoor lighting. To create saturated colors for a reflective LCD in low light conditions, a front light is often required. Extensive research and development into front lighting technology yielded very limited success. One challenge is how to create very efficient light coupling from the light source to the LCD while maintaining a light guide free of visual artifacts, because a viewer needs to look through the front light guide to see the displayed image. This requires tough trade-offs in thickness, shape and other parameters. After trials over several years, the industry appears to have come to a halt on the front lighting approach. In addition, the display in many of the modern mobile devices also serves a dual role as the input device, so often also functions as a touch panel. The front light and touch panel combination further worsens visual usability. Without a good solution to embrace color displays, reflective displays, although the most power-efficient, ceased to be used soon after mobile displays switched to color in early 2000.

To meet both power and lighting requirements, in some designs a compromise is to use a transflective configuration. As many of the current mobile displays use transflective LCDs, Chapter 5 focuses on the fundamentals of transflective display. Early versions of this configuration used a semi-transparent reflector and the ratio between transmittance and reflectance was tailored to optimize either the transmissive or reflective mode. New versions of the transflective LCD use a different approach by physically dividing a single pixel into two regions: one part for the transmissive mode and the other part for the reflective mode, as depicted in Figure 1.10(b). The transmissive region has no reflector and provides an opening for the backlight to pass through. On the other hand, at the reflective region, a reflector is built in to reflect incident ambient light. Again the ratio between the transmissive and reflective areas can be controlled to emphasise reflective for 'outdoor conditions' or transmissive for 'indoor conditions'. The flexibility in tuning the ratio between transmissive and reflective provides a good compromise and trade-off to handle power saving and offer readability in all lighting conditions. It meets both requirements reasonably well and thus has become a dominant display technology for mobile devices in the past decade. Early on, the transmission to reflection ratio was about 30:70, which is primarily for reflective mode usage because of its power saving, and then 50:50 became quite popular to balance more towards transmissive. Recently, this ratio has been reversed to around 70:30, which with good improvement in lighting control and material technologies, offers an even better balance between indoor and outdoor conditions. As discussed below, a trend to shift to even more transmissive seems to be taking place due to the rapid progress in LED efficiency and light collection technology.

Lighting the display from the back side, away from the viewer, like a laptop, a transmissive display can provide performance that is close to that of a desktop monitor. It has superior performance over the reflective design in most indoor and outdoor lighting conditions except for the brightest outdoor conditions. However, the always-on backlight can impose severe power requirements on the battery. Using the generic model example in Figure 1.8, at a moderate pixel count, say 1/8 of VGA, the display energy consumption already approaches 10% or more of the total battery capacity. On the other hand, at the same pixel count, a reflective display requires less than 1% of the total battery capacity. In addition to the high power consumption, the transmissive display also suffers from poor outdoor viewability. Without meeting both power and lighting requirements, the transmissive approach had found limited usage for mobile handsets in the past. However, the last few years have seen a new trend towards more transmissive designs due to the advances in power reduction from improvements in backlighting technology. On the application side, there has been re-thinking on the sunlight readability problem as it may not be as important as good indoor performance since mobile devices are increasingly being used indoors more often than outdoors. This has prompted more transmissive designs. Also, today's transmissive LCD power consumption has been reduced to a point that a designer is willing to trade off some of its power budget for its superior visual performance.

1.4.3 Viewing Angle and Illumination of AMLCDs

As a result of the advancements in light control, dual-cell gap design, improved color filter technologies, and better backlighting among many other innovations, the luminance level of mobile displays has made a major breakthrough. Within a few years, it is anticipated that the luminance, color saturation, and contrast of a mobile communication device like a cell phone will approach that of a mobile computing device like a laptop for most lighting conditions.

