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Potential Methods for Calculating Clock Skew

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Abstract **Some studies such as Aoki measure clock skew by filtering outliers by selecting the minimum offset that is collected using linear regression to calculate the slope of the accumulated minimum offset. Huang who uses the QPM (Quick Piecewise Minimum) algorithm to calculate the skew of the minimum offset at the beginning and end of the collected offsets and Moon's research that uses the LPA (Linear Programming Algorithm) algorithm which determines the clock skew of the line gradient that is below the offset. In addition, there are several methods that have the potential to be used in measuring clock skew including ant colony, bee colony, particle swarm, and also genetic algorithm. From these several methods, one method that has potential as a method that can be used for measuring clock skew will be selected. The method that can be used is particle swarm optimization because it is considered more efficient and flexible and easy to implement with few parameters used.**

***Key words*: Clock Skew, Ant Colony, Bee Colony Particle Swarm, Genetic Algorithm**

I. Introduction

Clock skew or the difference in clocking speed between two digital clocks, has been studied extensively over the last few decades, two properties of clock skew were identified [1]: stability over time and the ability to differentiate between the two devices. These properties make clock skew a potential candidate for device fingerprinting and physical device identification. Likewise, several studies [2] exploit clock skew to secure time synchronization between sensor nodes in a wireless sensor network. The clock skew measurement is initialized by collecting the time stamp sent from the device. Measurements can actively send Internet Control Message Protocol (ICMP) requests to devices, and collect time stamps from response packets [3].

Many experts researching clock skew measurements such as Paxson who complete the oulier filter using the median line procedure [4] which draws the skew line on the part of the cluster offset, Aoki who proposed the outlier filtering method [5] by selecting the minimum offset collected using linear regression to calculate the slope of the accumulated minimum offset and Huang who used the QPM (Quick Piecewise Minimum) algorithm [6] to calculate the skew of the minimum offset at the beginning and end of the segment. offsets collected and Moon's research that uses the LPA (Linear Programming Algorithm) [1] algorithm which determines the clock skew of the gradient of the line that lies below the offset. All existing methods focus on achieving an accurate clock skew in the presence of outliers by utilizing the offset characteristics that converge on the cluster bounded at the bottom [7]. However, the most widely adopted method is LPA, because the results are not significantly affected by outliers [1]. The hough transform research that combines the concept of clock skew to increase the measurement of clock skew when the lower limit is unstable due to the presence of low outliers in short time measurements is very suitable for security applications such as device fingerprinting, which requires a wireless network connection with high jitter [7]. To add a reference to methods that can produce stable and accurate clock skew measurements, this journal will discuss several methods that can be potential to be used in measuring clock skew values, including the ant colony method which can determine cluster offsets with the shortest path for searching for food in ants, particle swarm which determines the location or position of food as a cluster offset by searching for food in a repeated way to narrow the food search area and get the optimal location of food, bee colony searches for food randomly and can be used for a wider range, and genetics algorithm inspired by the theory of evolution which is then adopted into a computational algorithm to find a solution to a problem in a more natural way.

II. Literature Review

Clock skew occurs when clock signals arrive at adjacent storage elements sequentially at different times. Although it has been shown that intentional clock skew can be used to increase the clock frequency of a synchronous circuit [8], clock skew is usually minimized when designing a clock distribution network, as unintentional clock skew due to processing parameter variations can limit the maximum operating frequency, as well as cause failure. circuit regardless of clock frequency (i.e. race condition). In [1,2], it is shown that double clocking (the effect of triggering the same clock pulse of the same data into two adjacent storage elements) can be prevented when clock skew between these storage elements satisfies the equation: $T_{Skewij} \geq - T_{PDmin}$,

T_{PDmin} is the minimum propagation delay of the path connecting the two storage elements. Furthermore, it is also shown in [1,2] that zero clocking (data reaching the storage element late relative to the clock following pulse) is prevented when: $T_{Skewij} \leq T_{CP}$ - T_{Pdmax}

Where T_{CP} is the clock period and T_{PDmax} is the maximum propagation delay of the data path connecting the two storage elements.

