An Accurate Interconnection Length Estimation for Computer Logic

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Abstract

Important layout properties of electronic designs include space requirements and interconnection lengths. A reliable interconnection length estimation is essential for improving placement and routing techniques. Donath found an upper bound for the average interconnection length that follows the trends of experimentally obtained average lengths [2]. Yet, this upper bound deviates from the experimentally obtained value by a factor $\delta \approx 2$, which is not sufficiently accurate for some applications. We show that we obtain a significantly more accurate estimate by taking into account the inherent features of the optimal placement process.

1. Introduction

Creating a physical layout of an electronic design implies the placement and interconnection of elementary blocks on a carrier. Important properties of such a layout are area and interconnection length requirements. The ability to predict these properties, without having to perform the placement and routing itself, is important because most placement algorithms use estimates for interconnection lengths and area requirements to limit the search in the solution space [5, 7]. Also, the predictions offer a way to gain a more fundamental insight in the placement of designs on different carriers.

There have been many attempts to predict area requirements and interconnection lengths. A first upper bound for interconnection lengths has been found by Sutherland and Oestreicher [8]. It is based on a random placement and therefore yields excessively large estimates. Donath [2, 3] found that a hierarchical placement gives a much better estimate of interconnection lengths and his results have been used by several other researchers [1, 4]. Recently, we have extended Donath's technique to threedimensional and anisotropic architectures [9, 11, 12].

Donath estimates the average interconnection length using a relationship between the number of elementary blocks B in a module of a partitioned design, and the number of the module's external connections (pins) P, known as Rent's rule [6, 10]:

$$P = CB^r \quad (0 < r < 1), \tag{1}$$

where C is the average number of interconnections per elementary block, and r is called the Rent exponent. This exponent is a measure of the interconnection complexity of the design. Its value increases for increasing interconnection complexity. Generally, r varies from 0.4 for simple regular designs, up to 0.8 for complex designs. The validity of Rent's rule is a result of the fact that designers tend to build their designs hierarchically, imposing the same complexity at each level of hierarchy.

Experimentally obtained average interconnection lengths vary with the number of logic gates in a circuit and with the Rent exponent (and thus with the interconnection complexity of the design). Donath found that his theoretically obtained average interconnection length values seem to follow these variations [2]. However, Donath's calculated average interconnection length and the one experimentally found still differ by a factor $\delta \approx 2$. His method indeed results in an upper bound for the average interconnection length. We would like to estimate the average interconnection length more accurately. Therefore, it is important to understand the underlying mechanisms that are responsible for the overestimation in Donath's calculation.

Several aspects could contribute to the deviation of Donath's theoretical estimations from his experimentally found estimations. We believe that the most important one is the lack of more complete information on the placement of the design. We will consider this issue and we will present a way to introduce this information efficiently. This will lead to a better estimation for the average interconnection length, as will be verified experimentally. But first, we will explain the key issues of Donath's placement technique.

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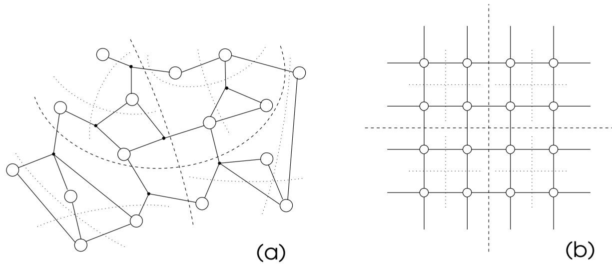

Figure 1. Recursive partitioning scheme of the design and the physical architecture.

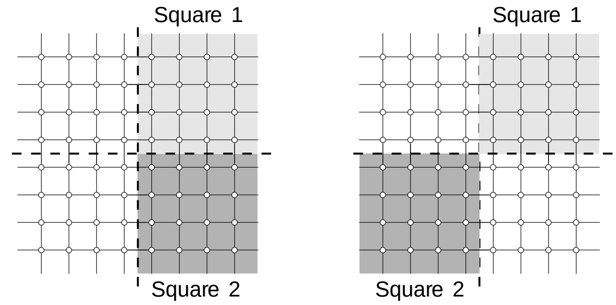

Figure 2. Two possible combinations at a hierarchical level k: an A-combination (left) and a D-combination (right).