One important advance for mobile display is in light control and manipulation [6]. This is based on the consideration that a mobile device such as a cellular phone is largely a personal device that is primarily intended for a single user and the need for sharing its display content is a secondary consideration. Taking advantage of this, the most efficient approach to channel the limited illumination energy, either from the ambient or its own light source, into a desired view cone for the user is determined in order to maximize the perceived brightness, color and contrast among other parameters. In doing so, we also end up with power saving benefits as less power is needed from the backlight to achieve the same level of visual performance. To achieve this objective, the light control technique needs to accomplish three tasks. First, it needs to collect the maximum amount of incoming illumination and concentrate it into a pre-defined viewing cone. This viewing cone is designed for the best viewing experience by the device user primarily by enhancing the perceived brightness of the display. Second, it needs to steer the light in this narrow viewing cone away from the glare angle of a display surface. This is primarily for contrast enhancement as undesirable glare provides a background illumination which reduces the contrast (see Figure 1.3). Third, the light control needs to create a large degree of diffusion within this viewing cone to mimic a Gaussian distribution. This property is highly desirable in order to eliminate angular dependence of the display performance within the pre-defined view cone and provide a good viewing experience.

For reflected light, one has the option to control the light either on its way into the display or on its way out of the display. In some instances, a combination of both could be used. Figure 1.11, below, illustrates the concept of light control. For a monochrome display, to meet these three requirements is relatively easy. One widely used technology is to use a thin optical film. The film is in general attached after the display is fabricated by a separate process step. Often this requires an approach that controls the reflected light on its way out of the display by attaching the film onto the lower substrate. In early implementations, the film was used to replace the conventional metallic reflector to serve as a modified reflector. For example, a holographic reflector has been shown to be very effective in meeting these requirements for a reflective display. Both contrast and luminance have been increased multiple times within the pre-defined viewing cone. By incorporating diffusion into the hologram by diffused exposure during the hologram creation process, it can also result in less angular dependence of the display viewing experience. Similar to the reasoning of a backlight being preferred to a front light as discussed earlier, another benefit from controlling the reflected light is the reduced sensitivity to visual artifacts, as the polarizer and other layers are quite effective in shielding undesirable artifacts from a typical backlight.

As the display on the mobile device migrates to color, the optical film approach becomes less effective than for a monochrome display. One challenge is the parallax that results in reduced reflectivity and color cross-talk. In a typical color display, each color pixel is made of three sub-pixels of primary colors. Color filters with red, green, and blue transmission spectrum are used to create each primary color through a planar and triad arrangement. With this arrangement, a sub-pixel is three times

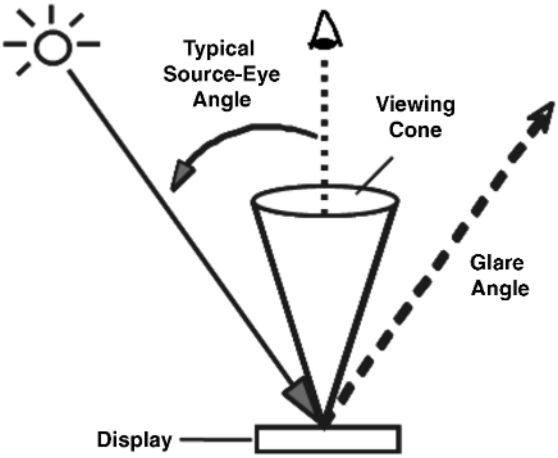

Figure 1.11 Concept of light control for reflective display.

smaller than a single monochrome pixel. The off-normal reflected light from an optical film affixed externally to the substrate partially impinges upon the adjacent color filters. A typical glass substrate used in the mobile display is about 0.7 mm in thickness and the sub-pixel dimension is a small fraction of the substrate glass thickness. Thus light rays at slight off-normal angles would cause parallax. For mobile applications, the display is often illuminated over a large angle range and this worsens the parallax problem to a point that is no longer acceptable to the viewer.

