Driving passive-matrix LCDs with low hardware complexity and reduced supply voltage

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Abstract — In passive-matrix liquid-crystal displays (LCDs), multiplexing is achieved by using the intrinsic non-linear characteristics of the liquid-crystal material. If the electro-optic characteristic is steeper than necessary for the matrix display, the selection ratio need not be maximized. Instead, the selection ratio can be reduced to match the electro-optic characteristics of the display. This leads to a reduction in the supply voltage of the drive electronics. We have considered the possibility of using addressing techniques with low hardware complexity along with displays having steep electro-optic characteristics. Supply voltages for these techniques are compared with that of multi-line addressing (MLA). The supply voltages of the Hybrid Addressing Technique (HAT), Improved Hybrid Addressing Technique-S3 (IHAT-S3), and Improved Hybrid Addressing Technique-S4 (IHAT-S4) are lower than that of MLA for the lower range of N. These hybrid addressing techniques with lower hardware complexity are a better choice for driving passive-matrix LCDs, especially in portable equipment.

Keywords — *Passive-matrix LCDs, addressing technique, multi-line addressing, hybrid addressing supply voltage.*

1 Background

The intrinsic non-linearity of the electro-optic effect is exploited to drive passive-matrix liquid-crystal displays (LCDs). During the last few decades, the addressing techniques for passive-matrix LCDs were optimized to achieve the maximum selection ratio. Selection ratio (SR) is defined as the ratio of the RMS voltage across an ON pixel (V_{on}) to that of an OFF pixel (V_{off}). Passive-matrix LCDs have been replaced by active-matrix LCDs in high-information-content applications requiring a large matrix size. Passive-matrix supertwisted nematic (STN) displays are now being used in mobile telephones, personal digital assistants (PDAs), and other medium- and low-information displays. In these applications, the matrix size is moderate and the electro-optic characteristics can be sharper than necessary. Supply voltage is another important parameter to be considered while using LCDs in portable devices. Several addressing techniques with low supply voltage have been proposed in the past (HAT,[1] IHAT,[2] IHAT-S3, and IHAT-S4[3]). The supply voltage of an addressing technique is determined by the maximum swing in the addressing waveforms. Supply voltage is a minimum when the maximum swings in the row and column waveforms are equal. Supply voltage is a minimum for the case of the Improved Hybrid Addressing Technique (IHAT)[2] as well as Multi-Line Addressing (MLA)[4] when $s = N^{1/2}$. Here, N is the total number of lines being scanned in a matrix LCD and s is the number of rows in the subgroups. The supply-voltage requirement can be further

TABLE 1 — Column voltages for the various hybrid addressing techniques.

Technique	Mismatches (i)	Column Voltage (V_c)
HAT (odd s)	$i < (s/2)$	$+V_c$
	$i > (s/2)$	$-V_c$
IHAT-S3 (even s)	$0 \le i \le m$	$+V_m$
	$m < i < (s-m)$	0
	$(s-m) \le i \le s$	$-V_m$
IHAT-S4 (odd s)	$0 \le i \le m_1$	$+V_{m1}$
	$m_1 < i < s/2$	$+V_{m2}$
	$s/2 \le i \le (s-m_1)$	$-V_{m2}$
	$(s-m_1) \le i \le s$	$-V_{m1}$

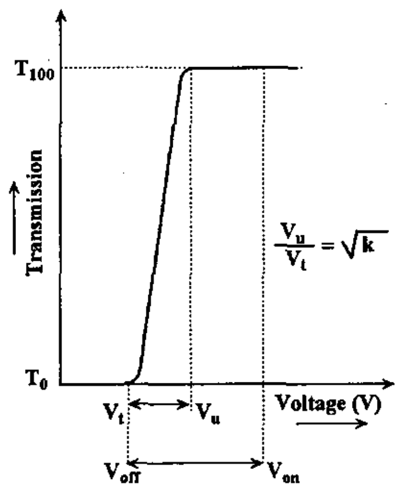

FIGURE 1 — Electro-optic characteristics curve ($V_{on} > V_u$).

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TABLE 2 — The coefficents α, β, γ, and δ for the various hybrid addressing techniques.

Technique	α	β	γ	δ
HAT	2^s	$2(4P-2^s)$	$2^s\left(\frac{N}{s}\right)$	$2^s\left(\frac{N}{s}\right)$
IHAT	2^s	$2\left(\frac{2^s}{s}\right)$	$2^s\left(\frac{N}{s^2}\right)$	$2^s\left(\frac{N}{s}\right)$
IHAT-S3	2^{s-1}	$2\left[\sum_{i=0}^{m}(A_i-B_i)\right]$	$\frac{N}{s}\left[\sum_{i=0}^{m}(A_i+B_i)\right]$	$2^{s-1}\left(\frac{N}{s}\right)$
IHAT-S4	2^{s-1}	$2\left[\left(\sum_{i=0}^{m1}(A_i-B_i)\right)+\frac{DG}{EF}\left(\sum_{i=m1+1}^{(s-1)/2}(A_i-B_i)\right)\right]$	$\frac{N}{s}\left[\left(\sum_{i=0}^{m1}(A_i+B_i)\right)+\left(\frac{DG}{EF}\right)^2\left(\sum_{i=m1+1}^{(s-1)/2}(A_i+B_i)\right)\right]$	$2^{s-1}\left(\frac{N}{s}\right)$
MLA	q	$2\left(\frac{q}{s}\right)$	$q\left(\frac{N}{s^2}\right)$	$q\left(\frac{N}{s}\right)$

where

$$A_i=\frac{(s-1)!}{i!(s-i-1)!} \qquad B_i=\frac{i(s-1)!}{i!(s-i)!} \qquad P=\sum_{i=0}^{(s-1)/2}A_i$$

$$D=\sum_{i=0}^{m1}(A_i+B_i) \qquad E=\sum_{i=m1+1}^{(s-1)/2}(A_i+B_i) \qquad F=\sum_{i=0}^{m1}(A_i-B_i)$$

$$G=\sum_{i=m1+1}^{(s-1)/2}(A_i-B_i)$$

and q is the total number of time intervals in the orthogonal matrix used in the case of MLA.

