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Multiobjective VLSI Circuit Partitioning Using ACO for Optimal Solution

Amit Prakash Sen, Atul Prakash, Praveen Kumar Singh, Dr. R. K. Lal

***Abstract*— The acceleration of the product to market cycle of VLSI based technology products dictates continuously refining design and implementation methodologies. Circuit partitioning is a physical design methodology which divides a given circuit into segments abiding by some constraints and meeting certain objectives such as minimizing the CutSet between the partitions, minimizing the delay between the partitions, maximizing the sleep time of the partition to minimize the power consumption and finding the time complexity of the algorithm.**

The circuit partitioning problem is NP hard; that means for this class of problems no algorithm of polynomial complexity was found. So a biologically inspired heuristic (ant colony) is used to solve such problem.

The Standard ISPD'98 benchmark formatted Net List files are used for testing and simulation. The simulation and algorithm are implemented in MATLAB Software which gives better results for all the circuits.

***Index Terms*— PSO, ACO, Cutsize, Sleep time, NP-hard**

I. INTRODUCTION

Present era VLSI chips contain millions of transistors. This has been achieved only due to the development of sophisticated design tools/software and highly scaled VLSI fabrication techniques. Such a highly integrated design can be handled through VLSI design tools that must be computationally fast and able to generate optimal designs. Partitioning is an important step in physical design of circuits. NP-hard problem of partitioning cannot be effectively solved by deterministic method. In this paper a heuristic iterative approach to solve the partitioning problem and simultaneously optimization of power, delay and cutsize is presented.

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Amit Prakash Sen, *Asst. Prof. ECE,B. A. College of Engineering & Technology, Jamshedpur, India.*

Atul Prakash, *Ph.D Scholar. ECE, Birla Institute of Technology, Mesra, Ranchi, India.*

.***Praveen Kumar Singh***, *Asst. Prof. ECE,B. A. College of Engineering & Technology, Jamshedpur, India.*

Dr. R. K. Lal, *Asos. Prof. ECE, Birla Institute of Technology, Mesra Ranchi, India.*

For complex digital logic circuits it is often essential to subdivide multi-million transistor circuit designs into manageable pieces. Partitioning is the one and only tool to break a large system into pieces to be implemented on separate interacting components and on the other hand it serves as an algorithmic method to solve difficult and complex combinatorial optimization problems as in logic or layout synthesis. Partitioning if done in a proper way can solve many design issues and simultaneously can reduce the delay, overall size of the circuit, the number of cutsize (or number of connections between two partitions) and can also lead the design process to design a low power consuming circuits

Kernighan and Lin [1] proposed the first heuristic search algorithm for bipartitioning with several times randomly generated initial partitions and to obtained the best solution based on swapping of vertices. Modified version [2] of [1] leading to a fast linear time algorithm for partitioning and improved time complexity but inefficient time complexity was improved. Krishnamurthy [3] by modified [2] introduce the concept of look ahead to choose the cell move. Multiway partitioning problem was effectively solved by recursive bipartitioning and improved time complexity [3].

Optimize the power and delay in VLSI with optimal sizing the transistor in a digital MOS VLSI circuit were proposed [4]. To perform multiway partitioning modified [3] by developing appropriate data structure and proved that the optimal number of gain levels necessary depends on the number of blocks to be partitioned net size and degree of distribution to the circuit network, but not on the size of the network [5]. One new methodology transforms the circuit optimization into multivariable optimization problem was shown to provide an optimum design with circuit analysis accuracy [6].

Kennedy and Eberhart [7] introduced a concept for the optimization of nonlinear function using particle swarm methodology, PSO is a robust stochastic optimization technique based on information sharing and movement of swarms. Another heuristic technique geometric partitioning were proposed [8] for partitioning of a system to maximize exploitable sleep time for low power synthesis with deactivate the memory refresh circuitry ,apply power down or disable clock signal during the inactive periods of operation of circuit elements and thus maximize the power consumption.