Although theoretically the front film approach could solve this problem, it demands a much tighter control of the film quality in terms of clarity and defect-free performance. An attempt has been made to move the film from the outside of the substrate to inside the liquid crystal cell but this has had limited success. With advanced photolithographic techniques, a method of building a reflector with micro-structures on the inner surface of a substrate has proven to be effective in reducing parallax. The resulting structure is also able to incorporate all three functions onto this single internal reflector. This improvement enables much improved luminance and color saturation for reflective or transflective displays. As the display goes to higher resolution, this internal structure will be critical in achieving the required performance.

Chapter 6 provides insight into the physics governing the viewing angle properties of LCD devices, and the fundamentals of backlighting technology. In Chapter 7, Watson *et al*. describe the details of product implementation aspects of the backlight structure and brightness enhancing technologies. While the illumination source for LCDs has predominantly been the cold cathode fluorescent lamp (CCFL), the increasingly popular LED provides important benefits in power, color, and form factors, which are discussed in Chapter 8.

1.4.4 Display Driving Electronics

There are several technical advances that have resulted in major improvements in mobile display visual performance while maintaining or improving its power performance. One of these areas is the electrical circuitry or driving electronics for small displays. As discussed earlier, the actual panel power consumption is only a small fraction of the final display module power for mainstay LCD technology based on the TN or STN mode liquid crystals. To reduce the system power, much research and development has gone into optimizing how the display is driven electronically. In addition, as data rates increase, enabled by higher bandwidth networks, how to effectively channel this large amount of image data becomes critical. Chapters 9, 10, and 11 provide broad and in-depth discussions on the issues and trends regarding mobile display driving electronics and interfaces. Clearly, increasing the data channel capacity is one way to accommodate increasing resolution, but another approach is to explore alternative sub-pixel layout schemes with considerations of the human visual system. Sub-pixel rendering is a technology that enables perceived high display resolution at comparatively low pixel counts on the display panel. In Chapter 12, Elliot describes both the theoretical and practical aspects of this technology along with recent applications and future trends.

1.5 Emerging Mobile Display Technologies

Among display technologies, the mobile display has probably been the most dynamic in its technological progress over the past decade. In the direct view display category, the technological advancement, in conjunction with established display manufacturing infrastructure of the passive STN and active matrix TN TFT, has proven to be a formidable barrier for new display technologies. However, much research and development investment has been devoted to create a vast number of new display mechanisms ranging from different liquid crystal modes for bi-stable operation to more exotic device architectures such as rotating micro-spheres with each semi-sphere coated with different colors/shade. Several promising contenders are moving out of research labs and into production. As an overview, we have chosen a promising subset from this plethora of emerging technologies for inclusion in this book. One of the major considerations in selecting a topic for detailed analysis for this book has been based on the assessment of its maturity and its broad impact on meeting the challenging mobile application requirements set forth earlier in this chapter. In this section we provide a brief overview and discuss the challenges facing several emerging technologies that have developed paths to commercialization. These topics are followed up with detailed discussion in the subsequent dedicated chapters.

1.5.1 System-on-Glass Technologies

The tough mobile requirements such as power, lighting, compact form factor, size limitation for resolution are increasing, and extreme cost-sensitivity calls for unique system-level solutions. One approach is to integrate more functionality onto the panel itself. With the traditional a-Si backplane technology this is difficult to achieve due to the low performance of a-Si circuitry in terms of electron mobility, among many other low performance transistor parameters. With the introduction of p-Si backplane technology, integration of many circuits, such as column or row drivers, becomes feasible. Limited by equipment and defect issues, large size p-Si panels are still difficult to fabricate at a low cost, but the small size of mobile displays makes them a very attractive application for this technology and also makes economic sense. Moving beyond p-Si, several performance-enhancement technologies are also moving out of research labs around the world into a commercial phase, which enables even higher levels of integration to build multiple functionalities into a single device or to explore dual functionality for a single component through system integration. Such attempts recently have resulted in integrated display and image reader combinations, display and touch panel combinations, display and speaker combinations, and display and energy harvesting device integration, etc. Chapter 13 details some of the notable technological advancements that use this integration approach.