reduced by following the scheme proposed by Kuijk (1999).[5] Here, the electro-optic characteristic is steeper than necessary for the matrix size. The difference between the RMS voltage across the ON and OFF pixels is more than necessary for multiplexing N rows of the matrix LCD as shown in Fig. 1. The voltage across the ON pixel can be lowered to V_u without affecting the contrast of the display. Hence, the selection ratio is reduced to V_u/V_t and is referred to as the reduced selection ratio. This will help to lower the supply voltage of the drive electronics without losing contrast. We have considered HAT, IHAT-S3, and IHAT-S4 with a low hardware complexity of drivers. The selection ratios of these techniques are lower than the maximum value due to the restrictions imposed on the number of voltage levels in the column waveforms. A lower selection ratio is not a problem since the electro-optic characteristic of the liquid crystal is steep enough for the small or moderate number of rows being multiplexed. The number of voltage levels in the column waveforms is restricted to two, three, and four in the cases of HAT, IHAT-S3, and IHAT-S4, respectively, as compared to $(s + 1)$ in the case of IHAT[2] or MLA[4]. The supply-voltage requirements of these techniques are compared with that of the multi-line addressing technique[5] when the selection ratio is reduced to match the electro-optic characteristic.

2 Hybrid addressing techniques

In the hybrid addressing techniques, the N rows in the matrix are divided into (N/s) non-intersecting subgroups with each subgroups consisting of s address lines. At a given instant of time, one subgroup is selected with voltages corresponding to an s–bit row select pattern. Here, a row select pattern corresponds to one of the 2^s binary patterns. The amplitudes of these voltages are either $+V_r$ for logic 0 and $-V_r$ for logic 1. The remaining $(N-s)$ unselected rows are grounded. The data to be displayed in the selected subgroup in any column is also an s–bit word with logic 0 representing an OFF pixel and logic 1 for an ON pixel. The column voltage is decided by the number of mismatches[1,3] between the row select pattern and the data in the selected subgroup. The number of mismatches i is given by

$$i = \sum_{j=1}^{s} a_j \oplus d_{ks+j}, \tag{1}$$

where $(a_1, a_2, a_3, \ldots a_s)$ is an s-bit row select pattern and d_{ks+j} is the data in the k^{th} subgroup $[k = 0,1,2, \ldots (N/S - 1)]$. Table 1 gives the column voltages for the various hybrid addressing techniques. The mismatches for all the columns in the matrix are computed and transferred to the column driver. Then both the row and column voltages are applied simultaneously to the matrix display for a time duration τ. The process is repeated with another row select pattern by selecting the same subgroup or a different subgroup. A cycle is completed when all the subgroups (N/s) are selected with all the 2^s row-select patterns once. The display is refreshed continuously by repeating this cycle.

Expressions for the RMS voltage across the ON and OFF pixels are of the form shown in Eqs. (2) and (3):

$$V_{on} = \sqrt{\frac{\alpha V_r^2 + \beta V_r V_c + \gamma V_c^2}{\delta}}, \tag{2}$$

$$V_{off} = \sqrt{\frac{\alpha V_r^2 - \beta V_r V_c + \gamma V_c^2}{\delta}}. \tag{3}$$

The coefficients α, β, γ, and δ for the various hybrid addressing techniques are given in Table 2.

With a steep electro-optic characteristic, the selection ratio can be reduced to V_u/V_t. Hence, the reduced selection ratio is

$$SR_{reduced} = \frac{V_u}{V_t} = \sqrt{k}. \tag{4}$$

The condition for the reduced selection ratio is determined as follows:

$$SR_{reduced} = \frac{V_{on}}{V_{off}} = \sqrt{\frac{\alpha V_r^2 + \beta V_r V_c + \gamma V_c^2}{\alpha V_r^2 - \beta V_r V_c + \gamma V_c^2}} = \sqrt{k}.$$

This expression can be simplified to

$$SR_{reduced} = \sqrt{\frac{\alpha x^2 + \beta x + \gamma}{\alpha x^2 - \beta x + \gamma}} = \sqrt{k},$$

wherein $x = V_r/V_c$. Solving for x, we get

$$x = \frac{\beta}{2\alpha}\left(\frac{k+1}{k-1}\right) \pm \sqrt{\left[\frac{\beta}{2\alpha}\left(\frac{k+1}{k-1}\right)\right]^2 - \frac{\gamma}{\alpha}}. \tag{5}$$

The RMS voltage across the OFF pixels is controlled to be near V_{th} in order to get a good contrast ratio in the display. Hence,

TABLE 3 — The coefficients α, β, γ, and δ of the hybrid addressing techniques for two differnet values of s.