Various hypergraph partitioning algorithms were proposed based on successively hypergraph and fixed

vertices which reduces the complexity of partitioning problem [10] [11]. A multiobjective h-metis partitioning were proposed [12] for simultaneously cutsize and circuit delay minimization using memetic algorithm for VLSI physical design. Various optimization algorithms were proposed for power and delay minimization [13] [14].
Ghafari et al. [15] focused on minimizing the average power consumption in CMOS circuits. A discrete PSO algorithm was proposed [16] for the optimization of VLSI interconnections (netlist) bipartitioning and giving good result as compared to GA. Gill et al. [17] proposed multiway circuit partitioning using genetic algorithm with objectives of mincut, ratio cut minimization and shows good result. Shanavas et al. [18] discussed the memetic algorithm was used to optimize the various objective functions.
The different objective function that may satisfied by partitioning are:

1. Maximization of sleep time due to partitioning.
2. Minimization of number of cuts.
3. Minimization of delay due to partitioning.
4. The percentage of saving power should be larger than the percentage of consumed power during switching activities.
5. To reduce the fabrication cost with minimum area or as a balance constraints.
6. The number of terminals should not exceed the terminals available on PCB.

From the literature review it is found that the various researchers have applied various optimization techniques for the partitioning optimization problems with mixed results. In the present work excellent optimization method of Particle Swarm Optimization has been applied to partitioning optimization problems.

II. PROBLEM FOMULATION

With the advancements in VLSI technology the chip complexity is increasing, leading to more and more integration and increased design sizes. A huge chip estate is being occupied by interconnects, which leads to increased delay. Improved physical design tools, are necessary to handle these issues. Circuit partitioning plays an important role in physical design automation of very large scale integration (VLSI) chips. In VLSI circuit partitioning, the problem of obtaining a minimum cut is of prime importance. To enhance, other criterion like power, delay and area in addition to minimum cut is included. Circuit net list partitioning is an important step in VLSI physical design and involves the division of a circuit into smaller parts for ease of design and layout. The main objectives of circuit net list partitioning include minimization of number of interconnections between the partitions, minimization of delay due to interconnections between partitions & ratio-cut minimization and minimization of power consumption by maximizing the total sleep time of different partitions. Present work demonstrates the versatility of PSO for bi-partitioning to minimize the Interconnections also called cuts, delay and maximizing sleep time.
Circuit partitioning problem is a non polynomial hard problem cannot be effectively solved by deterministic methods. PSO is a stochastic algorithm can be used effectively for circuit partitioning. In this paper a heuristic approach is presented to optimize the three design issues the cutsize, delay and sleep time. In this paper all the experiments have been done on MATLAB R2010.

1. Mincut minimization

The numbers of interconnections among partitions have to be minimized. Reducing the interconnections not only reduces the delay but also reduces the interface between the partitions making it easier for independent design and fabrication. It is also called the mincut problem or minimization of the number of cuts.

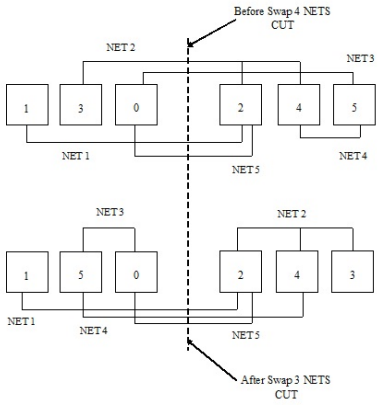

Figure 1 Circuit partitioning overview [Coe et al. (2004)]

The problem involves dividing the circuit net list into two subsets and some of the connections are also cut. The number of cut belonging in two different partitions is the cost of a partition, and this cost can be defined as follows

$$C = \sum_{i=1}^{k} \sum_{j=1}^{k} C_{ij} \ , (i \neq j) \quad (1)$$

where i , j are the vertices (nodes) of an edge (net)

C = cost of cut

C_{ij} = cost of an edge

The partitioning problem is to partition $'V'$ into $V_1, V_2, \ldots \ldots V_n$
Where $V_i \cap V_j = \emptyset$

$U_{i=1}^{n} V_i = V$
As the problem involves bipartitioning of a circuit, so equality condition must be satisfied as

$$\sum_{i=0}^{k} m_i = \sum_{j=0}^{k} n_j \quad (2)$$

Where, m_i & n_j are the nodes in two partitions [19].

2. Delay Minimization

The partitioning of a circuit might cause a critical path to go in between partitions a number of times. As the delay between partitions is significantly larger than the delay within the partition, it is an important consideration in circuit partitioning. Important considerations for partitioning constraints include minimization of delay due to partitioning.