The limit of the two inequalities,

$T_{Skewij(min)} = - T_{PDmin}$ and $T_{Skewij(max)} = T_{CP} - T_{PDmax}$,

defines a valid clock skew region for each pair of adjacent storage elements, which is called the allowable range [7] or certainty region [8]. Violation of the lower limit causes circuit failure while violation of the upper limit of the clock frequency of the circuit. Based on these observations, process variation, tolerance, calculation of the optimal clock skew. The problem can be divided into two sub-problems:

1. Specifies a minimum clock period that defines the permissible valid range for the two storage elements in the circuit.
2. Determine a minimum width for each allowable range so that unacceptable variations in the target clock skew remain within the limits of a allowable range.

Research using Ant Colony Optimization (ACO) is a heuristic method that adapts the behavior of ants to solve problems related to discrete optimization [9]. Ants implement a special chemical compound pheromone, where this compound serves to provide a signal that distinguishes the path between the food source and their colony. The path is then used as a reference by the next ant to find food. This is because pheromones increase the likelihood of a pathway being selected. ACO has several advantages that can be used to solve various Non Polynomial or NP problems [9]. These problems include traveling salesman problem (TSP), edge detection, network packet routing (NPR), vehicular routing, quadratic assignment problem, and various other problems [10].

Research using the Bee Colony Optimization Algorithm is a synthetic bee that represents an agent to solve a complex problem and to optimize the results of the analysis by applying the Bee Colony Optimization algorithm. This algorithm is an artificial bee colony that finds an alternative optimal problem solving simultaneously from existing problems, where each bee will produce an alternative solution [11]. There are two types of phases in the Bee Colony Optimization algorithm, namely the forward phase and the backward phase. The Bee Colony algorithm implements a metaheuristic algorithm method, which is a method that uses a random search. This algorithm can also be used for a wider range of problems. This algorithm is run with the aim of optimizing the behavior of bees. The habit in question is the habit of exploring to find alternative solutions that are more optimal. The purpose of using the BCO algorithm is to learn and recognize the basic principles of optimization in bees and to demonstrate the potential of BCO, especially in the fields of engineering, engineering and management.

The research uses Particle Swarm Optimization which adopts the social behavior and habits of a flock of birds in searching for food or food sources. The social behavior consists of the actions of an individual and the influence of other individuals who are in a group. Each individual or particle moves by using its own intelligence. In addition, individual behavior is also influenced by the behavior of the collective group, which is carried out repeatedly, resulting in a narrower food search location and an optimal position [12]. Based on this, it can be concluded that when a particle or a bird finds the right path or a shorter path to get to the food source, the rest of the group will be able to follow that path immediately. This also happens even though the location of the individual is far from the group, where each particle will look for food sources randomly, and is done repeatedly so that the location of the search for food is getting narrower and getting an optimal position.

Genetic Algorithm (GA) is a branch of science from evolutionary algorithm that serves to solve optimization problems. The GA algorithm is based on genetic processes that occur in living things. Based on this theory, GA can be an alternative solution to solve problems in everyday life. Genetic algorithms work in a population, where the population consists of individuals who represent existing solutions [13]. If associated with the algorithm, the individual is symbolized as a fitness value which will then be used to determine the best alternative solution.

III. Methodology

A. Implementation Plan

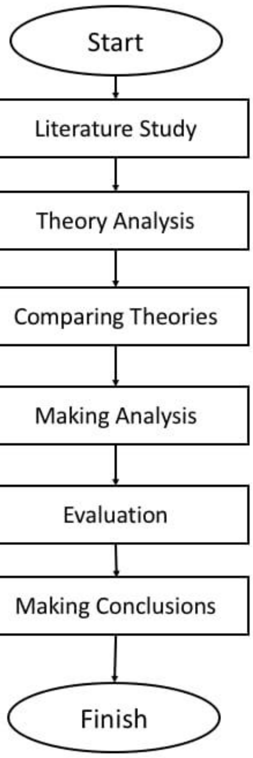

Fig. 1. Implementation Plan

1. Literature study stage, collecting relevant literature sources such as journals and books related to methods that have the potential to measure clock skew.
2. The theoretical analysis stage, analyzes and compares each method that has the potential to measure clock skew.
3. The workings of each method will discuss the results of the theoretical analysis in the form of explaining the workings and workflow of the method in the potential to measure clock skew and evaluating each method in order to get one of the potential methods for measuring clock skew.
4. In conclusion, we will choose one of these methods to be used in measuring clock skew.

