Chapter 5

5. Driving Passive Matrix LCDs With Lower Hardware Complexity And Reduced Supply Voltage

Driving Passive Matrix LCDs With Lower Hardware Complexity And Reduced Supply Voltage

5.1. Introduction

The intrinsic non-linearity of the electro-optic effect is exploited to drive passive matrix liquid crystal displays (LCDs). If the electro-optic characteristic is steeper than necessary for the matrix display, the selection ratio need not be maximized. In this case the selection ratio can be reduced to match the electro-optic characteristic of the liquid crystal material in the display. As a result supply voltage of the addressing technique can be reduced. Reducing hardware complexity of the drive electronics is an important step to reduce the cost. Hybrid Addressing Technique (HAT) [16], Improved Hybrid Addressing Technique–S3 (MAT–S3) [19] and Improved Hybrid Addressing Technique–S4 (MAT–S4) [19] have lower hardware complexity as compared to Improved Hybrid Addressing Technique (MAT) [18] or Multi-Line Addressing (MLA)[21][22] and these techniques are considered in this chapter. Supply voltage of these techniques are studied when the selection ratio is reduced to match the steeper electro-optic characteristics and the results are compared with MAT and MLA.

5.2. Principle

Supply voltage of an addressing technique is determined by the maximum swing in the addressing waveforms and it is minimum when maximum swings in the row and column waveforms are equal. Supply voltage is a minimum in the case of Improved Hybrid Addressing Technique (MAT) as well as Multi-Line Addressing (MLA) when $s = \sqrt{N}$. Where N is the total number of rows in the matrix LCD and s is the number of rows selected simultaneously. Supply voltage requirement can be further reduced by following a scheme proposed by Kuijk et.al., [39][40] for MLA technique. Walzen et.al., (1989) had shown the possible reduction of supply voltage in the case of line by line addressing technique [38]. In both the cases electro-optic characteristics of the display is steeper than necessary for the N rows matrix LCD. Here 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 the Figure 5-1. The rms voltage across the ON pixel can be lowered to V_u (see Figure 5-1) without affecting the contrast of the display. The selection ratio need not be maximized, instead selection ratio can be reduced to match the electro-optic characteristics of the display. That is selection ratio is reduced to $\frac{V_u}{V_t}$ and is referred to as the reduced selection ratio. This leads to a reduction in the supply voltage of the drive electronics without any loss of contrast in the display. The hybrid addressing (HA) techniques[17] HAT, MAT–S3 and MAT–S4 reviewed in chapter 2 section 2.5.1 have a lower hardware complexity as compared to MAT and MLA. The selection ratio of these addressing techniques are lower than that of IHAT due to the restrictions imposed on the number of voltage levels in the column waveforms. Lower selection ratio is not a problem since the electro-optic characteristics for driving N rows matrix is steeper than necessary. Supply voltage of these techniques are determined after reducing the selection ratio to match the electro-optic characteristics and the results are presented in this chapter.

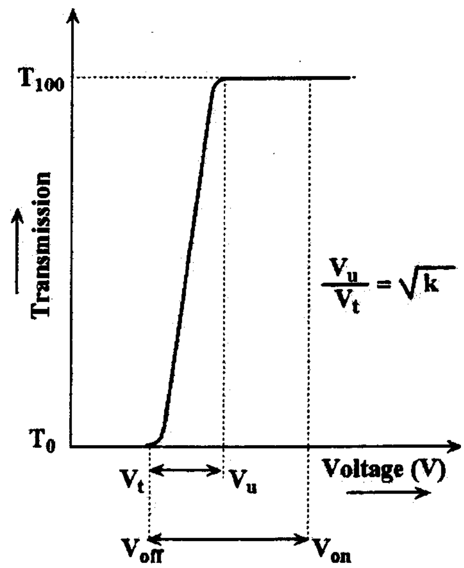

Figure 5-1 Schematic representation of the electro-optic characteristic curve ($V_{on} > V_u$).

5.3. Technique

Hybrid addressing (HA) techniques reviewed in section 2.5.1 of this thesis is briefly explained here. The N rows in the matrix are divided into $\left(\frac{N}{s}\right)$ non-intersecting subgroups with s rows in each subgroup. At a given instant of time, one subgroup is selected with s-bit row select patterns. Here, row select pattern correspond to one of the 2^s binary pattern.

The amplitudes of row select 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 for an ON pixel and logic 1 for an OFF pixel. The column voltage is decided by the number of mismatches (I) between the row select pattern and the data vector in the selected subgroup.

$$I = \sum_{i=1}^{s} O(i, j) \oplus d_{ks+i} \tag{5.1}$$

Where, $O(i,\text{j}) = O(1,\text{j}), O(2,\text{j})......O(i,\text{j})......O(s,\text{j})$ is an s-bit row select pattern $(1 \leq \text{j} \leq 2^s)$ and d_{ks+i} is the data in the k^{th} subgroup $(k = 0,1,2,. \quad -1))$ Column voltages are restricted to two, three and four in the case of HAT, MAT−S3 and MAT−S4 respectively. The groupings of mismatches for these addressing techniques are tabulated in Table 5-1.

Table 5-1

Technique	Mismatches (I)	Column Voltage (V_c)
HAT (odd s)	$I < \left(s/2\right)$ $I > \left(s/2\right)$	$+V_c$ $-V_c$
MAT-S3 (even s)	$0 \leq I \leq m$ $m < I < (s-m)$ $(s-m) \leq I \leq s$	$+V_m$ 0 $-V_m$
MAT-S4 (odd s)	$0 \leq I \leq m_1$ $m_1 < I < s/2$ $s/2 \leq I \leq (s-m_1)$ $(s-m_1) \leq$ I I s	$+V_{m1}$ $+V_{m2}$ $-V_{m2}$ $-V_{m1}$

The column data for all the columns in the matrix are computed and transferred to the column driver. 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 are selected with all the row select patterns once. The display is refreshed continuously by repeating this cycle.

5.4. *Analysis*

The general expressions for the rms voltage across the ON and OFF pixels is given by,

$$V_{on} = \sqrt{\frac{\alpha\ V_r^2 + \beta\ V_r\ V_c + \gamma\ V_c^2}{\delta}} \quad (5.2)$$

$$V_{off} = \sqrt{\frac{\alpha\ V_r^2 - \beta\ V_r\ V_c + \gamma\ V_c^2}{\delta}} \quad (5.3)$$

The coefficients α, β, γ and 6 for various addressing techniques are given in the Table 5-2. The grouping of mismatches of MAT–S3 and MAT–S4 have several possible combinations. The coefficients of a, β, y and 6 for HAT, **IHAT–S3** and MAT–S4 for some of the possible combination for various values of *s* are calculated and tabulated in Table 5-3. Selection ratio $\left(\frac{V_{on}}{V_{off}}\right)$ of the addressing techniques can be reduced to $\left(\frac{V_u}{V_t}\right)$ while using a steep electro-optic characteristic than necessary. Let the reduced selection ratio be $\sqrt{k}$. The condition for the reduced selection ratio is determined as follows,

$$SR_{reduced} = \frac{V_{on}}{V_{off}} = \sqrt{\frac{\alpha\ V_r^2 + \beta\ V_r\ V_c + \gamma\ V_c^2}{\alpha\ V_r^2 - \beta\ V_r\ V_c + \gamma\ V_c^2}} = \sqrt{k} \quad (5.4)$$

This expression can be simplified to

$$SR_{reduced} = \sqrt{\frac{\alpha\ x^2 + \beta\ x + \gamma}{\alpha\ x^2 - \beta\ x + \gamma}} = \sqrt{k} \quad (5.5)$$

Wherein $x = \frac{V_r}{V_c}$. Solving for x, we get

$$x = \frac{\beta}{2\alpha}\left(\frac{k+1}{k-1}\right) \pm \sqrt{\left[\frac{\beta}{2\alpha}\left(\frac{k+1}{k-1}\right)\right]^2 - \frac{\gamma}{\alpha}} \quad (5.6)$$

Table 5-2

Technique	β		γ	δ
APT	1	2	N	N
IAPT	1	2	N	N
MAT	2^s	$2\left(\frac{2^s}{s}\right)$	$2^s\left(\frac{N}{s^2}\right)$	$2^s\left(\frac{N}{s}\right)$
HAT	2^{s-1}	$4\sum_{i=0}^{(s-1)/2} A_i - 2^s$	$2^{s-1}\left(\frac{N}{s}\right)$	$2^{s-1}\left(\frac{N}{s}\right)$
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}	$2\left[F + \frac{DG^2}{EF}\right]$	$\frac{N}{s}\left[D + \left(\frac{DG}{EF}\right)^2 E\right]$	$2^{s-1}\left(\frac{N}{s}\right)$
MLA	q	$2\left(\frac{q}{s}\right)$	$q\left(\frac{N}{s^2}\right)$	$q\left(\frac{N}{s}\right)$
AA	q	$2\left(\frac{q}{N}\right)$	$q\left(\frac{1}{N}\right)$	q

Where,

$$A_i = \frac{(s-1)\,!}{i\,!\,(s-i-1)\,!} \qquad B_i = \frac{i\,(s-1)\,!}{i\,!\,(s-i)\,!} \qquad D = \sum_{i=0}^{m1}(A_i + B_i)$$

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

q is the total number of columns in the orthogonal matrix.

