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The Physical Design of on-Chip Interconnections: Part III: Statistical Model of Forecasting

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Abstract

Custom interconnect design complements automated route algorithms which do not guarantee the generation of robust, legal routes for all signals in a ULSI design. The ability to forecast the effect and degree of confidence that further intervention in an additional step will lead to similar improvement would also be valuable information. This paper is the third in a series on physical design of on-chip interconnections, and in this paper, we present analytical techniques to forecast when to continue and when to stop the addition of custom interconnections in a design. The analytical techniques presented in this series of papers can also be incorporated in semi-custom and ASIC designs and may serve as tools to evaluate and improve various route algorithms.

Keywords

Custom interconnect design, custom interconnection, netlength effectiveness, via effectiveness, cumulative effectiveness, forecast, design effect.

I. Introduction

An understanding of the role of interconnections in ultra-large-scale-integrated (ULSI) chip design is important to achieve optimal performance in high-speed microprocessors and has implications for the manufacturability and realization of increasingly complex circuits[1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]. The use of large numbers of signals in ULSI designs increases design complexity, and the importance of understanding the effects of this increasing complexity has been highlighted by the Semiconductor Industry Association[3]. Moreover, the detailed design of interconnections for these signals also impacts design yield, performance, and power dissipation as well as system cost and information processing ability[4], [13], [14], [15], [16], [17], [18], [19], [20].

Previous papers[21], [22] presented techniques to quantify physical characteristics of interconnections and to analyze changes in these characteristics when a pre-route algorithm is applied. With these techniques, interconnection complexity can be reduced for the case in which the pre-route algorithm is intervention with custom interconnections.

Tools to forecast the effect and degree of confidence that further intervention in an additional step will lead to similar improvement would be helpful, but are not currently available to designers. Currently, the default rule to determine when to stop the application of a pre-route algorithm such as the addition of custom interconnections is to send an existing violation-free design to manufacture at the time specified by project schedule constraints.

In this third paper in a series on physical design of on-chip interconnections, we present analytical techniques to forecast the potential effect of custom interconnect design on physical properties of routes in a proposed additional *trial*. We also present a method to measure the degree of confidence that further intervention in the proposed *trial* will lead to similar improvement in interconnect characteristics. The purpose of these forecasts is to help predict when to stop the addition of custom interconnections and consider the design complete.

II. Issues

The first issue that can influence a decision to stop addition of custom interconnections for unit-level signals is the ability of the automated router to complete the remaining design routes without route violations. If this task is impossible for the automated router, custom interconnections are added to the design. Otherwise, custom interconnections can be added as permitted within the project schedule constraints. In the latter case, for example, custom interconnections can be added until the normalized excess Steiner length[22] reaches some pre-specified value. For the IFU, this value lies between 0.01 μm and 0.022 μm per signal. As a second example, if the forecasted cumulative effectivenesses for netlengths and vias for a proposed trial $(n+1)$ are both greater than those in trial n, then the proposed custom interconnections can be added to the design. As described in[22], the cumulative effectiveness of netlengths $\epsilon_L^{(i)(0)}$ and vias $\epsilon_v^{(i)(0)}$ in a given trial i compared to trial 0 can monitor progress as expressed by the following relations,

$$\epsilon_L^{(i)(0)} = 1 - \frac{L^{(i)}}{L^{(0)}}, \tag{1}$$

and

$$\epsilon_v^{(i)(0)} = 1 - \frac{v^{(i)}}{v^{(0)}}, \tag{2}$$

where $\epsilon_L^{(i)(0)}$ is the cumulative effectiveness for netlengths for signal routes in trial i compared with trial 0, and $\epsilon_v^{(i)(0)}$ is the cumulative effectiveness for vias for signal routes in trial i compared with trial 0. Expressions for $\epsilon_L^{(i)(0)}$ and $\epsilon_v^{(i)(0)}$ in the projected trial are obtained from Eqns. 1 and 2 by setting $i = n + 1$ to obtain the relations,

$$\epsilon_L^{(n+1)(0)} = 1 - \frac{L^{(n+1)}}{L^{(0)}}, \tag{3}$$

and

$$\epsilon_v^{(n+1)(0)} = 1 - \frac{v^{(n+1)}}{v^{(0)}}, \tag{4}$$

respectively.

A. Application to the POWER4 DD1 IFU

Figures 1(a) and 1(b) show $\epsilon_L^{(i)(0)}$ and $\epsilon_v^{(i)(0)}$ for the DD1 IFU trials $i \leq 6$ and for the projected trial $n + 1 = 7$, based on the statistical model that will be presented in the following section. These figures show that $\epsilon_v^{(7)}(0)$ in trial 7 is projected to be 19.3%, which is the same as that in trial 6; $\epsilon_L^{(7)}(0)$ is projected to be reduced greatly from 0.41% to 0.093% from trial 6 to trial 7.

III. Statistical model of forecasting

Based on statistical considerations of a design that is routed with custom interconnections over a series of n trials[22], we now address the question of how to decide whether an additional trial $(n+1)$ should be attempted with the same pre-route algorithm. Here, the goal is to determine the degree of confidence with which an additional step of intervention with custom interconnections will result in further improvement in physical properties of the design routes. To obtain the lower confidence bound of the cumulative effect on routes predicted to occur in trial $(n+1)$, we calculate the estimated total effect and the expected value of the total effect.

We represent the estimated total effect and the expected value of the estimated total effect for netlengths with the variables $\hat{\mu}_L^{(n+1)}$ and $\mu_L^{(n+1)}$, respectively, which are given by the expressions,

$$\hat{\mu}_L^{(n+1)} = p_{L_t}^{(n)} \hat{\mu}_{L_c} + p_{L_o}^{(n)} \hat{\mu}_{L_o} + p_{L_r}^{(n)} \hat{\mu}_{L_r}, \tag{5}$$

and

$$\mu_L^{(n+1)} = p_{L_t}^{(n)} \mu_{L_c} + p_{L_o}^{(n)} \mu_{L_o} + p_{L_r}^{(n)} \mu_{L_r}, \tag{6}$$

respectively, where $\mu_L^{(n+1)} = E(\hat{\mu}_L^{(n+1)})$, $E(\hat{\mu}_{L_c}) = \mu_{L_c}$, $E(\hat{\mu}_{L_o}) = \mu_{L_o}$, and $E(\hat{\mu}_{L_r}) = \mu_{L_r}$. The estimate $\hat{\mu}_L^{(n+1)}$, however, is computed exclusively based on data obtained in the first

n trials. In a similar manner, the estimated total effect and the expected value of the estimated total effect for vias can be represented with the variables $\hat{\mu}_v^{(n+1)}$ and $\mu_v^{(n+1)}$, respectively, as given by the expressions,

$$\hat{\mu}_v^{(n+1)} = p_{v_t}^{(n)} \hat{\mu}_{v_c} + p_{v_o}^{(n)} \hat{\mu}_{v_o} + p_{v_r}^{(n)} \hat{\mu}_{v_r}, \tag{7}$$

and

$$\mu_v^{(n+1)} = p_{v_t}^{(n)} \mu_{v_c} + p_{v_o}^{(n)} \mu_{v_o} + p_{v_r}^{(n)} \mu_{v_r}, \tag{8}$$

respectively, where $\mu_v^{(n+1)} = E(\hat{\mu}_v^{(n+1)})$, $E(\hat{\mu}_{v_c}) = \mu_{v_c}$, $E(\hat{\mu}_{v_o}) = \mu_{v_o}$, and $E(\hat{\mu}_{v_r}) = \mu_{v_r}$. The estimate $\hat{\mu}_v^{(n+1)}$ is also computed exclusively based on data obtained in the first n trials.

The total netlength $L^{(n+1)}$ and total via number $v^{(n+1)}$ in a potential subsequent trial $(n+1)$ can be forecast with a statistical analysis of the results of the previous n trials; $L^{(n)}$; $v^{(n)}$; the estimators $\hat{\mu}_{L_c}$, $\hat{\mu}_{L_o}$, and $\hat{\mu}_{L_r}$ for netlengths; the estimators $\hat{\mu}_{v_c}$, $\hat{\mu}_{v_o}$, and $\hat{\mu}_{v_r}$ for vias; an estimated region of influence $R_{(n+1)}$ that is projected to contain the desired additional custom interconnections $\Delta N_c^{(n+1)}$; and Eqns.1 and 2 in[22]. From this calculation, one can project whether trial $(n+1)$ should be attempted and whether this additional trial has a reasonable chance to improve physical properties of the design interconnections.

