Aggressor Alignment for Worst-Case Coupling Noise

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ABSTRACT

In this paper we study signal alignment resulting in maximum peak interconnect crosstalk noise. We consider two cases. In the first one we assume that arbitrary arrival times of input signals are feasible. In the second case we assume that timing windows are given for each aggressor input. We propose a simple procedure to find aggressor alignment for worst-case coupling in both cases.

Keywords

Crosstalk noise, aggressor alignment, interconnect coupling, signal integrity, timing window.

1. INTRODUCTION

With technology shrinking to deep submicron regime coupling noise becomes a common effect. It is therefore essential to develop techniques that allow estimating accurately worst-case crosstalk conditions.

In this paper we study the problem of how crosstalk noise is affected by the switching times of aggressors acting on a victim net. We assume that driver strengths, wire spacing, spatial positions of aggressors and victim are given and not changing. Signal arrival times can be adjusted to achieve the maximum peak noise. In the first studied case we do not assume any bounds on timing windows of the aggressor signals; in the second case we assume that the timing windows are given.

1.1 Worst-case coupling scenario

For interconnect induced coupling noise, *worst-case* usually refers to the noise which has the maximum pulse height [1][9] for a fixed circuit structure and given input signals whose timing can be adjusted under certain constraints. The alignment of aggressors' switching times should be such that the resulting noise due to all switching aggressors has the maximum peak value. Throughout this paper we will consider the peak value of the coupling noise, and abbreviate the worst-case noise as *WCN*.

Similarly, *WCD* is an abbreviation of the worst-case coupling induced delay, which is the largest delay for a fixed circuit structure, given aggressor signals switching, and where only the signal arrival times are variable and can be adjusted. We mention *WCD* only in passing.

1.2 Previous work

Coupling noise analyzers usually assume linear models for drivers and apply the principle of superposition. A noise resulting from several switching aggressors is determined by considering one aggressor at a time and summing up the individual noise waveforms or peak amplitudes [2][6][8]. Adding up individual peak noises implies certain skew between the individual noise waveforms such that their peak values are aligned [1]. This in turn implies a particular alignment between aggressors inputs, however it was never proven that this particular alignment results in *WCN*. Aggressor alignment for the purpose of worst-case coupling noise has not been analyzed explicitly. Furthermore, simultaneous switching aggressors' inputs (with same arrival times) has been assumed as a condition resulting in *WCN* in some papers [3][4][11].

Capacitive coupling effects depend on the characteristics of drivers, interconnects and receivers. Interconnect coupling network consists of resistors and capacitors. The receiver functions as a loading capacitor. Aggressor driver is usually modeled by its Thevenin equivalent circuit or Norton equivalent circuit [1][5][7], with a fixed resistance *Rd*. All the above mentioned elements are linear, except for the victim driver whose modeling will be discussed below. When the noise amplitude resulting from switching of all the acting aggressors is small, the quiet victim driver works in its linear region, so it can also be treated as a linear element. Therefore, superposition should be applicable for coupling induced noise in such a case.

However, with stronger coupling, noise is no longer small. Thus the assumption that the victim's driver is in its linear range may not be true. The summation of individual peak noises may not result in an upper bound for coupling noise. Figure 7 shows inaccuracy caused by applying superposition. This point will be explained in greater detail in section 3. In other words, since the implicit alignment of aggressors fails to obtain *WCN*, an explicit method to determine the alignment between aggressors resulting in *WCN* is needed.

The alignment between aggressors and a switching victim has been researched [5][7] for the purpose of finding *WCD*. [5] and [7] are the first papers relating quantitatively the coupling induced noise and delay. The alignment between aggressor and the

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switching victim to achieve *WCD* depends on the amplitude of coupling noise, and the assumption in [5][7] is that the *worst-case delay coincides with maximum noise*, as illustrated in figure 1.

