Interstreet Crossing Issues In Single-Row Routing

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Abstract

In single-row routing, *doglegs* or the inter-street crossings, is an issue that greatly determines the congestion level in the printed-circuit board (PCB) layout. A single-row network consists of a set of nets formed from pairs of pins. The nets make up the wires in the PCB which are drawn from left to right in a non-crossing manner. In this scenario, the nets can be modeled as nodes in a planar graph. However, inter-street crossings in the node axis are allowed, and they are necessary to prevent the nets from crossing each other. Each inter-street crossing in the node axis creates a dogleg. A good PCB design requires evenly distributed doglegs that utilize the compact space to the maximum. Uneven distribution of doglegs may trigger technical glitches on the PCB such as the creation of electric and magnetic fields. In this paper, we discuss this issue and a technique for distributing the doglegs evenly in the pin intervals.

Keywords: Single-row routing, PCB design and dogleg.

Introduction

Single-row routing is a NP-complete problem [1] that contributes in the compact design of the printed-circuit boards (PCBs). The problem has been widely studied. In [1], single-row routing was proposed along with other routing techniques to help in minimizing the congestion level in the multilayer PCBs. In [2], Kuh *et al.* supported the NP-completeness of this problem, and presented some necessary and sufficient conditions to determine the optimality of the solutions to the problem. In addition, the authors suggested heuristics as a suitable approach to besides the classical graph theoretical and integer programming methods.

Various methods based on graph theory, mathematical programming and heuristics have been proposed to solve the single-row routing problem. In [3], Du and Liu proposed a heuristic for finding an optimal routing based on a method that sorts the nets according to their classes, internal cut numbers and residual cut numbers. In [4], a graph decomposition technique was proposed to obtain the least congested routing based on the overlapping intervals of a graph.

A metaheuristical method based on the stochastic simulated technique was proposed in [5] for minimizing the congestion based on an objective function as a function of the street congestions and the doglegs. The technique was further enhanced through a model called *Enhanced Simulated annealing for Single-row Routing* (ESSR) in [6]. The approach produces optimal solutions to the problem in most cases tested. As an application, a prototype model based on single-row routing was proposed in [7] for the multi-commodity problem of the demand-supply type. The model involves the transformation of complete graphs to the single-row network, which are suitable for applications such as in the channel assignments of the cellular telephone networks.

In this paper, we discuss some refinement to the problem of reducing the number of doglegs in the single-row network. The main objective is to produce a realization that distributes the doglegs evenly on the pin intervals. The paper is organized into six sections. Section 2 is the problem formulation while Section 3 describes the symbols used in this paper. The single-row routing problem and our earlier solutions using the simulated annealing approach are described in details in Section 4. Our model for distributing the doglegs evenly is described in Section 5, which is a refinement to the overall problem involving doglegs. Section 6 concludes the paper with the summary and some suggestions for further extension to the work.

Problem Formulation

Given N intervals, I_k for $k=1,2,...,N$, joining pairs of pins in S, the problem is to find a realization in the form of list ordering L that distributes the doglegs evenly on the pin intervals. Even distribution of doglegs is an important factor in keeping the circuitry free from electromagnetic interferences as wires that are close to each other generate intolerable amount of heat, and electric and magnetic fields.

The main objective in single-row routing is to minimize the street congestion so as to maximize the placement of electronic components in the PCB. Distributing the doglegs evenly on pin intervals is also an important objective which contributes to a practical, well-organized and scalable circuitry in the PCB. However, it is not possible to achieve both objectives at the same time as both parameters are independent of each other.

Symbols and Terminologies

Several common symbols and terminologies related to the single-row problem are explained briefly as follows:

b_k	Beginning pin in n_k.
e_k	Ending pin in n_k.
$h_{k,j}$	Height of segment j in net k.
m	Number of nets in S.
n_k	Net k in S.
s_i	Pin i in S.
D	Number of doglegs in the realization.
E	Energy in the realization.
I_k	Interval k.
L	Ordering list of nodes in the single-row axis S.
Q	Overall street congestion in the realization.
$R_{i,i+1}$	Pin interval between s_i and s_{i+1}.
S	Single-row network.