We obtain expressions for $\Delta L_c^{(n+1)}(R_{(n+1)})$, $L_o^{(n+1)}(R_{(n+1)})$, $L_r^{(n+1)}(\overline{R_{(n+1)}})$, where we assume that the effectivenesses of custom interconnections, other routes, and the rest of the routes in trial $(n+1)$ can be described by the average effectivenesses of all previous trials (that is, trials *0* to n), according to the expressions,

$$\hat{\mu}_{L_c} = 1 - \frac{\Delta L_c^{(n+1)}(R_{(n+1)})}{\Delta L_t^{(n)}(R_{(n+1)})}, \tag{9}$$

$$\hat{\mu}_{L_o} = 1 - \frac{L_o^{(n+1)}(R_{(n+1)})}{L_o^{(n)}(R_{(n+1)})}, \tag{10}$$

$$\hat{\mu}_{L_r} = 1 - \frac{L_r^{(n+1)}(\overline{R_{(n+1)}})}{L_r^{(n)}(\overline{R_{(n+1)}})}, \tag{11}$$

where the quantities $\hat{\mu}_{L_c}$, $\hat{\mu}_{L_o}$, and $\hat{\mu}_{L_r}$ represent the measured average effectivenesses of all previous trials. It follows from Eqns. 9 - 11 that $\Delta L_c^{(n+1)}(R_{(n+1)})$, $L_o^{(n+1)}(R_{(n+1)})$, and $L_r^{(n+1)}(\overline{R_{(n+1)}})$ are given by the expressions,

$$\Delta L_c^{(n+1)}(R_{(n+1)}) = \Delta L_t^{(n)}(R_{(n+1)})(1 - \hat{\mu}_{L_c}), \tag{12}$$

$$L_o^{(n+1)}(R_{(n+1)}) = L_o^{(n)}(R_{(n+1)})(1 - \hat{\mu}_{L_o}), \tag{13}$$

$$L_r^{(n+1)}(\overline{R_{(n+1)}}) = L_r^{(n)}(\overline{R_{(n+1)}})(1 - \hat{\mu}_{L_r}). \tag{14}$$

Then the total length $L^{(n+1)}$ of the routed signals in trial $(n+1)$ is given by the expression,

$$\begin{aligned} L^{(n+1)} &= L_c^{(n)} + \Delta L_c^{(n+1)}(R_{(n+1)}) + L_o^{(n+1)}(R_{(n+1)}) + L_r^{(n+1)}(\overline{R_{(n+1)}}), \\ &= L_c^{(n)} + \Delta L_t^{(n)}(R_{(n+1)})(1 - \hat{\mu}_{L_c}) + L_o^{(n)}(R_{(n+1)})(1 - \hat{\mu}_{L_o}) + L_r^{(n)}(\overline{R_{(n+1)}})(1 - \hat{\mu}_{L_r}), \end{aligned} \tag{15}$$

with Eqns. 12 - 14 as well as Eqn.1 in[22], where $i = n+1$. Similarly, the total via number $v^{(n+1)}$ in trial $(n+1)$ is given by the expression,

$$\begin{aligned} v^{(n+1)} &= v_c^{(n)} + \Delta v_c^{(n+1)}(R_{(n+1)}) + v_o^{(n+1)}(R_{(n+1)}) + v_r^{(n+1)}(\overline{R_{(n+1)}}), \\ &= v_c^{(n)} + \Delta v_t^{(n)}(R_{(n+1)})(1 - \hat{\mu}_{v_c}) + v_o^{(n)}(R_{(n+1)})(1 - \hat{\mu}_{v_o}) + v_r^{(n)}(\overline{R_{(n+1)}})(1 - \hat{\mu}_{v_r}) \end{aligned} \tag{16}$$

Values for $L^{(n+1)}$ and $v^{(n+1)}$ calculated with Eqns. 15 and 16 are compared with $L^{(n)}$ and $v^{(n)}$, respectively, to project whether intervention with the proposed custom interconnections in trial $n+1$ is projected to further reduce the total cumulative length and via number in the design interconnections.

The variance $Var(\hat{\mu}_L^{(n+1)})$ of the estimated total effect can be represented by the variable $Var(\hat{\mu}_L^{(n+1)}) = \sigma^2(\hat{\mu}_L^{(n+1)})$, according to the expression,

$$\begin{aligned} \sigma^2(\hat{\mu}_L^{(n+1)}) &= \langle(\hat{\mu}_L^{(n+1)} - \mu_L^{(n+1)})^2\rangle \\ &= (p_{L_t}^{(n)})^2 Var(\hat{\mu}_{L_c}) + (p_{L_o}^{(n)})^2 Var(\hat{\mu}_{L_o}) + (p_{L_r}^{(n)})^2 Var(\hat{\mu}_{L_r}) \\ &+ 2p_{L_t}^{(n)} \cdot p_{L_o}^{(n)} \cdot Cov(\hat{\mu}_{L_c}, \hat{\mu}_{L_o}) \\ &+ 2p_{L_t}^{(n)} \cdot p_{L_r}^{(n)} \cdot Cov(\hat{\mu}_{L_c}, \hat{\mu}_{L_r}) \\ &+ 2p_{L_o}^{(n)} \cdot p_{L_r}^{(n)} \cdot Cov(\hat{\mu}_{L_o}, \hat{\mu}_{L_r}), \end{aligned} \tag{17}$$

where $Var(\hat{\mu}_{L_c})$, $Var(\hat{\mu}_{L_o})$, and $Var(\hat{\mu}_{L_r})$ are given by Eqns. **??** - **??**, and where the covariance $Cov(\hat{\mu}_{L_c}, \hat{\mu}_{L_o})$ is defined by the relation,

$$Cov(\hat{\mu}_{L_c}, \hat{\mu}_{L_o}) = E((\hat{\mu}_{L_c} - \mu_{L_c})(\hat{\mu}_{L_o} - \mu_{L_o})) = \langle(\hat{\mu}_{L_c} - \mu_{L_c})(\hat{\mu}_{L_o} - \mu_{L_o})\rangle, \tag{18}$$

where E indicates that the expected value is to be taken. The other covariances are defined in a similar manner, namely,

$$Cov(\hat{\mu}_{L_c}, \hat{\mu}_{L_r}) = E((\hat{\mu}_{L_c} - \mu_{L_c})(\hat{\mu}_{L_r} - \mu_{L_r})) = \langle(\hat{\mu}_{L_c} - \mu_{L_c})(\hat{\mu}_{L_r} - \mu_{L_r})\rangle. \tag{19}$$

$$Cov(\hat{\mu}_{L_o}, \hat{\mu}_{L_r}) = E((\hat{\mu}_{L_o} - \mu_{L_o})(\hat{\mu}_{L_r} - \mu_{L_r})) = \langle(\hat{\mu}_{L_o} - \mu_{L_o})(\hat{\mu}_{L_r} - \mu_{L_r})\rangle. \tag{20}$$

To evaluate Eqn. 18, we rewrite the expressions for $\hat{\mu}_{L_c}$ and $\hat{\mu}_{L_o}$ in Eqns. **??** and **??** as the relations,

$$\hat{\mu}_{L_c} = \mu_{L_c} + \frac{\sum_{j=1}^{n} \Delta L_t^{(j-1)}(\epsilon_{L_c}^{(j)} - \mu_{L_c})}{\sum_{j=1}^{n} \Delta L_t^{(j-1)}} \tag{21}$$

and

$$\hat{\mu}_{L_o} = \mu_{L_o} + \frac{\sum_{j=1}^{n} L_o^{(j-1)}(\epsilon_{L_o}^{(j)} - \mu_{L_o})}{\sum_{j=1}^{n} L_o^{(j-1)}}. \tag{22}$$