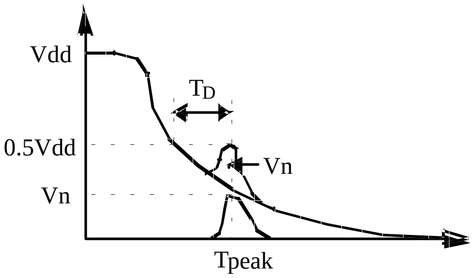


Figure 1. WCD vs. WCN

The resulting *WCD* strongly depends on the value of *WCN*. However, the *WCN* is obtained by superposition, which does not guarantee an upper bound of the maximum noise amplitude. Therefore, finding a better approximation of *WCN* will improve the *WCD* obtained in both [5] and [7].

Ignoring timing constraints can cause significant over-estimation of coupling effect, because some of the aggressor alignments can never be achieved. Timing constraints have rarely been considered in the existing worst-case coupling analysis methods, except [9]. In [9] the authors have applied mixed integer programming to find the worst-case coupling noise with consideration of timing windows. Moreover, this method assumes the “sharpness” of the crosstalk noise peak, which can cause a significant under-estimation of the worst-case noise.

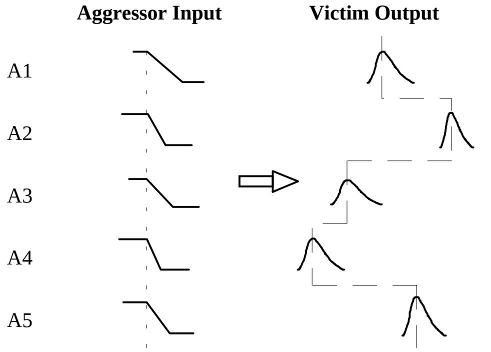
The rest of the paper is organized as follows. Section 2 gives a complete formulation for aggressor alignment with different conditions. In Section 3 we consider worst-case aggressor alignment when no signal arrival time bounds are specified. We also discuss driver modeling issues and compare worst-case coupling noise analysis methods. Section 4 describes our new aggressor alignment algorithm for given signal arrival timing windows. Some speedup strategies are discussed in section 5. The efficiency and accuracy of our method is experimentally demonstrated in Section 6. Section 7 concludes the paper.

2. PROBLEM FORMULATION

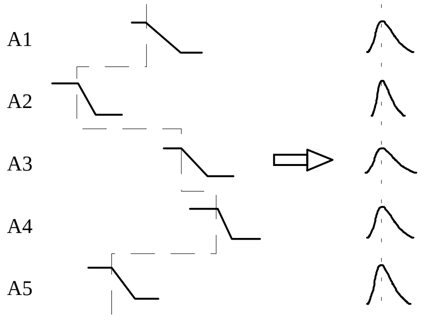
The goal of aggressor alignment is to find a set of proper arrival times for aggressor inputs such that the resulting total crosstalk noise on the quiet victim net is maximum (*WCN*).

2.1 Define the problem

In a multiple-aggressor situation, each aggressor has its corresponding driver strength, coupling length, wire spacing from the victim, transition time, etc., which are fixed, and input signal arrival time, which is variable. All of these can affect the peak noise occurrence time, peak amplitude, as well as the width of the waveform. For our worst-case analysis purpose, we would like to have every individual peak noise occur at the same time by changing the aggressor arrival times. Assume a coupling network with five aggressors, represented by *A1, A2, A3, A4, A5,* respectively in figure 2. To simplify the problem, we use inverters as drivers. Figure 2 shows a typical timing relationship between aggressor arrival times and peak noise occurring times. When all aggressors have the same arrival time (fig.2 (a)), peak noise occurring times are usually different (fig.2 (b)). In order to have peak noise occurring time the same (fig.2 (d)), the aggressors can not have the same arrival times (fig.2 (c)).



(a) Aligned arrival time (b) Skewed peak noise



(c) Skewed arrival time (d) Aligned peak noise

Figure 2. Alignment of Aggressor Inputs vs. Alignment of Victim Peak Noise

When no timing windows are considered, any arrival time of aggressor input is feasible. We define the aggressor alignment problem as follows:

Aggressor Alignment 1: Find the relative relationships among arrival times for all aggressor inputs such that all individual peak noises are aligned, assuming all the other conditions are fixed.