Technique	s	α	β	γ	δ	Column voltage levels with grouping of mismatches (i) for highest SR possible
HAT	3	8	8	$\frac{8N}{3}$	$\frac{8N}{3}$	(0,1): $+V_c$; (2,3): $-V_c$
	5	32	24	$\frac{32N}{5}$	$\frac{32N}{5}$	(0,1,2): $+V_c$; (3,4,5): $-V_c$
IHAT-S3	4	8	6	$\frac{5N}{4}$	$\frac{8N}{4}$	(0,1): $+V_c$; (2): 0; (3,4): $-V_c$
	6	32	20	$\frac{11N}{3}$	$\frac{16N}{3}$	(0,1,2): $+V_c$; (3): 0; (4,5,6): $-V_c$
IHAT-S4	5	16	$\frac{46}{5}$	$\frac{69N}{50}$	$\frac{16N}{5}$	(0,1): $+V_c$; (2): $+\left(\frac{3}{10}\right)V_c$; (3): $-\left(\frac{3}{10}\right)V_c$; (4,5): $-V_c$
	7	64	$\frac{688}{21}$	$\frac{9976N}{2205}$	$\frac{64N}{7}$	(0,1,2): $+V_c$; (3): $+\left(\frac{145}{525}\right)V_c$; (4): $-\left(\frac{145}{525}\right)V_c$; (5,6,7): $-V_c$

TABLE 4 — The minimum supply voltage (normalized to V_{th}) with reduced selection ratios for various values of s.

Technique	Reduced selection ratio	s	N_{min}(HA) ($x \equiv 1$)	V_{sup} (normalized to V_{th})	MLA	
					N_{min}(MLA) ($x \equiv 1$)	V_{sup} (normalized to V_{th})
HAT	1.1055	3	27	2.0000	51	3.3665
		5	30	1.9760	75	4.0825
	1.0668	3	42	2.0025	84	3.4059
		5	50	1.9828	130	4.2373
IHAT-S3	1.1055	4	40	2.4911	64	3.7712
		6	42	2.3525	84	4.3205
	1.0668	4	68	2.5020	108	3.8620
		6	72	2.3692	150	4.5518
IHAT-S4	1.1055	5	55	2.9183	75	4.0825
		7	56	2.7047	92	4.5766
	1.0668	5	90	2.9707	130	4.2373
		7	98	2.7481	168	4.8174

$$V_{off} = \sqrt{\frac{\alpha x^2 - \beta x + \gamma}{\delta}} V_c = V_{th},$$

$$V_c = \sqrt{\frac{\delta}{\alpha x^2 - \beta x + \gamma}} V_{th}. \tag{6}$$

The supply voltage is determined by the maximum swing in the addressing waveforms. The expressions for the supply voltage are

$$V_{sup} = 2V_c \quad \text{for} \quad V_r \le V_c,$$
$$V_{sup} = 2\sqrt{\frac{\delta}{\alpha x^2 - \beta x + \gamma}} V_{th} \quad \text{for} \quad V_r \le V_c, \tag{7}$$

$$V_{sup} = 2V_r = 2xV_c \quad \text{for} \quad V_r \ge V_c,$$
$$V_{sup} = 2x\sqrt{\frac{\delta}{\alpha x^2 - \beta x + \gamma}} V_{th} \quad \text{for} \quad V_r \ge V_c. \tag{8}$$

The coefficients α, β, γ, and δ of the hybrid addressing techniques for two different values of s are shown in Table 3. The column voltages of IHAT-S3 and IHAT-S4 have several possible values depending on the grouping of mismatches.[3] We have considered the grouping leading to the highest selection ratio. Both the grouping of mismatches and the corresponding voltage levels[3] are also shown in Table 3. Supply voltage is a minimum when the maximum swings in the addressing waveforms (row and column) are equal (when $x = V_r/V_c$ is 1); that is, when

$$\gamma = \beta\left(\frac{k+1}{k-1}\right) - \alpha. \tag{9}$$

Table 4 shows the minimum supply voltage (normalized to V_{th}) with reduced selection ratios for various values of s.

3 Results and discussions

Supply voltages of HAT, IHAT, IHAT-S3, and IHAT-S4 with a reduced selection ratio are compared with the results of Kuijk[5] for MLA. The IHAT has the same reduction in supply voltage as that of the MLA technique.[5] This is expected since the row-select patterns of MLA are a subset of the row select patterns of IHAT.[6] The number of time intervals to complete a cycle is the only parameter that differs between IHAT and MLA while all other parameters like supply voltage, selection ratio, *etc.*, are the same for IHAT and MLA. Two different liquid-crystal mixtures were considered to compute the supply voltage for the hybrid addressing techniques. Liquid-crystal mixture 1 (LC1), suitable for multiplexing 100 lines, *i.e.* (V_u/V_t) = 1.1055, and liquid-crystal mixture 2 (LC2), capable of multiplexing 240 lines, *i.e.*, (V_u/V_t) = 1.0668, were considered for the analysis. Supply voltages for HAT, IHAT-S3, and IHAT-S4 were calculated for different matrix sizes (N). The minimum supply voltage

TABLE 5 — The number of address lines for which supply voltages of HAT, IHAT-S3, and IHAT-S4 are almost equal to that of MLA (N_{eqs}).