First of all, the critical paths between the input/output ports (pads) are checked. The critical path is defined as the path having maximum delay between the I/O pads.

$$Delay = \max_{p_i \in P}(H(p_i)) \quad (3)$$

where $H(p_i)$=No. of times a hyper path, p_i is cut [19].
To calculate this delay we use the well-known Elmore Delay model. Our delay model has two components. The first component is the gate delay. For all gates we consider a typical intrinsic delay that is given for a typical input transition and a typical output net capacitance. The second component is the wire delay, which we approximate using the Elmore delay model. The Elmore delay for an edge *e* (an edge corresponds to the wire connecting the net source to one of its fanout sinks) is given by [12]:

$$Delay(e) = R_e\left(\frac{C_e}{2} + C_t\right) \quad (4)$$

$$R_e = L_{avg} + r_e \quad (5)$$

$$C_e = L_{avg} + c_e \quad (6)$$

where *Re* is the wire lumped resistance, C_e is the wire lumped capacitance, and C_t is the total lumped capacitance of the source node of each net, which is taken as zero [20]. To compute R_e and C_e we need the length of each edge. For that, we use the statistical net-length estimation method, also known as MRST (Minimum Rectilinear Steiner Tree) model. According to this method the average length of a net, connecting *m* cells enclosed in a rectangular area with width *a* and height *b*, is given by:

$$L_{avg} = (\alpha.m^{\gamma} - \beta)\frac{a.b}{a+b} + (a+b) \quad (7)$$

where α, β, and γ are fitting parameters computed as $\alpha \approx 1.1$, $\beta \approx 2.0$, and $\gamma \approx 0.5$, m is the number of nets, a and b are the net bounding area dimensions. During recursive partitioning, when a net is cut, it is assigned a certain wire delay that will be used to re-compute all delays on the paths that include that net. The higher the level in which a net is cut during recursive partitioning, the greater the back-annotated wire delay has to be. In our case, any net that is cut during the first bi-partitioning step is assumed to be bounded by a rectangular area which is the same as the chip area and for simplicity we consider an aspect ratio equal to 1.The delay of each net is set only the first time when it is cut. In our experiments we consider a 0.18µ copper process technology (unit length resistance r_e= 0.115, unit length capacitance c_e= 0.00015) [21].

3. Sleep Maximization

The idea about the low power consuming circuit partitioning is that for a given period of time if all the elements in the particular partition is idle then we can send that partition into sleep mode so that the power is save during the time interval. The idea is exploited in the Figure 1.It can be notice that higher discrete overlapping of idle time means greater number of switching and a more complicated control circuitry. Hence the gain function $G(S_1, S_2)$ should be an increasing function of t_i and a decreasing function of sw_i. For a bi-partitioning problem the gain function that needs to be maximized is defined as:

$$f = t_1 + t_2 - \beta(sw_1 + sw_2) \quad (8)$$

where t_i ,is the sleep time for i^{th} partition and sw_i is the switching activity of the i^{th} partition

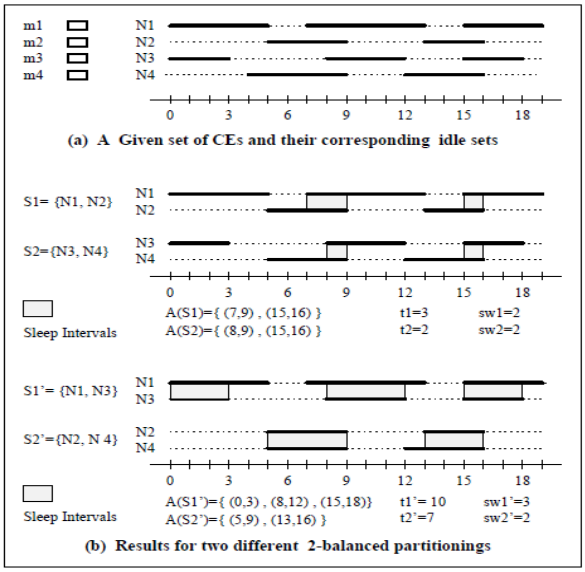

Figure 2 Partitioning to maximize sleep time [8]

In equation (8), summation of *ti's* accounts for the savings in power consumption due to sleep mode operation the partitions and β *(sw_1 + sw_2)* accounts for overhead in power consumption due to extra control circuitry. Parameter 'β' controls relative significance of power savings (*ti*) and the overhead terms (*swi*) and depends on the available technology and type of circuitry in modules *m*.