2. Donath's technique

Donath's technique to estimate the average interconnection length is based on a hierarchical placement of the design into a square 2-dimensional Manhattan grid [2]. The design is partitioned hierarchically into subdesigns. Each subdesign at a hierarchical level consists of four subdesigns (of equal size) at the next (lower) level of hierarchy (figure 1(a)). We thus assume that the number of gates in the logic design is a power of 4 (there are 4^K gates, with K the number of hierarchical levels).

The design is placed in a physical architecture which can be modeled as a square Manhattan grid. In this grid, each gridpoint corresponds to a location where one logic gate of the design can be placed. The gridlines correspond to the channels in which the connections between the gates can be routed. All lengths are thus measured using a Manhattan metric. Also this square grid is partitioned into four subsquares of equal size (figure 1(b)).

In Donath's partitioning and placement scheme, each subdesign is paired recursively with a subsquare until all gates are paired with (and essentially assigned to) exactly one grid location. The recursion levels will be numbered 0 (four subdesigns consisting of only one logic gate) up to $K-1$ (four subdesigns that constitute the whole design). Note that external interconnections are not included in the estimations (these interconnections belong to level K).

The partitioning of the design into four subdesigns of equal size should be done in such a way that the partition satisfies Rent's rule. That is, we want to keep the number of interconnections between the subdesigns as low as possible. This ensures that our placement scheme is a good model for the *optimal placement* of the design. We define an optimal placement as one that minimizes the total interconnection length. It is indeed obvious that such a placement tries to place densely interconnected logic gates as close as possible, resulting in clusters of such gates. Among clusters, there are fewer interconnections. A placement scheme that keeps the number of interconnections between the subdesigns as low as possible thus leads to many short interconnections and few long ones. This behavior is modeled accurately by Rent's rule.

Given the above model for the design, the physical architecture and Donath's placement, we want to find the average interconnection length. We can do this by calculating the average number of interconnections $\bar{n}_k$ and the average length of the interconnections $\bar{l}_k$ at every hierarchical level k ($0 \le k \le K-1$). The average interconnection length $\mathcal{L}$, computed over all hierarchical levels, is then given by

$$\mathcal{L} = \frac{\sum_{k=0}^{K-1} \bar{n}_k \bar{l}_k}{\sum_{k=0}^{K-1} \bar{n}_k}. \qquad (2)$$

The expected number of interconnections at each level of the hierarchy can be calculated using Rent's rule and can be seen to be [2]

$$\bar{n}_k = \alpha C 4^K (1 - 4^{r-1}) 4^{k(r-1)}, \qquad (3)$$

where, according to Donath, $\alpha \approx \frac{1}{2}$.

We now seek to find the average interconnection length $\bar{l}_k$ at hierarchical level k. The interconnections belonging to hierarchical level k are those interconnections between gates belonging to the same $(k+1)$-th level hierarchical subdesign, but to different k-th level hierarchical subdesigns. Those interconnections thus connect two gates placed in different squares at hierarchical level k. Only two different combinations are possible: either the squares are adjacent or they are diagonally opposed (figure 2). We will call the first combination an A-combination, the second one a D-combination. For each of these combinations, we compute the average interconnection length (denoted as $\bar{l}_{k,a}$ for A-combinations, $\bar{l}_{k,d}$ for D-combinations). For the calculation of $\bar{l}_{k,a}$ and $\bar{l}_{k,d}$ it is assumed that the starting points and the endpoints of the interconnections between two squares are uniformly distributed over those squares. This calculation (for squares of size λ^2) can be found in [2] and results in

$$\bar{l}_{k,a} = \frac{4\lambda}{3} - \frac{1}{3\lambda} \quad (4)$$

$$\bar{l}_{k,d} = 2\lambda, \quad (5)$$

with $\lambda = 2^k$.

Since there are four A-combinations and two D-combinations, the total average interconnection length $\bar{l}_k$ at the hierarchical level k is given by

$$\bar{l}_k = \frac{4\bar{l}_{k,a} + 2\bar{l}_{k,d}}{6}. \quad (6)$$

Combining equations 2 thru 6 yields

$$\mathcal{L} = \frac{14\,H(K,r,1) - 2\,H(K,r,3)}{9\,H(K,r,2)}, \quad (7)$$

with

$$H(K,r,x) = \frac{2^{K(2r-x)} - 1}{2^{2r-x} - 1}. \quad (8)$$

Note that this function should be extended continuously in the singular point $r = 1/2$.

