Adaptive charge sharing method for liquid crystal displays with lower power consumption

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Abstract. This paper proposes an adaptive charge sharing (ACS) method for reducing power consumption in liquid crystal displays (LCDs). Our ACS method involves calculating the power consumption of all data lines assuming the charge is shared and analyzing the analog characteristics of the data transitions. With conventional CS, charge is shared between data lines only when the polarities of data signals change. Our ACS method selectively shares charge even when no polarity change occurs, but only if CS provides an overall reduction in power consumption. To compare the performance of ACS and conventional CS, we applied the ACS method to common inversion methods, namely, column, two-dot, and Z inversion. Our simulation results demonstrate that the ACS method can effectively reduce power consumption, especially with the column and Z inversion methods. The average power consumption of the ACS method with column and Z inversion was 87.7% and 84.7%, respectively, of the conventional CS power consumption. © *The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI.* [DOI: 10.1117/1.OE.54.5.053111]

1 Introduction

Power consumption in liquid crystal displays (LCDs) is currently the subject of intensive research.[1–7] To achieve lower power consumption with higher image quality in LCDs, various techniques have been studied, including backlight dimming technologies,[8–15] inversion methods,[16–18] and charge sharing (CS) methods.[19–25] Column inversion provides very low power consumption because only one polarity change occurs per frame. However, column inversion is susceptible to line flicker, which is particularly noticeable when a vertical line pattern is displayed.[26] Dot inversion is widely recognized as the best inversion method for achieving a higher image quality.[27] However, dot inversion increases power consumption because multiple polarity changes occur per frame.[28] In addition, dot inversion is susceptible to flicker patterns corresponding to the dot pattern.[28] To reduce power consumption and avoid the visual imperfections of dot inversion, Z inversion and two-dot inversion methods have been developed.[29,30] Figures 1(a) and 1(b) depict the pixel arrangements and driving schemes of the Z and two-dot inversion methods, respectively. In Z inversion, pixels are alternately connected to one data (column) line. Thus, with Z inversion, the spatial arrangement of polarities is the same as that of dot inversion, though the voltages applied to a data line are similar to those of column inversion, as shown in Fig. 1(a). In this way, Z inversion consumes lower power than dot inversion. With two-dot inversion, the polarities of the data lines are the same for two adjacent lines, as shown in Fig. 1(b). Consequently, the operating frequency of two-dot inversion is reduced by half compared to

dot inversion, and thus the power consumption is also reduced by half.

To further reduce power consumption in LCDs, the CS technique was developed. Conventional CS involves electrically connecting all data lines whenever polarity changes. Because the positive and negative voltages in data lines are alternately applied column by column and row by row in dot inversion, charge is transferred to the neighboring data lines while the data lines are electrically connected. Thus, the voltage levels of adjacent data lines become the average value of the previous voltages of these two data lines. Power consumption with dot inversion is ideally reduced by half. With column and Z inversion, however, some data lines do not experience a polarity change from one frame to the next. Thus, unnecessary CS may lead to an increase in power consumption when conventional CS is applied to column and Z inversion.

In this paper, we propose an adaptive charge sharing (ACS) method intended to reduce power consumption when two-dot, column, or Z inversion is used. The proposed method analyzes image data and determines whether or not to share charge. By considering the various types of analog data transitions, the ACS method selectively shares charge between data lines only when CS provides an overall reduction in power consumption. In Sec. 2, we review the basic principle of CS. In Sec. 3, we describe the ACS method. In Sec. 4, we present the results of applying our method via simulations. Finally, we summarize and conclude the paper in Sec. 5.

