Effective algorithm for routing integral structures with two-layer switching

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Abstract. The paper presents an algorithm for routing switching objects such as large-scale integrated circuits (LSICs) with two layers of metallization, embossed printed circuit boards, microboards with pairs of wiring layers on each side, and other similar constructs. The algorithm allows eliminating the effect of mutual blocking of routes in the classical wave algorithm by implementing a special circuit of digital wave motion in two layers of metallization, allowing direct intersections of all circuit conductors in a combined layer. However, information about the belonging of the topology elements to the circuits is sufficient for layering and minimizing the number of contact holes. In addition, the paper presents a specific example which shows that, in contrast to the known routing algorithms using a wave model, just one byte of memory per discrete of the work field is sufficient to implement the proposed algorithm.

1. Introduction

The decisive tool in the development of new electronic equipment is the use of computer-aided design techniques that make it possible to create highly reliable equipment at relatively low costs in a short time. As a perspective element base, large and very large-scale integration circuits (LSICs) are used. In recent years, intensive research has been carried out on the possibility of using them in dual-use equipment for constructing various control and monitoring systems for space objects, nuclear power systems, research nuclear centers, and the like. This is due to the fact that a certain class of LSICs, for example, complementary ones, is most advantageous in terms of providing minimum power consumption, low cost, dimensions and weight; these circuits are operable under severe conditions of temperature actions, mechanical loads actions and various types of radiation effects.

Designing the above-mentioned LSICs is impossible without computer-aided design (CAD) tools. However, domestic CAD systems do not have well-developed tools to solve this problem. Foreign CAD systems, which have these tools, are very expensive, and the most modern tools are not for sale. Therefore, the development of domestic means of computer-aided design tools for LSICs and, in particular, systems for automatic routing of their interconnections, is an urgent task [1].

A bottleneck in the design of complementary LSICs leading to a reduction in the utilization of the chip area is the use of silicon bridges in a number of designs to eliminate routes conflicts. Broad prospects in this direction can be opened with the use of integral structures with two-layer switching, which make it possible to significantly increase the component density and take full advantage of the
algorithm of routing these structures proposed in this paper.

2. Materials and methods
The proposed method is based on the use of a special discrete operating field model, which allows generating the wave function in two metallization layers. Selecting the method of placement of such a model in computer memory is the subject of a separate study. The fact is that the minimum unit of information addressed to a computer using a single machine operation is 1 byte, so for the organization of, for example, a nine-bit cell of the discrete operating field, it is necessary to use artificial methods for addressing the ninth bit, which is associated with an increase in the number of machine operations in one cycle of access to this cell. However, when generating a wave function, the increase in the specified number for even one operation is critical with regard to the total time of routing. In this connection, it is very important to create an eight-bit cell of the discrete operating field suitable for routing two-layer models. One of the possible options for constructing such discrete operating field is as follows.

A model of the eight-bit cell of the discrete operating field is proposed to be built on the basis of the cell of a single-layer model of the discrete temporary field. It is known that the wave algorithm [3] is most widely used for layer-by-layer mounting, but the limitation associated with planar implementation of different routes in one layer is the reason for a number of its essential disadvantages: an increase in the average length of joints, low component density, and others. Since the classical wave algorithm at any given point of time monitors the state of only one conductor, blocking of many yet not separated routes inevitably occurs. This disadvantage can be eliminated if one allows the orthogonal intersection of conductors in the designed discrete operating field based on their subsequent layering.

To implement this approach, in each cell of the discrete operating field, it is necessary to have information about the direction of the segments passing through it and the presence of contact between them. For this purpose, let us place the cell of the discrete operating field in the memory of the computer in the form of a two-dimensional array and allocate one byte of RAM for each of them. Let us renumber the bits of each byte from No. 1 to No. 8 and assign each bit a strictly defined status: bits No. 1 and No. 2 will be responsible for the orientation of the conductors in the discrete operating field, bits No. 3 and No. 4 for the current wave number state (in Akers encoding), bit No. 5 when routing the next circuit will have the status of “own circuit”, and No. 6 will be set to “one” each time when generated conductor changes its direction. Bits No. 7 and No. 8 will have an auxiliary role.