IV. Results and Discussions

A. Ant Colony Optimization

In ant colony optimization, the search for food on ants is likened to a search for a cluster offset that will be used for measuring clock skew points. An ant colony method that can determine cluster offsets with the shortest path to find food in ants, where in ACO, ants will use certain chemical compounds known as pheromones as the "ph" variable to represent the path between the food source and their colony. The pheromone trajectory is used by the ants afterwards as a reference for detecting food because the pheromone increases the probability of the path being selected. Fig. 2 is an illustration of an ant colony in finding food.

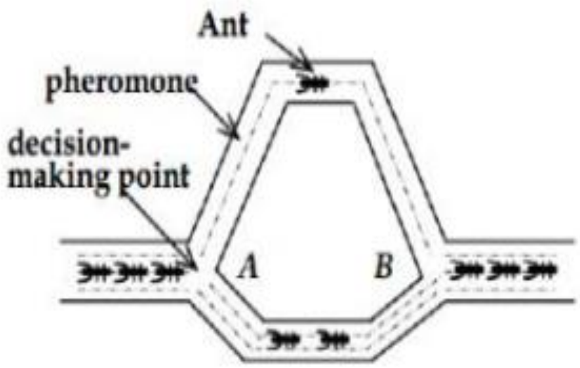

Fig. 2. ACO method illustration

Fig. 2 shows the process of selecting the shortest path by ants. In the process of their journey, there will be ants that reach their food source first, as in the picture it can be seen that the ants that choose the bottom path will first reach the food source because the bottom path is shorter than the top path, this causes the number of pheromones in the bottom lane to increase. more and more piled up because the number of ant colonies that pass through the bottom lane will be more and more, so that the path will become a cluster offset that can be used to measure clock skew.

Application of the ACO Algorithm Method on clock skew can be done with the following steps:

- The first step can be data collection.
- After the data is collected, each parameter of the ACO algorithm can be initialized, such as time c (t).
- Then the timing of each ant visit can be done on the route to each node.
- Perform time calculations on each ant with Route search with the smallest time.
- Calculate time changes in ant footprints between routes.
- Furthermore, it is possible to calculate the time intensity of ant footprints between routes for the next cycle.
- Take the smallest time sequence.
- New time value found.

B. Bee Colony Optimization

Bee colony optimization of searching for food in a bee colony is likened to a search for cluster offsets that will be used to measure clock skew, where the search for cluster offsets is carried out randomly and a swarm of bees is used to search for offsets with a wider range. Initially set the number of bees (N). This number of bees equals the number of offset or feed bee locations/points defined. After that, the forage stage is carried out, namely the bees move from one location to another to establish a path. When all the bees have arranged the journey (established a path), it is assumed that the bee cycle is complete. Because in the first cycle of the journey, the bee colony does not dance in determining the journey to the next location, so they travel to the next location randomly. Waggle dance is a means of communication used by bee colonies. If the bee detects the location of the food with the shortest path length with the best food quality, it will be determined by the length of the bee waggle dance.

Bee colony optimization works based on the number of bees that are released. For the 1st bee, the search carried out is a forward search. It is not the same as other bees. The search is carried out by knowing the final location of the previous bee (bee-1) then a backward search is carried out. After detecting a point that has more than 1 path choice and there is a path that has not been crossed by the previous bees, the new starting point is detected. This new starting point is used as the starting location (original position) for the forward search for the next bee [11].

The stages of the bee colony method on clock skew are done by entering data first into the system according to the time lapse data that occurs. This process is carried out by providing input time parameters to be carried out in calculating the time difference using a bee colony, then the output results that have been processed are obtained in the form of a new time difference value.