3. A critique of Donath's approach

Donath's technique is primarily based on his hierarchical placement scheme. Every hierarchical level is treated separately without any knowledge of the length of interconnections from other levels of hierarchy. If one calculates the average interconnection length at hierarchical level $k-1$, one doesn't know what happens to the interconnections crossing the border of that level (interconnections belonging to a level k or higher). Donath simply assumes that the starting points of these interconnections are uniformly distributed over the gates of the square grid. It is nevertheless clear that an optimal placement strategy will place interconnected logic gates as close as possible, regardless of the hierarchical level the interconnection belongs to. So it is reasonable to assume that the interconnections crossing the border of level $k-1$ will be as short as possible. This means that an optimal placement procedure will place gates that are interconnected to another square (at level k) preferably near the border of the two squares. Donath's technique provides no way to include this information in estimating the average interconnection length.

4. Refining Donath's model

In the remaining of this paper, we define an *interconnection length distribution* as a collection of values, indicating, for each length l, how many interconnections have this length. The sum of these values over all lengths l equals the total number of interconnections. By multiplying a distribution with a normalisation constant one can make this sum equal to 1. We will then call this a *normalised distribution*. A normalised distribution denotes, for each length l, the probability that an interconnection has length l. The *global distribution* is defined as the interconnection length distribution of the whole design. The global distribution contains information about all interconnections together. At each hierarchical level, we can also define a *local distribution*. Such a distribution only contains information about interconnections at a specified hierarchical level. We will assume that each local distribution can be estimated by a scaled version of the global distribution. This way, we will include information about the whole design into each hierarchical level.

In [3], simple theoretical considerations are used to indicate that the normalised distribution $f_D(l)$ of interconnection lengths for a good two-dimensional placement in a square Manhattan grid should be of the form

$$\begin{aligned} f_D(l) &= g/l^\gamma \quad (1 \le l \le L) \\ &\approx 0 \quad\quad (l > L), \end{aligned} \quad (9)$$

where γ is related to the Rent exponent r through the equation

$$2r + \gamma \approx 3. \quad (10)$$

In these equations g is a normalisation constant; L is a constant related to the size of the square grid; and γ is a constant characteristic of the logic[1].

We will now show that the trend of $f_D(l)$ (equation 9) mainly depends on the number of interconnections $\bar{n}_k$ (given by equation 3) at each hierarchical level and not on the way these interconnections are distributed locally. For the sake of simplicity, we will consider continuous approximations of the discrete distributions.

Consider the local distribution $g_k(l)$ of interconnection lengths at hierarchical level k ($g_k(l) = 0$, for $l > 4\lambda = 2^{k+2}$). Due to Rent's rule, which is a result of the self-similarity within designs, the interconnection complexity is similar at all hierarchical levels. This similar behavior at each hierarchical level k leads us to the assumption that the local distributions $g_k(l)$ have similar shapes. Now, consider the peak value f_k of $g_k(l)$ and the length $l_{p,k}$ for which $f_k = g_k(l)$. Since the local distributions $g_k(l)$ are similarly shaped, $l_{p,k}$ scales with 2^k (figure 3). We assume that the peak of the distributions $g_k(l)$ is sufficiently sharp so that every $g_k(l)$ constitutes to the global distribution $f(l)$ ($= \sum_{k=0}^{K-1} g_k(l)$) mainly around $l_{p,k}$. The global distribution $f(l)$ will then be approximated properly by a smooth continuous line through all f_k. Since the total number of in-

[1] The index D is used to denote the fact that the distribution has been derived by Donath.