The main problem that needs to be solved when designing the routing algorithm on the constructed model of the discrete operating field is to prohibit passage of the conductor along the previously constructed one, which eliminates the imposition of conductors on each other and mutual blocking of conductors will become impossible [4–7]. To solve this problem, it is enough to algorithmically prohibit the passage of two conductors along the same cells of the discrete operating field.

To solve the problem, let us consider two possible variants to make the wave reach the conductor segment, shown in Figure 1. In the first case, the wave reaches the conductor in a collinear direction (Figure 1, a), in the second – in the orthogonal direction (Figure 1, b).

In order to exclude the first variant, let us introduce the “Prohibition” status for introduction of the wave number for each cell of the discrete operating field. It is clear that such a cell will be ignored both at the stage of wave propagation and at the stage of reverse routing. Let us further enter this status in those cells in which it is not necessary to update it, these are the contacts that are to be connected,
and the cells are the ends of the previously constructed segments.

![Wavefront and Conductor](image)

**Figure 1.** Collinear (a) and orthogonal (b and c) tangency of the conductor wave

To eliminate the second variant of tangency of the conductor wave, after which the collinear direction of the wave motion still takes place, let us introduce the Prohibition state into the cells of the conductor adjacent to the point of contact by its wavefront, as shown by the “crosses” in Figure 1, c.

For the physical organization of the status of the Prohibition, let us use the single states of bits No. 3 and No. 4 of each cell of the discrete operating field. Indeed, the sequence of Akers wave numbers (1-1-2-2-1-1-2-...) requires 2 bits for its implementation – in this case, bits No. 3 and No. 4 of each cell are used to place them. When their state is zero, the cell is free to introduce the wave number. States 01 and 10 of bits No. 3 and No. 4 correspond to the values of the wave number 1 and 2. Thus, single states of these bits can be used to organize the specified status of “Prohibition”.

### 3. Model estimation of the algorithm for routing integral structures with two-layer switching

Let us demonstrate the operation of the proposed algorithm by example. Figure 2, a shows the initial state of the discrete operating field, in which the conductors connecting the contacts of circuits B and C are constructed. To construct circuit A, the classical algorithm is not applicable, since it is blocked by circuits B and C located in different layers. Figure 2, b shows the state of cells after the construction of all fronts by the proposed algorithm, and Figure 2, c – the state of the same cells after performing the reverse routing. The contact-source of the digital wave is marked with a black background here. Figure 2, c shows that the horizontal part of the constructed route intersects with vertical conductors located in different layers, so further it is necessary to perform layering of the resulting model, during which to perform distribution of the conductor sections along the layers and to determine the location of the contact contact passages (holes).

![Initial state](image)

![State of cells](image)

![State of cells after reverse routing](image)

**Figure 2.** Contacts (a), the wave function (b), and the result of the construction (c) of circuit A

To consider the general case, let us add one more circuit (D) to the current model, having executed its construction according to the proposed algorithm. The stage of constructing the wave function for it
and the resulting topology before the start of the layering are shown in Figures 3, a and 3, b, respectively. Attention should also be paid to the high density (≈ 93 %) of the obtained circuit, calculated without taking into account the area occupied by the contact elements.

![Figure 3](image1.png)

**Figure 3.** The wave function of circuit D (a), and the resulting topology (b)

The layering algorithm is described in the form of step-by-step instructions.

**Step 1.** The set of all segments of conductors in the discrete operating field is represented by the sum of two sets: \( M = M_{\text{BASIC}} \cup M_{\text{FREE}} \), where: \( M_{\text{BASIC}} \) – basic set, in which the segments intersecting in the discrete operating field without an electrical contact shall be included, \( M_{\text{FREE}} \) – a free set, in which all other segments shall be included.