Table 5-3

Technique	s	α	β	Y	δ	Column voltage levels with grouping of mismatches (I)				
HAT	3	4	4	$\frac{4N}{3}$	$\frac{4N}{3}$	(0,1) $+V_c$		(2,3) $-V_c$		
HAT	5	16	12	$\frac{16N}{5}$	$\frac{16N}{5}$	(0,1,2) $+V_c$		(3,4,5) $-V_c$		
HAT	7	64	40	$\frac{64N}{7}$	$\frac{64N}{7}$	(0,1,2,3) $+V_c$		(4,5,6,7) $-V_c$		
IHAT-S3	4	8	6	$\frac{5N}{4}$	$\frac{8N}{4}$	(0,1) $+V_c$	(2) 0	(3,4) $-V_c$		*
IHAT-S3	4	8	2	$\frac{N}{4}$	$\frac{8N}{4}$	(0) $+V_c$	(1,2,3) 0	(4) $-V_c$		
IHAT-S3	6	32	20	$\frac{22N}{6}$	$\frac{32N}{6}$	(0,1,2) $+V_c$	(3) 0	(4,5,6) $-V_c$		*
IHAT-S3	6	32	10	$\frac{7N}{6}$	$\frac{32N}{6}$	(0,1) $+V_c$	(2,3,4) 0	(5,6) $-V_c$		
IHAT-S3	6	32	2	$\frac{N}{6}$	$\frac{32N}{6}$	(0) $+V_c$	(1,2,3,4,5) 0	(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) $-V_c$	*
IHAT-S4	5	16	$\frac{16}{3}$	$\frac{26N}{5}$	$\frac{16N}{5}$	(0) $+V_c$	(1,2) $+\left(\frac{1}{3}\right)V_c$	(3,4) $-\left(\frac{1}{3}\right)V_c$	(5) $-V_c$	
IHAT-S4	7	64	$\frac{688}{21}$	$\frac{9976N}{2205}$	$\frac{64N}{7}$	(0,1,2) $+V_c$	(3) $+\left(\frac{24}{105}\right)V_c$	(4) $-\left(\frac{24}{105}\right)V_c$	(5,6,7) $-V_c$	*
IHAT-S4	7	64	$\frac{64}{3}$	$\frac{128N}{63}$	$\frac{64N}{7}$	(0,1) $+V_c$	(2,3) $+\left(\frac{1}{3}\right)V_c$	(4,5) $-\left(\frac{1}{3}\right)V_c$	(6,7) $-V_c$	
IHAT-S4	7	64	$\frac{848}{63}$	$\frac{424N}{441}$	$\frac{64N}{7}$	(0) $+V_c$	(1,2,3) $+\left(\frac{19}{63}\right)V_c$	(4,5,6) $-\left(\frac{19}{63}\right)V_c$	(7) $-V_c$	

* **Best grouping to get higher selection ratio.**

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

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

$$V_c = \sqrt{\frac{\delta}{\alpha\ x^2 - \beta\ x + \gamma}}\ V_{th} \qquad \textbf{(5. 7)}$$

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

$$V_{\text{sup}} = 2\ V_c \qquad \text{for } (V_r \le V_c)$$

$$V_{\text{sup}} = 2\sqrt{\frac{6}{\alpha\ x^2 - \beta\ x + \gamma}}\ V_{th} \qquad \text{for } (V_r \le V_c) \qquad \textbf{(5. 8)}$$

$$V_{\text{sup}} = 2\ V_r = 2\ x\ V_c \qquad \text{for } (V_r \ge V_c)$$

$$V_{\text{sup}} = 2x\sqrt{\frac{\delta}{\alpha\ x^2 - \beta\ x + \gamma}}\ V_{th} \qquad \textbf{for } (V_r \ge V_c) \qquad \textbf{(5. 9)}$$

Supply voltage is a minimum when the maximum swing in the addressing waveforms (row and columns) are equal (When $x = \frac{V_r}{V_c}$ is 1). That is when

$$\gamma = \beta\left(\frac{k+1}{k-1}\right) - \alpha \qquad \textbf{(5. 10)}$$

Table 5-4 shows the minimum supply voltage (Normalised to V_{th}) with the reduced selection ratios for various values of s.

Table 5-4

Technique	Reduced Selection Ratio	s	N_{min}(HA) ($x \cong 1$)	V_{sup} (Norm. to V_{th})	MLA	
					N_{min}(MLA) ($x \cong 1$)	V_{sup} (Norm. to V_{th})
HAT	1.1055	3	27	2.0000	51	3.3665
		5	30	1.9760	75	4.0825
		7	35	1.9428	91	4.4969
	1.0668	3	42	2.0025	84	3.4059
		5	50	1.9828	130	4.2373
		7	56	1.9680	168	4.8174
MAT-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
MAT-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

5.5. *Results and Discussions*

Supply voltages of hybrid addressing techniques with reduced selection ratio were studied by using two different liquid crystal mixtures. The liquid crystal mixture 1 (LC1) suitable of multiplexing 100 lines i.e., $\left(\frac{V_u}{V_t}\right) = 1.1055$ and the liquid crystal mixture 2 (LC2) capable of multiplexing 240 lines i.e., $\left(\frac{V_u}{V_t}\right) = 1.0668$ were considered for the analysis. The IHAT has the same reduction in supply voltage as that of MLA technique[20]. This is expected since the row select patterns of MLA[21] is a subset of the row select patterns of

IHAT[18]. The number of time intervals to complete a cycle is the only parameter that differs between MAT and MLA while all other parameters like supply voltage, selection ratio etc., are the same for MAT and MLA (see section 2.5.1 and 2.5.2). Supply voltages for HAT, MAT-S3 and IHAT-S4 were calculated for different matrix size (N). In the case of IHAT-S3 and IHAT-S4 some of the possible combination of grouping of mismatches were considered while assigning the column voltage levels and they are tabulated in the Table 5-3, in the same table the best groupings which gives a higher selection ratio are also shown. Figures 5-2 to 5-15 shows the supply voltage (normalised to V_{th}) versus the number of address lines (N) for different s values in the case of HAT, IHAT-S3 and IHAT-S4 as compared to the MLA (or MAT). Minimum supply voltage is achieved when maximum swings in the row and column waveforms are equal. Supply voltages of HAT, IHAT-S3 and IHAT-S4 are less than that of MLA[40] over certain ranges of N. From the analysis and the plots in the Figures 5-2 to 5-15, supply voltage for the case of IHAT-S3 and IHAT-S4 is lower only for the best grouping of mismatches as marked in the Table 5-3. Hence, only best grouping for MAT-S3 and MAT-S4 are considered for comparison with the results of MLA. Table 5-4 gives the number of lines being multiplexed when the supply voltage is a minimum (N_{min}) for the hybrid addressing (i.e., for HAT, IHAT-S3 and IHAT-S4) N_{min}(HA) and multi-line addressing N_{min}(MLA). 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 5-5. Supply voltage of hybrid addressing is lower than that of MLA when N (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 $\left(\frac{V_{\sup}(MLA) - V_{\sup}(HA)}{V_{\sup}(MLA)}\ 100\right)$ is almost constant when N is less than or equal to N_{min}(HA) compared with MLA[40]. This reduction in supply voltage is plotted in Figure 5-16 for the various hybrid addressing techniques. Table 5-6 gives the maximum reduction (percentage) in supply voltage compared to MLA[40] technique when N is equal to N_{min}(HA). The supply voltage for line by line addressing is calculated by lowering the selection ratio to match the electrooptic characteristics. The supply voltages of Alt and Pleshko Technique (APT) [4] and Improved Alt and Pleshko Technique (IAPT)[6] are the same for lower values of N (in the region where the reduced row select pulse $V_{r(reduced)} \leq V_{c(reduced)}$). The supply voltages for APT and IAPT are almost equal to that of HAT as shown in Figures **5-17** and **5-18** in the region $V_{r(reduced)}$ **I** $V_{c(reduced)}$. The supply voltage is a minimum when amplitudes of row and column waveforms are equal (when N = **19** and **N =30** for **the liquid** crystal mixtures **LC1** and **LC2** respectively).