If P *and* P' be the power consumption with and without using sleep mode then

$$P = \frac{[P_0(T - t_1) + P_s t_1] + [P_0(T - t_2) + P_s t_2]}{T} = \frac{P_0[2T - (t_1 + t_2)] + P_s(t_1 + t_2)}{T}$$

and

$$P' = \frac{[(P_0 T) + (P_0 T)]}{T} = 2P_0 \quad (9)$$

Where P_0 *and* P_s be the power consumption of each partition in operating and sleep mode and T is the operation time.
Then the percentage of power saving can be given by [8],

$$S = \frac{P' - P}{P'} \times 100$$

For a given memory chip typically we have $\frac{P_0}{P_s} > 25$, [8] therefore the percentage of power consumption would be atleast:

$$S_{min} = 48 \times \frac{t_1+t_2}{T} \quad (10)$$

The combined objective function used to optimization of the above stated quantities is taken as,

$$C_c = max\left[\left(\gamma_s\left(\sum_{i=0}^{p} t_i - \beta \sum_{i=0}^{p} sw_i\right) + \gamma_c\left(\sum_{i=0}^{k} \sum_{j=0}^{k} y_{ij}\,(i \neq j \times 1ReCe2+Ct \quad (11)$$

Where $\gamma_s and\ \gamma_c$ are the weight given to the sleep time and mincut, y_{ij} is the inverse of C_{ij} .

III. SOLUTION METHODOLOGY

In the present work, ACO algorithm for optimization of multimodal continuous functions is proposed.

ACO is based on the ant intelligence, which can be applied into both scientific research and engineering use. It has no overlapping and mutation calculation. The search in this technique is carried out by the pheromone generated by the ants. During the development of several generations, only the most optimist ant can transmit information onto the preceding ant, and the speed of the researching is very fast. The algorithm is comparatively easy than the other intelligence based search algorithm as it adopts the real number code, and it is decided directly by the solution. The number of the dimension is equal to the constant of the solution.

The PSO algorithm easily suffers from the partial optimism, which causes the less exact at the regulation of its speed and the direction. Again it cannot be work out for the problem having scattering optimization, non-coordinate system such as the solution to the energy field and the moving rules of the particles in the energy field

The demerits which have been possessed by the PSO can easily be overcome by applying the ACO algorithm as it has Inherent parallelism and positive Feedback accounts for rapid discovery of good solutions. Furthermore it can be used in dynamic applications (adapts to changes such as new distances, etc). Applying ACO can lead to some more difficulties such as it has random decision making ability which is not independent. Again the probability distribution changes by iteration.

In this, ACO is applied for global optimization by updating positions of ants to attain rapid convergence. One of the advantages of ACO is that it takes real numbers as ants. It is not like GA, which needs to change to binary encoding, or special genetic operators have to be used. The searching is a repeat process, and the stop criteria are that the maximum iteration number is reached or the minimum error condition is satisfied.

In ACO, the potential solutions, called "ANTS" move in a one-dimensional path, to discover an optimal or sub optimal solution by competition as well as co-operation among themselves. The system initially has population of random solutions. Each ant is given a random position in d-dimensional problem space. The position (χ_{id}) of each ant in dimension d is updated based on its previous position and the density of pheromone generated by the ant, the previous best ant location, *pbest* (p_{id}) and the previous global best location of an ant in the population, *gbest* (p_{gd}). [24]

The basic concept lies in moving each ant towards its pbest and gbest locations at each time step. The main three factors on which ACO depends are: (1) The knowledge of the environment (explorative factor); (2) The individual's previous history of states (cognitive factor); (3) The previous history of states of the individual's neighborhood (social factor).

ACO works in three steps:

1. Construct Ant Solutions(which has been found using PSO)
2. Daemon action and
3. Updating of Daemon

An Ant will move from node i to j with probability

$$P_{i,j} = \frac{\left(\tau_{i,j}^{\alpha}\right)\left(\eta_{i,j}^{\beta}\right)}{\sum\left(\tau_{i,j}^{\alpha}\right)\left(\eta_{i,j}^{\beta}\right)} \quad (14)$$

Where,

$\tau_{i,j}^{\alpha}$ *is the amount of pheromonr on edge* i,j

$\eta_{i,j}^{\beta}$ *is the desirability of edge* i,j $\left(typically \frac{1}{d_{i,j}}\right)$