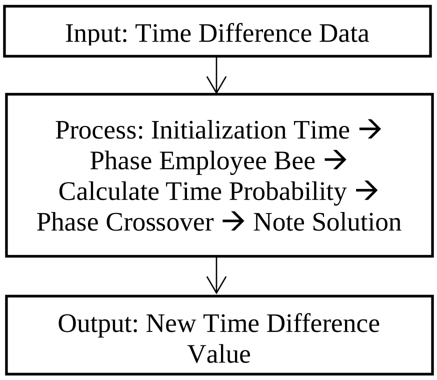

Fig. 3. Block Diagram of Clock Skew Calculation System

C. Particle Swarm Optimization

Particle Swarm Optimization which determines the location or position of the food as its offset cluster by searching for offsets in an iterative way until it narrows the offset search area and obtains the optimal location of the cluster offset as a clock skew measurement point. Each particle will look for food sources randomly, and other particles will influence the rest of the flock when it finds the location or position of the best food. The search for food locations will be carried out repeatedly so as to produce increasingly narrow food search locations and get an optimal position. Fig. 4 is an illustration of particle swarm in finding food.

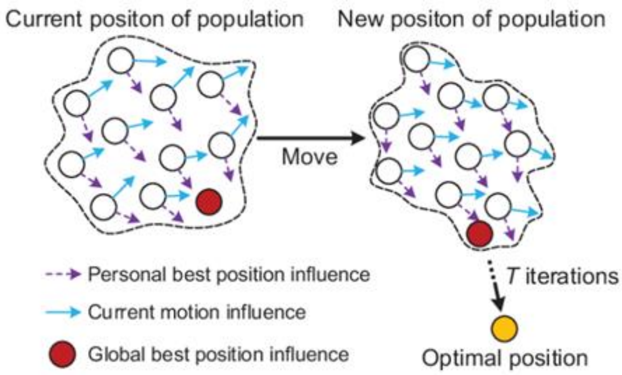

Fig. 4. Illustration of the PSO method

Fig. 4 shows the process of narrowing the foraging area in the PSO method. In the process, the swarm or a collection of particles will move randomly to determine the position in the repeated food search with the "pbest" variable, the "gbest" variable will take the best position from pbest and "T" as a food search repetition will encourage the optimization process that determines the direction in which a food is searched. Particles are needed to go somewhere else. So if it is adopted into the concept of clock skew, the offsets that have been collected will be narrowed or gathered so that they get the optimal position which will become the offset cluster.

In the PSO method for clock skew can be done in several stages, namely:

- Determine the initial parameters of the PSO such as time (t).
- Determine the number of swarms (n).
- Determine the initial position of each swarm (x-axis and y-axis).
- Try the position value of each specified swarm so you can see the response.
- Take the result of setting time value from each selected swarm.
- Determine the objective function of each swarm.
- Check whether the solutions obtained are convergent.

D. Genetic Algorithms

Genetic algorithms are search algorithms and optimization methods that have many stages such as initialization, selection, crossover, mutation and replacement. Search optimization algorithm in increasing or decreasing the shared function. The genetic algorithm determines the decisive step in determining individuals from the population to be imported into the mating pond. Individuals from mating pools are used to obtain new populations by creating offspring obtained in the form of genetic algorithms that can determine the population in the population that is the best from the past. This selection pressure supports the genetic algorithm in increasing the fitness of the population in subsequent successors. The level of convergence of genetic algorithms is determined by selection pressure, through higher selection pressures, higher levels of convergence are obtained. However, if the determination of the pressure is very low, the convergence level will decrease, and the genetic algorithm does not need more time to detect the optimal solution. If the selection pressure is too high, there is an opportunity to increase the previous genetic algorithm to be combined in one of the optimal (suboptimal) solutions.

The determination process in determining the population based on several stages, such as: the initial population through gene coding techniques from chromosomes, this method will explain the initial population as a potential solution to the problem into the type of chromosome as the main key type of the problem. The coding method includes the input of gene and chromosome codes. Genes are parts of chromosomes that can be represented in the form of bit strings, trees, arrays of real numbers, rule lists, permutation elements, program indicators, or other representations that can be applied to genetic operators. Next through the evaluation stage which serves as a performance parameter. Individuals with fitness values above on their chromosomes can be applied, while individuals on their chromosomes with lower fitness values can be changed. The fitness function corresponds to these constraints through the representation used. Then, this algorithm will pass the individual selection procedure used in handling the Tournament Selection method. Tournament Selection is used because of its efficiency and ease of application, Tournament Selection is the more popular genetic selection method. In Tournament Selection, individuals in the entire population compete with each other. The individual with the largest fitness value dominates and is determined for further action. Finally, reproduction is carried out through two operators, namely: crossover at the stage of the genetic algorithm which performs the work of assembling two parental chromosomes in one new chromosome as the initial population and mutation in the stage of converting some or more of the genes of a chromosome. This method can be written as follows:

Procedure Genetic Algorithm
Begin
(t) → o;
Initialization P(t);
Evaluation of P(t);
While (not different times) **do**
    Combine P(t) to get C(t);
    Evaluation C(t);
    Choose P(t+l) from P (t) and C(t);
    (t) → t+l;
End while
End

E. Selected Potential Method

Based on the above method, by looking at the advantages and disadvantages of each method, one method that is considered to have potential in measuring clock skew is chosen, namely the particle swarm optimization method due to the application of the PSO method which is easy and the theory of a collection of particles that searches for food systematically. repeatedly with speed in moving food locations can result in a narrower and optimal food search location. If adopted into the concept of clock skew, a collection of particles will form a cluster offset from the results of the search for offsets that will be used as a measurement of clock skew.

Based on the observations, the problem of calculating the optimal clock skew that is tolerant of process variations can be divided into two sub-problems: determining the minimum clock period that defines the valid allowable range for the two storage elements in the circuit, and determining the minimum width for each allowed element. the range is such that unacceptable variations in the target clock skew remain within the limits of the allowable range.

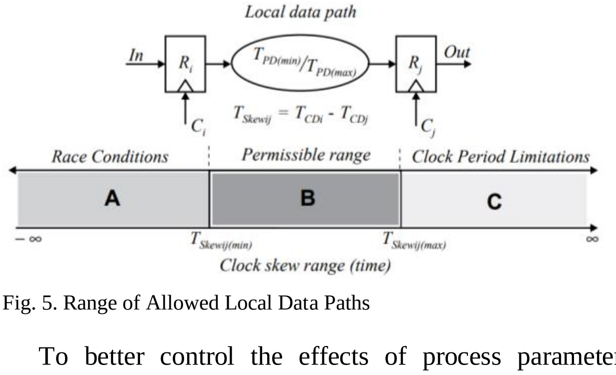

Fig. 5. Range of Allowed Local Data Paths

To better control the effects of process parameter variations, we recommend specifying the allowable range of each local data line, selecting a clock skew value that allows maximum slope variation within the allowable range and, finally, specifying the clock delay for each register.

Synchronous digital circuit C can be modeled as a finite multi-directed graph G(V,E). Each node in the graph, vj V, is associated with a register, circuit input, or circuit output. Each edge in the graph, eij E, represents a physical connection between vertices vi and vj, with an optional combinational logic path between the two vertices.

An edge is a two-weighted connection representing the maximum (minimum) TPDmax (TPDmin) propagation delay between two consecutively adjacent storage elements, where the TPD includes the register, logic, and interconnection delays of the local data path [7]. The local data path Lij is the set of two vertices connected by an edge, Lij = {vi, eij, vj} for any vi, vj V. The global data path Pv v kl k p = →□ l is the set of alternating edges and vertices {vk, ek1, v1, e12, ..., en-1l, vl}, represents the physical connection between nodes vk and vl, respectively. A multi-input circuit can be modeled as a single input graph, where each input is connected to vertex v0 by a zero-weight edge. Also, Pl(Lij) is defined as the allowed local data path range and Pg(Pkl) the global allowed data path range. Finally, the clock skew of the local data path is defined as TSkewij(Lij) = TCDi - TCDj, where TCDi and TCDj are the clock signal delays of nodes vi and vj. Clock skew is described as negative if TCDi precedes TCDj (TCDi < TCDj) and as positive if TCDi follows TCDj (TCDi > TCDj).