When timing windows are given, each aggressor’s input has a range for its arrival time. According to figure 2(c), the alignment of peak noises introduces a relationship among the arrival times, which can be represented by an imaginary *sweep line*, shown in figure 3. The shape of this imaginary line is fixed, but the location is unknown. When this *sweep line* moves along the timing zone, it intersects with some timing windows at each location. The intersection indicates the alignment of peak noises of the corresponding intersected timing windows. For example, in figure 3, the *sweep line* intersects with the timing window of A1, A2, and A5, so the total noise contribution of this case is from A1, A2, and A5 only.

We formulate the aggressor alignment problem with timing constraints as follows:

Aggressor Alignment 2: Find a location for the imaginary *sweep line* (figure 3) within the given timing windows, such that the total contribution of coupling noise from each intersected aggressor at this location is maximum.

Aggressor alignment 1 searches for the relative relationships among arrival times, while *aggressor alignment 2* searches for the absolute values of arrival times (maybe more than 1). *Aggressor* *alignment 1* is the foundation for *aggressor alignment 2*, because the *sweep line* is obtained through the first alignment.

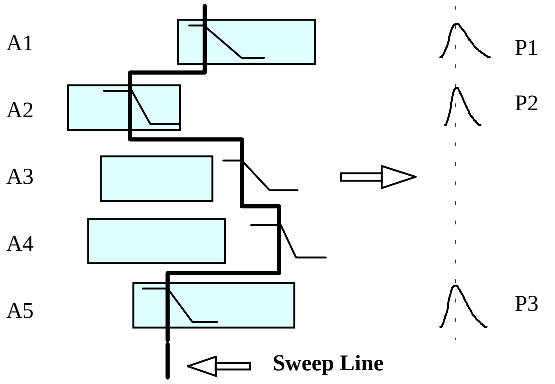


Figure 3. Timing window vs. aggressor alignment

2.2 Uncertainty and trend in aggressor alignment

When we refer to aggressor inputs, skew is the difference between two arrival times. When we refer to coupling noise, skew is the difference between two peak noise occurring times.

Figure 4 shows a typical relationship between peak noise and the skew of aggressor inputs, for a coupling network with two aggressors. The horizontal axis is the input skew. Peak noise is obtained through simulation.

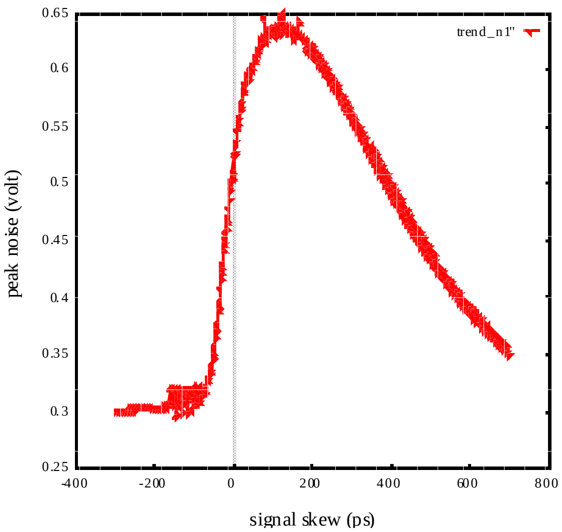


Figure 4. The trend and uncertainty in aggressor alignment

From the above curve, we can draw the following observations:

1. There is a *trend* for the peak noise vs. the skew. From global point of view, with the increase of the skew, the peak noise increases until it reaches a maximal value. Then it starts to decrease with the increase of the skew. However, it is not a strictly monotonic trend, due to existence of local minimal and maximal values, which we refer to as the *uncertainty* of the worst-case aggressor alignment for coupling noise.
2. There exists *accuracy tolerance* for input signal skew estimation. There exists an optimal value of skew (*Ts*) which gives *WCN*. However, within a certain **range of skews**, the peak noise difference from the actual *WCN* is small. For the curve shown in figure 4, the optimal skew value is 159ps (type A), with a peak noise of 1.1948 v (*WCN*). But when the skew value is in the range of 100ps to 220ps, the difference between the peak noise and the *WCN* is less than 5%. It is also true for the skews that are far away from the optimal value. This suggests that a simple estimation approach of the input skew could be proposed to achieve a good approximation to the actual *WCN*. This also invalidates the “sharpness” feature assumed by [9] when considering the interaction of two noise waveforms.
3. When the skew is far away from the best skew value, the peak noise stabilizes. This implies the *valid range* of aggressor alignment. In our example, this valid range is {-100ps, 700ps}. Outside of this range, the two individual noise waveforms become two unrelated noise pulses, and the larger of them will be the maximum peak noise. It is worth to mention that in such a situation, superposition would be a huge over estimation.

3. WCN AND SUPERPOSITION

This section is devoted to the aggressor alignment and its corresponding worst-case analysis when no timing constraints are specified.

Full simulation of designs with complicated non-linear driver models is often too much time and resource consuming. Linear driver models are used in fast noise estimation.

Superposition holds for linear systems [12]. When the noise amplitude becomes larger, the coupling network is no longer purely linear which causes inaccuracy in noise estimation when superposition principle is applied. A modified linear network with a piece-wise linear victim driver model can capture the non-linear voltage dependency. In this section we compare superposition-based approach and other noise analysis methods. We will show inaccuracies caused by superposition for different coupling conditions. For relatively small coupling noise, we derive a theorem that quantifies the relationship between peak noise value obtained by applying superposition and the actual *WCN*. For relatively large coupling noise, we give an observation which shows a different trend compared with smaller noise.

Below we summarize the four possible worst-case noise analysis strategies based on aggressor alignment method. Assume *m* is the number of aggressors, *M* is the total number of noise calculations (excluding addition).

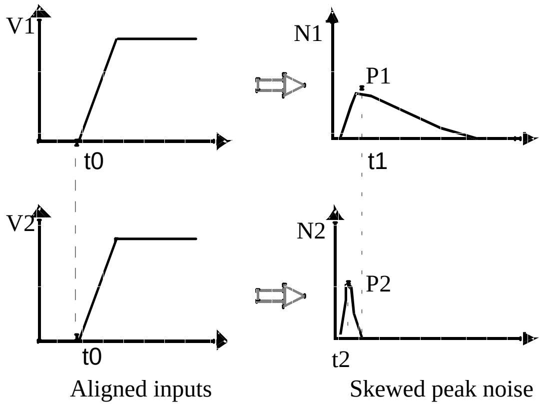
Type A: *Explicit aggressor alignment*. Noise output waveform is obtained by properly aligning switching of all aggressors, with certain skew between their inputs. The largest amplitude of this type is *WCN*. Usually $M >> m$.

Type B: *No aggressor alignment*. Noise output waveform is obtained for simultaneous switching of all aggressors, with zero skew between aggressor’s inputs. This is a special type of *explicit aggressor alignment*, with zero skew. $M = 1$.

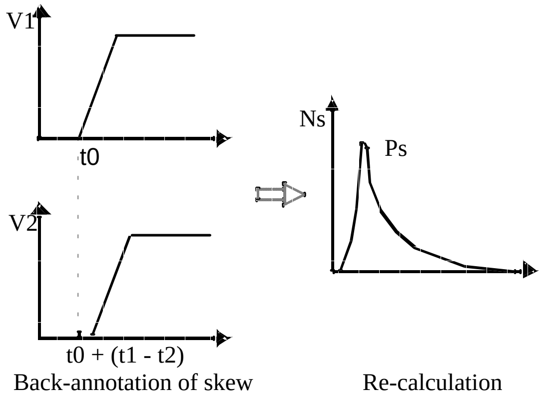
Type C: *Implicit aggressor alignment (superposition)*. Noise output waveform is obtained by applying *superposition* principle. Each individual noise waveform is obtained for only one switching aggressor while all the others are quiet, and aligned such that their peak amplitudes occur at the same time. Total peak noise is the summation over every individual peak noise. $M = m$.

