On Terminal Assignments That Minimize the Density

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Abstract

Terminal assignment problems are placement problems in channel routing in which each one of \( n \) entry terminals on one side of the channel is assigned to one of \( m \) exit terminals on the other side of the channel. We study solutions to terminal assignment problems that minimize the density, a cost measure closely related to the minimum channel width needed to wire the resulting channel routing problem. We present a new characterization of the optimal achievable density that leads to efficient algorithms for a number of terminal assignment problems, and we show that other assignment problems are NP-hard.

Key Words

Analysis of algorithms, channel routing, density, binary search, NP-hard problems.
1. Introduction

Channel routing, the problem of connecting terminals across a channel, arises in many layout systems for integrated circuits. The decisions of where to place the terminals and how to select the terminals to be connected are made before the routing and have considerable influence on the cost measures of the routing, such as the channel width. In this paper we consider problems in which an optimal assignment of every terminal on the upper row to a terminal on the lower row of the channel is determined so that given conditions are satisfied and the routing step produces a channel of minimum width. For a number of such assignment problems we present efficient algorithms, and others we show to be NP-hard.

We are given the positions of $n$ entry terminals, $p_1, \ldots, p_n$, $p_1 < \cdots < p_n$, on the upper row of the channel, and the positions of $m$ exit terminals, $q_1, \ldots, q_m$, $q_1 < \cdots < q_m$, on the lower row of the channel, $1 \leq p_i, q_i \leq M$, $m \geq n$. Two of the problems discussed in this paper are the one-to-any problem and the choice problem. In the one-to-any problem we have to compute a one-to-one function $f : [1,n] \rightarrow [1,m]$ so that every entry terminal $p_i$ is assigned to the exit terminal $q_{f(i)}$. Furthermore, the channel routing problem (CRP) consisting of the pairs, called nets, $(p_1,q_{f(1)})$, $\ldots$, $(p_n,q_{f(n)})$ must have minimum density over all assignments. The density of the CRP is the maximum over all $x$ of the number of nets $(p_i,q_{f(i)})$ for which $p_i \leq x < q_{f(i)}$ or $p_i > x \geq q_{f(i)}$. The density is closely related to the minimum channel width, and minimizing the density also minimizes the channel width in routing models that consist of at least 2 layers [BB, PL, RBM]. The choice problem is similar to the one-to-any problem, except that each entry terminal $p_i$ has a set $P_i$ of exit terminals associated with it, and we require that $q_{f(i)} \in P_i$ for every $i$. One of the results of this paper is that the one-to-any problem can be solved in $O(n + m)$ time, while the choice problem is NP-hard.
Both problems, the one-to-any and the choice problem, can be viewed as bipartite matching problems in which a quantity, namely the density, has to be minimized. But none of the known bipartite matching algorithms [L] provide any insight into matchings that minimize the density. In this paper we develop a technique that solves a number of problems, including the one-to-any problem, by a factor of \( \log n \) faster over the solutions which use previously known techniques. We also show that more general assignment problems, such as the choice problem, are NP-hard. Thus, the complexity of matching problems which minimize the density differs considerably from the complexity of the standard bipartite matching problems.

The main contribution of this paper with respect to efficient algorithms is a new combinatorial characterization of the best achievable density. This characterization allows us to compute the best achievable density for assignment problems efficiently. The actual assignment achieving this optimal density is determined once this density is known. Using this approach we solve the one-to-any problem in time \( O(n+m) \), compared to time \( O((n+m)\log n) \) achieved by previously known techniques. We also consider the one-to-any problem with fixed nets in which the input includes \( h \) additional nets, each of which has its entry and exit terminals already determined. Thus, even before the assignment is done, some positions in the channel have a non-zero density because of the fixed nets. We show (i) how to compute the best achievable density for the one-to-any problem with \( h \) fixed nets in time \( O(n+m+h) \), and (ii) how to obtain an assignment achieving this density in time \( O((n+m+h)\log(n+h)) \). In both cases we improve results obtained by known techniques by a factor of \( \log n \).

A natural extension of the one-to-any problem is the range problem. Each entry terminal \( p_i \) now has a range \([l_i, r_i]\) associated with it, and the assigned exit terminal \( q_{f(i)} \) has to be in this range. If \( l_1 \leq l_2 \leq \cdots \leq l_n \) and
We show how to generate the optimal assignment for this problem in $O(n + m)$ time. We also consider the ordered range problem when fixed nets are present.