Technique	Reduced selection ratio	s	N_{eqs}	V_{sup} (normalized to V_{th})
HAT	1.1055	3	44	3.4115
		5	61	4.1527
	1.0668	3	72	3.4008
		5	108	4.2979
IHAT-S3	1.1055	4	60	3.7534
		6	77	4.4337
	1.0668	4	102	3.8616
		6	138	4.5963
IHAT-S4	1.1055	5	73	4.0752
		7	87	4.5592
	1.0668	5	127	4.2384
		7	161	4.8306

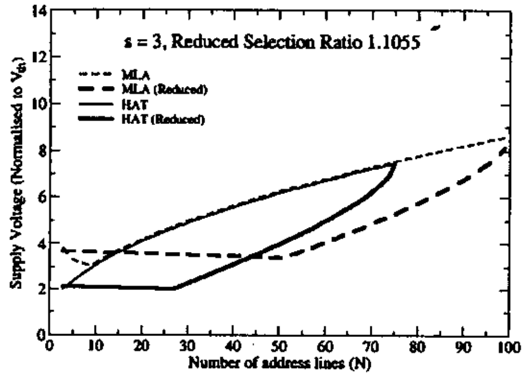

FIGURE 2 — Supply voltage (normalized to V_{th}) vs. N for HAT and MLA when $s = 3$ and SR = 1.1055.

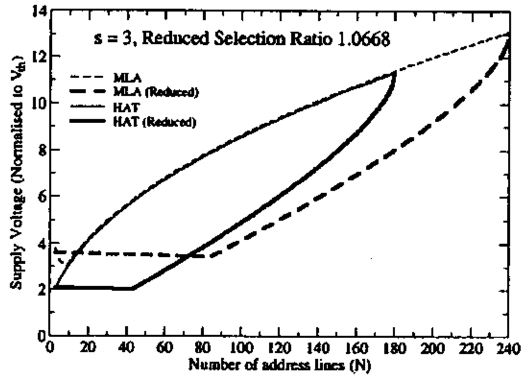

FIGURE 3 — Supply voltage (normalized to V_{th}) vs. N for HAT and MLA when $s = 3$ and SR = 1.0668.

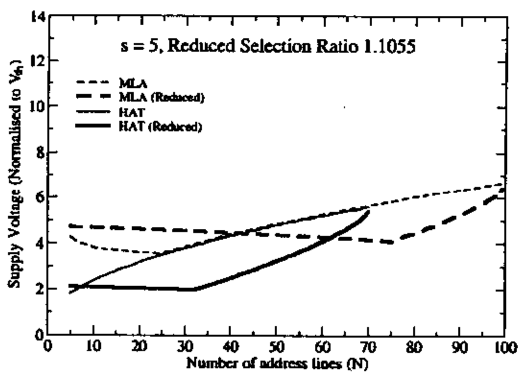

FIGURE 4 — Supply voltage (normalized to V_{th}) vs. N for HAT and MLA when $s = 5$ and SR = 1.1055.

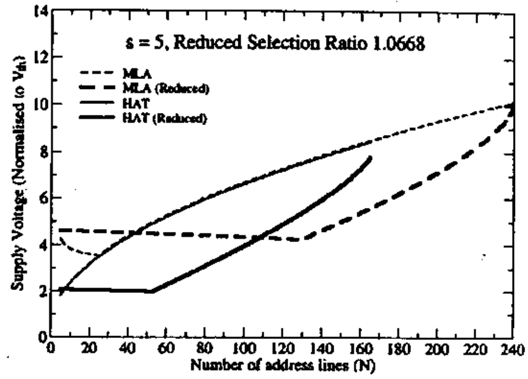

FIGURE 5 — Supply voltage (normalized to V_{th}) vs. N for HAT and MLA when $s = 5$ and SR = 1.0668.

is achieved when the maximum swings in the row and column waveforms are equal. Table 4 gives the number of lines being multiplexed when the supply voltage is a minimum (N_{min}) for hybrid addressing N_{min}(HA) and multi-line addressing N_{min}(MLA). Supply voltages of HAT, IHAT-S3, and IHAT-S4 are less than that for MLA over certain ranges of N. Figures 2–13 show the supply voltage (normalized to V_{th}) vs. the number of address lines (N) for two s values in the case of HAT, IHAT-S3, and IHAT-S4 as compared to MLA.[5] The supply voltage of MLA when the selection ratio is a maximum has also been plotted for comparison. The number of address lines for which supply voltages of HAT, IHAT-S3, and IHAT-S4 are almost equal to that of MLA (N_{eqs}) are shown in Table 5. The supply voltage of hybrid addressing is lower than that of MLA when N (the number of lines being multiplexed) is less than N_{eqs}. A good reduction in supply voltage is achieved when N is less than N_{min}(HA). The percentage reduction in supply voltage com-

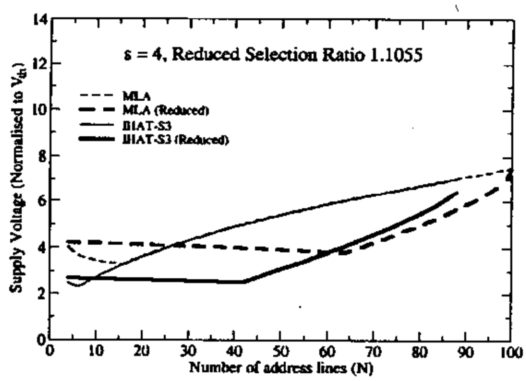

FIGURE 6 — Supply voltage (normalized to V_{th}) vs. N for IHAT-S3 and MLA when $s = 4$ and SR = 1.1055.