Single-Row Routing Problem

Single-row routing is a combinatorial optimization problem that has been proven to be NP-complete [1]. Traditionally, single-row routing is one of the techniques employed for designing the routes between the electronic components of a printed-circuit board. Each path joining the pins is called a *net*. In single-row routing problem, we are given a set of $2m$ evenly-spaced pins (terminals or vias), s_i, for $i=1,2,...,2m$, arranged horizontally from left to right in a single horizontal row called *single-row axis*. The problem is to construct m nets from the list $L=\{n_k\}$, for $k=1,2,...,m$, formed from the horizontal intervals, (b_k, e_k), in the node axis, where b_k and e_k are the beginning and end pins of the intervals, respectively. Each horizontal interval is formed from a pair of two (or more) pins through non-intersecting vertical and horizontal lines. The nets are to be drawn from left to right, while the reverse direction is not allowed.

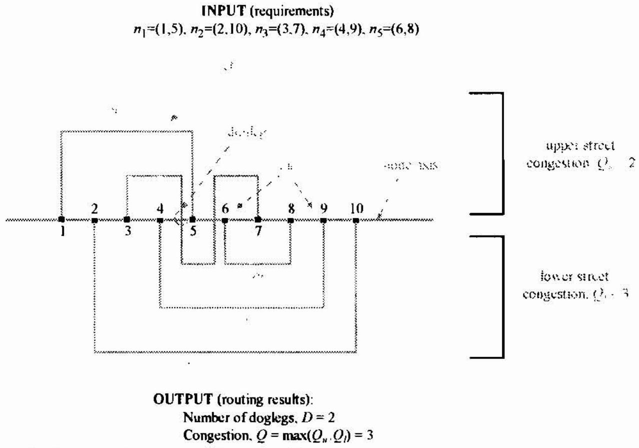

Figure 1: Terminologies in the single-row routing problem

Figure 1 shows a realization in a single-row routing from the ordering list $L=\{n_1,n_3,n_5,n_4,n_2\}$. Physically, each net in the single row represents a conductor path for its pins to communicate. The area above the single-row axis is called the *upper street*, while that below is the *lower street*. The number of horizontal tracks in the upper and lower streets is called the *upper street congestion* Q_u and the *lower street congestion* Q_l, respectively. The overall street congestion Q of a realization is defined as the maximum of its upper and lower street congestions, that is, $Q=\max(Q_u,Q_l)=3$ in the above figure. A crossing on the node axis, as shown through a line between nodes 4 and 5 in the figure, is called a *dogleg* or interstreet crossing. It can be seen that there are two doglegs in this example.

One important objective in single-row routing is to minimize both the street congestion Q and number of doglegs D. This objective is difficult to achieve as the two components are separate but are dependent entities. While having one component minimized, the other tends to show some resistance to its minimization. In [5], we proposed the simulated annealing approach for solving the single-row routing problem. In this work, the energy in a given net ordering is a function of the street congestion Q and number of doglegs D. This requirement is expressed as the total length of all the tracks, according to the energy function E as follows:

$$E=f(Q,D)=\sum_{k=1}^{m}\sum_{j=1}^{m_k}\left|h_{k,j}\right|. \tag{1}$$

In the above equation, $h_{k,j}$ is the height of segment j in net k, while m is the number of nets in the problem and m_k is the number of segments in net k. The routing produced in Figure 1 with $L=\{n_1,n_3,n_5,n_4,n_2\}$ has an energy given by $E=11$ which suggests it may not be optimum. A better solution can be obtained by reforming the list with different orderings of nets.

Our simulated annealing approach produces reasonably good optimal results in terms of both minimum street congestion and number of doglegs through a series of iterative steps. The idea in simulated annealing is to place the nets in a list L in order according to their position. Starting at a high temperature the process starts with a random list L_0 where the energy E_0 is recorded. The temperature is then lowered gradually where, at the same time, the position of a set of nets in the list are swapped. The new energy is recorded and its difference from the old energy ΔE determines whether the new list is accepted or rejected. The new list is accepted if $\Delta E \le 0$. If $\Delta E > 0$ then the new list if accepted only if its Boltzmann probability given by $P(\Delta E)=e^{-\Delta E/T}$ is greater than some threshold value ε. This annealing step is repeated until the energy is minimum, and that no further improvement is noted after several iterations. The list corresponding to this minimum energy is then the solution to the problem, and this list produces the desired least-congested routing.