Table 5-5

Technique	Reduced Selection Ratio	s	N_{eqs}	V_{sup} (Norm. to V_{th})
HAT	1.1055	3	44	3.4115
		5	61	4.1527
		7	–	–
	1.0668	3	72	3.4008
		5	108	4.2979
		7	130	4.9355
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

The active addressing [23] where in all the rows are selected simultaneously needs the same supply voltage as that of APT. The hardware complexity of column drivers as well as the controller is high for the active addressing. Hence this technique is not attractive for practical implementation even though the reduced supply voltage is also same as that of APT. Comparison of lowered supply voltages of hybrid addressing techniques with that of APT, IAPT and **MLA** with reduced selection ratios is shown in Figures **5-17** and **5-18.** The hybrid addressing techniques show a good reduction in supply voltage. The addressing techniques which has the lowest supply and the range of N over which the supply voltage is low are given in Tables 5-7 and 5-8 for LC1 and LC2 respectively. The 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 lower values of N. The MAT-S3 and IHAT-S4 has the lowest supply voltage for the mid range of N while the MAT as well as MLA has the lowest supply voltage for higher values of N.

Table *5-6*

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
	7	1.1055	35	63.3475
		1.0668	56	62.8546
IHAT-S3	4	1.1055	40	37.2776
		1.0668	68	37.0377
	6	1.1055	42	51.4586
		1.0668	72	51.1898
MAT-S4	5	1.1055	55	32.2687
		1.0668	90	32.0971
	7	1.1055	56	46.8262
		1.0668	98	46.5939

The row and column waveforms of HAT, MAT-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 multi-meter capable of measuring true rms voltage. Table 5-9, Table 5-10 and Table 5-11 shows the measured rms voltages and the percentage of error as compared to the theoretical value for different values of N and *s* in the case of HAT, MAT-S3 and MAT-S4 respectively. The rms voltages and the selection ratio 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 are lower than that of MAT and MLA. It is important to note that the higher number of time intervals to complete a cycle for the hybrid addressing techniques as compared to MLA is not a disadvantage. In fact, the Hadamard as well as the Walsh matrices are. subset of the matrix corresponding to the Rademacher functions. For example, the Rademacher functions for selecting four rows at a given instant of time has 16 row select patterns (4x16 matrix). This matrix can be interpreted as four orthogonal matrix of 4x4. Hence the large number of row select patterns just corresponds to using more than one orthogonal matrix or functions. This helps in increasing the brightness uniformity of the pixels and decrease the hardware complexity of the column drivers. In summary the hybrid addressing techniques with lower hardware complexity and reduced supply voltage are a better choice for driving passive matrix LCDs, especially in portable equipment like mobile phones and PDAs.

Table 5-7

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

Table 5-8

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

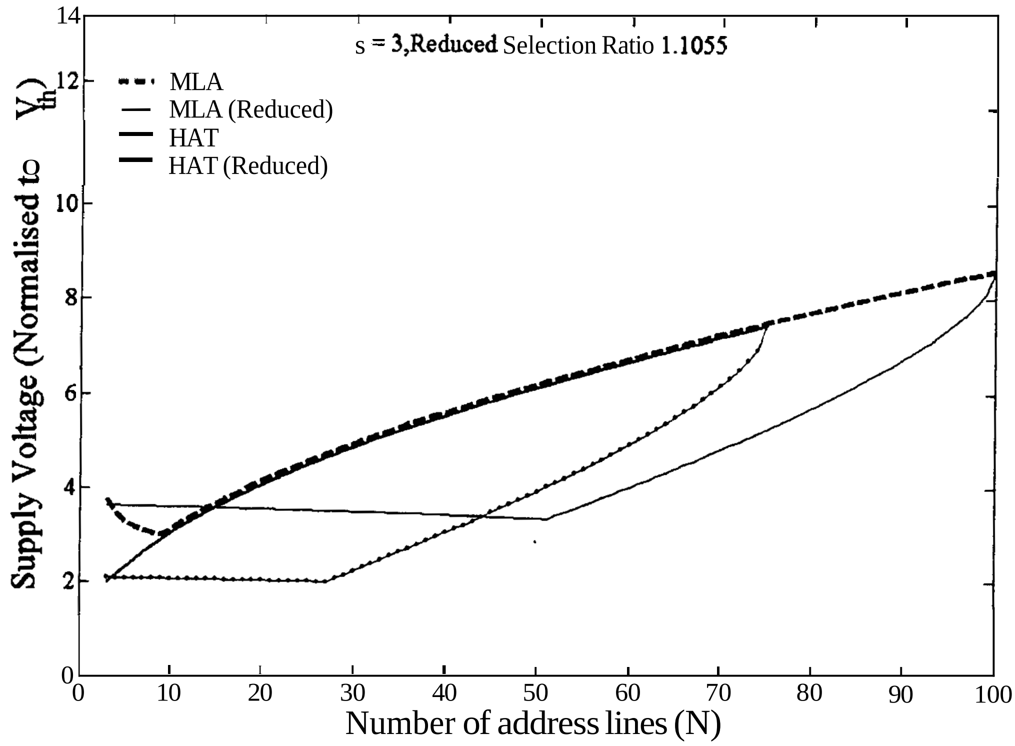

Figure 5-2 Supply voltage (Normalised to V_{th}) versus N for HAT and MLA when s = 3 and SR=1.1055.

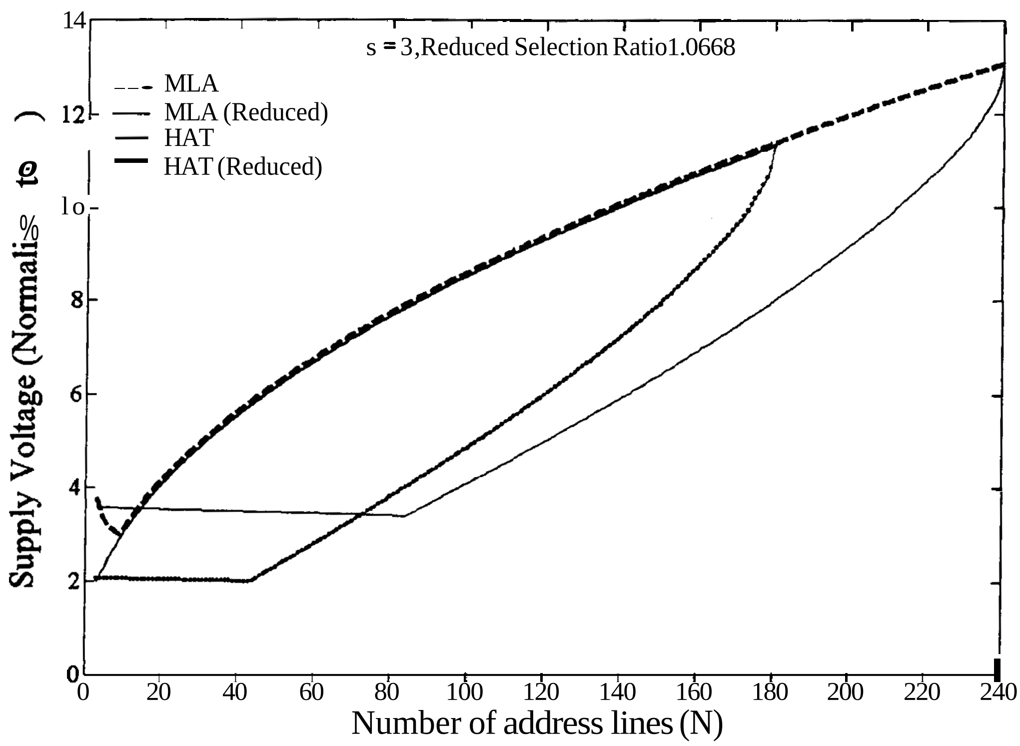

Figure 5-3 Supply voltage (Normalised to V_{th}) versus N for HAT and MLA when s = 3 and SR=1.0668.