2 Basic Principle of Charge Sharing

Figure 2 depicts the analog voltage transitions of two adjacent data lines when CS occurs. The CS technique conserves energy by using the electric charge of data lines with higher potential to raise the voltages of the other data lines. The

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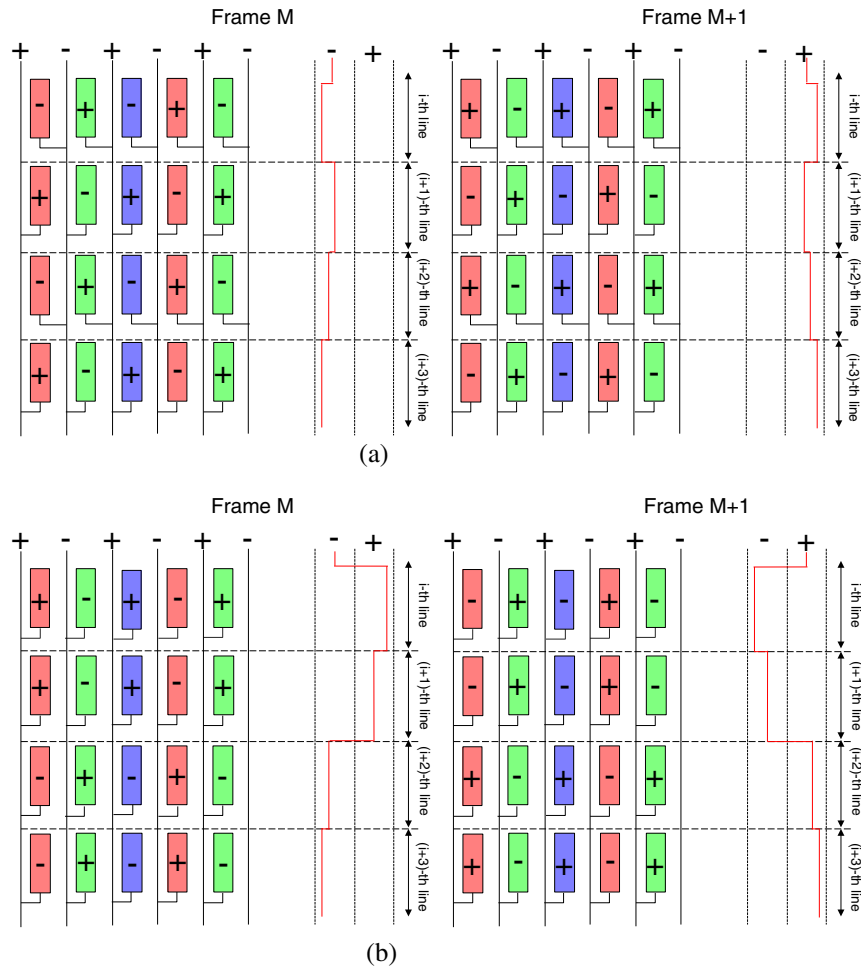
Fig. 1 Pixel arrangement and driving scheme of (a) the Z inversion method and (b) the two-dot inversion method.

electric charge is shared by electrically connecting the data lines. When data lines are tied together and are also disconnected from any active sources, electric charge drifts from data lines of higher potential to data lines of lower potential. The transferred charge raises the potential of these latter data lines using energy that would otherwise be lost. When CS
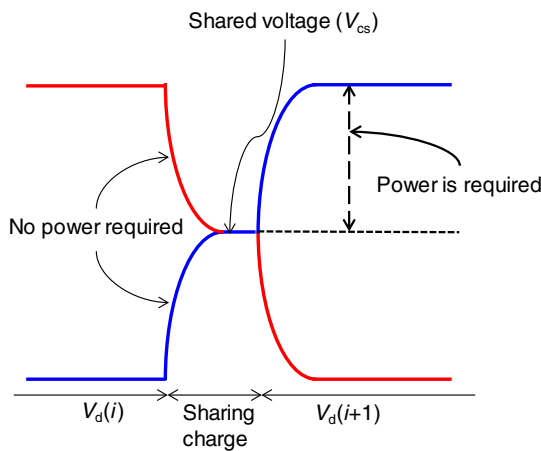

Fig. 2 Voltage waveforms of data lines when two data lines are electrically connected—that is, when charge sharing (CS) occurs.