α *is a parameter to control the influence of* $\tau_{i,j}$

β*is a parameter to control the influence of* $\eta_{i,j}$

α *and* β *has been taken eaqul to* 0.5 *for this experiment*

Amount of pheromone is updated according to the equation

$$\tau_{i,j} = (1-\rho)\tau_{i,j} + \Delta\tau_{i,j} \quad (15)$$

Where,

ρ *is the rate of pheromone evaporation*

$\Delta\tau_{i,j}$ *is the amount of pheromone deposited, typically given by*

$$\Delta\tau_{i,j}^{k} = \begin{cases} \frac{1}{L_k} & if\ ant\ k\ travels\ on\ edge\ i,j \\ 0, & otherwise \end{cases},$$

Where,

L_k*is the cost of the* k^{th} *ant's tour (typically length)*

Pheromone values are updated by all the ants that have completed the tour

$$\tau_{i,j} \leftarrow (1-\rho) + \sum_{k=1}^{m} \Delta\tau_{ij}^{k}, \quad (16)$$

Where *m* is the number of ants.

IV. RESULTS AND DISCUSSION

As the objective of the paper is to optimize the interconnections, the delay and the sleep time between two partitions (bi-partitioning), all the parameters have been optimized simultaneously in this work. First of all, the interconnections, delay and sleep time were calculated before applying the proposed ACO approach; then the

proposed approach was applied to optimize all the parameters simultaneously with 50% weight to mincut and the sleep. The coding was done using MATLAB R2010. A number of netlists consisting of 10-25 nodes were used for this purpose. PSO algorithm has been applied to all the aforesaid netlists; the results of few (showing the best results) are shown in the Table 1. From Table 1, it is seen that the proposed approach has been exhaustively tested and results have been obtained on circuit netlist files of varying size ranges. The proposed approach performs better overall size ranges. The computational time for calculation of the sleep time is taken as 100 clock period.

The interconnection, delay and sleep time when optimized simultaneously as a multi-objective fitness function, with 50% weight to sleep and mincut, the two quantity mincut and delay try to minimize and the sleep time try to be maximize and finally become stagnant as the number of iterations goes on. As shown in Figure 3 the interconnections minimize, delay minimizes and the sleep time maximizes as the iteration goes on, and finally become constant. It means that there is no further scope of optimization and are the ultimate results of interconnections, delay and sleep time.

V. CONCLUSION

VLSI circuit bi-partitioning using Multi-objective PSO Algorithm have been proposed for mincut and circuit delay minimization along with maximization of sleep time. The advantages of the proposed PSO approach are:

(1) It is fast, thus applicable to large-sized circuits.

(2) It performs better suitable partitioning, as it optimizes all the parameters with some cutsize, delay and sleep time trade-off. The proposed approach is tested on various circuit partitioning instances (netlists) given in ISPD'98 Benchmark Suite.

The Particle Swarm Optimization algorithm applied to VLSI partitioning produces a very good result of these three objectives simultaneously .In this paper the sleep time maximization along with minimization of cutsize and delay were explored. This triple objective function was separately formulated and then combined into one objective function. The combined problem is NP hard, hence heuristic approach was successfully introduced. There is an average improvement of 38 percent in cutsize, 65.67 percent in delay and in sleep time 43.36 percentage improved simultaneously for the netlist series used in Table 1.

As compared to GA the better results shown by this proposed algorithm. The comparison of results obtained through the proposed algorithm is better than the [15] as objectives of sleep time and mincut and also one more objective delay find out in this paper and shows a very good improvement. Moreover, results obtained show the versatility of the proposed method in solving non-polynomial hard problem of circuit netlist partitioning. It is proved that PSO approach is an excellent method of global search to achieve better solutions.

VI. FUTURE SCOPE

There are many ways to extend the proposed work. The delay optimized is the net based delay. The same approach can be used to optimize path based delay. After finding path delay, combined net and path based delay can be calculated by giving weights to each delay. Then, the proposed PSO approach can be applied for mincut and combined delay minimization with sleep time maximization. This PSO is used to solve two-way circuit partitioning problem. The results can be improved by combining it with other evolutionary algorithms to make hybrid PSO. The algorithm can also be improved by multi-way partitioning techniques and multi-point crossover with different selection methodologies.

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Mr Amit prakash Sen had done his B.tech from Biju Patnaik university of Technology, Rourkela and received his M.tech degree from West Bengal University of Technology, Kolkata. Mr. Amit Prakash Sen worked as a Project Engineer in SkyVoice Telecom Pvt. Ltd in the Year 2009. Thereafter he joined to Shniwal Enterprises Pvt. Ltd. In Year 2010. After then hemoved in the field of teaching and joined B.I.T Sambhalpur as a Lecturer in the year 2010. From 2011 he is working in B.A. College of Engineering & Technology, Jamshedpur. Presently, he is working as an Asst. Professor in the Dept. of Electronic & Communication Engineering. His field of research is VLSI and he is working on VLSI circuit partitioning.