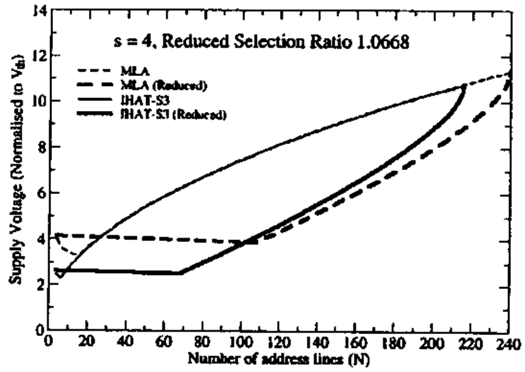

FIGURE 7 — Supply voltage (normalized to V_{th}) *vs.* N for IHAT-S3 and MLA when $s = 4$ and SR = 1.0668.

pared with MLA[5] is almost constant when N is less than or equal to N_{min}(HA):

$$\text{percentage reduction} = \frac{V_{sup}(\text{MLA}) - V_{sup}(\text{HA})}{V_{sup}(\text{MLA})} \times 100.$$

This reduction in supply voltage is plotted in Fig. 14 for the various hybrid addressing techniques. Table 6 gives the maximum reduction (percentage) in supply voltage compared to the MLA[5] technique when N is equal to N_{min}(HA).

The supply voltage for line-by-line addressing may also be reduced by lowering the selection ratio to match the electro-optic characteristics. The supply voltages of the Alt and Pleshko Technique[7] (APT) and the Improved Alt and Pleshko Technique[8] (IAPT) are the same for lower values of N (in the region where the reduced row select pulse $V_{r(\text{reduced})} \leq V_{c(\text{reduced})}$). The supply voltages for APT and IAPT are almost equal to that of HAT as shown in Figs. 15 and 16 in the region $V_{r(\text{reduced})} \leq V_{c(\text{reduced})}$. The supply voltage is

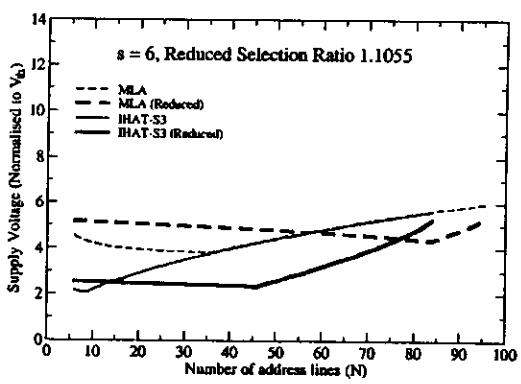

FIGURE 8 — Supply voltage (normalized to V_{th}) *vs.* N for IHAT-S3 and MLA when $s = 6$ and SR = 1.1055.

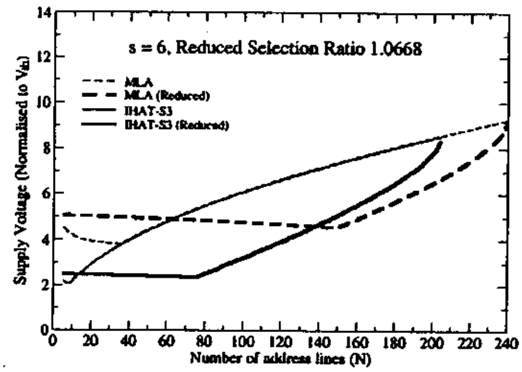

FIGURE 9 — Supply voltage (normalized to V_{th}) *vs.* N for IHAT-S3 and MLA when $s = 6$ and SR = 1.0668.

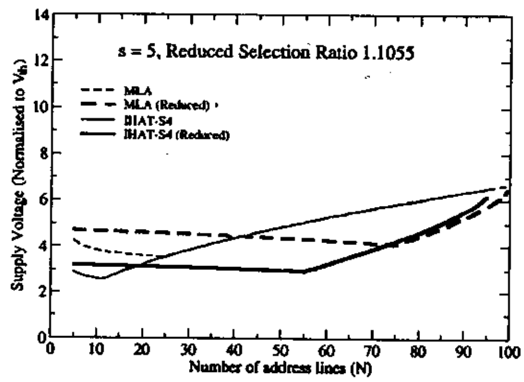

FIGURE 10 — Supply voltage (normalized to V_{th}) *vs.* N for IHAT-S4 and MLA when $s = 5$ and SR = 1.1055.

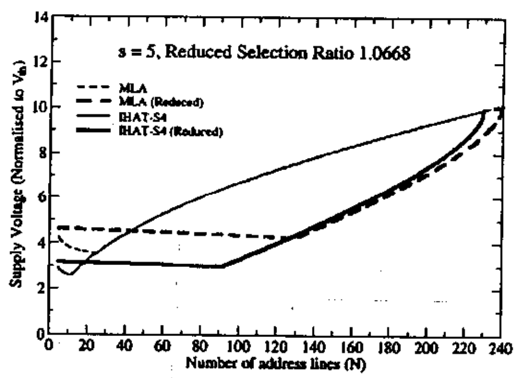

FIGURE 11 — Supply voltage (normalized to V_{th}) *vs.* N for IHAT-S4 and MLA when $s = 5$ and SR = 1.0668.

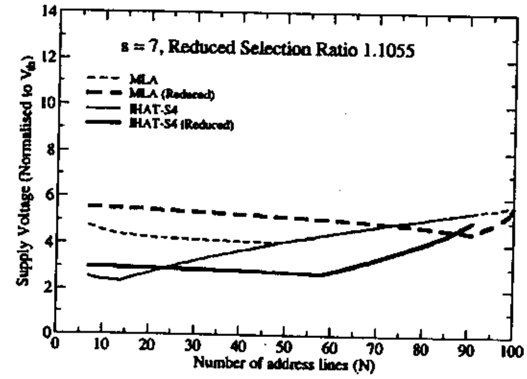

FIGURE 12 — Supply voltage (normalized to V_{th}) *vs.* N for IHAT-S4 and MLA when $s = 7$ and SR = 1.1055.