According to the chosen method, an algorithm for calculating clock skew can be presented to determine the minimum clock period which ensures that each allowable time range in the circuit satisfies the following equation:

$$Pg(P_{kl}) = (\cap_{i=1}^{m} Pg(P_{kl}^{i})) \cap (\cap_{j=1}^{n} Pg(P_{lk}^{j})) \neq \emptyset \text{ (X)}$$

The starting hour of the period is given by the following equation:

$$T_{CPmin} = MAX\left[min_{V_{ij}\in V}(T_{PDmaxij} - T_{PDminij}), max_{vi\in V}(T_{PDmasii})\right]$$
(X)

and, for each register pair in the circuit, the local and global allowable ranges are calculated. The contents of the allowable range are evaluated and if empty, the clock period is increasing, otherwise, the clock period is decreasing. Binary search is performed on each new clock period in the intercept algorithm until the minimum clock period has been reached.

Intercept(G(V,E),T_{CP})
  for each $v_x \epsilon$ ***V do***
  for each $v_y \epsilon$ ***V and*** $v_y \neq v_x$ ***do***
    for *i*←1 **to** *m* **do** (intersection of *m* parallel paths)
calculate the bounds of the permissible range $Pg(P_{xy}^{j})$
      if $Set_{parallel} = \emptyset$ **then** $Set_{parallel} = Pg(P_{xy}^{i})$
        else $Set_{parallel} = Set_{parallel} \cap Pg(P_{xy}^{i})$
    for *j* ← 1 **to** *n* **do** (intersection of *n* feedback paths)
calculate the bounds of the permissible range $Pg(P_{xy}^{j})$

if $Set_{feedback} = \emptyset$ **then** $Set_{feedback} = Pg(P_{xy}{}^{j})$
else $Set_{feedback} = Set_{feedback} \cap Pg(P_{xy}{}^{j})$
$Pg(P_{xy}) = Set_{parallel} \cap Set_{feedback}$
if $Pg(P_{xy}) = \emptyset$ **then**
return “permissible ranges do not intercept”
else if $|T_{Skew}[Pg(P_{xy})_{max}] - T_{Skew}[Pg(P_{xy})_{min}]| < C_1$
then return “permissible range too small”
else return “succes”
end *Intercept*

Optimal_T_{CP}(C)
lower=T_{Cpmin};upper=T_{Cpmax};
while *(upper – lower)>ε*
T_{CP}=(upper – lower)/2;
Intercept(C,T_{CP});
*i***If** “no success” **then** *lower=T_{CP};*
else *upper= T_{CP};*
end

Minimum hour period T_{CPmin} is determined from the 6th algorithm line and is the 7th tu (unit of time), which is the difference in propagation delay in the v1-vf local data path logic block. TCPmax maximum clock period is the maximum propagation delay through logic blocks in the circuitwhich is 12 tu. Starting with TCPmin, the allowable range of each local data path is used to calculate the allowable range of each global data path connecting nodes vi to vf . Since a unique clock skew must exist between nodes vi and vf, this clock skew value must be within the allowable range of each global data path connecting the two nodes..

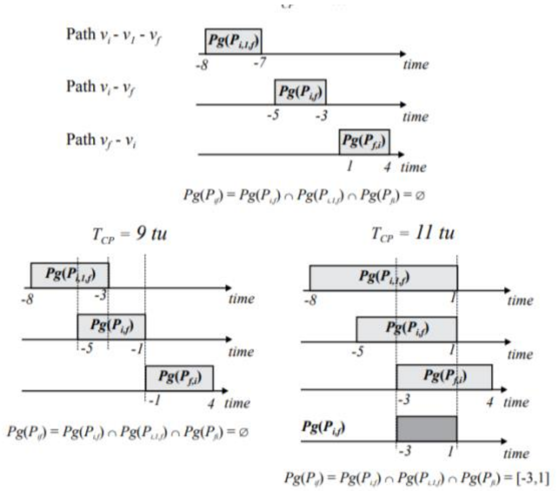

Fig. 5. Selection of Clock Period T_{CP}

From Fig. 6 with TCP = 7 tu, the allowable ranges do not intersect, so there is no clock skew value that allows the circuit to function correctly. Upgrading TCP to 9 tu allows the allowed ranges of vi-v1-vf and vi-vf global data paths to intersect, but the ranges of vi-v1-vf allowed paths do not intersect with the ranges of paths allowed by vf-vi. Therefore, the clock period again increases. In the example shown in Fig. 5, the clock period is increased beyond the optimal clock period to 11 tu to illustrate the existence of an allowable range for nodes vi and vf that allows selecting more than one clock skew value between nodes vi and vf. The single allowable value range is obtained using the algorithm in Fig. 3, setting the minimum clock period for this example to be 9.67 tu.