occurs (see Fig. 2), all analog voltages at the i'th line time, $V_d(i)$, reach the shared voltage level V_{CS} without any additional power. Thus, power is consumed only when the analog voltage at the $(i+1)$'th line time, $V_d(i+1)$, is higher than V_{CS}. Therefore, the efficacy of CS depends on the distribution of the different types of analog voltage transitions among shared lines. Thus, it is necessary to carefully consider these analog voltage transitions. Figure 3 depicts four types of analog voltage transitions. Figure 3(a) and 3(b) represent the large voltage swings, that is, $|V_d(i+1) - V_d(i)| \gg 0$. Figures 3(c) and 3(d) represent the small voltage swings, that is, $V_d(i+1) \sim V_d(i)$. In the case of Fig. 3(a), power consumption is reduced by an amount proportional to $V_{CS} - V_d(i)$. The power consumption for Figs. 3(b) and 3(d) is zero because these transitions do not require any charge from the source drivers. In the case of Fig. 3(c), however, power consumption is increased by an amount proportional to $V_d(i+1) - V_{CS}$ as a result of unnecessary CS.

3 Adaptive Charge Sharing Method

To further reduce power consumption in LCDs driven by column, Z, and two-dot inversion techniques, we consider a situation in which data lines are connected for CS even when no polarity change occurs. Then we identify the number of beneficial [Fig. 3(a)] and detrimental [Fig. 3(c)] voltage
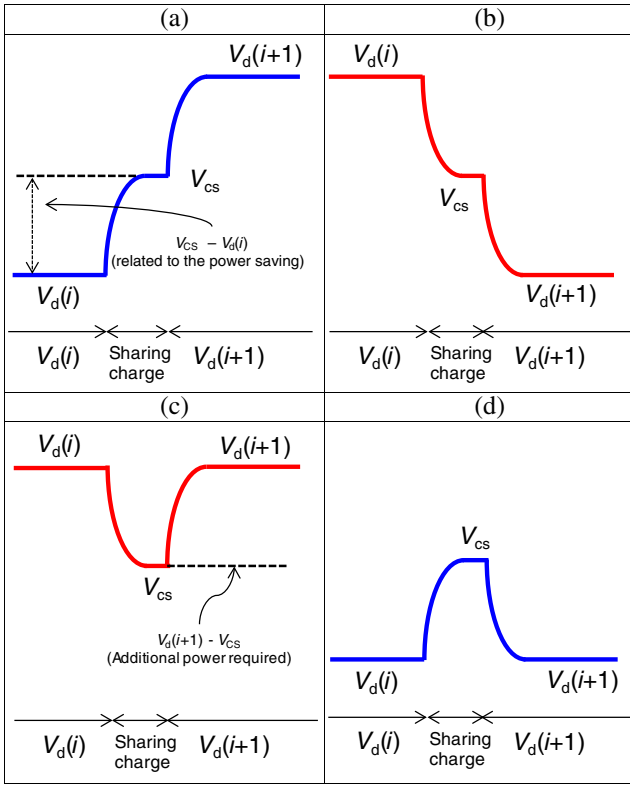
Fig. 3 Four types of analog signal transitions in relation to CS. (a) and (b) represent the large voltage changes $[|V_d(i+1) - V_d(i)| \gg 0]$; (c) and (d) represent the small voltage changes $[V_d(i+1) \sim V_d(i)]$.

transitions as N_i and M_i, respectively. Even if N_i is larger than M_i, this does not ensure that overall power consumption will be reduced because the amplitude of analog voltages influences power consumption more than the ratio of beneficial to detrimental transitions. The power savings can be calculated using Eq. (1), and the power wasted as a result of unnecessary CS can be calculated using Eq. (2). Thus, as shown in Eq. (3), the net power savings can be determined based on the values generated by Eqs. (1) and (2). When Eq. (3) >0, net power savings are achieved, thus CS is desirable