TABLE 6 — The maximum reduction (percentage) in supply voltage compared to the MLA techniqe when N is equal to N_{min}(HA).

Technique	s	Reduced selection ratio	N_{min}(HA)	$\left(\frac{V_{sup}(MLA) - V_{sup}(HA)}{V_{sup}(MLA)}\right)$ 100 %
HAT	3	1.1055	27	43.1181
		1.0668	42	42.7758
	5	1.1055	30	56.2569
		1.0668	50	55.8848
IHAT-S3	4	1.1055	40	37.2776
		1.0668	68	37.0377
	6	1.1055	42	51.4586
		1.0668	72	51.1898
IHAT-S4	5	1.1055	55	32.2687
		1.0668	90	32.0971
	7	1.1055	56	46.8262
		1.0668	98	46.5939

a minimum when the amplitudes of row and column waveforms are equal (when $N = 19$ and $N = 30$ for the liquid-crystal mixtures LC1 and LC2, respectively). A comparison of the lowered supply voltages of hybrid addressing techniques with that of APT, IAPT, and MLA with reduced selection ratios is shown in Figs. 15 and 16. The hybrid addressing techniques show a good reduction in supply voltage. The addressing techniques which have the lowest supply voltage and the range of N over which the supply voltage is low are given in Tables 7 and 8 for LC1 and LC2, respectively. The hybrid addressing technique (HAT) has low hardware complexity (two voltage levels in the column waveforms and three voltage levels in the row waveforms) and has the lowest supply voltage for the lower values of N. IHAT-S3 and S4 have the lowest supply voltage for the mid-range of N, while IHAT as well as MLA have the lowest supply voltage for the higher values of N. Active addressing[9] wherein all the rows are selected simultaneously requires the same supply voltage as APT. The hardware complexity of column drivers and the controller is high for active addressing, so this technique is not attractive for practical implementation even though the reduced supply voltage is also same as that of APT.

The row and column waveforms of HAT, IHAT-S3, and IHAT-S4 were generated using the waveform-generator *WFG 500* for various values of s and N in order to verify the results experimentally. The RMS voltage across the ON and OFF pixels were measured using the HP 3467A, a logging multimeter capable of measuring true RMS voltage. Tables 9–11 show the measured RMS voltages and the percentage of error as compared to the theoretical value for different values of N and s for the cases of HAT, IHAT-S3, and IHAT-S4. The RMS voltages and the selection ratios obtained from these measurements agree within ±0.8% of the theoretical values.

The hybrid addressing techniques have a lower supply voltage. The hardware complexity of the column drivers of these techniques is lower than that for IHAT and MLA. It is important to note that the higher number of time intervals to complete a cycle for the hybrid addressing techniques compared to MLA is not a disadvantage. In fact, the Hadamard as well as the Walsh matrices are subsets of the

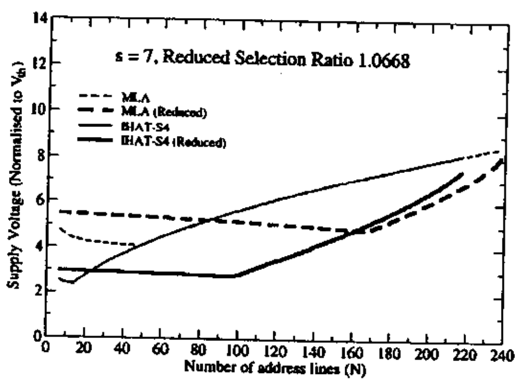

FIGURE 13 — Supply voltage (normalized to V_{th}) *vs.* N for IHAT-S4 and MLA when $s = 7$ and SR = 1.0668.

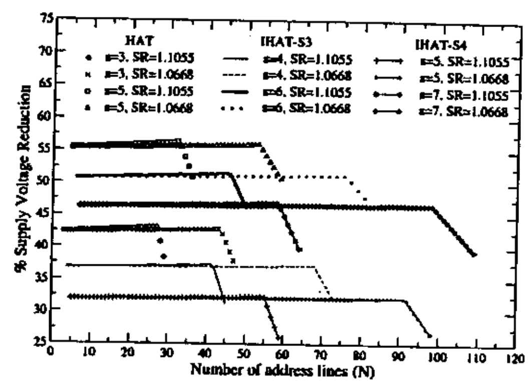

FIGURE 14 — Percentage reduction in supply voltage *vs.* number of address lines (N) in comparison with MLA (Ref. 5).

TABLE 7 — Addressing techniques which have the lowest supply voltage and the range of N over which the supply voltage is low for LC1.

