Finite State Machine State Assignment for Area and Power Minimization

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Outline

- Motivation
- Genetic Algorithm
- State Assignment for Minimized Area
- State Assignment for Low Power
- State Assignment for Minimized Area and Power.

Motivation

- State assignment of an FSM determines complexity of its combinational circuit, area and power dissipation of the implementation.
- FSM State assignment is an NP hard problem.
- Huge number of possible encoding combinations.
- Genetic algorithm has shown promising results in optimizing combinatorial optimization problems.
- Current set of heuristics vary in quality of results.

Genetic Algorithm (GA)

- GA is a non-deterministic iterative algorithm.
- GA iterates recursively between
  - Crossover
  - Mutation
  - Selection of next Generation
- The above operators are experimented with in the design of GA.

Chromosome Representation

PS	NS				z	Code-α
	I_a	I_b	I_d	I_c		
	$\overline{I_0 I_1}$	$\overline{I_0} I_1$	$I_0 I_1$	$I_0 \overline{I_1}$		$F_2 F_1 F_0$
A	C	A	D	B	0	100
B	E	C	B	D	0	111
C	C	D	C	E	0	000
D	E	A	D	B	0	110
E	E	D	C	E	1	010

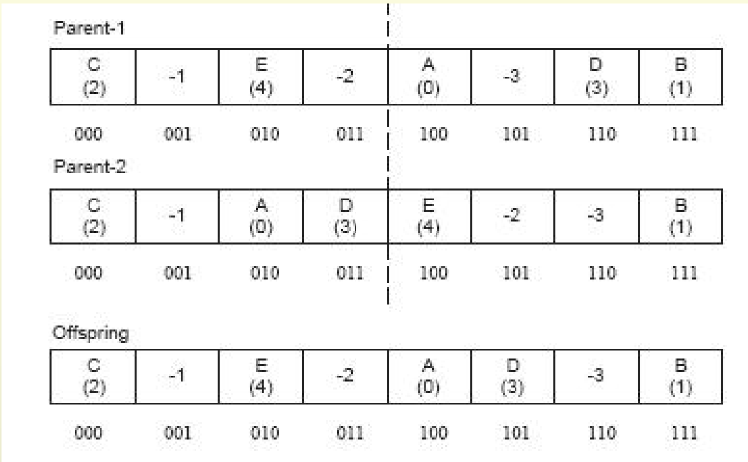
C (2)	-1	E (4)	-1	A (0)	-1	D (3)	B (1)
000	001	010	011	100	101	110	111

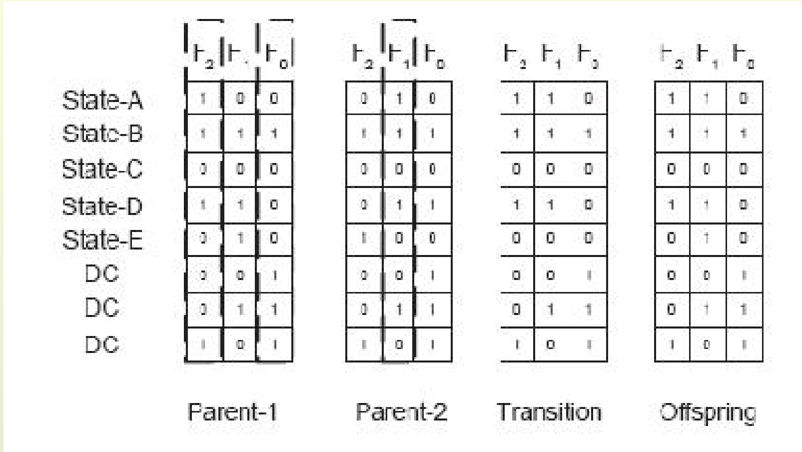
Representation - 1

	F_2	F_1	F_0
State-A	1	0	0
State-B	1	1	1
State-C	0	0	0
State-D	1	1	0
State-E	0	1	0
DC	0	0	1
DC	0	1	1
DC	1	0	1