The method is further improved in [6] in a model called ESSR where a set of nets, rather than just one pair, are swapped to produce a faster convergence to its solution. ESSR produces reasonably good optimal results in terms of both the street congestion and number of doglegs.

Refinement by Distributing Doglegs Evenly in the Pin Intervals

A few issues arise in the final realization produced from the objective function in Equation (1). While the overall congestion in the network is greatly reduced, the final realization may produce uneven distribution of doglegs in the pin intervals which may cause technical glitches such as the creation of electric fields within the circuitry. This is because wires that are too close to each other produce intolerable amount of heat and electric field which may cause some interference to the circuit. A good network design requires the doglegs to be evenly distributed between the pins so that the wires are positioned some distance apart.

We discuss the case of uneven distribution of doglegs in the pin intervals. Figure 2 (left) shows a case of multiple doglegs in the pin interval (s_i, s_{i+1}). As shown in this figure, the occurrence of many doglegs in a pin interval is caused by a separation in the ordering of two successive pins from different nets. The doglegs in the interval are created as the endpoints of the nets n_k and n_{k+1} are covered by three other nets. In this case, n_k and n_{k+1} are separated by three steps in the ordering, and this creates three doglegs.

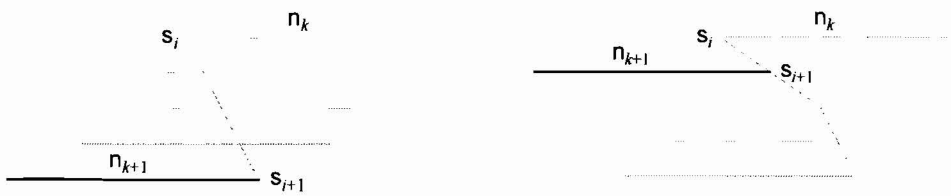

Figure 2: Uneven dogleg distribution (left) and its rectification (right).

A quick solution to the above problem is to move n_{k+1} immediately above or below n_k, as shown in Figure 2 (right). This move eliminates the three doglegs in the interval (s_i, s_{i+1}) but it may affect the distribution of doglegs originating from the left pin of n_{k+1}. The move can backfire as a reduction of doglegs in one interval may result in an increase in other intervals. Therefore, a comprehensive solution requires the participation of all pins in the network.

Our solution to the problem requires the participation of both the left and right pins of all nets. At every step, the occurrence of doglegs at each endpoint of the nets is calculated. A net whose sum of doglegs from its endpoints is the highest is selected for swapping into a new position. The new location of the net is determined from the proximity of the net endpoints to the endpoints of the nets in the new position.

We illustrate this technique using an example as shown in Figure 3. The figure shows an initial single-row network consisting of ten nets on 20 pins. The nets are numbered from 1 to 10 into the list $L_0 = \{1,2,3,4,5,6,7,8,9,10\}$ according to their order from top to bottom. Table 1 shows the left and right pins of each net $n_k = (b_k, e_k)$ defined in columns 2 and 3 of Table 1, respectively. There are $m-1=19$ equal-width pin intervals in the network.

Table 1: The initial list $L_0 = \{1,2,3,4,5,6,7,8,9,10\}$

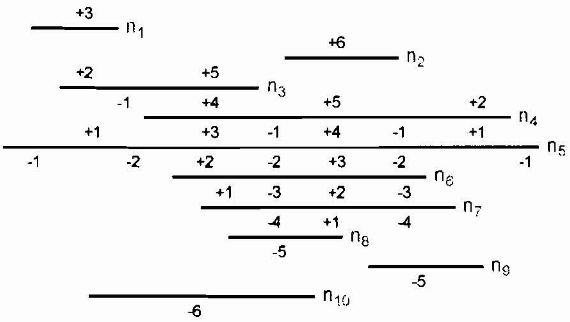

Figure 3: The list $L_0 = \{1,2,3,4,5,6,7,8,9,10\}$ having $E = 86$, $Q = 6$ and $D = 21$.