Type D: *Extension of the implicit aggressor alignment*. This method first finds each noise waveform with only one switching aggressor while all the others are quiet. Instead of adding the individual waveforms, it "*back-annotates*" the signal skews, implied by the alignment of individual peak noise to each aggressor's inputs, and uses those skewed aggressor inputs to simulate or estimate the coupling stage again. $M = m+1$.

Figure 5 is an illustration of *type D* method. Assume we have two aggressors. *V1* is the input of aggressor 1, *V2* is the input of aggressor 2. Noise waveform *N1* is created when aggressor 1 is switching and aggressor 2 is quiet. *N2* is obtained when aggressor 2 is switching and aggressor 1 is quiet. The peak noise occurring time is *t1* and *t2*, respectively. And the peak amplitude is *P1* and *P2*, respectively. *Ns* is the noise waveform obtained when both aggressors are switching with input arrival time difference of *t1-t2*. *Ps* is its peak amplitude.



(a) Individual noise waveforms



(b) Final noise waveform

Figure 5. Type D worst-case analysis

Figure 6 shows a coupling network that consists of one victim and two aggressors. Figure 7 shows typical simulation results obtained through different noise analysis strategies.

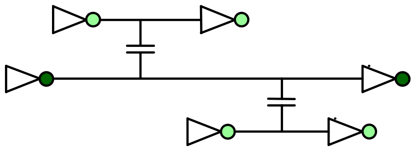


Figure 6. One stage of coupling network

Figure 7 shows about 31% difference in peak amplitude between *type A* and *type B*, about 23% difference in peak amplitude between *type A* and *type C*. *Type A* always has the largest peak noise. *Type D* is usually a close approximation to *type A*. There is no consistent relationship between *type B* and *C*.

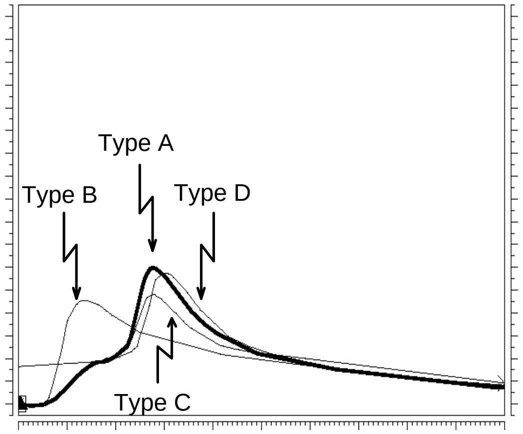


Figure 7. Comparison of superposition vs. explicit aggressor alignment (*gnd_rise* noise)

In terms of complexity, *type B* is the easiest to carry out. *Type C and type D* have linear complexities. Both *type B* and *type C* are commonly used in practice. *Type A* is the most complicated one. Due to the uncertainty feature of *peak noise vs. signal-skew* curve, indicated by figure 4 in section 3, only exhaustive search guarantees the actual *WCN*, which is quite time-consuming and not practical. Figure 4 has also indicated *accuracy tolerance* in skew estimation, which has been applied in *type D*, and resulted a good approximation to *type A*. Therefore, *type D* is our preferred worst-case analysis method when no timing constraints are specified.

It can be observed that for different noise types, the relationship between the results obtained from *type A* and *type C* strategies are different. This can be explained by the following theorem:

<u>*Theorem 1*</u>: Consider a coupling network with two aggressors. When no timing constraints are given, for coupling noise with moderate (not too large) amplitude, *WCN* is always *larger than or equal to* the peak noise determined by superposition when the victim transistor's *Id-Vds* curve has a *monotonic non-increasing* slope. On the other hand, *WCN* is always *smaller than or equal to* the peak noise determined by superposition when the victim transistor's *Id-Vds* curve has a *monotonic non-decreasing* slope.