Representation - 2

Crossover Operators



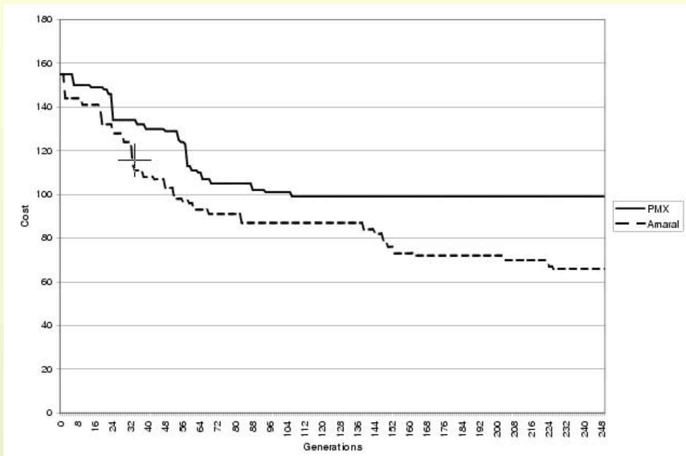


- PMX Crossover
  - Based on 1st type of chromosome representation
- Amaral Crossover
  - Based on 2nd type of chromosome representation

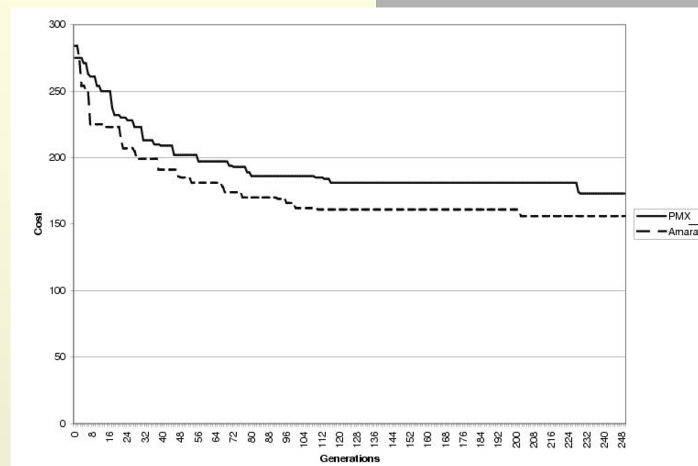
Other GA parameters

- Selection of Parents for Crossover
  - Roulette Wheel Mechanism
- Selection Mechanism for Next Generation
  - Half Greedy, Half Random
- Mutation
  - Swapping of two state codes
  - 20% mutation rate used
- Population size = 64.
- Maximum generation size = 350.

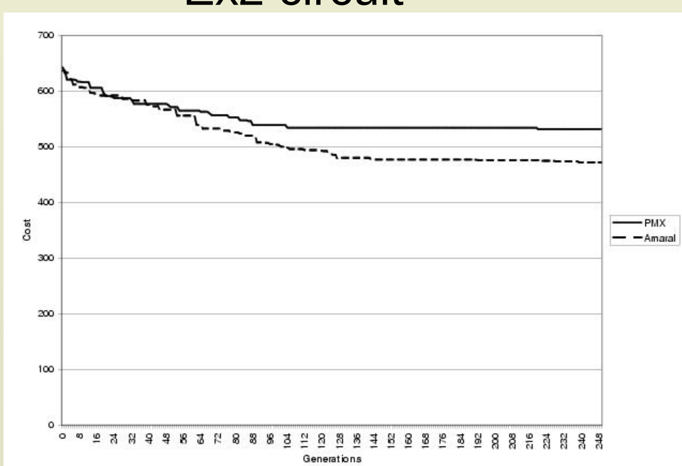
PMX vs Amaral



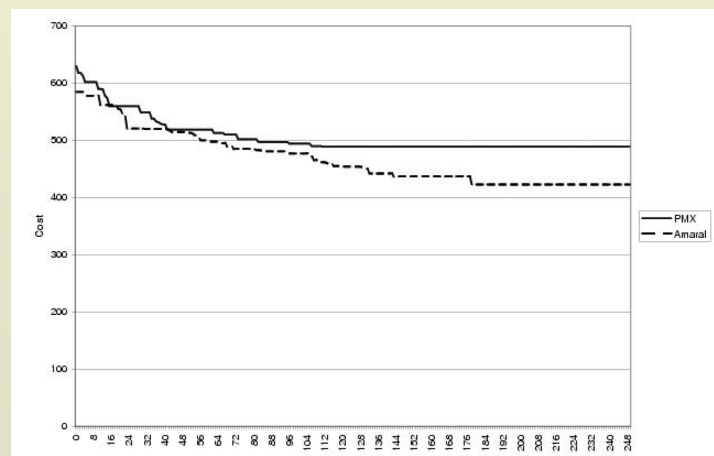
Ex2 circuit



Keyb circuit



Styr circuit



Planet circuit

State Assignment for Area Minimization

- Quality for multilevel implementation is measured in number of literals.
- Multilevel area can be minimized by extracting common expressions.
- Most of the work done tries to utilize this principle for multilevel optimization.
- Contemporary approaches towards multilevel FSM area minimization based on weighted-graph
  - weights between edges of states define the relative proximity in assignment (affinity).