Substituting Eqns. 21 and 22 into Eqn. 18, Eqn. 18 becomes,

$$\begin{aligned} Cov(\hat{\mu}_{L_c}, \hat{\mu}_{L_o}) &= \frac{\sum_{j=1}^{n} \Delta L_t^{(j-1)} L_o^{(j-1)} \cdot \frac{\sigma_{L_c}}{\sqrt{\Delta L_t^{(j-1)}}} \cdot \frac{\sigma_{L_o}}{\sqrt{L_o^{(j-1)}}} \cdot \rho(\epsilon_{L_c}^{(j)}, \epsilon_{L_o}^{(j)})}{(\sum_{j=1}^{n} \Delta L_t^{(j-1)})(\sum_{j=1}^{n} L_o^{(j-1)})} \\ &= \frac{\sigma_{L_c}}{\sqrt{\sum_{j=1}^{n} \Delta L_t^{(j-1)}}} \cdot \frac{\sigma_{L_o}}{\sqrt{\sum_{j=1}^{n} L_o^{(j-1)}}} \cdot \frac{\sum_{j=1}^{n} \rho(\epsilon_{L_c}^{(j)}, \epsilon_{L_o}^{(j)}) \cdot \sqrt{\Delta L_t^{(j-1)} \cdot L_o^{(j-1)}}}{\sqrt{(\sum_{j=1}^{n} \Delta L_t^{(j-1)})(\sum_{j=1}^{n} L_o^{(j-1)})}} \\ &= \sqrt{Var(\hat{\mu}_{L_c}) \cdot Var(\hat{\mu}_{L_o})} \cdot \rho_{L_c,L_o} \cdot f_{L_t,L_o}, \end{aligned} \tag{23}$$

where the covariance $Cov(\epsilon_{L_c}^{(j)}, \epsilon_{L_o}^{(j)})$ is related to the correlation coefficient $\rho(\epsilon_{L_c}^{(j)}, \epsilon_{L_o}^{(j)})$ according to the expression,

$$Cov(\epsilon_{L_c}^{(j)}, \epsilon_{L_o}^{(j)}) = \rho(\epsilon_{L_c}^{(j)}, \epsilon_{L_o}^{(j)}) \cdot \frac{\sigma_{L_c}}{\sqrt{\Delta L_t^{(j-1)}}} \cdot \frac{\sigma_{L_o}}{\sqrt{L_o^{(j-1)}}}, \tag{24}$$

and where the quantity f_{L_t,L_o} (Note that $0 \le f_{L_t,L_o} \le 1$) represents the expression,

$$f_{L_t,L_o} = \frac{\sum_{j=1}^{n} \sqrt{\Delta L_t^{(j-1)} \cdot L_o^{(j-1)}}}{\sqrt{(\sum_{j=1}^{n} \Delta L_t^{(j-1)})(\sum_{j=1}^{n} L_o^{(j-1)})}}, \tag{25}$$

and where in the last line of Eqn. 23, we make the assumption that the correlation coefficient is independent of trial j such that $\rho(\epsilon_{L_c}^{(j)}, \epsilon_{L_o}^{(j)}) = \rho_{L_c,L_o}$.

To obtain an estimate of ρ_{L_c,L_o}, which we represent with the variable $\hat{\rho}_{L_c,L_o}$, we use expressions for the *B-values* $\{B_{L_c}^{(i)}\}$ and $\{B_{L_o}^{(i)}\}$ given in Eqns.42 and 43 in[22]. The *B-values* $\{B_{L_c}^{(i)}\}$ and $\{B_{L_o}^{(i)}\}$ are linear combinations of the effectivenesses $\{\epsilon_{L_c}^{(i)}\}$ and $\{\epsilon_{L_o}^{(i)}\}$, respectively, and are distributed according to the normal distribution with mean 0 and variance

$\sigma^2_{L_c}$ and $\sigma^2_{L_o}$, respectively. We write the estimate $\hat{\rho}_{L_c,L_o}$ according to the expression,

$$\begin{aligned}
\hat{\rho}_{L_c,L_o} &= \frac{1}{n}\sum_{i=1}^{n}\frac{(\epsilon^{(i)}_{L_c}-\hat{\mu}_{L_c})(\epsilon^{(i)}_{L_o}-\hat{\mu}_{L_o})}{\frac{\hat{\sigma}_{L_c}}{\sqrt{\tilde{v}^{(i-1)}_{L_t}}}\cdot\frac{\hat{\sigma}_{L_o}}{\sqrt{\tilde{v}^{(i-1)}_{L_o}}}} \\
&= \frac{\frac{1}{n}\sum_{i=1}^{n}B^{(i)}_{L_c}\cdot B^{(i)}_{L_o}}{\sqrt{\frac{1}{n}\sum_{j=1}^{n}(B^{(j)}_{L_c})^2}\cdot\sqrt{\frac{1}{n}\sum_{j=1}^{n}(B^{(j)}_{L_o})^2}} \\
&= \frac{\frac{1}{n}\sum_{i=1}^{n}B^{(i)}_{L_c}B^{(i)}_{L_o}}{\hat{\sigma}_{L_c}\hat{\sigma}_{L_o}}, \qquad (26)
\end{aligned}$$

where in the first equality of Eqn. 26, the expression $\frac{\hat{\sigma}_{L_c}}{\sqrt{\tilde{v}^{(i-1)}_{L_t}}}$ is the estimated standard deviation of the term $(\epsilon^{(i)}_{L_c}-\hat{\mu}_{L_c})$, and the expression $\frac{\hat{\sigma}_{L_o}}{\sqrt{\tilde{v}^{(i-1)}_{L_o}}}$ is the estimated standard deviation of the term $(\epsilon^{(i)}_{L_o}-\hat{\mu}_{L_o})$. The expressions for the standard deviations normalize each term by the correct value since each of the effectivenesses $\{\epsilon^{(i)}_{L_c}\}$ are from different distributions (likewise, each of the effectivenesses $\{\epsilon^{(i)}_{L_o}\}$ are from different distributions). Note that $-1 \leq \hat{\rho}_{L_c,L_o} \leq 1$.

Substituting Eqn. 26 into Eqn. 23, the expression for the covariance becomes:

$$Cov(\hat{\mu}_{L_c},\hat{\mu}_{L_o}) = \sqrt{Var(\hat{\mu}_{L_c})\cdot Var(\hat{\mu}_{L_o})}\cdot\hat{\rho}_{L_c,L_o}\cdot f_{L_t,L_o}. \qquad (27)$$

Expressions for $Cov(\hat{\mu}_{L_c},\hat{\mu}_{L_r})$ and $Cov(\hat{\mu}_{L_o})(\hat{\mu}_{L_r})$ are obtained with a similar procedure, and the *f-factors* f_{L_t,L_r} and f_{L_o,L_r}, and correlation coefficients $\hat{\rho}_{L_c,L_r}$ and $\hat{\rho}_{L_o,L_r}$ are given by the expresssions,

$$f_{L_t,L_r} = \frac{\sum_{j=1}^{n}\sqrt{\Delta L^{(j-1)}_t\cdot L^{(j-1)}_r}}{\sqrt{(\sum_{j=1}^{n}\Delta L^{(j-1)}_t)(\sum_{j=1}^{n}L^{(j-1)}_r)}}, \qquad (28)$$

$$f_{L_o,L_r} = \frac{\sum_{j=1}^{n}\sqrt{\Delta L^{(j-1)}_o\cdot L^{(j-1)}_r}}{\sqrt{(\sum_{j=1}^{n}\Delta L^{(j-1)}_o)(\sum_{j=1}^{n}L^{(j-1)}_r)}}, \qquad (29)$$

$$\begin{aligned}
\hat{\rho}_{L_c,L_r} &= \frac{\frac{1}{n}\sum_{j=1}^{n}B^{(j)}_{L_c}B^{(j)}_{L_r}}{\sqrt{\frac{1}{n}\sum_{j=1}^{n}(B^{(j)}_{L_c})^2}\sqrt{\frac{1}{n}\sum_{j=1}^{n}(B^{(j)}_{L_r})^2}} \\
&= \frac{\frac{1}{n}\sum_{j=1}^{n}B^{(j)}_{L_c}B^{(j)}_{L_r}}{\hat{\sigma}_{L_c}\hat{\sigma}_{L_r}}, \qquad (30)
\end{aligned}$$

$$\hat{\rho}_{L_o,L_r} = \frac{\frac{1}{n}\sum_{j=1}^{n} B_{L_o}^{(j)} B_{L_r}^{(j)}}{\sqrt{\frac{1}{n}\sum_{j=1}^{n}(B_{L_o}^{(j)})^2}\sqrt{\frac{1}{n}\sum_{j=1}^{n}(B_{L_r}^{(j)})^2}} = \frac{\frac{1}{n}\sum_{j=1}^{n} B_{L_o}^{(j)} B_{L_r}^{(j)}}{\hat{\sigma}_{L_o}\hat{\sigma}_{L_r}}. \quad (31)$$