<u>*Observation 1*</u>: With large individual coupling noise, total noise obtained through addition of each peak noise may overestimate the actual *WCN*. In this case, superposition may give a value well above the power supply voltage, which is not feasible.

Theorem 1 and observation 1 tell us that direct addition of individual peak noise can cause significant inaccuracy in *WCN* estimation. However, there is no clear boundary as when the over-estimation will occur, or when the under-estimation will occur. To avoid over-estimation or under-estimation induced by simple application of superposition, two further steps are necessary: *explicit aggressor alignment* to find the proper arrival times and *re-calculation* to obtain the total peak noise. Due to the *accuracy* *tolerance* in signal skew estimation, a simple method can be used to find the required arrival times. This has been applied in *type D* method: the first step is back-annotation of individual peak noise occurring time to the corresponding aggressor arrival time; the second step is re-calculation of total coupling noise when every aggressor is switching, with the new arrival time. To increase accuracy, iteration can be involved until no more changes in arrival times. Usually, one iteration is good enough.

4. AGGRESSOR ALIGNMENT WITH TIMING CONSTRAINTS

In this section we consider worst-case coupling analysis when timing constraints are specified. This is defined as *aggressor alignment 2* in section 3.

4.1 A more accurate formulation

First we introduce the concept and formula for "*effective pulse width (EPW)*"[13][14] of a noise waveform.

EPW is a measure of the range of a noise waveform. Given $v_0(t)$ as noise output, its *EPW* is defined as follows:

$$EPW = \frac{\int_0^\infty t v_0 \, dt}{\int_0^\infty v_0 \, dt} \tag{1}$$

There exists an easy yet efficient formula to estimate *EPW* [13][14]:

$$EPW = \sum_{C_i \in C} C_i R_{ii} \tag{2}$$

C is the set of capacitances, *Ci* is the *i-th* capacitance and *Rii* is the resistance seen across capacitor *Ci* when all other capacitances are open. In other words, *EPW* can be estimated by the sum of open circuit time constants.

Through simulation, we have found that the width of the noise pulse can not be neglected (several hundred pico-second is not an unusual value), and the actual shape of noise pulse is not always "sharp" at its top. Therefore, partial contribution (when the peak noise is not aligned) of each coupling noise which has been ignored in [9] should still be considered.

Aggressor alignment 2 can be re-formulated as shown in figure 8. Figure 8(a) shows the original timing window and sweep line. In figure 8(b), the sweep line has been straightened. Consequently, the timing windows have been moved and satisfy the following condition: A line sweep in (a) is equivalent to that of (b), in terms of vertical intersections with particular aggressor windows. In figure 8(c), timing window has been expanded to include the width of the noise pulse. The total expanded portion for each timing window is the corresponding pulse width *EPW*.

Now with a set of adjusted and expanded timing windows, as well as an imaginary straightened sweep line, we re-formulate the aggressor alignment problem as a ***Weighted Channel Density*** problem:

> *Find the maximum vertical channel density, subject to the following conditions:*
>
> 1. *Each timing window shown in figure 8 (c) is considered as a line segment in the channel.*
> 2. *The width of the timing window is considered as the length of the segment.*
> 3. *The peak noise is considered as a weight of the segment for the original window portion. The expanded portion has a weight equal to a fraction of the peak noise. The leftmost and rightmost points of the expanded window have zero weighty. A linear function can be used to approximate the weight in the expanded portion.*

Classic density of a channel computation algorithm [10] finds maximum number of segments intersecting a vertical line. Our weighted channel density algorithm finds the location for maximum vertical channel density with segments weighted. It is a direct extension of the original channel density algorithm and we do not list it here. The location information will be used to decide the switching aggressors involved in maximum noise as well as their corresponding arrival times. The last step is to re-calculate the maximum total coupling noise with all involved switching