The paper is organized as follows. In Section 2 we consider the one-to-any problem, and we discuss the main ideas used for pre-computing the best achievable density. Section 3 shows how this technique can be extended to the one-to-any problem with fixed nets. In Section 4 we solve the ordered range problem with or without fixed nets efficiently. Section 5 contains the NP-hardness results: We show that the choice problem and the weighted version of the one-to-any problem are NP-hard. In Section 6 and 7 we present efficient solutions for two other terminal assignment problems. The first of these is range problem when every $l_i = 1$, and $m = M$, for which we we give an $O(n \log n)$ time algorithm. The second of these is the version of the previous problems in which only $s$ of the $n$ entry terminals have to be assigned to an exit terminal.

Different placement problems for channel routing have been discussed and analyzed in recent papers. The offset problem [DKSSU, LaP, M] and the rotation problem [AH] can be solved efficiently on a number of routing models. Other efficiently solvable placement problems can be found in [LeP, GCW]. Inherently difficult placement problems for channel routing are discussed in [GCW, LL, P].

2. The One-to-Any Problem

Throughout this paper the input includes two lists. One list contains $n$ entry terminals $p_1, \ldots, p_n$, $1 \leq p_1 < \cdots < p_n \leq M$, and the second list contains $m$ exit terminals $q_1, \ldots, q_m$, $1 \leq q_1 < \cdots < q_m \leq M$, $m \geq n$. In the one-to-any problem we compute a one-to-one function $f : [1,n] \to [1,m]$ such that if every $p_i$ is assigned to $q_{f(i)}$, then the CRP consisting of the nets $(p_i, q_{f(i)})$ has
minimum density. We use \( p_i (q_j) \) to denote both the terminal \( p_i \) \((q_j)\) and the value of its abscissa (which is an integer between 1 and \( M \)). Hence, \( q_j < p_i \) means that exit terminal \( q_j \) is to the left of entry terminal \( p_i \). We will furthermore assume that \( p_i \neq q_j \) for every \( i \) and \( j \). This assumption is made only for convenience, because if \( p_i = q_j \), then we can assign \( q_j \) to \( p_i \) (i.e., set \( f(i) = j \)) and ignore the net.

If the solution contains \( p_i \) and \( p_j \) with \( p_i < p_j \) and \( q_f(i) > q_f(j) \), then we can always 'uncross' by assigning the exit terminal \( q_f(j) \) to \( p_i \) and \( q_f(i) \) to \( p_j \). Doing this cannot increase the density. Thus, there exists an optimal solution with \( q_f(1) < q_f(2) < \cdots < q_f(n) \). Therefore the crucial step of the algorithm is to select \( n \) of the \( m \) exit terminals which, when assigned to the entry terminals, result in a CRP of minimum density. See Fig. 2.0 for an non-optimal and an optimal selection.

Given an integer \( d \), \( d \leq n \), we can determine in time \( O(n + m) \) whether or not there exists an assignment whose density is \( \leq d \). The algorithm for doing this simultaneously scans, from left to right, the list of the entry terminals and that of the exit terminals. Throughout the paper, we use "assigning \( p_i \) to \( q_j \)" and "joining \( p_i \) to \( q_j \)" interchangeably. Assume we are at \( p_i \) and \( q_j \) in our scan of the list of entry and exit terminals, respectively. We assign \( q_j \) to \( p_i \) only when doing so does not cause the density to exceed \( d \). If we join \( p_i \) and \( q_j \), then we continue with \( p_{i+1} \) and \( q_{j+1} \), otherwise we continue with \( p_i \) and \( q_{j+1} \). The scan terminates with success as soon as it joins \( p_n \), and with failure if it fails to join some \( p_i \) to \( q_m \) (i.e., it 'runs out' of exit terminals). The fact that the scan is at \( p_i \) and \( q_j \) implies that each of \( p_1, \ldots, p_{i-1} \) already has an exit terminal assigned to it, and that \( q_j > q_f(i-1) \). We note an interesting property of the nets produced by this strategy: If \( p_i \) gets joined to \( q_j \) and \( p_i < q_j \), then all of the exit terminals between \( p_i \) and \( q_j \) have been joined to entry terminals to the left of \( p_i \); i.e., none of them is available. We call this the left-
compressed property. For example, the solution of Figure 2.0(b) is not left-compressed (it would be left-compressed if \(P_3\) was joined to \(q_3\) instead of \(q_4\)).

We now briefly outline how to determine whether joining \(p_i\) to \(q_j\) causes the density to exceed \(d\). Consider first the case when \(q_j < p_i\). Let \(p_k\) be the leftmost entry terminal with \(p_k > q_j\). We can join \(p_i\) and \(q_j\) without causing the density to exceed \(d\) if and only if \(i - k < d\). Now consider the case when \(q_j > p_i\). Let \(p_k\) be the leftmost entry terminal with \(q_f (k) > p_i\). We can join \(p_i\) and \(q_j\) if and only if \(i - k < d\). The reader may notice that if \(i - k = d\), then we already know that the algorithm will stop with failure.