State Assignment for Area Minimization

- Affinity cost modeled in adjacency graph used to minimize

$$\sum_{i=1}^{n_s} \sum_{j=1}^{n_s} A_{s_i s_j} \Delta(S_i, S_j)$$

  - $\Delta(S_i, S_j)$ hamming distance between codes of states s_i and s_j.
  - $A_{s_i s_j}$ affinity between states s_i and s_j.
- Several literal saving measures including Jedi, Mustang, Armstrong investigated.
- All these measures weakly correlate with the actual literal savings measure.

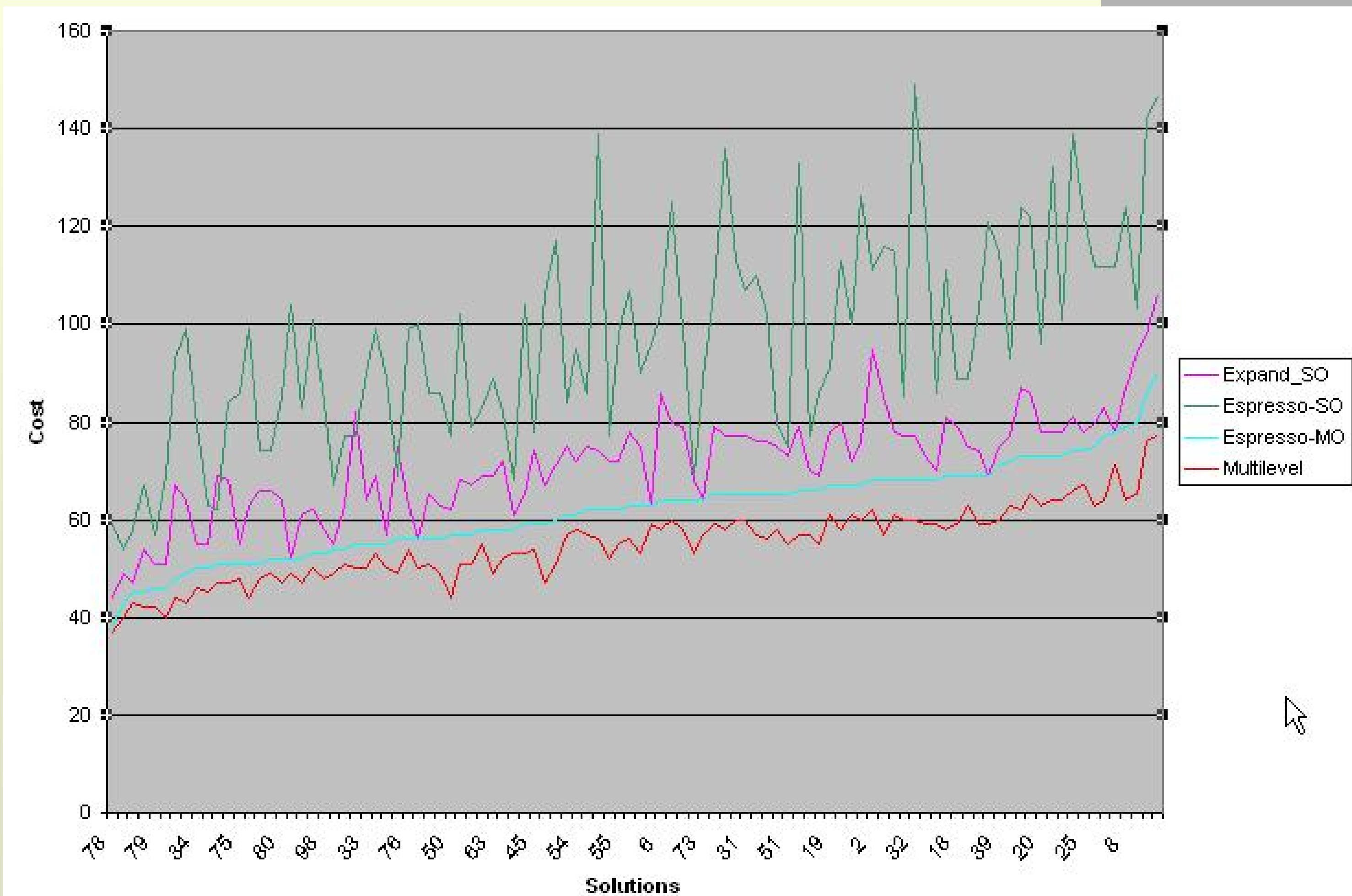
State Assignment for Area Minimization

- Need efficient but accurate measure for area estimation.
- Espresso is an efficient heuristic two-level minimization algorithm
- Espresso iteratively applies Expand, Reduce Irredundant functions
  - Expand: Makes a cover prime and minimal
  - Reduce: Tries to reduce the number of implicants such that the reduced cover still covers the function.
  - Irredundant: Removes redundant implicants that are covered within other implicants.