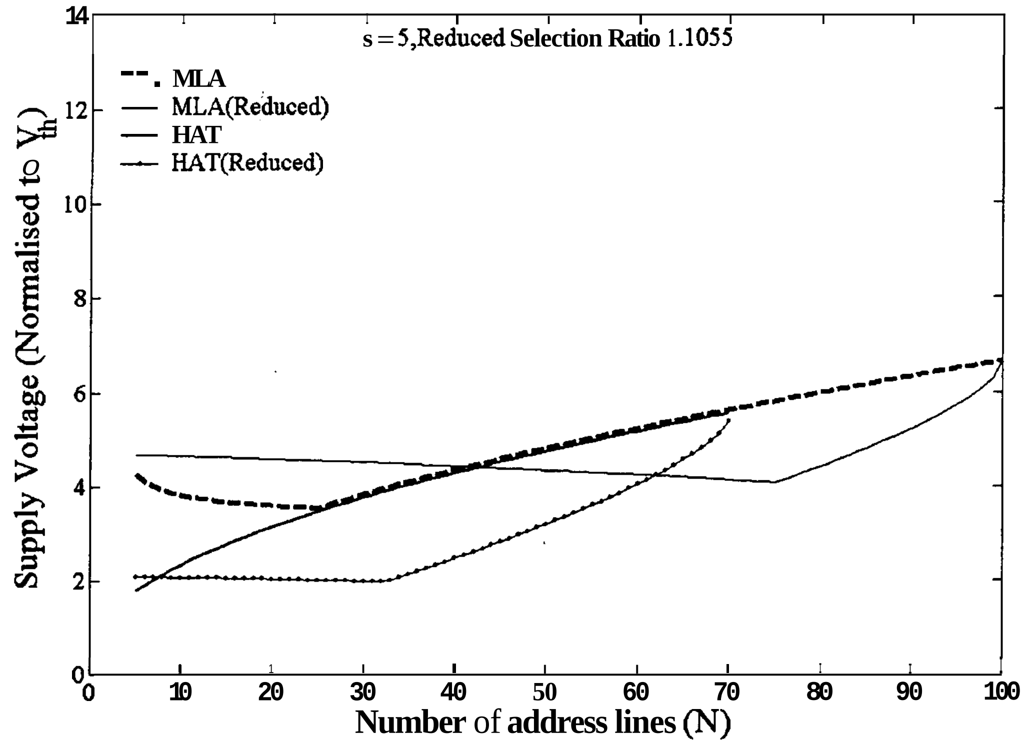

Figure 5-4 Supply voltage (Normalised to V_{th}) versus N for HAT and MLA when s = 5 and SR=1.1055.

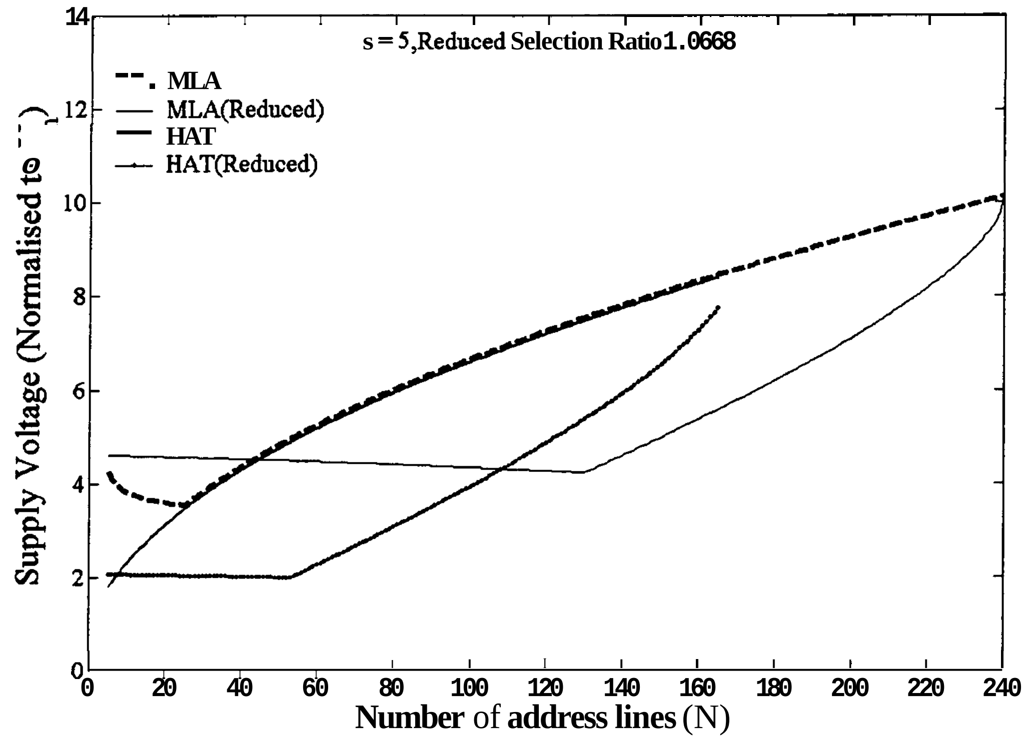

Figure 5-5 Supply voltage (Normalised to V_{th}) versus N for HAT and MLA when s = 5 and SR=1.0668.

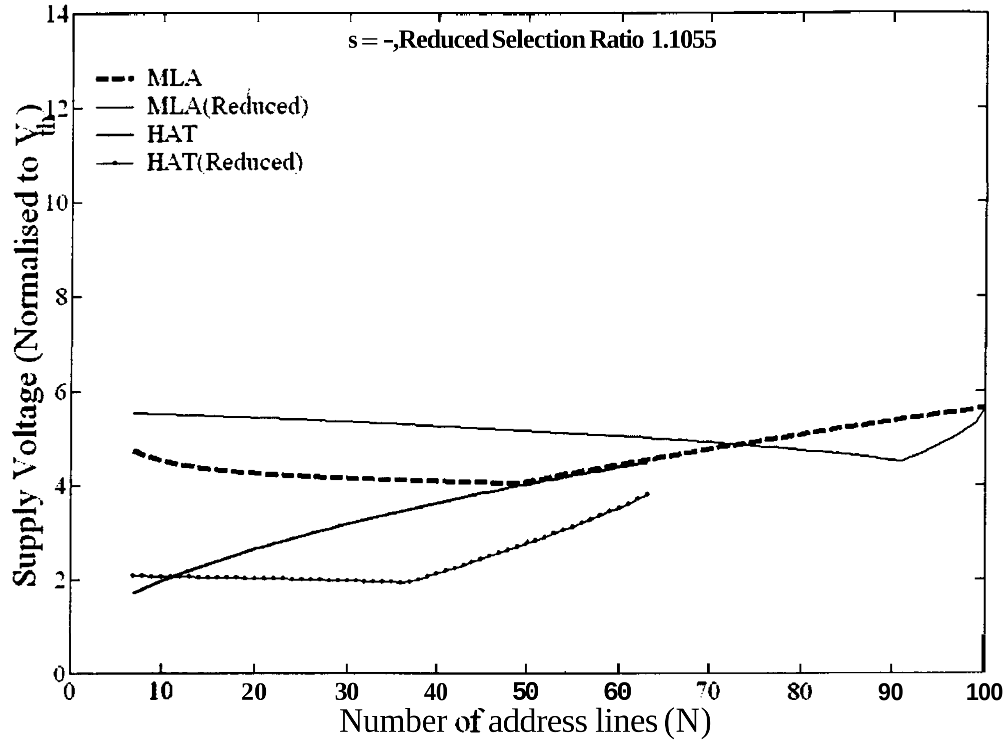

Figure 5-6 Supply voltage (Normalised to V_{th}) versus N for HAT and MLA when s = 7 and SR=1.1055.