Power Savings

$$= \left\langle \sum_{i=1}^{1080} \{V_{CS} - V_d(i)\}^2 | V_{CS} > V_d(i) \ \& \ V_{CS} < V_d(i+1) \right\rangle,$$

$$(1)$$

$$\text{Power Wasted} = \left\langle \sum_{i=1}^{1080} \{V_d(i+1) - V_{CS}\}^2 | V_{CS} \right.$$

$$\left. < V_d(i) \ \& \ V_{CS} < V_d(i+1) \right\rangle, \qquad (2)$$

$$\text{Net Power Saving} = (1) - (2). \qquad (3)$$

Figure 4 presents a flowchart for determining when to share charge in the ACS method. First, the shared voltage V_{CS} should be calculated. To calculate V_{CS}, we need to analyze image data for two horizontal lines in advance. Thus,
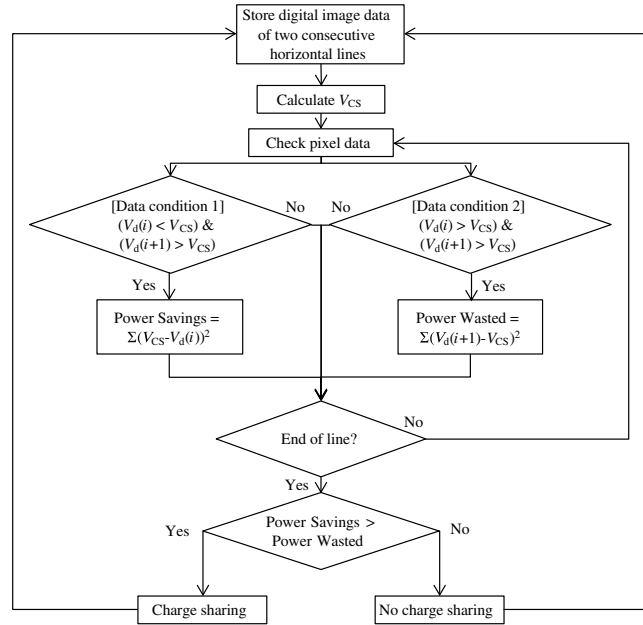

Fig. 4 Flowchart of the proposed adaptive charge sharing (ACS) method.

image data for two consecutive horizontal lines must be stored in memory. Second, data for every pixel are analyzed to determine whether the data transition corresponds to data condition 1 or 2. Here, conditions 1 and 2 correspond to Eqs. (1) and (2), respectively. Third, power savings and power wasted are calculated until the end of the i'th line time. Finally, CS is enabled if the power savings are greater than the power wasted. In this method, one horizontal line time is needed to store image data for the next horizontal line [the $(i + 1)$'th line], and one more line time is required to determine whether or not to share charge. Thus, the method involves a delay of two horizontal line times, corresponding to a delay of approximately $1/60 \ s \times 1/1080 \times 2 = 1/32,400 \ s = 31 \ \mu s$.
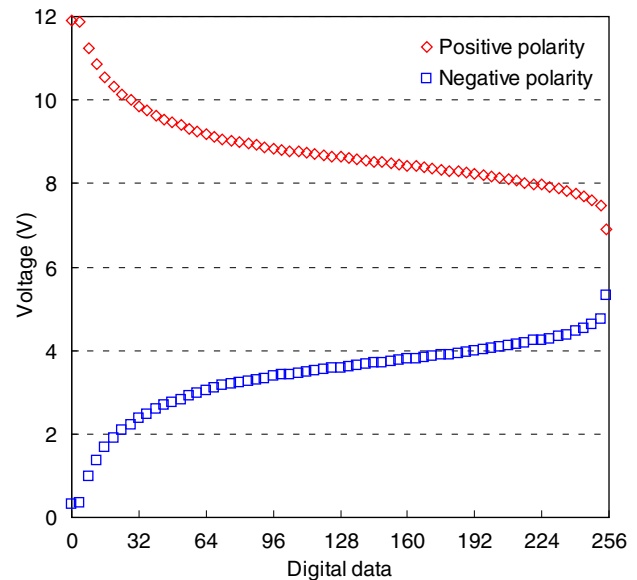

Fig. 5 Analog voltage versus digital data curve used in the power consumption simulations.