When considering what functionality should be integrated onto a display panel, one needs to carefully evaluate its trade-offs. Some important guidelines need to be established and functionality priority should be considered with intended-use cases and applications in mind. One must keep in mind that the ultimate priority should be given to the display function and the resulting device ought to maintain at least the same level of visual performance as a standalone unit. Further illustrating this with an example, we consider the approach of integrating a solar panel into a display panel for energy harvesting in an attempt to address the power constraints imposed by the limited battery power capacity of a mobile device.

The concept of using a solar panel to power small electronic devices has been successfully used in many applications. The solar powered calculator is a good example. However, powering a mobile communication device such as a cell phone is quite different from powering a calculator in many respects. Even in its standby operation, a typical cell phone requires from a few to more than ten milliwatts (mW) of power compared to a fraction of a mW for a calculator. Moreover, the standby state of a mobile phone runs at 100% duty cycle for communication needs. Solar power generation is proportional to the solar panel dimension or surface area. Surface area on a mobile communication device is at much more of a premium than on a calculator as there are other user interface components such as the keypad competing for the surface area. This renders mounting a solar panel side-by-side on the display – as is done on a solar powered calculator – impractical for a mobile device.

To overcome this, a new approach was proposed: to put a solar panel behind the display, taking advantage of the display size increase trend [7]. A conventional reflective display is virtually non-transparent as it contains many light absorption layers such as the polarizer and the reflector. For a reflective display, the reflector is the highest light blocking element among all the layers. Overall, a reflective LCD may transmit less than 5% of the incoming light over the entire solar spectrum. As only the irradiation within relatively narrow bands of three primary colors are needed for visual perception, a method was devised to selectively control the reflected wavelength for image formation while maximizing the transmission of all other wavelengths. Then, a photon-electron converting device, such as a solar panel, can be placed behind the display for power generation. This approach has been demonstrated using a conventional monochrome STN liquid crystal display, where a conventional metallic reflector was replaced with a green holographic reflector. Optical modeling and optimization, taking into account the spectrum responses of all layers and the solar panel, show that the majority of the incoming light, $\sim$60%, can pass through to reach the solar panel. A prototype was built to verify the theoretical modeling, and power measurement with simulated solar irradiation was carried out. Figure 1.12, below, shows the measured results with a green reflector as a function of the solar irradiation level. As a reference, the bare solar panel power collection was also measured and approximately 60% reception was verified. With such large throughput, outdoor lighting conditions can generate substantial power per unit display area to maintain stand-by power usage. With typical indoor lighting, however, the resulting power collection is too small to be useful for power budget purposes. These characteristics point to a highly use-dependent scenario with this technology. One good application could be for emergency use to charge a dead battery. A mobile phone with a small display of 1 square inch has been demonstrated to show that with a dead battery, enough energy can be generated in sunlight conditions through three minutes' irradiation to allow the user to make a short duration – 30 seconds to 1 minute – phone call. As the mobile display size keeps increasing, more power will become available with this approach. With color displays becoming the mainstream display option, the available light for collection will decrease accordingly. However, with a broad spectrum source, there is still much energy that can be extracted outside and between the red green and blue filter spectral bands.

1.5.2 Organic Light-Emitting Diode (OLED) Displays

There has been much activity in the research and development of OLED technology in recent decades and much progress has been made in material properties, device architecture, and manufacturing technologies. OLED provides a set of attractive attributes for use as a mobile display. It has vivid color with a