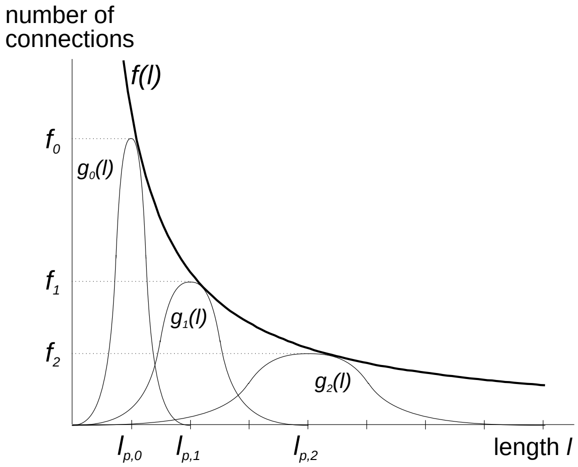

Figure 3. Interconnection length distributions at every hierarchical level constitute to the global distribution $f(l)$. Only the first three local distributions are shown.

terconnections at hierarchical level k equals $\bar{n}_k$, we have

$$\int g_k(l)dl = \bar{n}_k \quad (0 \leq k \leq K-1). \tag{11}$$

The integral is proportional to the product of the peak value f_k and the length of the domain of $g_k(l)$ by a factor C. Because we assume that the $g_k(l)$ have similar shapes, this factor is the same for all k. We can thus write

$$f_k\, 2^{k+2} = C\, \bar{n}_k \quad (0 \leq k \leq K-1). \tag{12}$$

Using the value of $\bar{n}_k$ (equation 3) this yields

$$f_k = f_0\, 2^{k(2r-3)}, \tag{13}$$

and, since the values of $l_{p,k}$ scale with 2^k,

$$f(l) \approx g l^{2r-3}, \tag{14}$$

where g is the normalisation constant.

These simple considerations show that the global distribution $f(l)$ follows the trend of Donath's $f_D(l)$ (equation 9) independently of the local distributions $g_k(l)$. This also explains why Donath's average interconnection length estimations follow this trend very well even with a uniform distribution of the starting points and endpoints of interconnections in A- and D-combinations.

Note that by enumerating all possible interconnections in each A- and D-combination on every hierarchical level, one obtains a distribution depending only on the physical architecture the design will be placed in. We will call this the *structural distribution*. We then assign to each length the probability that an interconnection with this length would be laid out in a real placement procedure and with a real design with the specified Rent exponent. This leads to a *probability distribution*. Each local distribution can be factorized as the product of the structural distribution and the probability distribution. Donath assumes a constant probability distribution, but we already showed that this is not a good model for an optimal placement. In a good model, the probability should decrease with increasing length. Since it is reasonable to assume that the probability distribution follows the trend of the global distribution, we multiply the structural distribution with the global distribution $f(l)$.

5. Mathematical derivation of the average interconnection length

The enumeration of the structural distributions for the two combinations on every hierarchical level k, is straightforward. The distributions are given by ([1])

$$P_{k,a}(l) = \begin{cases} \frac{-l^3+3\lambda l^2+l}{3\lambda^4} & (0 \leq l < \lambda) \\ \frac{2l^3-12\lambda l^2+(21\lambda^2-2)l-9\lambda^3+3\lambda}{3\lambda^4} & (\lambda \leq l < 2\lambda) \\ \frac{-l^3+9\lambda l^2-(27\lambda^2-1)l+27\lambda^3-3\lambda}{3\lambda^4} & (2\lambda \leq l < 3\lambda) \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

for an A-combination, and

$$P_{k,d}(l) = \begin{cases} \frac{l^3-l}{6\lambda^4} & (0 \leq l < \lambda) \\ \frac{-3l^3+12\lambda l^2-(12\lambda^2-3)l+4\lambda^3-4\lambda}{6\lambda^4} & (\lambda \leq l < 2\lambda) \\ \frac{3l^3-24\lambda l^2+(60\lambda^2-3)l-44\lambda^3+8\lambda}{6\lambda^4} & (2\lambda \leq l < 3\lambda) \\ \frac{-l^3+12\lambda l^2-(48\lambda^2-1)l+64\lambda^3-4\lambda}{6\lambda^4} & (3\lambda \leq l < 4\lambda) \\ 0 & \text{otherwise} \end{cases} \tag{16}$$

for a D-combination. In these equations $\lambda = 2^k$.