4 Results and Discussion

In order to verify the effectiveness of our ACS method, we designed MATLAB simulations to analyze the effects on power consumption when two-dot, column, and Z inversion methods are used. According to survey data, Internet browsing, productivity applications, e-mail, and instant messaging account for 76% of the usage of mobile devices, and these are all text based.[31] Thus, reducing power consumption for text-based applications is critical for extending battery life. We calculated the power consumption for 30 images, with 10 images per usage category (i.e., Internet, productivity, and e-mail). We also used images taken from the International Electrotechnical Commission (IEC) 62087 standard video clip. The running time of the IEC 62087 standard video clip with a 30 Hz refresh rate is 10 minutes. We sampled the video every 50 frames and thus acquired 360 images for our simulation. In addition, we included in the simulation images captured from game applications. We simulated the

power consumption with two-dot, column, and Z inversion based on an analog voltage versus digital data curve, as shown in Fig. 5. We extracted the analog voltage versus digital data curve by directly measuring the output voltage of the driver ICs in a twisted nematic LCD display. We measured positive and negative polarity voltages simultaneously depending on the data of the displayed full-screen image. The actual power consumption is determined by voltage transitions, not by digital data, thus we need to calculate the power consumption using analog voltages corresponding to the image data.

Figure 6 shows the power consumption of the ACS method as a percentage of the power consumption of conventional CS for the 360 images acquired from the IEC 62087 standard video clip. Figures 6(a), 6(b), and 6(c) represent the power consumption percentage when the display uses two-dot, column, and Z inversion methods, respectively. As shown in Fig. 6(a), the ACS method consumes an average of
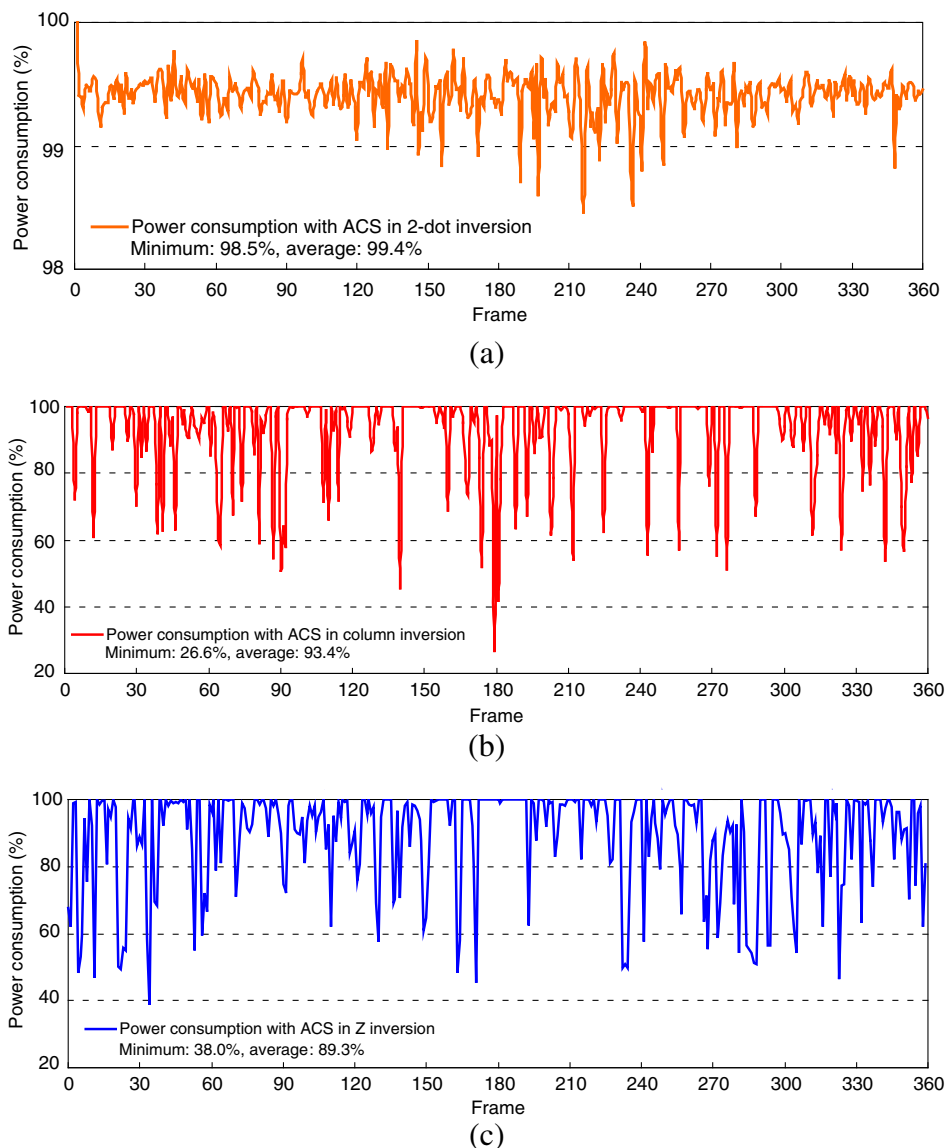