From Eqn. 17 and Eqns. 26 - 31, we obtain an expression for the standard error of $\hat{\mu}_L^{(n+1)}$ which we represent with the variable $\hat{\sigma}(\hat{\mu}_L^{(n+1)})$, where $\hat{\sigma}^2(\hat{\mu}_L^{(n+1)})$ is given by the relation,

$$\begin{aligned}\hat{\sigma}^2(\hat{\mu}_L^{(n+1)}) &= (p_{L_t}^{(n)})^2\hat{\sigma}^2(\hat{\mu}_{L_c}) + (p_{L_o}^{(n)})^2\hat{\sigma}^2(\hat{\mu}_{L_o}) + (p_{L_r}^{(n)})^2\hat{\sigma}^2(\hat{\mu}_{L_r}) \\ &+ 2p_{L_t}^{(n)} \cdot p_{L_o}^{(n)} \cdot \hat{\sigma}(\hat{\mu}_{L_c}) \cdot \hat{\sigma}(\hat{\mu}_{L_o}) \cdot f_{L_t,L_o} \cdot \hat{\rho}_{L_c,L_o} \\ &+ 2p_{L_t}^{(n)} \cdot p_{L_r}^{(n)} \cdot \hat{\sigma}(\hat{\mu}_{L_c}) \cdot \hat{\sigma}(\hat{\mu}_{L_r}) \cdot f_{L_t,L_r} \cdot \hat{\rho}_{L_c,L_r} \\ &+ 2p_{L_o}^{(n)} \cdot p_{L_r}^{(n)} \cdot \hat{\sigma}(\hat{\mu}_{L_o}) \cdot \hat{\sigma}(\hat{\mu}_{L_r}) \cdot f_{L_o,L_r} \cdot \hat{\rho}_{L_o,L_r}. \end{aligned} \quad (32)$$

A similar analysis for vias yields an expression for the standard error $\hat{\sigma}(\hat{\mu}_v^{(n+1)})$ of the mean $\hat{\mu}_v^{(n+1)}$, where $\hat{\sigma}^2(\hat{\mu}_v^{(n+1)})$ is given by the relation,

$$\begin{aligned}\hat{\sigma}^2(\hat{\mu}_v^{(n+1)}) &= (p_{v_t}^{(n)})^2\hat{\sigma}^2(\hat{\mu}_{v_c}) + (p_{v_o}^{(n)})^2\hat{\sigma}^2(\hat{\mu}_{v_o}) + (p_{v_r}^{n})^2\hat{\sigma}^2(\hat{\mu}_{v_r}) \\ &+ 2p_{v_t}^{(n)} \cdot p_{v_o}^{(n)} \cdot \hat{\sigma}(\hat{\mu}_{v_c}) \cdot \hat{\sigma}(\hat{\mu}_{v_o}) \cdot f_{v_t,v_o} \cdot \hat{\rho}_{v_c,v_o} \\ &+ 2p_{v_t}^{(n)} \cdot p_{v_r}^{(n)} \cdot \hat{\sigma}(\hat{\mu}_{v_c}) \cdot \hat{\sigma}(\hat{\mu}_{v_r}) \cdot f_{v_t,v_r} \cdot \hat{\rho}_{v_c,v_r} \\ &+ 2p_{v_o}^{(n)} \cdot p_{v_r}^{(n)} \cdot \hat{\sigma}(\hat{\mu}_{v_o}) \cdot \hat{\sigma}(\hat{\mu}_{v_r}) \cdot f_{v_o,v_r} \cdot \hat{\rho}_{v_o,v_r}, \end{aligned} \quad (33)$$

where f_{v_t,v_o}, f_{v_t,v_r}, f_{v_o,v_r} are the *f-factors* for vias and $\hat{\rho}_{v_c,v_o}$, $\hat{\rho}_{v_c,v_r}$, $\hat{\rho}_{v_o,v_r}$ are the estimates of the correlation coefficients ρ_{v_c,v_r}, ρ_{v_c,v_r}, ρ_{v_o,v_r} for vias. Expressions for these quantities are obtained by substituting v for L in the corresponding equations for netlengths obtained in the previous derivation.

A simple approach to compute the value of $\hat{\sigma}^2(\hat{\mu}_L^{(n+1)})$ given in Eqn. 32 is simply to establish the significance of the correlation coefficients and to drop terms that are not statistically significant. We have from statistical theory that, under the assumption that $\rho_{L_c,L_o} = 0$, we can construct a variable z according to the following expression,

$$z = \frac{\sqrt{n-3}}{2}\ln\left(\frac{1+\hat{\rho}_{L_c,L_o}}{1-\hat{\rho}_{L_c,L_o}}\right) \sim N(0,1), \quad (34)$$

where z is distributed according to the normal distribution with zero mean and unity variance. To test the hypothesis that $\rho_{L_c,L_o} = 0$, we compute z and the *p-value*(ρ_{L_c,L_o}),

$$p - value(\rho_{L_c,L_o}) = Pr\{\mid Z \mid > \mid z \mid\} = 2 \cdot Pr\{Z > \mid z \mid\}, \quad (35)$$

where z is the standard normal variable given in Eqn. 34. If any of the quantities *p-value*(ρ_{L_c,L_o}), *p-value*(ρ_{L_c,L_r}), or *p-value*(ρ_{L_o,L_r}) is less than 0.05, we will consider that term to be significant and will keep the corresponding term in Eqn. 32; otherwise we will drop that term.

The *p-values* for netlengths and vias in the projected trial $(n+1)$ are represented by the variables *p-value*$(\mu_L^{(n+1)})$ and *p-value*$(\mu_v^{(n+1)})$ and are given by the expressions,

$$p - value(\mu_L^{(n+1)}) = 2 \cdot Pr\{T_{n-1} > |\frac{\hat{\mu}_L^{(n+1)}}{\hat{\sigma}(\hat{\mu}_L^{(n+1)})}|\}, \tag{36}$$

$$p - value(\mu_v^{(n+1)}) = 2 \cdot Pr\{T_{n-1} > |\frac{\hat{\mu}_v^{(n+1)}}{\hat{\sigma}(\hat{\mu}_v^{(n+1)})}|\}, \tag{37}$$

respectively.

The 95% Lower Confidence Bounds ($LCBs$) for $\mu_L^{(n+1)}$ and $\mu_v^{(n+1)}$ are represented by the variables $LCB_{0.95,\mu_L^{(n+1)}}$ and $LCB_{0.95,\mu_v^{(n+1)}}$, which are given by the relations,

$$LCB_{0.95,\mu_L^{(n+1)}} = \hat{\mu}_L^{(n+1)} - t_{n-1,0.95} \cdot \hat{\sigma}(\hat{\mu}_L^{(n+1)}), \tag{38}$$

$$LCB_{0.95,\mu_v^{(n+1)}} = \hat{\mu}_v^{(n+1)} - t_{n-1,0.95} \cdot \hat{\sigma}(\hat{\mu}_v^{(n+1)}), \tag{39}$$

respectively.

We will use the term *design effect* to refer to the *combined impact* on the design (that is, the design impact on the total netlength and total via number) as a result of treatment with a pre-route algorithm (in this case, custom interconnection design). We represent the *design effect* with the variable $\hat{\mu}_{design}$,[1] and we can express $\hat{\mu}_{design}$ as a weighted average of the projected effect for netlength and the projected effect for vias, as described by the expression,

$$\hat{\mu}_{design} = \frac{a \cdot v^{(n)} \cdot \hat{\mu}_v^{(n+1)} + b \cdot L^{(n)} \cdot \hat{\mu}_L^{(n+1)}}{a \cdot v^{(n)} + b \cdot L^{(n)}}, \tag{40}$$

where a represents the cost per via, and b represents the cost per length of wire in trial n. To evaluate Eqn. 40, it is necessary to specify the *cost ratio* b/a. We provide insight into the decision-making process by determining minimum value of b/a, namely $(b/a)_{min}$.