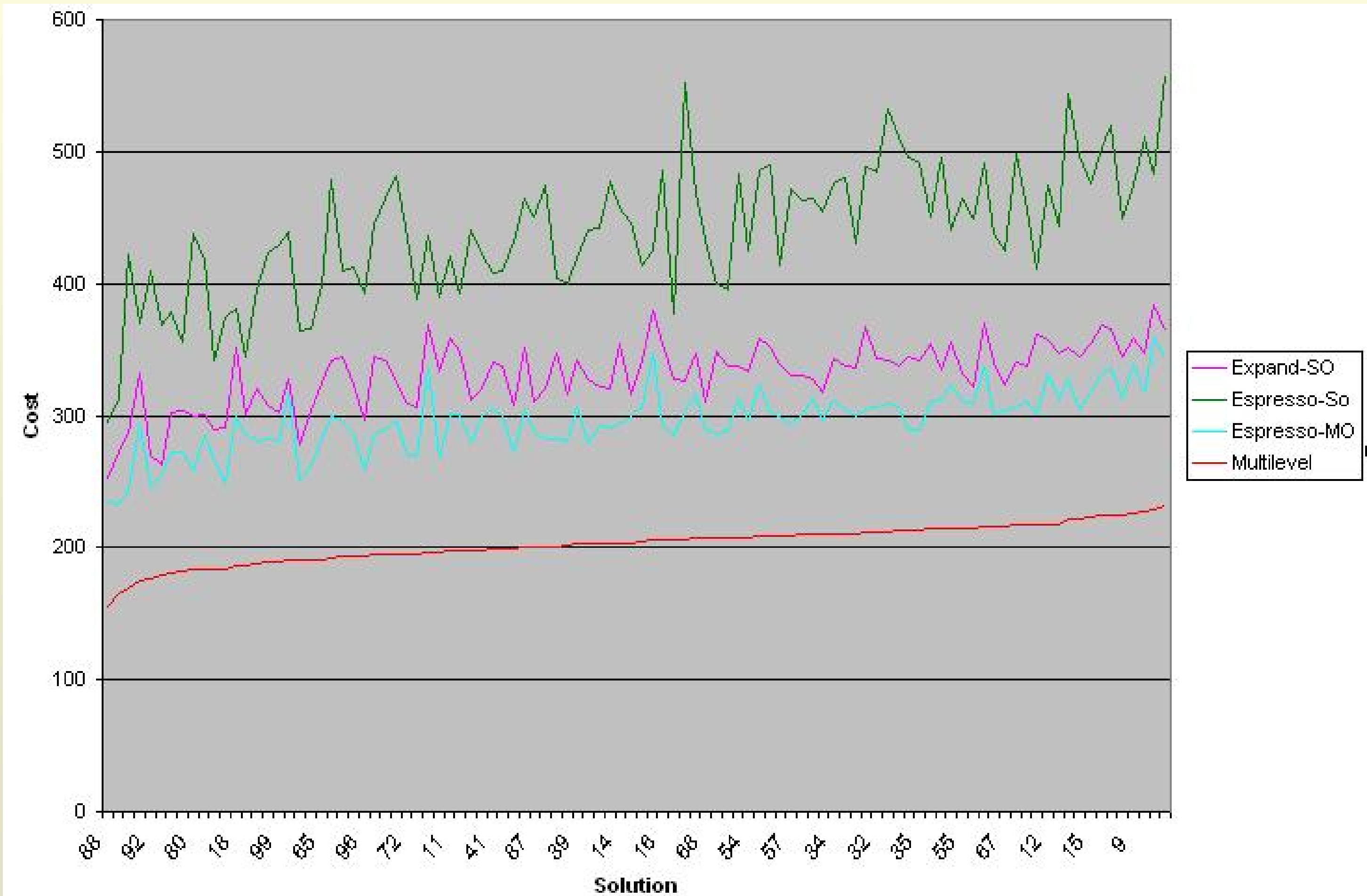
State Assignment for Area Minimization

- Espresso with single output optimization correlates with multilevel literal count.
- Propose the use of Expand with single output optimization for efficient area estimation.
- Expand is a subset of Espresso and more efficient.

Espresso/Expand Correlation ï Train11



Espresso/Expand Correlation ï Ex2



-SO Measure vs. Other Area Minimization Heurstics

Benchmark	EXPAND-SO	ESPRESSO-SO+FX	EXPAND-MO	Jedi ([1])	Nova	Mustang [2]	Armstrong([3])
bbara	56(52)	51	57	73(57)	57	64	59(86)
bbsse	110(105)	100	120	134(111)	140	106	127(180)
cse	198(228)	183	239	240(200)	214	206	220(NA)
dk14	104(86)	101	115	108(76)	111	117	124(NA)
donfile	87(72)	68	106	82(76)	154	160	171(NA)
ex2	78(68)	66	130	123(122)	127	119	131(NA)
ex3	56(48)	53	67	65(66)	71	71	68(NA)
keyb	199(205)	161	161	260(140)	201	167	334(NA)
lion9	11(11)	10	25	19(13)	27	17	27(21)
planet	486(436)	469	557	603(547)	591	544	607(NA)
pma	165(152)	153	189	263(NA)	241	NA	218(NA)
s1	227(105)	155	285	282(152)	340	183	291(NA)
s1494	570(624)	543	717	679(NA)	715	NA	696(NA)
s832	231(218)	215	307	357(NA)	274	NA	301(NA)
sand	498(494)	473	514	554(437)	558	462	619(NA)
shiftreg	2(2)	2	4	2(2)	2	2	2(10)
styr	419(429)	423	466	518(508)	502	546	546(NA)
tbk	353(268)	312	493	305(278)	365	547	711(NA)
traian11	22(20)	18	29	34(27)	32	37	32(47)
%Improvement		-8.89	15.48	17.63(6.51)	18	22.56	26.72(41.57)

State Assignment for Low Power

- Power is consumed due to logic switching in circuit.
- To reduce power dissipation in an FSM, one can:
  - Minimize switching activity at the flip-flops.
  - Minimize the capacitance on flip-flops being switched, i.e., fanout branches from flip-flops.