Reduced selection ratio: 1.1055				
Technique	Range of N	Supply voltage (Normalized to V_{th}) V_{sup}	Minimum supply voltage	
			N	V_{sup} (Normalized to V_{th})
APT / IAPT	$3 \le N \le 19$	$2.1002 \le V_{sup} \le 2.0548$	19	2.0548
HAT ($s = 3$)	$3 \le N \le 27$	$2.0975 \le V_{sup} \le 2.0000$	27	2.0000
HAT ($s = 5$)	$5 \le N \le 32$	$2.0851 \le V_{sup} \le 1.9653$	30	1.9761
HAT ($s = 7$)	$7 \le N \le 43$	$2.0802 \le V_{sup} \le 2.3101$	35	1.9428
IHAT-S3 ($s = 6$)	$43 \le N \le 52$	$2.3468 \le V_{sup} \le 2.6896$	42	2.3525
IHAT-S4 ($s = 7$)	$52 \le N \le 87$	$2.7324 \le V_{sup} \le 4.5592$	56	2.7048
MLA ($s = 7$)	$87 \le N \le 100$	$4.6005 \le V_{sup} \le 5.6344$	91	4.4969

TABLE 8 — Addressing techniques which have the lowest supply voltage and the range of N over which the supply voltage is low for LC2.

Reduced selection ratio: 1.0668				
Technique	Range of N	Supply voltage (Normalized to V_{th}) V_{sup}	Minimum supply voltage	
			N	V_{sup} (Normalized to V_{th})
APT / IAPT	$3 \le N \le 30$	$2.0646 \le V_{sup} \le 2.0348$	30	2.0348
HAT ($s = 3$)	$3 \le N \le 43$	$2.0635 \le V_{sup} \le 2.0008$	42	2.0025
HAT ($s = 5$)	$5 \le N \le 53$	$2.0601 \le V_{sup} \le 1.9770$	50	1.9828
HAT ($s = 7$)	$7 \le N \le 72$	$2.0567 \le V_{sup} \le 2.3489$	56	1.9680
IHAT-S3 ($s = 6$)	$72 \le N \le 88$	$2.3692 \le V_{sup} \le 2.7727$	72	2.3692
IHAT-S4 ($s = 7$)	$88 \le N \le 161$	$2.7712 \le V_{sup} \le 4.8306$	98	2.7481
MLA ($s = 7$)	$161 \le N \le 240$	$4.8531 \le V_{sup} \le 8.1275$	168	4.8174

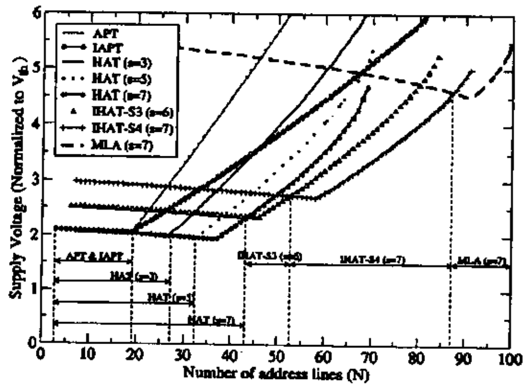

FIGURE 15 — Supply voltage *vs.* *N* for various addressing techniques indicating the range wherein the supply voltage is the lowest for LC1.

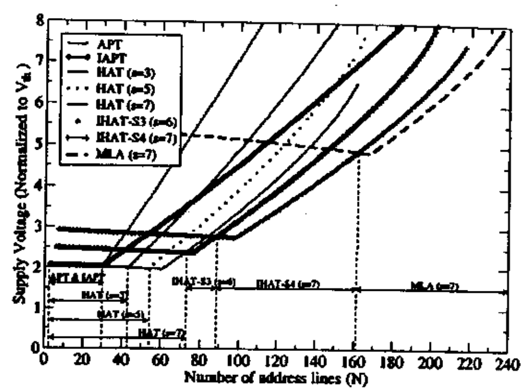

FIGURE 16 — Supply voltage *vs.* *N* for various addressing techniques indicating the range wherein the supply voltage is the lowest for LC2.

matrix corresponding to the Rademacher functions. For example, the Rademacher functions for selecting four rows at a given instant of time have 16 row-select patterns (4 × 16 matrix). This matrix can be interpreted as four orthogonal matrices of 4 × 4. Hence, the large number of row-select patterns just corresponds to using more than one orthogonal matrix or set of functions. This helps in increasing the brightness uniformity of the pixels and decreases the hardware complexity of the column drivers. In summary, the hybrid addressing techniques with lower hardware com-

TABLE 9 — The measured RMS voltages and the percentage of error compared to the theoretical value for different values of *N* and *s* for HAT.

Hybrid addressing technique								
Liquid-crystal material (LC1) : Selection ratio (SR) = 1.1055								
Theoretical : V_{on} = 1.1055 *V*, V_{off} = 1.0000 *V*, V_{th} = 1 *V*								
N	*s*	$V_{sup}(V)$	$V_{on}(V)$	% Error	$V_{off}(V)$	% Error	SR	% Error
18	3	2.04	1.1044	0.0995	0.9995	0.0500	1.1049	0.0543
27	3	2.00	1.1047	0.0724	0.9983	0.1700	1.1065	-0.0905
51	3	4.05	1.1022	0.2985	0.9972	0.2800	1.1053	0.0181
20	5	2.02	1.1025	0.2714	0.9965	0.3500	1.1063	-0.0724
30	5	2.00	1.1055	0.0000	0.9997	0.0300	1.1058	-0.0271
50	5	3.20	1.1051	0.0362	0.9986	0.1400	1.1066	-0.0995
Liquid-crystal material (LC2) : Selection ratio (SR) = 1.0668								
Theoretical : V_{on} = 1.0668 *V*, V_{off} = 1.0000 *V*, V_{th} = 1 *V*								
N	*s*	$V_{sup}(V)$	$V_{on}(V)$	% Error	$V_{off}(V)$	% Error	SR	% Error
18	3	2.04	1.0645	0.2156	0.9986	0.1400	1.0660	0.0750
42	3	2.00	1.0640	0.2625	0.9982	0.1800	1.0659	0.0844
84	3	4.02	1.0625	0.4031	0.9965	0.3500	1.0662	0.0562
126	3	6.38	1.0677	-0.0844	1.0023	-0.2300	1.0652	0.1500
20	5	2.04	1.0661	0.0656	0.9986	0.1400	1.0675	-0.0656
45	5	2.00	1.0663	0.0469	0.9971	0.2900	1.0694	-0.2437
100	5	3.94	1.0681	-0.1219	0.9996	0.0400	1.0685	-0.1594
130	5	5.38	1.0655	0.1219	0.9982	0.1800	1.0674	-0.0562

TABLE 10 — The measured RMS voltages and the percentage of error compared to the theoretical value for different values of N and s for IHAT-S3.