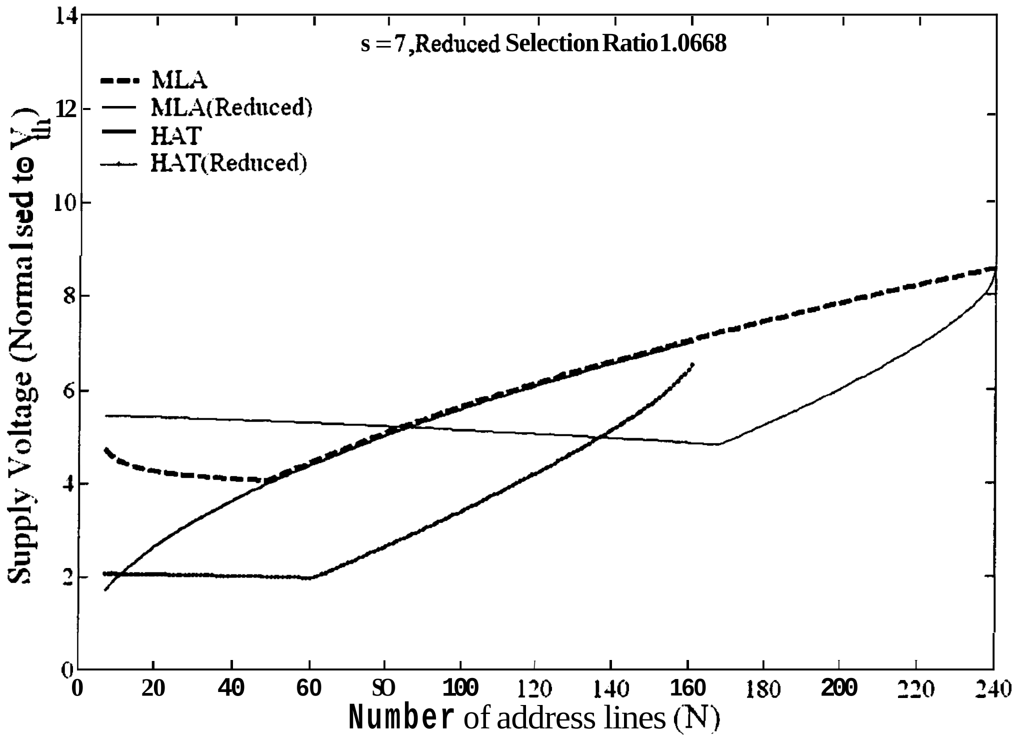

Figure 5-7 Supply voltage (Normalised to V_{th}) versus N for HAT and MLA when s = 7 and SR=1.0668.

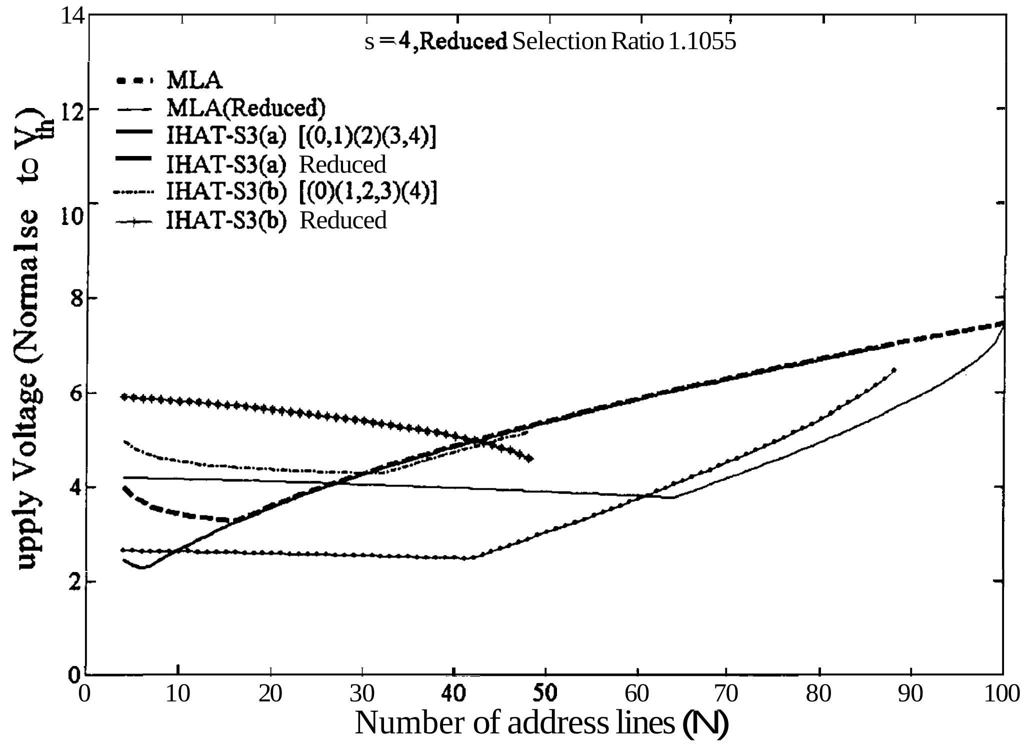

Figure 5-8 Supply voltage (Normalised to V_{th}) versus N for **IHAT–S3** and **MLA** when s = 4 and **SR=1.1055.**

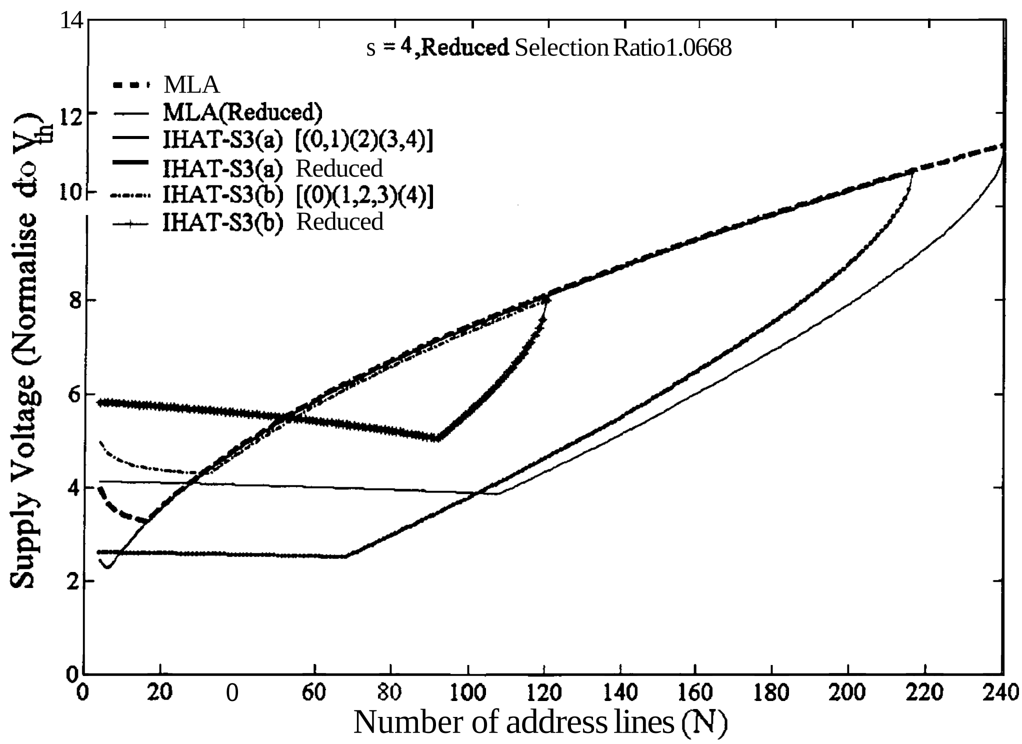

Figure 5-9 Supply voltage (Normalised to V_{th}) versus N for IHAT–S3 and **MLA** when s = 4 and **SR=1.0668.**