[1]A similar parameter can be defined if multiple variables need to be incorporated into the decision-making process.

Setting $\hat{\mu}_{design} = 0$ in Eqn. 40, we obtain the following expression for $(b/a)_{min}$,

$$(b/a)_{min} = \frac{-v^{(n)} \cdot \hat{\mu}_v^{(n+1)}}{L^{(n)} \cdot \hat{\mu}_L^{(n+1)}}. \tag{41}$$

For values of $b/a \geq (b/a)_{min}$, then $\hat{\mu}_{design} \geq 0$, and we can proceed with trial $n+1$. In principle, we can also determine confidence bounds and *p-values* for $\hat{\mu}_{design}$ with standard statistical methods.

A similar statistical analysis can forecast results on another chip design, treating first step in analysis of the new design as *trial* $n+1$, following the n trials of the first design. In this way, results on different designs can be accumulated.

A. Application to POWER4 DD1 IFU

We now apply the preceeding statistical framework to analyze the POWER4 Instruction Fetch Unit (IFU).[23], [24], [25], [26] As discussed in[22], the IFU is routed with a series of $n = 6$ *trials* of custom interconnections, and the statistical framework will predict whether additional improvement in interconnect physical properties is expected if we proceed with trial $n+1 = 7$.

First, the *sample means*, *standard errors*, and *p-values* for netlengths and vias over $n = 6$ trials are obtained.[22] With this information, and the statistical framework presented in this paper, we calculate the projected *sample mean* and *standard error* for proposed trial $n+1 = 7$. Table I summarizes the values of the projected interconnect effectivenesses for netlengths $\epsilon_L^{(7)}$ and for vias $\epsilon_v^{(7)}$ in the DD1 IFU, the proportions $p_{Lt}^{(6)}$, $p_{L_o}^{(6)}$, $p_{L_r}^{(6)}$, and total netlength $L^{(7)}$ and total number of vias $v^{(7)}$ for the proposed trial $i = 7$. The values are calculated with Eqn. 5 in[22] and Eqns. 15- 16. To obtain the values shown in this table, the proposed region of influence R_7 is estimated from locations of bus signals with largest values of the normalized excess Steiner lengths *NESL* in trial $i = 6$, as listed in Table II. For this case, *NESL* ≥ 0.20 is chosen to be the criterion to select buses for custom interconnections. Figure 2 shows R_7 (shaded region) for the proposed $i+1 = 7$ trial.

Tables III and IV show values for the *f-factors* f_{L_t,L_o}, f_{L_t,L_r}, f_{L_o,L_r}, and correlation coefficients $\hat{\rho}_{L_c,L_o}$, $\hat{\rho}_{L_c,L_r}$, and $\hat{\rho}_{L_o,L_r}$ for IFU DD1 interconnect lengths and vias obtained with Eqns. 25 - 26 and Eqns. 28 - 31. Table IV shows that for $i = n+1 = 7$, the *p-*

value$(\rho_{L_o,L_r}) < 0.05$. Therefore, we reject the hypothesis that $\rho_{L_o,L_r} = 0$ and include the corresponding term in Eqn. 32. Since *p-value*$(\rho_{L_c,L_o}) > 0.05$ and *p-value*$(\rho_{L_c,L_r}) > 0.05$, we cannot reject the hypotheses that $\rho_{L_c,L_o} = 0$ and $\rho_{L_c,L_r} = 0$; therefore, we neglect the corresponding terms in Eqn. 32. With these simplifications, the standard error for $\hat{\mu}_L^{(7)}$ simplifies to the relation,

$$\begin{aligned} \hat{\sigma}^2(\hat{\mu}_L^{(7)}) &= (p_{L_t}^{(6)})^2[\hat{\sigma}(\hat{\mu}_{L_c})]^2 + (p_{L_o}^{(6)})^2[\hat{\sigma}(\hat{\mu}_{L_o})]^2 + (p_{L_r}^{(6)})^2[\hat{\sigma}(\hat{\mu}_{L_r})]^2 \\ &+ 2p_{L_o}^{(6)} \cdot p_{L_r}^{(6)} \cdot \hat{\sigma}(\hat{\mu}_{L_o}) \cdot \hat{\sigma}(\hat{\mu}_{L_r}) \cdot f_{L_o,L_r} \cdot \hat{\rho}_{L_o,L_r}. \end{aligned} \tag{42}$$

Note that in future experiments we will still maintain scatterplots of $(\{B_{L_c}^{(i)}\}$ versus $\{B_{L_o}^{(i)}\})$, $(\{B_{L_c}^{(i)}\}$ versus $\{B_{L_r}^{(i)}\})$, and $(\{B_{L_o}^{(i)}\}$ versus $\{B_{L_r}^{(i)}\})$ and will test whether the correlation coefficients are insignificant. To obtain a value for $\hat{\sigma}(\hat{\mu}_v^{(7)})$ for the DD1 IFU interconnect, the results in Table IV show that *p-value*(ρ_{v_c,v_o}), *p-value*(ρ_{v_c,v_r}), and *p-value*(ρ_{v_o,v_r}) are all greater than 0.05; therefore, in this case, terms 4, 5, and 6 can all be dropped in Eqn. 33 to obtain the simplified expression for the standard error for $\hat{\mu}_v^7$,

$$\hat{\sigma}^2(\hat{\mu}_v^{(7)}) = (p_{v_t}^{(6)})^2[\hat{\sigma}(\hat{\mu}_{v_c})]^2 + (p_{v_o}^{(6)})^2[\hat{\sigma}(\hat{\mu}_{v_o})]^2 + (p_{v_r}^{(6)})^2[\hat{\sigma}(\hat{\mu}_{v_r})]^2. \tag{43}$$

Equation 42 and Eqns. 43 - 39 obtain the *p-values* and *LCBs* shown in Table V; this table summarizes the projected results for proposed trial $i = n + 1 = 7$. For the case of the DD1 IFU, one of the projected *sample means* is positive, and the other is negative: in particular, the netlength projected *sample mean* is negative, and the via projected *sample mean* is positive. The next step is to calculate the *design effect* with Eqn. 40. From Eqn. 41, $(b/a)_{min} = -(53562 \cdot 0.10)/(5.49m \cdot [-1.0]) = (-5356.2)/(-5.49) = 0.000976$ *vias/micron*. Therefore, in order to proceed with trial $n+1$, b/a must exceed approximately 1 via per 1025 microns of wire. We obtain an empirical estimate of b/a, namely $(b/a)_{empirical}$, from the DD1 IFU data for the total number of vias $((53562 - 7872))$ and total netlength $(5.49 - 2.01)m$ routed with the automated router in trial n. It follows that $(b/a)_{empirical} = (53562 - 7872)/(5.49 - 2.01)m = 45690/3.48m = 0.013$ *vias/micron*. Since $(b/a)_{empirical} >> (b/a)_{min}$, we have evidence for a positive *design estimate*, and therefore we proceed with trial $n + 1$.

B. Application to the POWER4 DD2 IFU (reduced-area design)

The results obtained by applying the statistical method for forecasting in DD2 IFU are uniformly consistent with the results obtained in the DD1 IFU. Figure 3 shows R_7 (shaded region) for the proposed $i+1=7$ trial. Table VI summarizes the values of the projected interconnect effectivenesses for netlengths $\epsilon_L^{(7)}$ and for vias $\epsilon_v^{(7)}$ in the DD2 IFU, the proportions $p_{L_t}^{(6)}$, $p_{L_o}^{(6)}$, $p_{L_r}^{(6)}$, and total netlength $L^{(7)}$ and total number of vias $v^{(7)}$ for the proposed trial $i=7$. As in the case of the DD1 IFU, the netlength *sample mean* is projected to be negative, and the via *sample mean* is projected to be positive. Table VII lists the bus signals with largest values of the normalized excess Steiner lengths *NESL* in trial $i=6$ for the DD2 IFU. Figure 3 shows R_7 (shaded region) for the proposed $i+1=7$ trial in DD2 IFU. Tables VIII and IX show values for the *f-factors* f_{L_t,L_o}, f_{L_t,L_r}, f_{L_o,L_r}, and correlation coefficients $\hat{\rho}_{L_c,L_o}$, $\hat{\rho}_{L_c,L_r}$, and $\hat{\rho}_{L_o,L_r}$ for IFU DD2 interconnect lengths and vias. Table X summarizes the projected results for *p-values* and *LCBs* for proposed trial $i=n+1=7$ in the DD2 IFU. As in the case of the DD1 IFU, the netlength projected *sample mean* is negative, and the via projected *sample mean* is positive.