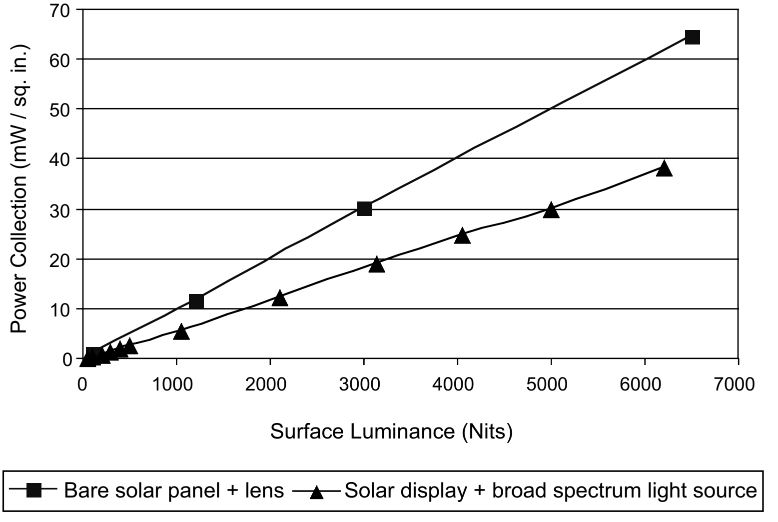

Figure 1.12 Power collection versus solar illumination with a monochrome solar display.

Lambertian emitting profile that is very easy on the eye. If used indoors, it offers excellent contrast and vivid color. Unlike liquid crystal displays which are voltage driven, an OLED is a current-driven device. More importantly, its luminance is extremely linear with drive-current. This characteristic makes it easier to control gray levels and enables a much more detailed rendering of color images. It has a very fast response time, making it a perfect video display. Mechanically, OLED offers a thinner and simpler structure without the need for a backlight, enabling a thinner display module than a comparable LCD. An OLED display with less than 1 mm in thickness has been shown with high contrast and saturated colors. At the time of writing this book, active matrix OLED displays of up to 2.8″ diagonal have started shipping commercially.

While the OLED technology has very positive attributes as noted above, it also has some challenges to overcome in order to gain wide acceptance in the mobile display market. OLED is a Lambertian emitter and emits light into the full 4π solid angle. To increase the perceived luminance of an OLED display, the emitted light needs to be controlled and confined to only the upper hemisphere. To that end, the cathode in an OLED display often uses highly reflective metallic materials to redirect the downward irradiation to the upper hemisphere, after transmission through other transparent OLED material layers. As a result, ambient light is also reflected, thereby degrading contrast of the image. Another challenge is the sensitivity of the OLED materials to photon irradiation of shorter wavelengths, a photoluminescence effect, which creates secondary emission as a background when exposed to short wavelength irradiation. Under outdoor illumination, short wavelength irradiation at UV and blue wavelengths will excite the OLED material to emit in the visible range. Several remedies for this problem have been implemented with good visual improvement, for example, a circular polarizer to block the reflected ambient light. A 60% luminance penalty from the insertion loss of a circular polarizer is an issue which directly relates to the power consumption of an OLED. The power consumption of an OLED display depends on the number of 'ON' pixels and their gray-levels. If the primary use is to show photographs or video content, then the total power consumption can be lower than an equivalent transmissive LCD module. It is known that a typical picture is equivalent to about only a quarter of a total white field. Based on this, OLED power data are often quoted for a 25% white image. For applications that require whiter content screen, the power consumption estimate needs to be adjusted upward accordingly, and can reach comparatively high values. Another issue is the higher cost of OLED displays relative to the prevalent AMLCD displays at the current time. Intense effort is underway to improve these deficiencies as the mobile display provides the best market and opportunity for OLED to get a foothold given its attractive attributes discussed earlier. In Chapter 14, Tsai *et al.* provide a detailed account of the material, device, and driving scheme fundamentals as well as summarizing recent progress and future trends in this promising technology area.