The local distribution for each combination on hierarchical level k is now found by multiplying $P_{k,C}(l)$ (where $C \in \{a, d\}$) with $f(l)$

$$\bar{l}_{k,C} = \frac{\sum_{l=0}^{4\lambda} l P_{k,C}(l) f(l)}{\sum_{l=0}^{4\lambda} P_{k,C}(l) f(l)} \tag{17}$$

$$= \frac{\sum_{l=0}^{4\lambda} P_{k,C}(l) l^{2r-2}}{\sum_{l=0}^{4\lambda} P_{k,C}(l) l^{2r-3}}. \tag{18}$$

The average interconnection length at hierarchical level k is then given by equation 6:

$$\bar{l}_k = \frac{4\bar{l}_{k,a} + 2\bar{l}_{k,d}}{6}.$$

Note that we still assume that the probability of an interconnection is the same for A- and for D-combinations.

In reality, an optimal placement will favour A-combinations slightly over D-combinations, since the average interconnection length is larger in the latter combination. We could consider using the global distribution $f(l)$ as a probability measure for interconnections at the whole hierarchical level instead of at each combination separately. This requires though that our partitioning scheme would have to be different. The adjustment of the partitioning scheme will be a topic for further research.

The sums in equation 18 can not be computed analytically without knowledge of the value for $\lambda = 2^k$. Yet, if we want to compare our results with those of Donath, both numerically and theoretically, an analytical form of the average interconnection length is needed. A way around this problem is to approximate the discrete distributions by continuous ones. One can easily verify that the continuous form of the equations 15 and 16 is given by

$$P^c_{k,a}(l) = \begin{cases} \frac{-l^3+3\lambda l^2}{3\lambda^4} & (0 \le l \le \lambda) \\ \frac{2l^3-12\lambda l^2+21\lambda^2 l-9\lambda^3}{3\lambda^4} & (\lambda \le l \le 2\lambda) \\ \frac{-l^3+9\lambda l^2-27\lambda^2 l+27\lambda^3}{3\lambda^4} & (2\lambda \le l \le 3\lambda) \\ 0 & \text{otherwise,} \end{cases} \tag{19}$$

and

$$P^c_{k,d}(l) = \begin{cases} \frac{l^3}{6\lambda^4} & (0 \le l \le \lambda) \\ \frac{-3l^3+12\lambda l^2-12\lambda^2 l+4\lambda^3}{6\lambda^4} & (\lambda \le l \le 2\lambda) \\ \frac{3l^3-24\lambda l^2+60\lambda^2 l-44\lambda^3}{6\lambda^4} & (2\lambda \le l \le 3\lambda) \\ \frac{-l^3+12\lambda l^2-48\lambda^2 l+64\lambda^3}{6\lambda^4} & (3\lambda \le l \le 4\lambda) \\ 0 & \text{otherwise.} \end{cases} \tag{20}$$

A substitution of the sums in equation 18 by integrals, yields

$$\bar{l}_{k,C} = \frac{\int_0^{4\lambda} P^c_{k,C}(l) l^{2r-2} dl}{\int_0^{4\lambda} P^c_{k,C}(l) l^{2r-3} dl}.$$

This results in

$$\bar{l}_{k,a} = \lambda R_a(r) \tag{21}$$
$$\bar{l}_{k,d} = \lambda R_d(r), \tag{22}$$

with

$$R_a(r) = \frac{(r-1)}{(r+1)} \frac{3^{2r+2}-(r+4)2^{2r+2}+(4r+7)}{3^{2r+1}-(2r+7)2^{2r}+(4r+5)}, \tag{23}$$
$$R_d(r) = \frac{(r-1)}{(r+1)} \frac{4^{2r+1}-3^{2r+2}+32^{2r+1}-1}{4^{2r}-3^{2r+1}+32^{2r}-1}, \tag{24}$$

and

$$\bar{l}_k = \lambda R(r), \tag{25}$$

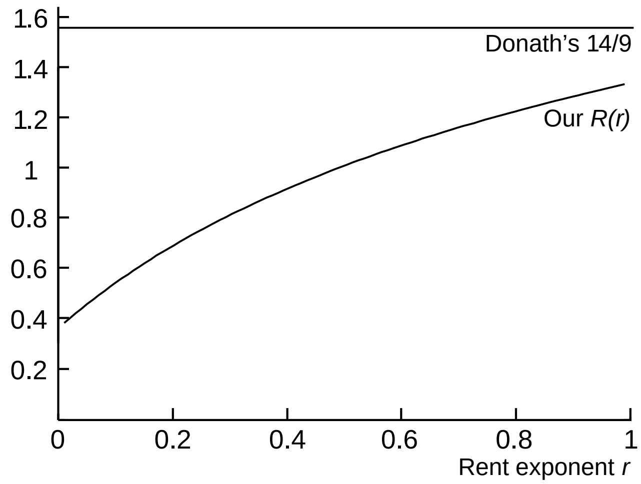

Figure 4. $R(r)$ (equation 26) versus Donath's factor for $0 < r < 1$.