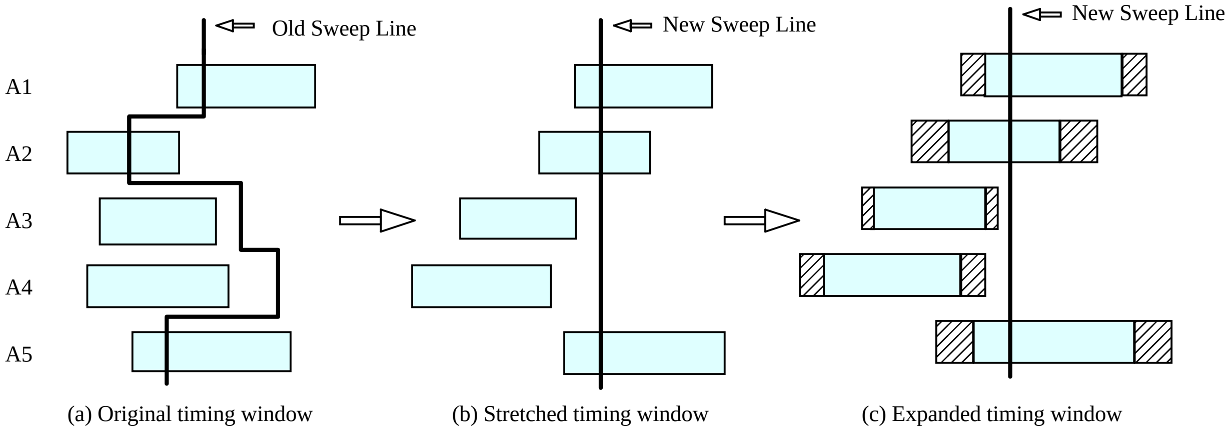


Figure 8. Re-formulation of aggressor alignment

aggressors and their new arrival times, same as *type D* method described in section 4.

The algorithm is dominated by the time complexity of the sorting algorithm which is *O(n log n)*.

Based on the weighted channel density algorithm, for the given timing windows, our algorithm usually finds a much tighter upper bound than those obtained by applying superposition of individual peak noises. This could save considerable design overhead.

4.2 Extension to WCD

Even though our algorithm targets finding *WCN* for given timing windows, it can be easily applied on *WCD* analysis, with slight modification. Knowing the relationship between *WCN* and *WCD* [5][7], we are able to obtain the upper bound for coupling induced delay, the only modification is that we need to include the victim arrival time, and use it to limit the range for our *Weighted-Channel-Density* algorithm.

5. SPEEDUP STRATEGIES

Our aggressor alignment strategy is applicable to both non-linear device model based simulation and piece-wise linear model based estimation. However, simulation is usually expensive. Furthermore, due to the uncertainty and accuracy tolerance property described in section 3, there is a certain range of values with acceptable accuracy. Therefore, several fast estimation methods can be included in our alignment algorithm.

5.1 Peak noise occurring time and pulse width

The procedure can be accelerated applying the formula derived in [14] to obtain the peak noise occurring time.

EPW (effective pulse width) of each noise pulse can be obtained through simulation if run time is not a concern. We can also calculate it using equation 2, given in section 4.1, which has a linear complexity.

5.2 Peak noise

The peak noise estimator presented in [13] gives an efficient method to find *WCN*; furthermore, it can handle simultaneous switching of multiple aggressors with arbitrary arrival and transition times. Therefore we choose it as our noise estimator. The expression is as follows:

$$V_P^A = \frac{\sum_{R_i \in P(O)} X_i R_i}{\sum_{C_i \in C} C_i R_{ii}} \qquad (3)$$

With the substitution of equivalent driver resistances, the coupling network becomes a RC network, whose root is the input of the victim driver. Every connection between two elements (*R* or *C*) is a node. P(o) is the unique path from the *i-th* node to the root, *Xi* is the downstream coupling capacitance at the *i-th* node along the path, *Ri* is the upstream resistance along the path. *C* is the set of capacitances, *Ci* is the *i-th* capacitance and *Rii* is the resistance seen across capacitor *Ci* when all other capacitances are open. There are slight modifications to the formula (3) when we consider arrival time and transition time [13].