1.5.3 Bistable Displays

One way to get around the stringent power requirements for mobile displays is to use a bistable display. The bistable display, as the name indicates, is a display that has two separated and energetically stable states. In order to switch from one state to another, an electrical voltage is required. In the absence of an applied voltage, the display will stay at either of these states. Bistability enables a display to maintain a static image without consuming power. In some cases, these states may not be absolute energy minimum states, and with time, could migrate to other states. However, for all intents and purposes, these devices can be treated as truly bistable for mobile applications. Examples include cholesteric, zenithal bistable, twist bistable, and surface stabilized ferrolectric liquid crystal displays, as well as electrochromic, electrophoretic, and MEMS displays. In these displays very different electro-optical effects have been explored to create visual images that are stable at zero power. The electrophoretic display, a well known electro-optical effect, has gained renewed interest during the last several years as its encapsulation technology matures. The commercial launch of Motofone from Motorola and E-reader from Sony, both using an Electrophoretic display, signals its entry, finally, into the mobile market place. Zehner covers this technology in Chapter 15, along with a detailed overview of the electronic paper displays in general. Yang and Angeles *et al.* cover liquid crystal based approaches in Chapter 16 and Chapter 17, respectively. While much progress has been made in these emerging technologies, the challenges facing these candidates remain for them to become the mainstay technology choice for mobile displays. One issue has to do with the required frame update rate. In a true bistable display, there is no power required to maintain a static image. However, in these devices, the power required to update an image can be higher than in the case of conventional LCDs. Another challenge for the bistable technologies is color generation. In some bistable devices continuous gray scale and non-monochome displays are difficult to achieve. In summary, bistable display technologies have great potential for new mobile display applications, but the gains resulting from their use depend on the particular application being considered.

1.5.4 Electrowetting Displays

The electrowetting display is an emerging technology targeted for use in mobile applications. Currently still in the early stages of development, this approach promises to deliver low power consumption and full-color video display capability in the future. Based on this technology, displays can be constructed in all optical modes in principle – transmissive, reflective and transflective – while the current implementation efforts are focused on low-power reflective structures that do not require a backlight. In Chapter 18, Feenstra discusses electrowetting display technology fundamentals, as well as its potential applications and advantages in future mobile devices.

1.5.5 Three-Dimensional (3D) Displays

Another area of emerging application interest for mobile display is the 3D display. While the current bandwidth of wireless devices and the lack of content have limited the application of this technology thus far, it continues to generate excitement for future applications. In Chapter 19, Travis describes the visual perception fundamentals of a 3D display and explains several enabling technologies for the 3D display system, emphasizing its application to the small display format.

1.5.6 Beyond Direct-View and Rigid Displays

As we have discussed, the pace of display resolution increase is accelerating and is outpacing the increase in size of mobile displays to meet increasing visual application demands. Early mobile displays used STN technology and typical pixel counts were of several thousands. Since then we have seen pixel count doubling every few years. Even at this fast pace, the resolution increase is still outpaced by even faster increases in the wireless network bandwidth besides the processing and memory capabilities of mobile devices. More importantly, as discussed earlier, resolution increase on a mobile display will reach a limit imposed by the small display size from a handheld form factor and the human vision resolution limit. This is the next technical frontier to challenge the mobile display industry. To meet these challenges, multiple approaches have been researched and explored. There are three general approaches to obtain a large image size without increasing the physical size of the display. These are eyewear or virtual displays, mobile projection displays, and flexible/foldable displays. These three categories of technology are comparatively immature compared to mainstream LCDs and the several emerging display technologies discussed earlier. Their immaturity not only reflects in the technology itself but also in many cases the applications that these devices are targeting. However, given the major trends and constraints discussed earlier, the need for enabling large images for a mobile device is truly fundamental and the associated challenges in technology and applications need to be met. After brief introduction of these technologies in this chapter, we have three chapters devoted to these topics in the last section of the book.

1.5.6.1 Eyewear Displays

As the name implies, an eyewear display uses optics to magnify the image from a microdisplay to form a much larger perceived image. The availability of high resolution micro-imagers from a variety of microdisplay technologies laid the foundation for this approach. The advances in micro-optical elements provided further paths to compact sizes. SVGA or higher resolution microdisplays with diagonal dimensions of less than 1 inch are commercially available. A major advantage of this approach is the relatively low power needed to create a large and bright virtual image. Chapter 20 provides a system-level analysis to help readers understand the issues and challenges in integrating the micro-imager, optics, and electronics into an ultra-compact form factor to meet consumer demands.