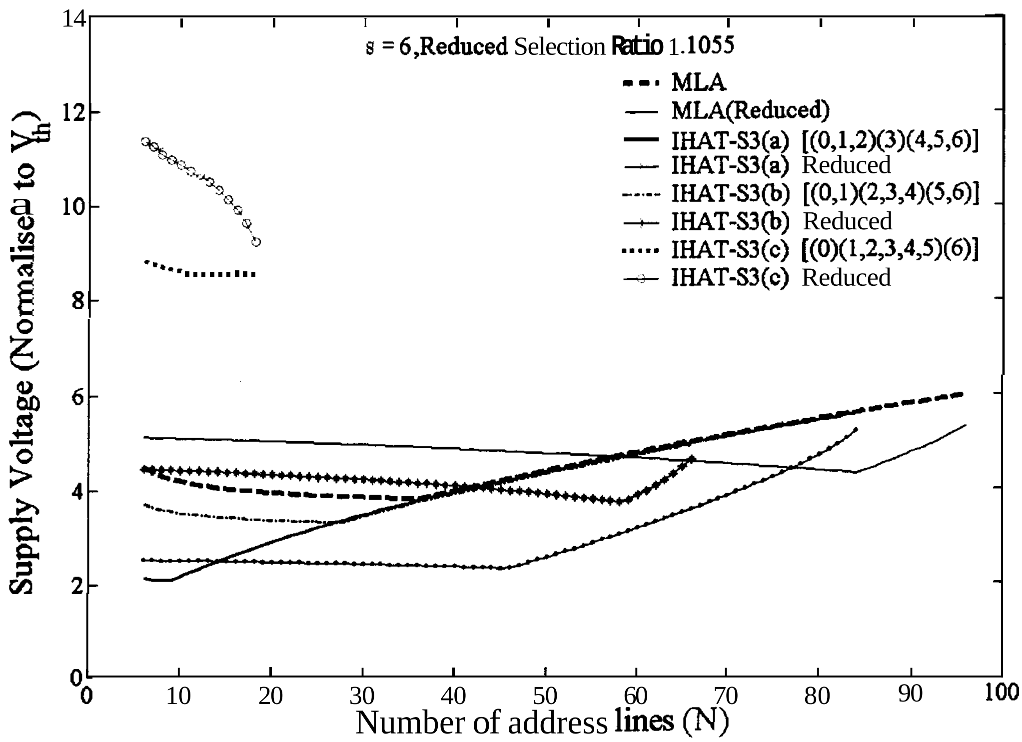

Figure 5-10 Supply voltage (Normalised to V_{th}) versus N for IHAT–S3 and MLA when s = 6 and SR=1.1055.

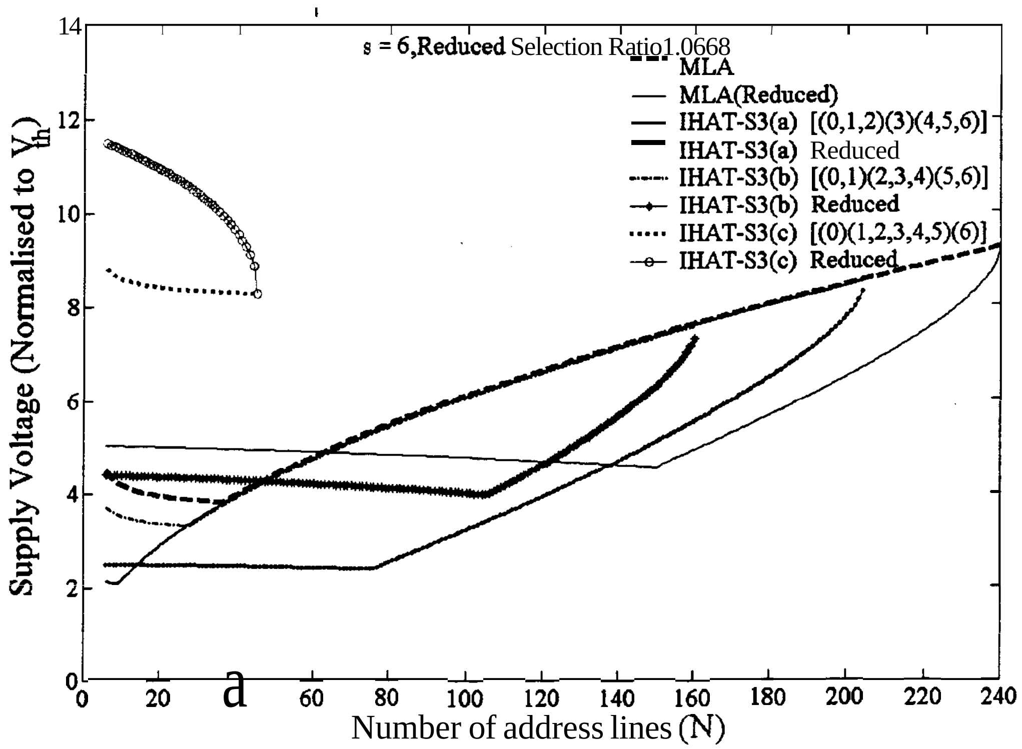

Figure 5-11 Supply voltage (Normalised to V_{th}) versus N for IHAT–S3 and MLA when s = 6 and SR=1.0668.

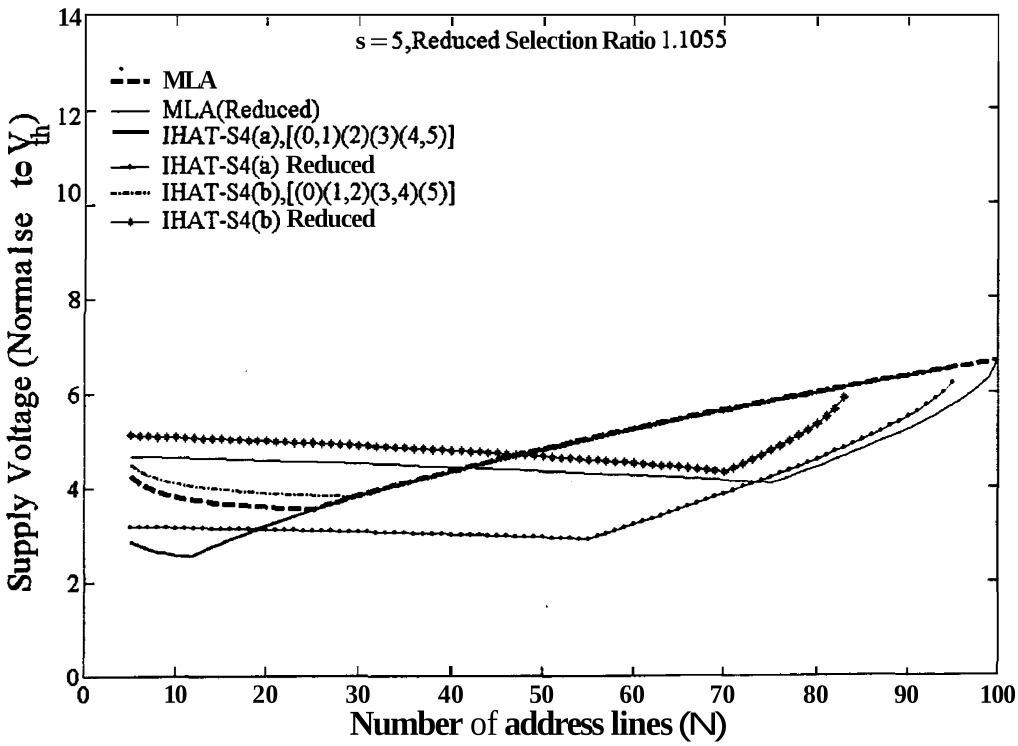

Figure 5-12 Supply voltage (Normalised to V_{th}) versus N for IHAT–S4 and MLA when s = 5 and SR=1.1055.