(a)

(b)

(c)

Fig. 6 Power consumption with the ACS method for (a) two-dot, (b) column, and (c) Z inversion.

Table 1 Power consumption results with two-dot, column, and Z inversion for different usage categories and different charge sharing methods.

	Power consumption with usage behavior (arb. unit)									
	Two-dot inversion				Column inversion			Z inversion		
Usage	CS	No CS	Forced CS	ACS	No CS/CS	Forced CS	ACS	No CS/CS	Forced CS	ACS
Internet	4.26×10^6	1.60×10^7 (375.2%)	4.64×10^6 (109.0%)	4.22×10^6 (98.9%)	7.41×10^5	1.35×10^6 (181.5%)	5.93×10^5 (82.9%)	1.09×10^6	1.35×10^6 (122.9%)	8.82×10^5 (82.6%)
Productivity	6.29×10^6	2.13×10^7 (339.5%)	6.64×10^6 (105.7%)	6.17×10^6 (98.2%)	1.84×10^6	2.66×10^6 (144.6%)	1.43×10^5 (78.4%)	2.42×10^6	2.66×10^6 (110.1%)	1.84×10^6 (76.9%)
E-mail	4.12×10^6	1.55×10^7 (375.6%)	4.53×10^6 (109.9%)	4.10×10^6 (99.3%)	4.73×10^5	1.46×10^6 (309.1%)	3.98×10^5 (85.0%)	6.49×10^5	1.46×10^6 (225.2%)	5.58×10^5 (85.7%)
IEC 62087	1.88×10^7	7.48×10^7 (397.6%)	1.90×10^6 (100.8%)	1.87×10^7 (99.4%)	1.66×10^4	1.86×10^6 (11235.6%)	1.59×10^4 (93.4%)	1.28×10^6	1.44×10^6 (144.5%)	1.01×10^6 (89.3%)
Games	1.53×10^8	6.08×10^8 (396.3%)	1.60×10^8 (104.1%)	1.53×10^8 (99.9%)	2.79×10^5	1.35×10^6 (181.5%)	2.75×10^5 (98.7%)	1.12×10^6	1.84×10^6 (163.9%)	1.02×10^6 (89.2%)
Average	100%	376.8%	105.9%	99.1%	100%	2410.5%	87.7%	100%	153.3%	84.7%

99.4% of the conventional CS power with two-dot inversion. The average relative power consumption with column inversion [Fig. 6(b)] and Z inversion [Fig. 6(c)] are 93.4% and 89.3%, respectively. Table 1 summarizes the power consumption results with two-dot, column, and Z inversion for images corresponding to five categories: Internet, productivity, e-mail, IEC 62087, and games. There are four columns for two-dot inversion in Table 1. The CS column presents power consumption when conventional CS is applied. The No CS column presents power consumption when CS is not applied. The forced CS column is included for additional comparison; these data indicate the power consumption when CS is applied every line time. Conventionally, the CS method is performed by electrically connecting all data lines whenever the polarities of the data signals change. The conventional CS method reduces the