1.5.6.2 Mobile Projection Displays

To counter issues with a virtual display and meet the increasing demand for high resolution information, attempts to create an extremely compact projection display have picked up momentum in the last few years. Both micro-imager based and laser-scan based approaches have been explored and demonstrated. In addition to facing similar miniaturization challenges as a virtual display, from the illumination system to the projection optics, a micro-projection display needs to overcome another formidable barrier: large light output in terms of total lumens provided from a small device volume. Projection devices require increased power over eyewear devices due to the need to form a real image. Thus far, prototypes have been demonstrated with more than 10 lumen output, some using high power LEDs and others using lasers. However, they still require multiple watts of electrical power to operate and they have a system volume of several 10s–100 cubic centimeters, based on published reports.

Clearly, major improvements are needed at component and system integration levels before this new category of display can become widely adopted for mobile devices. However, there are many industry trends favoring the projector approach, primarily rapid progresses in LED efficacy, semiconductor lasers, micro-optical elements, and optical system integration. Chapter 21 provides in-depth analysis focusing on the laser scan approach. In the near future, the micro-imager based solutions are expected to become commercially available as they are based on relatively mature components and better-understood system operations.

1.5.6.3 Flexible/Rollable Displays

Flexible or rollable displays are generic terms used to describe displays that are not rigid. Early on, the display industry paid little attention to rigidity. Only very recently, driven by much larger differences in both technology and application among different flexible display configurations, the display industry has started to make clear distinctions. To provide a large image, scrollable or rollable flexible displays are needed. Rollable displays are being developed aggressively in both industry and government-funded research efforts.

Electrophoretic, electrochromic, cholesteric, and OLED displays are candidate technologies to enable a display that can be rolled or folded into a smaller form factor for storage and then extended when needed. In recent years we have seen substantial progress in this area, with the demonstration of rollable reflective black and white displays. Maturity of a rollable display is still at an early stage, and it remains to be seen whether it will meet the full set of tough mobile display requirements imposed by the mobile environment and the high-end performance expected from such displays. Substantial research and development as well as infrastructure building are needed. To enable a truly rollable display, the single most challenging and formidable task is to develop a rollable backplane technology. Much progress has been made in the flexible electronics as well as corresponding front plane display media [8]. Chapter 22 provides a review and an update on the organic transistor technology that enables circuitry for the flexible/rollable displays for the future mobile devices.

1.6 Summary

Mobile display applications have been one of the fastest growing segments among all display applications and we expect this trend will continue for the foreseeable future. Mobile display applications can be generally divided into two broad classes: mobile communication and mobile computing. Mobile communication has primarily been represented in the form of mobile phones or smart phones, while mobile computing has been carried out on the laptop or mobile computer. However, a new trend is forming to blend these applications and devices. Increasingly, we see mobile communication devices with more computing and large display capabilities, and mobile computing devices with communication link to broadband wireless networks and smaller form factor. No matter how these trends continue, these devices provide a fertile ground for new and emerging display technologies, that range from new types of LCDs to OLED to micro-projection displays, which will be discussed in detail in the rest of the book. As the nature of the mobile environment dictates, displays that are intended for mobile applications require a set of more stringent display performance requirements than their domestic counterpart display terminals. For the time being, AMLCD is still the dominant display technology choice due to its flexible device architectures and maturity. With time, a number of emerging technologies are expected to enter mobile applications, e.g. system-on-glass technologies, OLED, bistable display, electrowetting display, etc., to name a few. Another actively researched area is the beyond direct-view display technologies. Among these, the eyewear display needs to overcome human ergonomics constraints associated with a virtual display arrangement. Micro-projection and flexible displays are new frontiers in mobile display technology aimed at providing high display resolutions in a compact mobile form factor. The chapters in the rest of the book provide detailed analysis of the fundamental technologies, applications, recent progress, future trends and challenges in each of these areas.

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