  - Minimize the combinational logic being switched.
- Average switching can be reduced if frequently visited states can be assigned codes with smaller hamming distance.

State Assignment for Low Power

- Minimum Weighted Hamming Distance (MWHD):

$$\sum_{i=1}^{n_s}\sum_{j=1}^{n_s} A_{s_i s_j}\Delta\left(S_i, S_j\right) \qquad A_{s_i, s_j} = P_{ij} + P_{ji}$$

  - P_{ij} is the state transition probability from s_i to s_j.
- Propose new cost function for low power, Minimum Weighted Fanout (MWF):

$$\sum_{i=1}^{n} T_i B_i$$

  - T_i is the flip-flop transition probability
  - B_i is the number of fanouts of flip-flop i

Power Minimization Results

Benchmark	MWHD		MWF		Jedi	
	Power	Area	Power	Area	Power	Area
bbara	214.7	82	150.5	55	187.7	74
bbsse	446.1	140	412.2	122	538.8	149
cse	528.9	217	424.8	211	495.8	251
dk14	661.2	140	561.4	103	714.4	157
donfile	895.9	206	513.7	109	380.8	89
keyb	655.3	263	645	237	767.6	260
lion9	142	20	116.7	19	145.6	19
planet	1788.6	656	1795.1	553	2001.5	675
pma	653.4	198	778	180	883.7	236
s1	1165.1	406	766.5	187	1205.3	353
s1494	1376.3	734	1553.1	625	1668.9	679
s832	922.1	368	677.5	271	1068.4	376
sand	1645.5	599	1541.4	559	1458.9	651
shiftreg	163.3	27	96.3	2	132.5	9
styr	1277.5	540	1062.9	431	1118.6	567
tbk	1682	630	1589.3	488	721.2	305
train11	180.4	38	136.3	23	218.2	35
Average	846.96	309.65	754.16	245.59	806.35	287.35

ignment for Minimized Area and Power

- Area and power objectives aggregated
  - MWFA = MWF x A
  - Ordered Weighted Averaging (OWA)
- In OWA, Max and Min fuzzy operators employed

$$\mu = \beta \times O(\mu_a, \mu_p) + (1 - \beta) \times \frac{1}{2}(\mu_a + \mu_p)$$