Fig. 7 Relative power consumption according to usage category.

power consumption with two-dot inversion because CS is performed when polarities change every second line time. Thus, the average power consumption with no CS is 376.8% relative to the power consumption with CS, as shown in Table 1. Forced CS increases power consumption by 5.9% compared to conventional CS with two-dot inversion because CS is applied every line time with this method. Because all data lines do not experience a polarity change with column or Z inversion until the next frame time, power consumption with no CS is almost the same as that with conventional CS when column or Z inversion is used. Thus, there are only three columns for column and Z inversion: no CS/CS, forced CS, and ACS. As shown in Table 1, the relative average power consumption with two-dot inversion was only reduced to 99.1% when ACS was applied. However, the relative average power consumption was reduced to 87.7% and 84.7% when ACS was applied to column and Z inversion, respectively. This indicates that, in general, the column and Z inversion methods are desirable for low power applications. These results demonstrate that our ACS method can significantly reduce power consumption in LCDs using column inversion or Z inversion. Our results also show that the ACS method is more beneficial when text-based images are displayed. Figure 7 presents the relative power consumption according to usage category. The red, green, and blue bars correspond to the relative power consumption with the two-dot, column, and Z inversion method, respectively. As shown in Fig. 7, the proposed method provides greater power savings with text-based images. Thus, with our ACS approach, laptops and mobile devices will offer significantly increased battery life, considering that these devices are used primarily for text-based applications. We calculated the weighted power consumption for each inversion method by taking into consideration the percentage of device usage for each category. Table 2 presents the weighted power consumption ratios. As shown in Table 2, the relative power consumption of the ACS
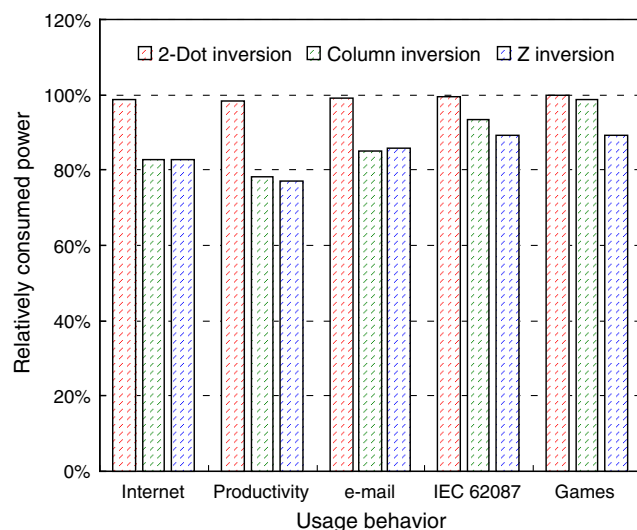
Table 2 Weighted power consumption results with the ACS method for two-dot, column, and Z inversion.

	Weighted power consumption with usage behavior			
Usage	Usage ratio (%)	Two-dot inversion (%)	Column inversion (%)	Z inversion (%)
Internet	62	61.3	51.4	51.2
Productivity	8	7.9	6.3	6.2
E-mail	3	3.0	2.6	2.6
IEC 62087	21	20.9	19.6	18.8
Games	6	6.0	5.9	5.4
Total	100	99.1	85.8	84.2

method is 85.8% and 84.2% with column and Z inversion, respectively, when usage characteristics are considered.

5 Conclusion

We proposed an ACS method for reducing power consumption in LCDs driven with two-dot, column, and Z inversion methods. By considering all types of analog data transitions, the ACS method shares the charge between data lines only when CS ensures an overall reduction in power consumption. Our simulation results demonstrate that this ACS method successfully reduces power consumption, especially when column or Z inversion is used. Furthermore, our method ensures that power consumption never increases as a result of CS, regardless of the inversion method. There is currently much interest in incorporating higher resolution displays into mobile devices, and our ACS technique can contribute to significantly lower LCD power consumption and thus to significantly longer battery life.

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