Atul Prakash Pursued his B.E. degree from The University of Burdwan , West Bengal and M.Tech Degree from Guru Nanak Dev Engineering College, Ludhiana, Punjab. After Completing his master degree he joined B. A. College of Engineering & Technology, Jamshedpur in the capacity of Assistant Professor in the year 2010. Then he moved to pursue his Ph.D at Birla Institute of Technology, Mesra, Ranchi under the guidance of Dr. R. K. Lal in the year 2014. His research area includes the optimization technique for engineering design and at present hi is working in the field of VLSI Design. He has published several research papers on VLSI Physical design optimization.

Praveen Kumar Singh has completed B.E degree in Electronics & Communication Engineering from Thapar Institute of Engineering & Technology (Deemed University), Patiala, Punjab and pursued M.E in Microwave Engineering from Jabalpur Engineering College under RGPV,Bhopal. He joined B.A. College of Engineering & Technology as a Assistant Professor in Electronics & Communication Engineering Department in the year 2010 and still working there. His research area of interest includes antenna design, digital signal processing and microprocessor & peripheral devices.

Dr Rajesh Kumar Lal has received his postgraduate degree from D.D.U. University, Gorakhpur and received his Ph. D Degree from Department of Electronics Engineering, IT, BHU, Varanasi. After accruing his Ph. D. in 2005, Dr. Lal joined BIT Mesra, Ranchi as lecturer under EFIP Program of AICTE and currently working as Associate Professor. Dr. Lal has more than ten year teaching and research experience. He also received CSIR-SRF fellowship in year 2003-2005. Semiconductor and optoelectronic devices are the main area of interests of Dr. Lal and his field of research is the Modelling of Infrared Detectors. Dr Lal work on modeling of InAsSb and HgCdTe based Infrared Photodetectors and QWIP. Dr. Lal also worked in field of VLSI design and published quality papers. His research findings appear in a wide variety of reputed journals such as IEE proceeding of optoelectronic (IEE), Infrared physics and Technology (Elsevier), Progress in Crystal Growth and Characterization of Materials (Elsevier], Optical and Quantum Electronics, Infrared and millimeter wave etc. Dr. Lal is a Member of IEEE, AM of Institution of Engineers (India), MIETE, LMISTE. Dr Lal has worked as reviewer for international conferences and journals and also chaired the session.

TABLE 1

S. N.	File Name	Before optimization			After optimization			Percentage improvement			
		Min-cut	Delay(ps)	Sleep	Mincut	Delay(ps)	Sleep	Min-cut	Delay	Sleep	Power
1.	Spp_N10_E11_R1_6866	5	1.0656	30	3	0.0177	47	40	98.33	56.67	22.56
2.	Spp_N16_E17_R2_1403	11	12.4628	10	3	0.0177	17	72.72	99.85	70.00	8.16
3.	Spp_N18_E17_R1_3306	9	7.8305	5	5	1.0656	9	44.44	86.39	80.00	4.32
4.	Spp_N20_E19_R2_1038	9	7.8305	5	4	0.2367	7	55.55	96.97	40.00	3.36
5.	Spp_N20_E20_R1_1344	18	32.1605	4	8	5.7680	7	55.55	82.06	75.00	3.36
6.	Spp_N20_E20_R2_942	16	26.1130	5	8	5.7680	9	50.00	77.91	80.00	4.32
7.	Spp_N21_E18_R2_1659	14	20.3654	3	6	2.3267	4	57.14	88.58	33.33	1.92
8.	Spp_N22_E22_R2_1232	18	32.1605	2	11	12.4628	4	38.88	61.25	100.00	1.92
9.	Spp_N23_E27_R2_1796	22	44.9729	6	14	20.3654	8	36.36	54.72	33.33	3.84
10.	Spp_N24_E25_R3_823	16	26.1130	3	8	5.7680	4	50.00	77.91	33.33	1.92
Average		**13.8**	**21.11**	**7.3**	**7**	**5.38**	**11.6**	**50.06**	**82.39**	**60.16**	**5.56**

Mincut, delay and sleep time for different circuits using ACO approach for partitioning