  - O is max/min type fuzzy operator
  - μ_i represents cost for area or power objectives
  - β is 0.5.

Minimized Area and Power Results

Benchmark	MWHD		MWF		Jedi		MWFA		MWF(Fuzzy-Max)		MWF(Fuzzy-Min)	
	Power	Area	Power	Area	Power	Area	Power	Area	Power	Area	Power	Area
bbara	214.7	82	150.5	55	187.7	74	181.2	65	181.2	58	181.2	58
bbsse	446.1	140	412.2	122	538.8	149	394.5	118	437.1	123	448.2	128
cse	528.9	217	424.8	211	495.8	251	391.3	209	455.2	205	459.9	210
dk14	661.2	140	561.4	103	714.4	157	561.4	103	551.3	101	579.2	115
donfile	895.9	206	513.7	109	380.8	89	474.1	100	355.2	82	295.8	75
keyb	655.3	263	645	237	767.6	260	517.3	215	535.6	210	511.7	192
lion9	142	20	116.7	19	145.6	19	100.8	15	105.3	16	129.9	11
planet	1788.6	656	1795.1	553	2001.5	675	1889.7	510	1702.5	470	1843.2	465
pma	653.4	198	778	180	883.7	236	693.1	165	651.2	155	675.2	145
s1	1165.1	406	766.5	187	1205.3	353	771.4	197	751.2	191	625.8	161
s1494	1376.3	734	1553.1	625	1668.9	679	852.4	569	838.2	530	1025.5	505
s832	922.1	368	677.5	271	1068.4	376	665.2	260	650.2	242	621.5	249
sand	1645.5	599	1541.4	559	1458.9	651	1617.2	585	1289.9	490	1352.2	498
shiftreg	163.3	27	96.3	2	132.5	9	98.8	4	96.3	2	96.3	2
styr	1277.5	540	1062.9	431	1118.6	567	1086.8	453	1022.3	432	1100	376
tbk	1682	630	1589.3	488	721.2	305	1766.6	556	1095.2	422	1350	398
train11	180.4	38	136.3	23	218.2	35	142.4	22	122.2	23	150.1	21
Average	846.96	309.65	754.16	245.59	806.35	287.35	717.89	243.88	637.65	220.71	673.28	212.29

Power and Area % Reduction vs. JEDI

	MWF(Fuzzy-Max)		Pedram [10]		Ciesielski [12]	IITG8 [13]	Almaini [11]	
	Power	Area	Power	Area	Power	Power	Power	Area
bbara	3.46	21.62	17.97	-10.14		16.07	-25.68	21.62
bbsse	18.88	17.45	18.37	6.56	5.66			
cse	8.19	18.33	12.15	-1.41		18.48	2.58	18.33
dk14	22.83	35.67	4.92	-0.98		16.19		
donfile	6.72	7.86	6.22	22.64			-5.57	7.86
keyb	30.22	19.23			35.56	20.87	2.53	19.23
lion9	27.68	15.79						
planet	14.93	30.37					-19.22	30.37
pma	26.3	34.32						
s1	37.68	45.89				-22.46	-7.32	45.89
s1494	49.78	21.94			6.89			
s832	39.14	35.64			7.75	26.68		
sand	11.58	24.73	10.52	16.12			-19.29	-30.32
shiftreg	27.32	77.78				-29.08		
styr	8.61	23.81				-9	9.16	23.81
tbk	-51.86	-38.36			5.03			
train11	44	34.28				11.61	13.2	34.29
%Improvement			2.09	73.9	29.31	74.74	130	24.36

Conclusion

- Genetically engineered state assignment solution for area and power minimization.
- Proposed efficient cost functions that highly correlate with actual literal count and power dissipation of a multilevel circuit implementation.
- Experimental results demonstrate effectiveness of proposed measures in achieving lower area and power dissipation in comparison to techniques reported in the literature.