The next step is to calculate the *design effect* with Eqn. 40. With Eqn. 41, $(b/a)_{min} = -(48197 \cdot 0.097)/(5.42m \cdot [-0.44]) = (-4675.1)/(-2.38) = 0.00196$ *vias/micron*, which shows that in order to proceed with trial $n+1$, the ratio b/a must exceed approximately 1 via per 510 microns of wire. The empirical estimate of b/a, $(b/a)_{empirical}$, is obtained from the total number of vias $((48197 - 7997))$ and total netlength $((5.42 - 1.99)m)$ routed with the automated router in trial n. It follows that $(b/a)_{empirical} = (48197 - 7997)/(5.42 - 1.99)m = 40200/3.43m = 0.012 vias/micron$. As for the DD1 IFU, since $(b/a)_{empirical} >> (b/a)_{min}$, we again have evidence for a positive *design estimate*, and we proceed with trial $n+1$.

The cumulative effectiveness in the DD2 IFU also exhibits a similar behavior to that observed in the DD1 IFU. Figures 4(a) and 4(b) show the cumulative effectivenesses for netlengths $\epsilon_L^{(i)(0)}$ and vias $\epsilon_v^{(i)(0)}$, respectively, for trials $i \leq n = 6$. As in DD1, the projected cumulative effectiveness for both netlengths and vias tend to increase with each additional trial i. The figure shows that the cumulative effectivenesses for netlengths and vias are 1.45% and 20.7%, respectively, after trial $n=6$.

IV. Conclusions

Analytical techniques to forecast when to stop the addition of custom interconnections in a ULSI design are presented. These technique provide designers with tools to help determine when to stop the addition of custom interconnections in the design and consider the design complete.

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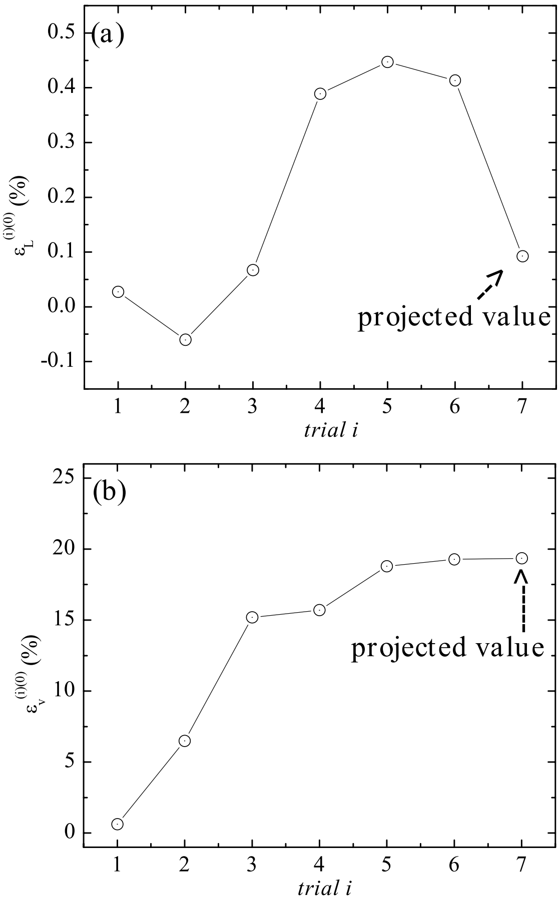

Fig. 1. Measured cumulative effectiveness (a) for netlengths $\epsilon_L^{(i)(0)}$ and (b) for vias $\epsilon_v^{(i)(0)}$ in the DD1 IFU for each trial $i \leq 6$. The projected cumulative effectiveness for netlengths and vias is also shown in (a) and (b), respectively, at trial $i = 7$.

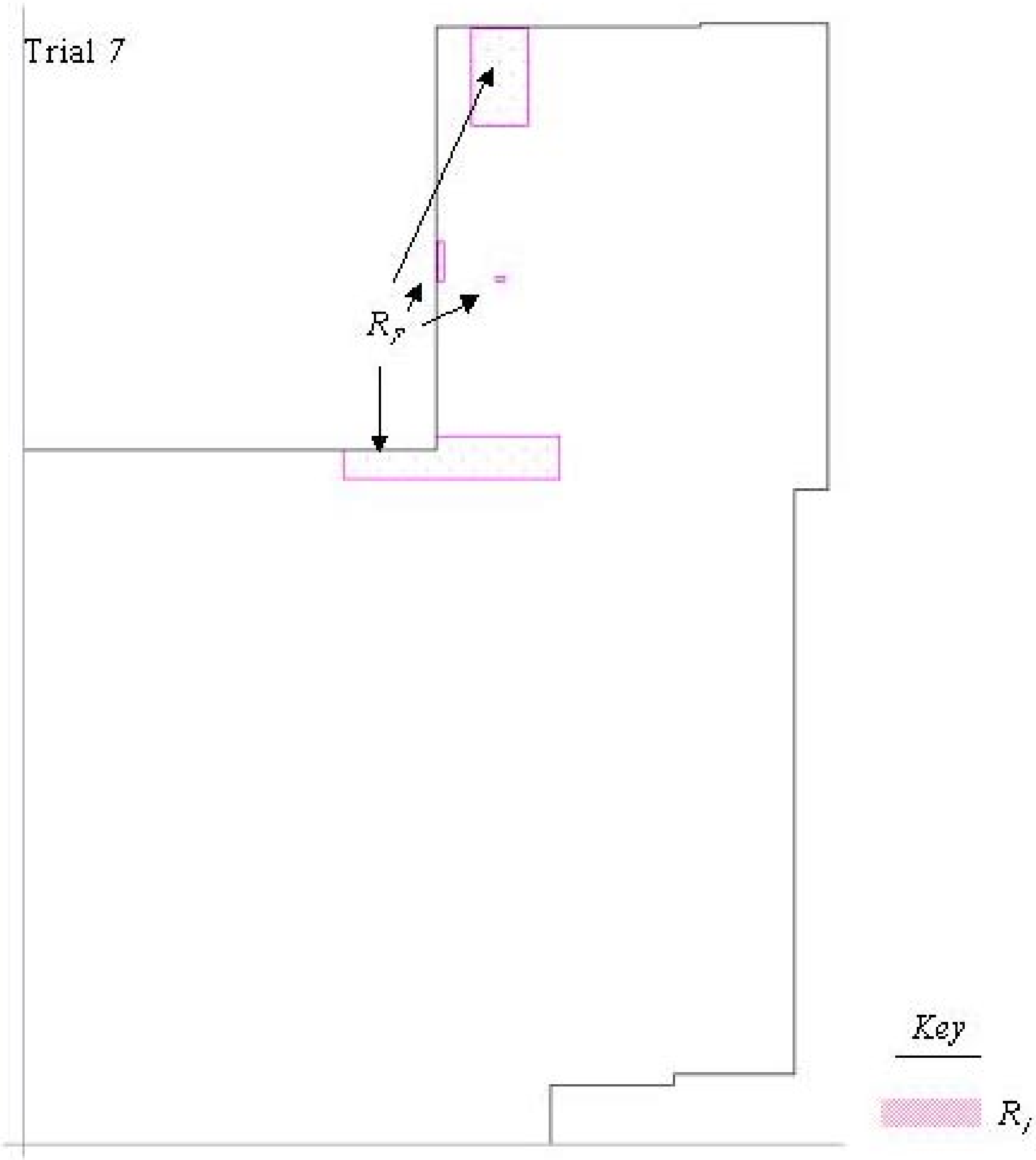

Fig. 2. R_7 (shaded) for the proposed trial $i + 1 = 7$ in the DD1 IFU.