			Doglegs		
n_k	b_k	e_k	Left	Right	Total
n_1	2	5	0	3	3
n_2	11	15	5	6	11
n_3	3	10	1	4	5
n_4	6	19	1	1	2
n_5	1	20	0	0	0
n_6	7	16	1	2	3
n_7	8	17	0	0	0
n_8	9	13	4	0	4
n_9	14	18	4	1	5
n_{10}	4	12	3	5	8

Figure 3 also displays the energy values of the net segments from the list. From Equation (1), the total energy produced from the ordering in the list is $E = 86$, and this results in $Q = 6$ and $D = 21$. Doglegs are distributed unevenly in the pin intervals as follows: $R_{3,4} = 1$, $R_{4,5} = 2$, $R_{5,6} = 1$, $R_{6,7} = 1$, $R_{9,10} = 4$, $R_{11,12} = 5$, $R_{14,15} = 4$, $R_{15,16} = 2$ and $R_{18,19} = 1$. Note that other pin intervals in the network have no doglegs. This initial list produces a realization which is not optimal.

Our objective here is to redistribute the doglegs so that each pin interval will not have more than the threshold value, defined as follows:

$$\text{Threshold, } H = \lceil D/(m-1) \rceil$$

In Figure 3, D is 21 while the number of pins, m, is 20. Therefore, $H = 2$, and each pin interval should not have more than two doglegs.

We discuss a technique to achieve the evenly distributed doglegs. Columns 4 and 5 of Table 1 plot the number of doglegs produced from the left and right pins of each net as the output from $L = \{1,2,3,4,5,6,7,8,9,10\}$. Column 6 is its total number which is the sum of left and right doglegs. Obviously, n_2 has the highest occurrence, and this net has to be moved to help in reducing the number. Our strategy in selecting a new position for n_2 consists of placing the net in such a way it interlocks with the present nets with its left and right pins close to the pins in those nets. For this reason, n_2 is ideally placed in between n_8 and n_9, as shown in Figure 4, to produce $L_1 = \{1,3,4,5,6,7,8,2,9,10\}$. The list results in an improvement with $E = 73$, $Q = 6$ and $D = 17$. The threshold value becomes $H = 1$, and this implies every pin interval should not have more than one dogleg.

Table 2: First move with $L_1 = \{1,3,4,5,6,7,8,2,9,10\}$

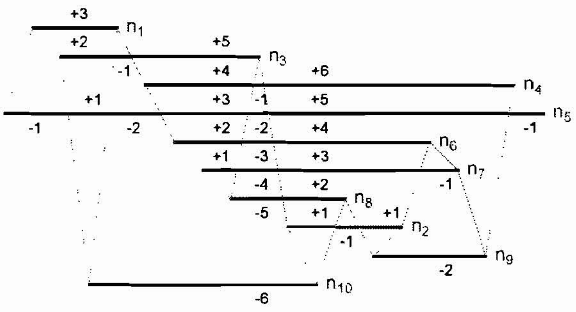

Figure 4: The list $L_1 = \{1,3,4,5,6,7,8,2,9,10\}$ having $E = 73$, $Q = 6$ and $D = 17$.

			Doglegs		
n_k	b_k	e_k	Left	Right	Total
n_1	2	5	0	3	3
n_2	11	15	5	1	6
n_3	3	10	1	9	10
n_4	6	19	2	1	3
n_5	1	20	0	0	0
n_6	7	16	1	0	1
n_7	8	17	0	0	0
n_8	9	13	4	2	6
n_9	14	18	1	1	2
n_{10}	4	12	3	1	4

The next step is to select the net with the highest pin doglegs from Table 2, which is n_3. This net is repositioned in between n_8 and n_2 as its left pin is a direct alignment with the left pin of n_1, while the right pin fits nicely between the left pins of n_8 and n_2. The new move produces $L_2 = \{1,4,5,6,7,8,3,2,10\}$, as shown in Figure 5. The move improves the solution to $E = 40$, $Q = 6$ and $D = 7$. A positive development is the doglegs are distributed quite evenly where only $R_{4,5} = 2$ is uneven.