6. EXPERIMENTAL RESULTS

This section shows experimental results of *WCN* obtained through our aggressor alignment algorithm. We show the peak noise values and CPU times. We compare our peak noise with the peak noise obtained by applying superposition principle that allows arbitrary arrival times. We also compare our peak noise with that obtained through trial-and-error simulation, which we consider as accurate.

We have laid out simple circuits and extracted parasitic parameters using industrial tools. The technology is *0.35μm*. We selected ten different coupling stages that have one victim and two aggressors for our analysis. Each stage differs in signal arrival timing windows, victim's driver strength, aggressors driving strength, coupling length, wire spacing, etc. Table 1 and Table 2 show the comparison of peak noise amplitude for different timing constraints. The shortest timing window has a width of 100ps. Each simulation takes about 2 seconds. We also show the peak noise error percentage with respect to simulation results.

Table 1. Comparisons with no timing constraints

Coupling Stage	Superposition		Simulation	Our Method	
1	0.4884	0.9%	0.4932	0.4905	0.5%
2	0.5979	4.7%	0.6277	0.6120	2.5%
3	0.6469	7.4%	0.6986	0.6846	2.0%
4	0.7755	9.1%	0.8530	0.8357	2.0%
5	0.8410	13.0%	0.9671	0.9619	0.6%
6	0.9064	16.0%	1.0786	1.0678	1.0%
7	0.9679	19.0%	1.1948	1.1906	0.4%
8	1.0262	17.0%	1.2365	1.1858	4.1%
9	1.2654	17.4%	1.5311	1.5035	1.8%
10	1.3995	23.1%	1.8193	1.8011	1.0%
Average Error	12.8%		0	1.6%	

Table 2. Comparisons when timing constraints are given

Coupling Stage	Superposition		Simulation	Our Method	
1	0.4884	65.8%	0.2945	0.3033	3.0%
2	0.5979	61.3%	0.3706	0.4002	8.0%
3	0.6469	77.3%	0.3648	0.3910	7.2%
4	0.7755	52.5%	0.5086	0.5406	6.3%
5	0.8410	27.1%	0.6618	0.6976	5.4%
6	0.9064	65.9%	0.5463	0.5615	2.8%
7	0.9679	91.5%	0.5054	0.5160	2.1%
8	1.0262	74.2%	0.5892	0.6469	9.8%
9	1.2654	69.5%	0.7467	0.7728	3.5%
10	1.3995	42.8%	0.9803	1.0704	9.1%
Average Error	62.8%		0	5.7%	

We would like to point out two interesting facts regarding the existing methods:

1. The larger the number of aggressors in one coupling stage, the larger the error that superposition can potentially cause. The largest potential error with two aggressors is *100%*, and the largest potential error with *n* aggressors is *(n-1)100%*.
2. The wider the timing window, the longer the run time of the trial-and-error simulation to find *WCN*. This is so because the simulation run time is proportional to the multiplication of the lengths of all timing windows.

On the other hand, the accuracy of our algorithm does not depend on the number of aggressors. Furthermore, our run time does not depend on the widths of timing windows.

7. CONCLUSION

We have analyzed and compared different methods to obtain worst-case coupling noise with no timing constraints. We have also developed a simple yet efficient algorithm for aggressor alignment for any timing constraints. The energy of coupling noise has not received much attention in coupling analysis. Our method is the first to include the effective pulse width, an energy-related factor, in the consideration of maximum peak noise for multiple aggressors. This algorithm can be easily extended to determining the worst-case coupling induced delay. Results of our research have many potential applications, such as delay testing, performance optimization, etc.

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