The allowable range of the local data path Pl(Lij) delimited by (1) and (2) defines a valid set of clock skew for a single local data path. However, for circuits consisting of multiple local data paths connected to form parallel and/or feedback paths, not all valid clock skew values for the local data paths can be used to satisfy the global allowable range of global data paths. Consider, for example, the path Pi,1,f shown in Fig. 6 with TCP = 11 tu. A clock skew from TSkewi, 1 + TSkew1,f = -3 + -5 = -8 tu is a clock skew value that is not in Pg(Pif), even though each clock skew is within the allowable range, Pl(Li1) = [-3,2] and Pl(L1f) = [-5,-1]. This example shows that only a sub-set of the allowed ranges of each local data path can be used to obtain the allowable range of the circuit's global data path..

Let L_{ij} be local data path inside P_{kl} global data path. Given a TCP clock period that satisfies (3), the sub-set of values in $Pl(L_{ij})$ which is used to determine $Pg(P_{kl})$ is called the allowable effective range of the local data path (L_{ij}), so that $\rho(L_{ij})$ $Pl(L_{ij})$.

The actual choice of allowable effective range is limited by additional criteria, such as reducing the absolute value of the clock skew, or ensuring the largest allowable effective range for each local data path to maximize tolerance for process parameters variation. Observe that the possible multiple solutions are consistent with the existence of multiple solutions to the non-zero clock skews indirect selection problem by computing a set of clock path delays to satisfy a valid clock period. Therefore, the selection of a certain clock skew value for each local data path is carried out in two stages. In the first stage, the allowable effective range is determined for each local data line, while in the second stage, a certain local clock skew is chosen to maximize the tolerance for processing parameter variations. Assigning the largest allowed effective range to the local data path starts with defining a unique solution for the allowable range of each global data path.

Given a synchronous circuit C modeled by graph G(V,E), let two vertices, vk and vl V, be the origin and destination of the global data path Pkl with m forward paths and n feedback paths. Let Pg(Pkl) be determined by (3). If Pg(Pkl) , the width of Pg(Pkl) is greatest if the Pg(Pkl) limit is defined by (4) and (5) respectively.

Determining the allowable effective range and selecting the clock skew value for each local data path is done as follows:

1) The range of global data paths allowed Pg(Pkl) is divided equally between each local data path connecting nodes vk and vl (line 5);
2) each allowable effective distance (Lij) is placed as close as possible to the upper limit of the initial permissible distance Pl(Lij) (lines 6 and 7), thereby

minimizing the possibility of creating any race conditions; and

3) clock skew is selected in the middle of the allowable effective range, because there is no prior information about the variation of a particular clock skew value (line 8). From this clock skew schedule, the minimum clock path delay is determined.

Select_Skew(G(V,E), T_{CP})
  Intercept(G(V,E), T_{CP})
  for each $P_{kl}{}^{n} \in G(V,E)$ **do**
    for $i \leftarrow k$ **to** $l \in P_{kl}{}^{n}$ **do**
   Width[$\rho(L_{ij})$]=MAX[Pg($P_{kl}{}^{i}$)] – MIN[Pg($P_{kl}{}^{i}$)]/#$L_{ij}\in P_{kl}{}^{n}$
   Upper bound of $\rho(L_{ij})$=MAX[Pl(L_{ij})];
   Lower bound of $\rho(L_{ij})$=MAX[Pl(L_{ij})] - Width($\rho(L_{ij})$);
   T_{Skewij}=MAX[$\rho(L_{ij})$] – MIN[$\rho(L_{ij})$]/2;
end *Select_Skew*