![Figure 4](image2.png)

**Figure 4.** The sets of segments MBASIC (a) and MFREE (b)

**Step 2.** Set MBASIC is represented by the sum of subsets: \( M_{\text{BASIC}} = M_{\text{BASIC}}^H \cup M_{\text{BASIC}}^V \), the sum of the basic horizontal and basic vertical. For the current example, the sets and are shown respectively in Figures 4, a and 4, b.

**Step 3.** The set of the segments is to be placed in the first layer and in the second, as shown in Figure 5, a.
Figure 5. Preliminary (a) and final (b) topology layering

Step 4. In the first layer it is necessary to transfer all those segments of the set that form the tree of the orthogonal graph on the set.

Step 5. The remaining segments of the set should be placed in the second layer.

The result of the conductors layering is shown in Figure 5 (b).

To complete the layering of the combined model, it is necessary to determine the set of K of contact passages, which is described by a formula of the form: \( K = M^r \cap B_{\text{BASIC}} \cap S \), where:

- set \( S \) represents the set of cells of the discrete operating field in which the route changes direction – in Figure 3, and the cells of set \( S \) are marked by black squares.

The physical meaning of the last formula is that contact passages (holes) must be at the intersection of the vertical and horizontal segments of the base set, if there is an electrical contact in the cell of their intersection. The geometrically given formula of intersections is implemented by superimposing Figure 4, a in Figure 3, a, at which only two cells, marked with black squares in Figure 4, b, will pass through the second intersection.

Figure 6. The state of bits No. 1 (a) and bits No. 7 (b) of adjacent segments

In conclusion, let us consider the assignment of auxiliary bits No. 7 and No. 8 of each byte of the discrete operating field. These bits are actively used at the stage of forming the set of segments \( M \). The fact is that the elements of these sets (route segments) are present in the bytes of the discrete operating field model in the form of the state of their bits No. 1 and No. 2. The selection of the horizontal sections occurs by line scanning of the discrete operating field, and vertical sections – by scanning its columns. During the selection of horizontals, the status of bits No. 1 is scanned, and during the selection of verticals – the status of bits No. 2. The problem with scanning in both cases is the same – to determine the cell in which the current selected segment ends. The bit that marks the turn of the conductor is not suitable for this purpose, since it is also installed in the cell of the route branching.

The foregoing is described in Figure 5, a, which shows the model (bit No. 1 of each cell) of adjacent conductors moving along the second horizontal of the discrete operating field. Since the location of their joint can not be determined only by scanning bit No. 1 (left-to-right) without additional information, additional bit No. 7 is needed, in which the information about the end of each segment is formed at the stage of reverse routing (Figure 5, b). For visual clarity, the selected segments are superimposed on both models.

The practical implementation of the algorithm shows that it is possible to obtain metallized wiring of LSICs with a very high component density reaching 80 or more percent.
4. Conclusion
A modification of the classical wave algorithm for routing interconnections of switching boards was proposed, which allows eliminating its main disadvantage – the property of mutual blocking of routes, and the scope of its application was defined: LSICs with double-layer switching, embossed printed circuit boards [2], microboards with pairs of wiring layers on each side, composite additive microboards and the like [9–11].

The structure of the original combined model of the discrete operating field of the routing was developed and presented, which requires, in contrast to known implementations, a smaller amount of RAM (one byte per disc of the operating field).

The specific example shows the procedure for synthesizing conductors on the proposed model, including the mechanism of digital wave movement simultaneously in two layers of the switching space, and the algorithm for its subsequent layering is described by steps.

The proposed new solutions can be effectively used not only for routing integral structures with two-layer switching, but also for routing any multilayer switching structures in which the size of the contact window between pairs of wiring layers does not exceed the width of the conductor.

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