Table 3: Second move with $L_2 = \{1,4,5,6,7,8,3,2,9,10\}$

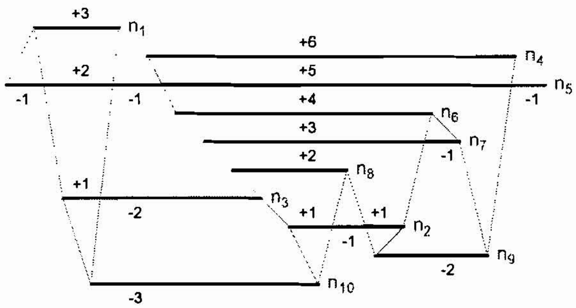

Figure 5: The list $L_2 = \{1,4,5,6,7,8,3,2,9,10\}$ having $E = 40$, $Q = 6$ and $D = 7$.

			Doglegs		
n_k	b_k	e_k	Left	Right	Total
n_1	2	5	1	2	3
n_2	11	15	0	1	1
n_3	3	10	1	0	1
n_4	6	19	1	0	1
n_5	1	20	1	1	2
n_6	7	16	1	1	2
n_7	8	17	0	0	0
n_8	9	13	0	2	2
n_9	14	18	1	1	2
n_{10}	4	12	2	1	3

Next, from Table 3 we select n_{10} (or n_1) which has the highest number of pin doglegs. This net is placed in between n_7 and n_8 as its left and right pins are in direct alignment with the left and right pins of the two nets. The new move produces $L_3 = \{1,4,5,6,7,10,8,3,2,9\}$ with $E = 38$, $Q = 6$ and $D = 8$, as shown in Figure 6. The final realization is shown in Figure 7. This time the doglegs are evenly distributed with every pin interval has not more than $H = 1$ dogleg.

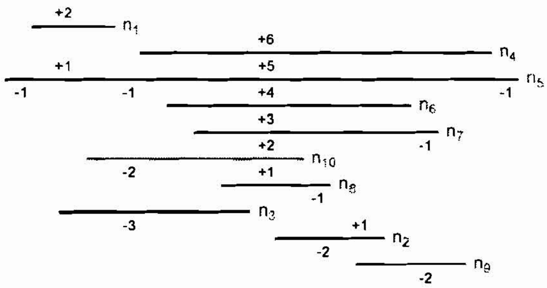

Figure 6: The list $L_3 = \{1,4,5,6,7,10,8,3,2,9\}$ having $E = 38$, $Q = 6$ and $D = 8$.

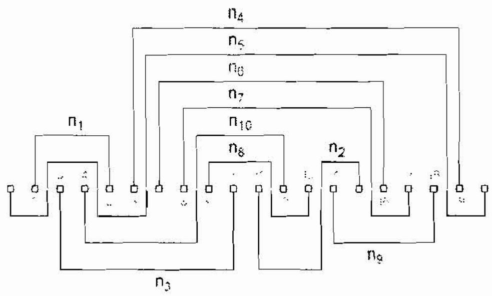

Figure 7: The final realization from $L_3 = \{1,4,5,6,7,10,8,3,2,9\}$.

Summary and Conclusion

In this paper, we propose a novel technique for reducing the number of doglegs and distributing them evenly on the pin intervals. The technique involves choosing the net whose sum of doglegs from its left and right pins with the maximum value, for swapping into a new position in the ordering. The technique successfully achieves the objective of distributing the doglegs evenly on the pin intervals.

As an extension to the problem, the objective of having minimum congestion in the single-row network needs to be integrated with the task of balancing the distribution of doglegs. This is an open problem which requires the modification of the objective function in Equation (1) to cater the two objectives. This challenging issue is the basis of our future work.

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