The problem of calculating clock path delays so that a deliberate local clock skew is used to improve performance and reliability while considering the effects of variations in process parameters is examined in this paper. Results are presented to determine the minimum hour period and allowable range of each local data line. The process of determining the limits of this range and selecting the clock skew value for each local data line to minimize the effects of variations in process parameters is described. Rather than placing limits or limits on the variation of clock skew, this approach ensures that any selected clock skew value is within the allowable range despite the worst variation of clock skew. A clock skew calculation algorithm to compensate for process variations has been incorporated into a top-down, bottom-up clock tree synthesis environment. In the top-down phase, the clock skew schedule and the allowable range of each local data line are determined to allow maximum variation of clock skew. In the bottom-up phase, possible clock skew violations due to variations in process parameters are compensated for by selecting the correct clock skew for each local data path and a controlled increase in the TCP clock period. The clock period of a number of ISCAS-89 benchmark circuits is minimized by this clock calculation algorithm. Calculation of clock skews to make the clock distribution network more tolerant of variations in process parameters is presented for several network examples.

The results of the simulation carried out in this section show the performance improvement obtained through the use of non-zero clock skew while considering the effects of variations in process parameters. The unit fanout delay model (one unit delay per gate plus 0.2 units for each gate fanout) was used to predict the minimum and maximum propagation delays of the logic blocks.

TABLE I. PERFORMANCE IMPROVEMENT WITH NON-ZERO CLOCK SKEW

Circ.	size #reg./#gates	T_{CPo} T_{Skewij}=0	T_{CPi} $T_{Skewij}\neq$0	Gain (%)	T_{CP} $T_{SkewI/O}$=0	Gain (%)
Ex1	20/-	11.0	6.3	43	7.2	35
S28	8/10	9.3	6.4	42	7.2	32
S297	22/119	17.2	12.6	28	12.6	28
S388	22/159	19.9	19.9	0	19.9	0
S444	32/181	18.7	12.1	41	12.1	41
S520	34/211	19.9	17.5	13	17.5	13
S888	67/447	28.0	13.7	50	15.8	42

The results shown in Table I describe the reduction of the minimum clock period when intentional clock tilt is exploited. The magnitude of the reduction depends on the characteristics of each circuit, in particular the difference in propagation delay between each local data line. Also note that by limiting the slope of the I/O register clock to zero, the circuit speed can be increased, though less than without this limitation.

An example of a clock distribution network that utilizes intentional clock slopes and is less sensitive to the effects of process parameter variations is given in Table 2. Clock trees were synthesized. The clock slope value is derived from the simulation of the clock path delay circuit from the clock tree. The minimum clock period assuming a zero T_{CPo} clock skew and an intentional T_{CPi} clock skew are shown in Column 2. The allowable ranges that are most susceptible to process parameter variations are depicted in Column 3. Target clock skew values are shown in Column 4. In Column 5 and 6, nominal and maximum clock slopes are depicted, assuming a 15% variation of the IDO current drain of each inverter. Note if the face value and worst case of clock tilt are within the allowable range. Percent variations in clock slope due to the effects of variations in process parameters are shown in column 7. A 20% speed increase with a nominal clock slope variation of up to 30%, and a 33% speed increase to an 18% variation in nominal clock slope are noted in the example circuits listed in Table II.

TABLE II. WORST CASE VARIATIONS IN CLOCK SKEW

circuit	T_{Cpo}/T_{CPi}	Permissible range	Selected clock skew	Simulated skew (ns)		Error (%)	
				nom	Worst case	nom	Worst case
Cdn 1	12/9	[-8,-3]	-3.0	-3.0	-2.11	0.0	30.0
Cdn 2	18/16	[-6.9,-1.4]	-4.4	-4.2	-3.4	2.4	21.4
Cdn 3	27/18	[-14,2.3]	1.2	1.24	1.5	3.7	18.3

V. CONCLUSION

Based on the discussion about the workings of the several methods above, it can be determined that a better method and has the potential to be used in calculating clock skew is the particle swarm optimization method. This is because the use of the Particle Swarm Optimization method is easier to apply and the required parameters are few, there is no evolution in the operator, for example crossover and mutation occur as in the Genetic Algorithm. Grouped PSOs make this method more robust, because the offset search process is carried out repeatedly to collect offsets that will become narrower or clustered so as to get the optimal position which will become a cluster offset. In addition, PSO is also more efficient because it requires less computation than the other three methods. PSO is also more flexible in maintaining a balance between global and local searches for their searches.

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