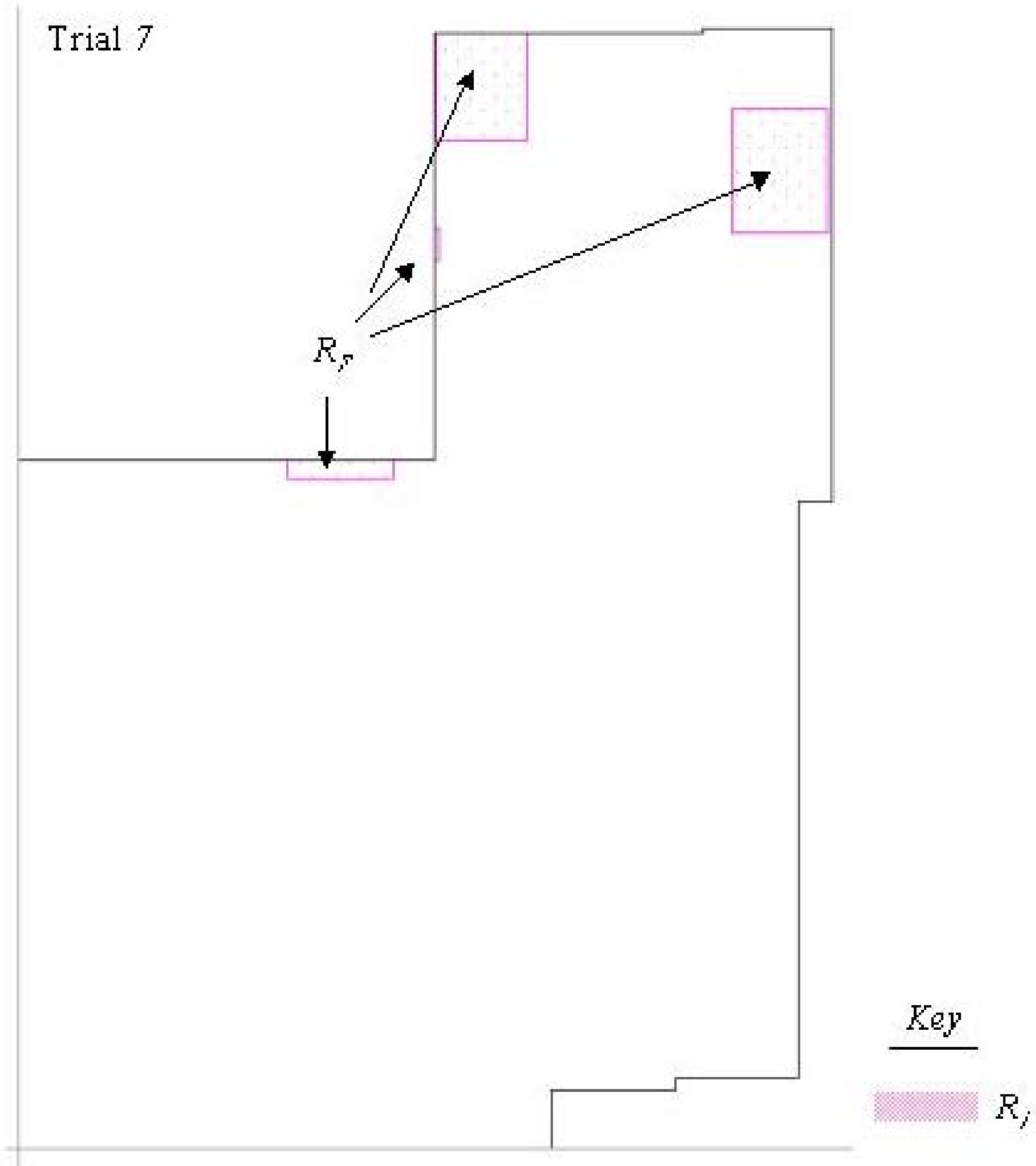

Fig. 3. R_7 (shaded) for the proposed trial $i + 1 = 7$ in the DD2 IFU.

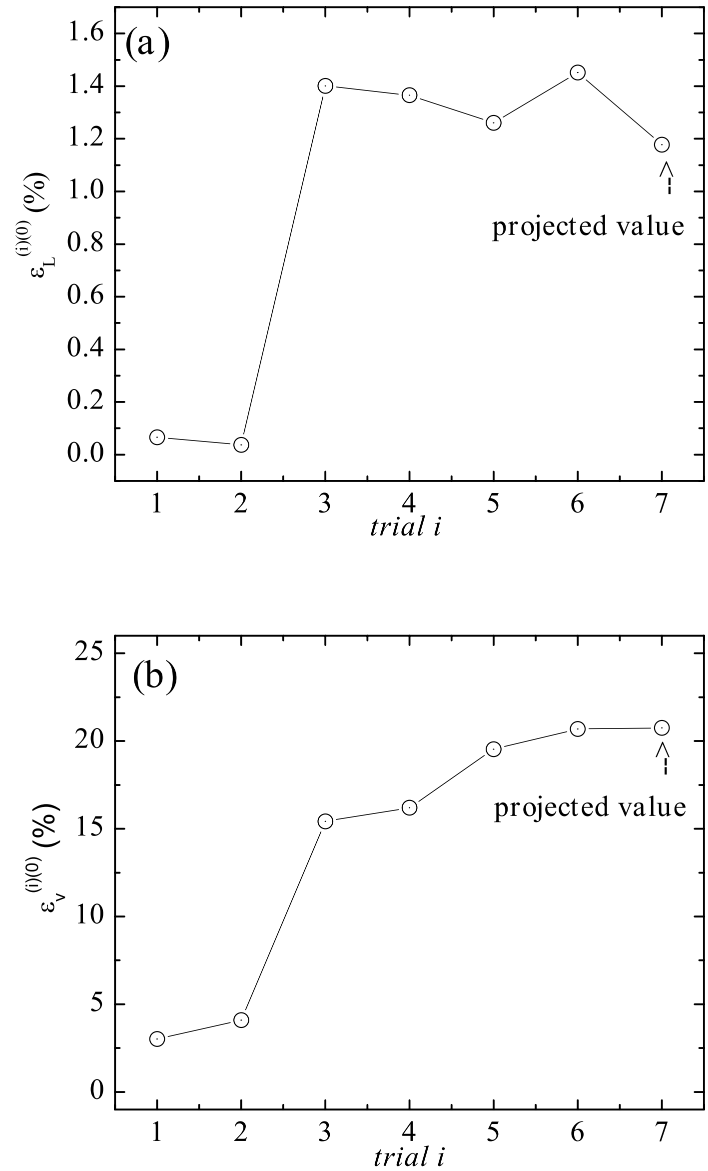

Fig. 4. Measured cumulative effectiveness for netlengths (a) $\epsilon_L^{(i)(0)}$ and (b) vias $\epsilon_v^{(i)(0)}$ in the DD2 IFU for each trial $i \leq 6$. The projected cumulative effectiveness for netlengths and vias is also shown in (a) and (b), respectively, for proposed trial $i = 7$.

TABLE I

PROJECTED INTERCONNECT EFFECTIVENESSES FOR NETLENGTHS $\epsilon_L^{(7)}(\%)$ AND VIAS $\epsilon_v^{(7)}(\%)$ AND TOTAL NETLENGTH $L^{(7)}$ AND TOTAL NUMBER OF VIAS $v^{(7)}$ FOR PROPOSED TRIAL $i = n + 1 = 7$ IN THE DD1 IFU WITH REGION OF INFLUENCE R_7. THE LENGTHS $\Delta L_t^{(6)}$, $L_o^{(6)}$, $L_r^{(6)}$, $L^{(6)}$ AND $L^{(7)}$ ARE EXPRESSED IN UNITS OF *meters*. THE PROPORTIONS $p_{L_t}^{(6)}$, $p_{L_o}^{(6)}$, $p_{L_r}^{(6)}$ ARE ALSO SHOWN.