Improved hybrid addressing technique – S3								
Liquid-crystal material (LC1) : Selection ratio (SR) = 1.1055								
Theoretical : $V_{on} = 1.1055\,V$, $V_{off} = 1.0000\,V$, $V_{th} = 1\,V$								
N	s	$V_{sup}(V)$	$V_{on}(V)$	% Error	$V_{off}(V)$	% Error	SR	% Error
20	4	2.58	1.1053	0.0181	0.9990	0.1000	1.1064	-0.0814
40	4	2.50	1.1051	0.0362	0.9986	0.1400	1.1066	-0.0995
60	4	3.75	1.1058	-0.0271	0.9998	0.0200	1.1059	-0.0362
80	4	5.88	1.1050	0.0452	0.9982	0.1800	1.1069	-0.1266
18	6	2.47	1.1044	0.0995	0.9963	0.3700	1.1085	-0.2714
42	6	2.35	1.1051	0.0362	0.9951	0.4900	1.1105	-0.4523
66	6	3.58	1.1058	-0.0271	0.9942	0.5800	1.1122	-0.6061
84	6	5.24	1.1054	0.0090	0.9944	0.5600	1.1116	-0.5518
Liquid-crystal material (LC2) : Selection ratio (SR) = 1.0668								
Theoretical : $V_{on} = 1.0668\,V$, $V_{off} = 1.0000\,V$, $V_{th} = 1\,V$								
N	s	$V_{sup}(V)$	$V_{on}(V)$	% Error	$V_{off}(V)$	% Error	SR	% Error
32	4	2.56	1.0633	0.3281	0.9951	0.4900	1.0685	-0.1594
64	4	2.50	1.0654	0.1312	0.9973	0.2700	1.0683	-0.1406
128	4	4.97	1.0611	0.5343	0.9942	0.5800	1.0673	-0.0469
160	4	6.47	1.0665	0.0281	0.9991	0.0900	1.0675	-0.0656
36	6	2.43	1.0634	0.3187	0.9944	0.5600	1.0694	-0.2437
66	6	2.38	1.0624	0.4124	0.9955	0.4500	1.0672	-0.0375
126	6	4.13	1.0653	0.1406	0.9937	0.6300	1.0721	-0.4968
186	6	6.80	1.0628	0.3750	0.9942	0.5800	1.0690	-0.2062

TABLE 11 — The measured RMS voltages and the percentage of error compared to the theoretical value for different values of N and s for IHAT-S4.

Improved hybrid addressing technique – S4								
Liquid-crystal material (LC1) : Selection ratio (SR) = 1.1055								
Theoretical : $V_{on} = 1.1055\,V$, $V_{off} = 1.0000\,V$, $V_{th} = 1\,V$								
N	s	$V_{sup}(V)$	$V_{on}(V)$	% Error	$V_{off}(V)$	% Error	SR	% Error
25	5	3.09	1.1049	0.0543	0.9974	0.2600	1.1078	-0.2081
55	5	2.92	1.1051	0.0362	0.9963	0.3700	1.1092	-0.3347
85	5	5.00	1.1070	-0.1357	0.9985	0.1500	1.1087	-0.2895
28	7	2.87	1.1026	0.2623	0.9927	0.7300	1.1107	-0.4704
56	7	2.70	1.1012	0.3890	0.9944	0.5600	1.1074	-0.1719
84	7	4.30	1.1024	0.2804	0.9960	0.4000	1.1068	-0.1176
Liquid-crystal material (LC2) : Selection ratio (SR) = 1.0668								
Theoretical : $V_{on} = 1.0668\,V$, $V_{off} = 1.0000\,V$, $V_{th} = 1\,V$								
N	s	$V_{sup}(V)$	$V_{on}(V)$	% Error	$V_{off}(V)$	% Error	SR	% Error
25	5	3.10	1.0650	0.1687	0.9956	0.4400	1.0697	-0.2718
90	5	2.97	1.0604	0.5999	0.9930	0.7000	1.0679	-0.1031
125	5	4.16	1.0586	0.7687	0.9908	0.9200	1.0684	-0.1500
195	5	6.88	1.0608	0.5624	0.9934	0.6600	1.0678	-0.0937
49	7	2.85	1.0594	0.6937	0.9914	0.8600	1.0686	-0.1687
98	7	2.74	1.0600	0.6374	0.9918	0.8200	1.0688	-0.1875
161	7	4.83	1.0598	0.6562	0.9948	0.5200	1.0653	0.1406
189	7	5.94	1.0584	0.7874	0.9930	0.7000	1.0659	0.0844

plexity and reduced supply voltage are a better choice for driving passive-matrix LCDs, especially in portable equipment such as mobile phones and PDAs.

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