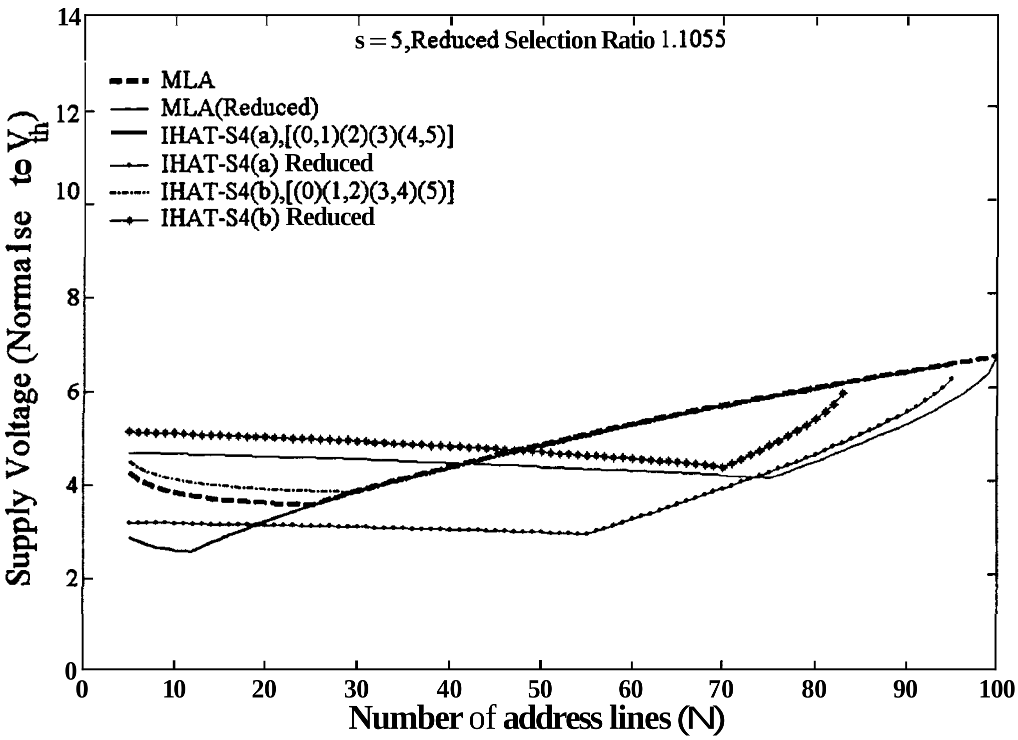

Figure 5-13 Supply voltage (Normalised to V_{th}) versus N for IHAT–S4 and MLA when s = 5 and SR=1.0668.

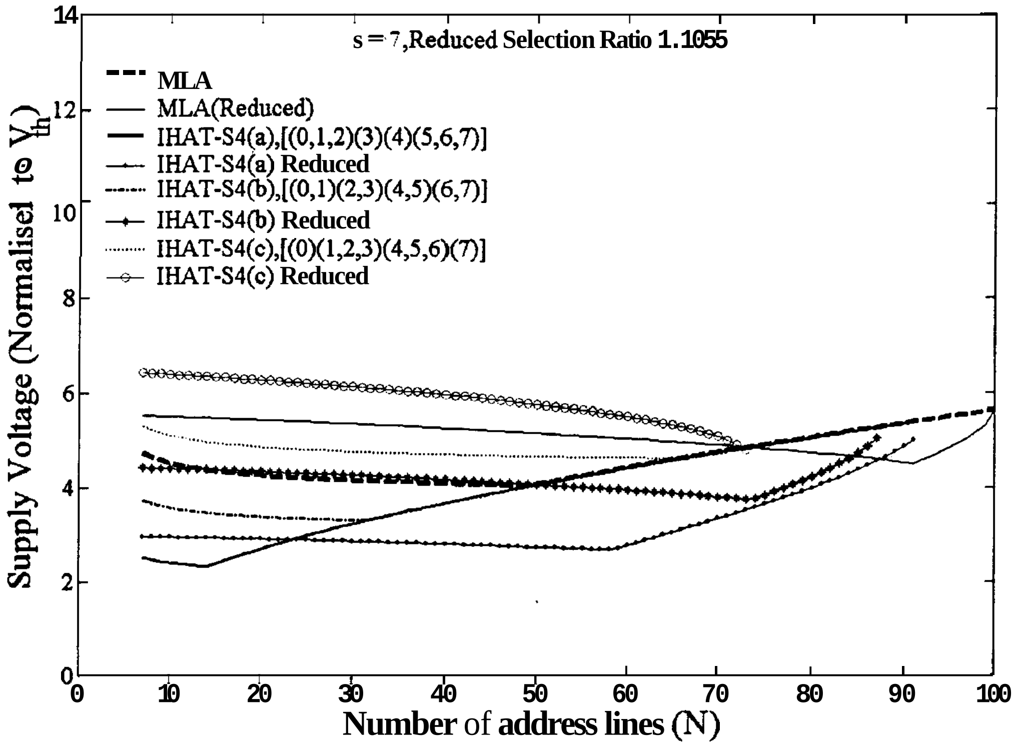

Figure 5-14 Supply voltage (Normalised to V_{th}) versus N for IHAT–S4 and MLA when s = 7 and SR=1.1055.

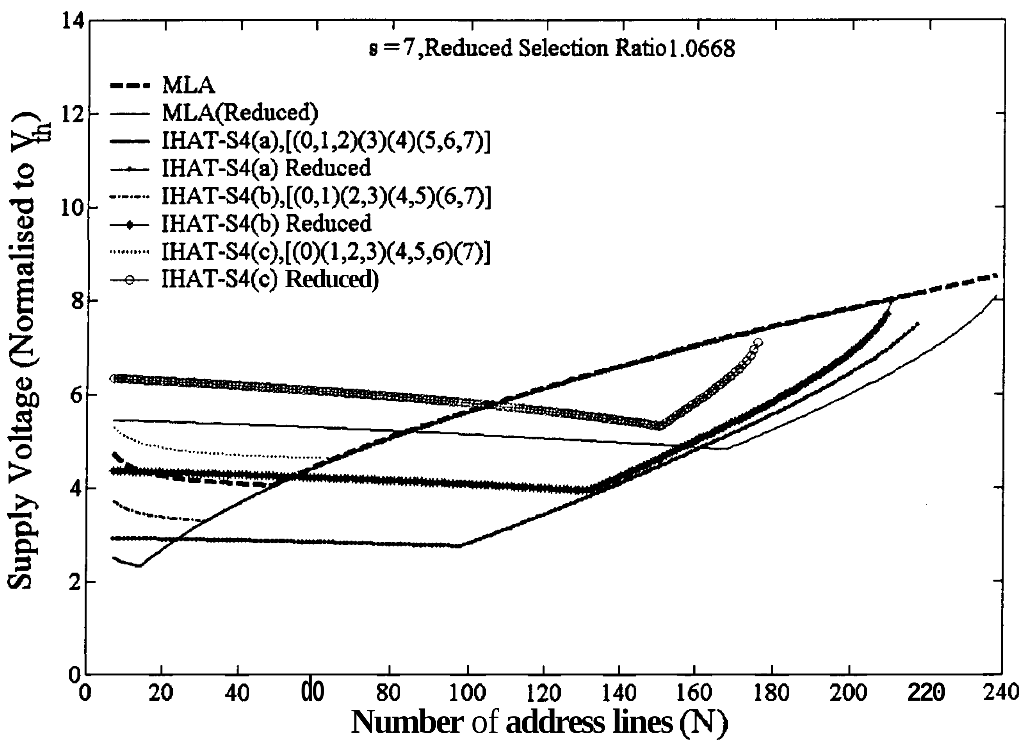

Figure 5-15 Supply voltage (Normalised to V_{th}) versus N for IHAT–S4 and MLA when s = 7 and SR=1.0668.