L	*custom interconnections in* R_i		*other routes in* R_i		*rest of routes in* $\overline{R}_i$		*all routes*		
i	$p_{L_t}^{(6)}$	$\Delta L_t^{(6)}$	$p_{L_o}^{(6)}$	$L_o^{(6)}$	$p_{L_r}^{(6)}$	$L_r^{(6)}$	$\hat{\mu}_L^{(7)}(\%)$	$L^{(6)}$	$L^{(7)}$
7	0.0080	0.028	0.21	0.74	0.78	2.71	-1.0	5.49	5.50

V	*custom interconnections in* R_i		*other routes in* R_i		*rest of routes in* $\overline{R}_i$		*all routes*		
i	$p_{v_t}^{(6)}$	$\Delta v_t^{(6)}$	$p_{v_o}^{(6)}$	$v_o^{(6)}$	$p_{v_r}^{(6)}$	$v_r^{(6)}$	$\hat{\mu}_v^{(7)}(\%)$	$v^{(6)}$	$v^{(7)}$
7	0.020	927	0.31	14259	0.67	30504	0.10	53562	53516

TABLE II

BUS SIGNALS WITH $NESL \geq 0.20$ IN TRIAL $i = 6$.

bus signal	*NESL*
if-ppc-istat$\langle 2 \rangle$	0.248
sb-cru-iop-x1$\langle 0 \rangle$	0.246
iftc-br-slot0-lk1$\langle 2 \rangle$	0.242
ib-btag-data$\langle 4 \rangle$	0.240
ifcb-ppc-instr-1-b-x1$\langle 5 \rangle$	0.211

TABLE III

f-factors FOR DD1 IFU INTERCONNECTIONS.

Netlengths	*Vias*
$f_{L_t,L_o} = 0.90$	$f_{v_t,v_o} = 0.85$
$f_{L_t,L_r} = 0.89$	$f_{v_t,v_r} = 0.92$
$f_{L_o,L_r} = 0.90$	$f_{v_o,v_r} = 0.86$

TABLE IV

Correlation coefficients and *p-values* for DD1 IFU interconnections.

Netlengths		*Vias*	
Correlation	*p-value*	*Correlation*	*p-value*
$\hat{\rho}_{L_c,L_o} = -0.50$	p-$value(\rho_{L_c,L_o}) = 0.35$	$\hat{\rho}_{v_c,v_o} = 0.059$	p-$value(\rho_{v_c,v_o}) = 0.92$
$\hat{\rho}_{L_c,L_r} = -0.71$	p-$value(\rho_{L_c,L_r}) = 0.12$	$\hat{\rho}_{v_c,v_r} = -0.24$	p-$value(\rho_{v_c,v_r}) = 0.67$
$\hat{\rho}_{L_o,L_r} = 0.88$	p-$value(\rho_{L_o,L_r}) = 0.016$	$\hat{\rho}_{v_o,v_r} = -0.73$	p-$value(\rho_{v_o,v_r}) = 0.11$

TABLE V

PROJECTED *mean effectiveness*, *standard error*, *p-value*, AND *lower confidence bound* FOR IFU DD1 INTERCONNECTIONS FOR PROPOSED TRIAL $i = n + 1 = 7$. THE *lower confidence bounds* SHOWN ARE THE 95% *LCBs*.

All nets	*mean(%)*	*standard error(%)*	*p-value*	*LCB(%)*
Netlengths	$\hat{\mu}_L^{(7)} = -1.0$	$\hat{\sigma}(\hat{\mu}_L^{(7)}) = 0.24$	$p\text{-}value(\mu_L^{(7)}) = 0.996$	-1.5
Vias	$\hat{\mu}_v^{(7)} = 0.10$	$\hat{\sigma}(\hat{\mu}_v^{(7)}) = 0.75$	$p\text{-}value(\mu_v^{(7)}) = 0.45$	-1.4

TABLE VI

PROJECTED INTERCONNECT EFFECTIVENESSES FOR NETLENGTHS $\epsilon_L^{(7)}(\%)$ AND VIAS $\epsilon_v^{(7)}(\%)$ AND TOTAL NETLENGTH $L^{(7)}$ AND TOTAL NUMBER OF VIAS $v^{(7)}$ FOR PROPOSED TRIAL $i = n + 1 = 7$ IN THE DD2 IFU WITH REGION OF INFLUENCE R_7. THE LENGTHS $\Delta L_t^{(6)}$, $L_o^{(6)}$, $L_r^{(6)}$, $L^{(6)}$ AND $L^{(7)}$ ARE EXPRESSED IN UNITS OF *meters*. THE PROPORTIONS $p_{L_t}^{(6)}$, $p_{L_o}^{(6)}$, $p_{L_r}^{(6)}$ ARE ALSO SHOWN.

L	*custom interconnections in* R_i		*other routes in* R_i		*rest of routes in* $\overline{R}_i$		*all routes*		
i	$p_{L_t}^{(6)}$	$\Delta L_t^{(6)}$	$p_{L_o}^{(6)}$	$L_o^{(6)}$	$p_{L_r}^{(6)}$	$L_r^{(6)}$	$\hat{\mu}_L^{(7)}(\%)$	$L^{(6)}$	$L^{(7)}$
7	0.0061	0.021	0.19	0.65	0.80	2.76	-0.44	5.42	5.43

V	*custom interconnections in* R_i		*other routes in* R_i		*rest of routes in* $\overline{R}_i$		*all routes*		
i	$p_{v_t}^{(6)}$	$\Delta v_t^{(6)}$	$p_{v_o}^{(6)}$	$v_o^{(6)}$	$p_{v_r}^{(6)}$	$v_r^{(6)}$	$\hat{\mu}_v^{(7)}(\%)$	$v^{(6)}$	$v^{(7)}$
7	0.012	483	0.26	10290	0.73	29427	0.097	48197	4815[illegible]

TABLE VII

BUS SIGNALS WITH $NESL \geq 0.40$ IN TRIAL $i = 6$.

bus signal	*NESL*
ib-btag-pcp4$\langle 0 \rangle$	12.467
if-ppc-instr-address$\langle 10 \rangle$	0.990
iflb-lbht-read-data$\langle 4 \rangle$	0.864
ifgr-lbht-write-en$\langle 3 \rangle$	0.658
sb-cru-iop$\langle 0 \rangle$	0.586
sb-cru-imm-x1$\langle 6 \rangle$	0.557
ifgr-lbht-write-en$\langle 2 \rangle$	0.445

TABLE VIII

f-factors for DD2 IFU interconnections.

Netlengths	*Vias*
$f_{L_t,L_o} = 0.86$	$f_{v_t,v_o} = 0.80$
$f_{L_t,L_r} = 0.81$	$f_{v_t,v_r} = 0.89$
$f_{L_o,L_r} = 0.82$	$f_{v_o,v_r} = 0.85$

TABLE IX

CORRELATION COEFFICIENTS AND *p-values* FOR DD2 IFU INTERCONNECTIONS.

Netlengths		*Vias*	
Correlation	*p-value*	*Correlation*	*p-value*
$\hat{\rho}_{L_c,L_o} = -0.60$	$p\text{-}value(\rho_{L_c,L_o}) = 0.23$	$\rho_{v_c,v_o} = -0.32$	$p\text{-}value(\rho_{v_c,v_o}) = 0.56$
$\hat{\rho}_{L_c,L_r} = 0.078$	$p\text{-}value(\rho_{L_c,L_r}) = 0.89$	$\rho_{v_c,v_r} = 0.091$	$p\text{-}value(\rho_{v_c,v_r}) = 0.50$
$\hat{\rho}_{L_o,L_r} = 0.33$	$p\text{-}value(\rho_{L_o,L_r}) = 0.56$	$\rho_{v_o,v_r} = 0.66$	$p\text{-}value(\rho_{v_o,v_r}) = 0.17$

TABLE X

PROJECTED *mean effectiveness*, *standard error*, *p-value*, AND *lower confidence bound LCB* FOR IFU DD2 INTERCONNECT NETLENGTHS AND VIAS FOR THE PROPOSED TRIAL $i = n + 1 = 7$. THE 95% *lower confidence bounds* ARE SHOWN.

All nets	*mean(%)*	*standard error(%)*	*p-value*	*LCB*(%)
Netlengths	$\hat{\mu}_L^{(7)} = -0.44$	$\hat{\sigma}(\hat{\mu}_L^{(7)}) = 0.20$	$p\text{-}value(\mu_L^{(7)}) = 0.96$	-0.85
Vias	$\hat{\mu}_v^{(7)} = 0.097$	$\hat{\sigma}(\hat{\mu}_v^{(7)}) = 0.75$	$p\text{-}value(\mu_v^{(7)}) = 0.45$	-1.4

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