with

$$R(r) = \frac{4R_a(r) + 2R_d(r)}{6}. \tag{26}$$

The sum over all hierarchical levels (equation 2) then yields

$$\mathcal{L} = R(r)\frac{H(K,r,1)}{H(K,r,2)}, \tag{27}$$

with

$$H(K,r,x) = \frac{2^{K(2r-x)}-1}{2^{2r-x}-1}.$$

6. Results

The average interconnection length computed in the previous section has the same scaling behavior[2] as the average interconnection length computed by Donath. This is a necessary consequence of the fact that we used the same hierarchical placement technique with the number of interconnections at every hierarchical level estimated by Rent's rule. However, the multiplying factor $R(r)$ is always smaller than the factor $14/9$ found by Donath (figure 4). The factor $R(r)$ increases with increasing r, corresponding to the fact that more complex designs (with a higher r) tend to have longer interconnections. In all cases ($0 < r < 1$) our estimation of the average interconnection length is more accurate than the one found by Donath.

In order to experimentally verify our theoretical average interconnection length estimation, we compare it with Donath's theoretical estimation for five benchmark designs used by Donath in [2]. The results are shown in table 1.

[2] This means that they both have the same behavior if the number of hierarchical levels increases to infinity ($K \to \infty$), i.e. if the number of gates goes to infinity.

No.	N_g	N_c	r	$\mathcal{L}_{exp}$	$\mathcal{L}_D$	$\mathcal{L}$	$\frac{\mathcal{L}_{exp}}{\mathcal{L}_D}$	$\frac{\mathcal{L}_{exp}}{\mathcal{L}}$
1	528	1007	0.59	2.15	4.02	2.88	0.53	0.75
2	576	1111	0.75	2.85	5.26	4.13	0.54	0.69
3	671	1670	0.57	2.63	4.07	2.89	0.65	0.91
4	1239	2687	0.47	2.14	3.76	2.45	0.57	0.87
5	2148	7302	0.75	3.50	7.37	5.74	0.48	0.61
6	1024	3047	0.40	1.96	3.28	2.02	0.60	0.97
7	1024	2979	0.50	2.21	3.79	2.60	0.58	0.85
8	1024	2893	0.60	2.58	4.61	3.32	0.56	0.78

Table 1. Average interconnection length of some benchmark designs: experimental results ($\mathcal{L}_{exp}$) versus Donath's analysis ($\mathcal{L}_D$) and our analysis ($\mathcal{L}$). The number of gates is shown in the column N_g and N_c is the number of connections. The circuits numbered 1 thru 5 are those used by Donath in [2], the others were generated by us.

One problem with using existing benchmark designs is that they could well be not uniformly complex as is required when using Rent's rule. Since our interconnection length estimations strongly depend on this exponent, a small variation in the value of r could have large effects for our estimations. We have generated some benchmark designs with a uniformly complex Rent exponent r, based on Rent's rule and Donath's hierarchical placement scheme[3]. This way we generate circuits that should fulfill the assumptions made by Donath quite well. We have used simulated annealing to obtain a good placement of the benchmark designs and we have determined the average interconnection length experimentally. Those results can also be found in table 1. Especially for low values of the Rent exponent, there is a strong correspondence to the theoretical results.

A comparison between the last two columns in table 1 clearly shows the improvement in the average interconnection length estimation.

7. Conclusion

In this paper we have presented a modification of Donath's technique, introducing the behavior of the global distribution into the local distributions at each hierarchical level. This way, we have obtained a new average interconnection length estimation corresponding more closely to the experimental values than the upper bound found by Donath. Especially for designs characterised by a low interconnection complexity, the estimate of the average interconnection length is very accurate.

Further research will focus on the adjustment of the partitioning scheme in order to also include a different probability distribution for A- and D-combinations. The resulting estimates are expected to be extremely accurate.

[3] A report on the generation method is forthcoming.

8. Acknowledgement

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