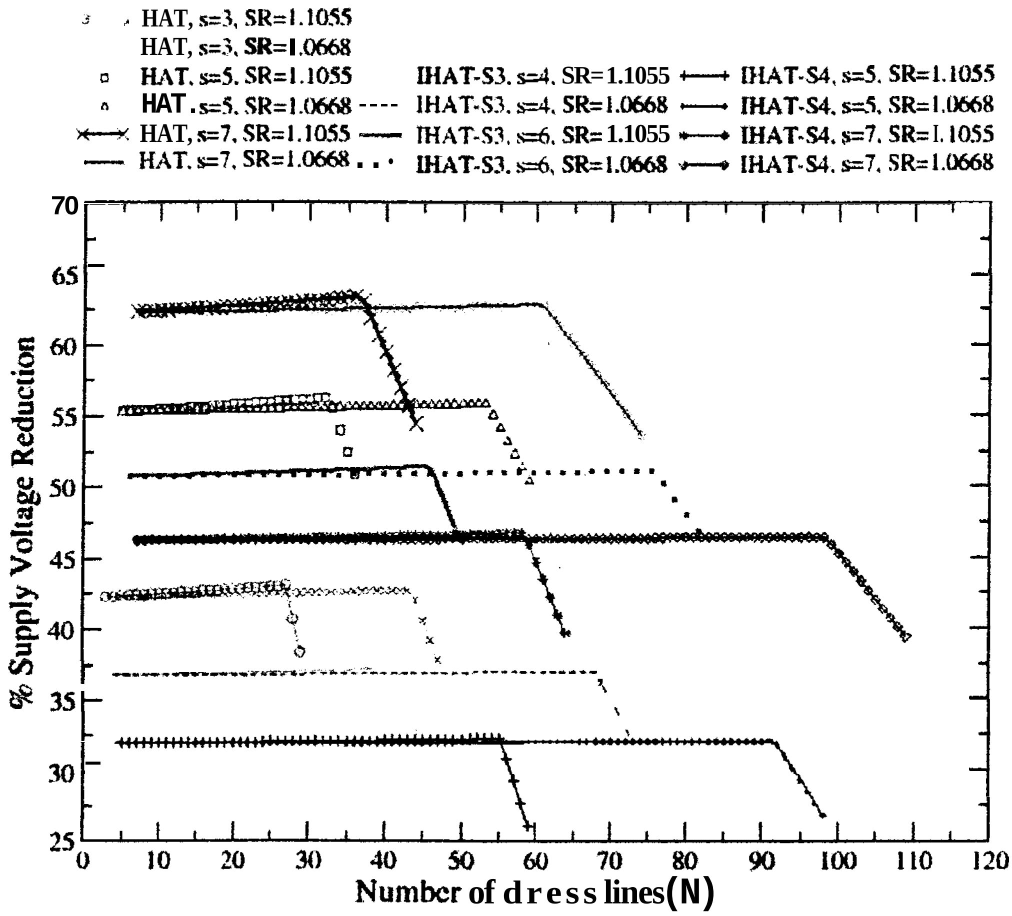

Figure 5-16 Percentage reduction in supply voltage versus number of address lines (N) in comparison with MLA.

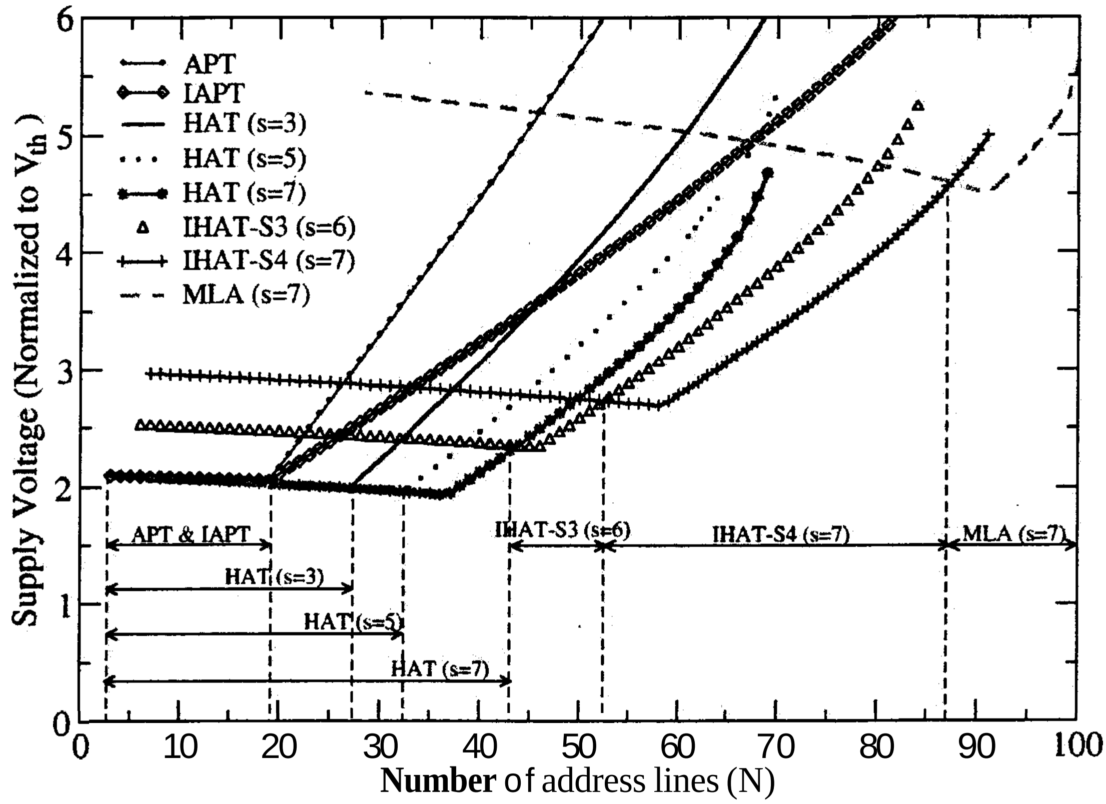

Figure 5-17 Supply voltage versus N for various addressing techniques indicating the range where in the supply voltage in the lowest for LC1.

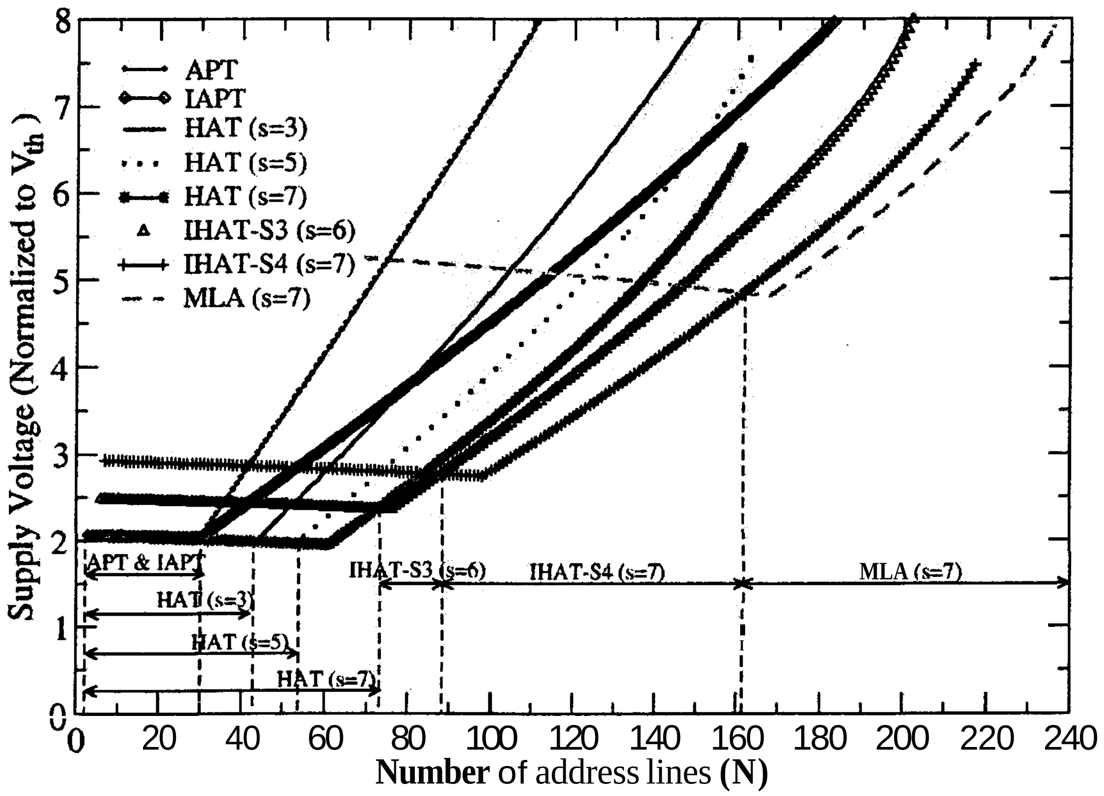

Figure 5-18 Supply voltage versus N for various addressing techniques indicating the range where in the supply voltage in the lowest for LC2.

Table 5-9

Hybrid Addressing Technique (HAT)								
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 5-10

Improved Hybrid Addressing Technique–S3 (IHAT–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 5-11

Improved Hybrid Addressing Technique–S4 (MAT–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