The proof of correctness of the greedy verification algorithm described above is left to the reader. The algorithm can clearly be implemented to run in time \(O(n + m)\), and it suggests an \(O((n + m) \log d)\) time algorithm for determining the optimal density \(\hat{d}\) by binary search. Such a binary search technique has been used in [LeP] for River Routing problems. The main result of this section is to give a new combinatorial characterization of the optimal density, resulting in an \(O(m + n)\) time algorithm for computing it. Once we have the optimal density, the \(O(m + n)\) time verification algorithm outlined above can be used to produce an optimal assignment of exit to entry terminals.

Throughout the paper, a net which crosses from position \(x\) to position \(x + 1\) will be said to cross column \(x\). More formally, a net \((p_i, q_f (i))\) crosses column \(x\) if \(p_i \leq x < q_f (i)\) or \(q_f (i) \leq x < p_i\).

**Definition 2.1** For all \(x\) and \(y\), \(1 \leq x \leq y \leq M\), we define \(up(x, y)\) (resp. \(down(x, y)\)) to be the number of entry (resp. exit) terminals whose position is \(\geq x\) and \(\leq y\). Let \(out(x, y) = up(x, y) - down(x, y)\).

We now define a quantity \(\Phi\) which, we will later show, equals the optimal density \(\hat{d}\).
Definition 2.2 Let \( \Phi \) be defined as follows:
\[
\Phi = \max \left\{ \max_{x,y} \left[ \text{out}(x,y)/2 \right], \max_{x} \text{out}(1,x), \max_{x} \text{out}(x,M) \right\}
\]
Note that \( \text{out}(p_i,p_i) = 1 \), and therefore \( \Phi \geq 1 \).

Lemma 2.3 \( \hat{d} \geq \Phi \).

Proof: For every \( x \) and \( y \), \( 1 \leq x \leq y \leq M \), at least \( \text{out}(x,y) \) nets must cross columns \( x-1 \) and column \( y \). Therefore, at least one of these columns is crossed by \( \left[ \text{out}(x,y)/2 \right] \) nets. This implies that \( \hat{d} \geq \left[ \text{out}(x,y)/2 \right] \). For every \( x \), \( 1 \leq x \leq M \), at least \( \text{out}(1,x) \) (resp. \( \text{out}(x,M) \)) wires cross column \( x \) (resp. column \( x-1 \)), which implies that \( \hat{d} \geq \text{out}(1,x) \) (resp. \( \geq \text{out}(x,M) \)). \( \Box \)

We now show that \( \Phi \) can be computed in time \( O(m+n) \). In order to do so, we need the following Lemma.

Lemma 2.4 Given a sequence of positive and negative numbers \( c_1, \ldots, c_n \), it is possible to find, in time \( O(n) \), indices \( i \) and \( j \), \( i \leq j \), such that \( c_i + c_{i+1} + \cdots + c_j \) is largest over all possible values \( i \) and \( j \).

Proof: The proof is easy and is omitted. \( \Box \)

Lemma 2.5 \( \Phi \) can be computed in time \( O(n+m) \).

Proof: It is clear that computing each of \( \max_{x} \text{out}(1,x) \) and \( \max_{x} \text{out}(x,M) \) can be done in time \( O(m+n) \). Note that \( \max_{x,y} \left[ \text{out}(x,y)/2 \right] \) is equal to \( \left\lfloor \frac{1}{2} \max_{x,y} \text{out}(x,y) \right\rfloor \). Computing \( \max_{x,y} \text{out}(x,y) \) can be done in time \( O(n+m) \) by (i) merging the list of the \( p_i \)'s and that of the \( q_i \)'s, (ii) in the resulting sorted sequence \( a_1, \ldots, a_{m+n} \), replacing every \( a_i \) by \( +1 \) if \( a_i = p_j \) and by \( -1 \) if \( a_i = q_j \), then (iii) in the resulting (not sorted) sequence \( c_1, \ldots, c_{m+n} \) of \(+1\)'s and \(-1\)'s, finding \( i \) and \( j \), \( i \leq j \), for which \( c_i + \cdots + c_j \) is largest. \( \max_{x,y} \text{out}(x,y) \) is the sum \( c_i + \cdots + c_j \). Steps (i) and (ii) can clearly be done in time \( O(m+n) \). Step (iii) takes time \( O(m+n) \) as a consequence of Lemma 2.4. \( \Box \)
We now show that a solution which achieves density equal to $\Phi$ exists.

**Lemma 2.6** $\hat{d} = \Phi$.

**Proof:** Lemma 2.3 implies that it suffices to show that $\hat{d} \leq \Phi$. To do this, we use the assigning strategy described in the verification algorithm: Simultaneously scan the list of the entry terminals and that of the exit terminals, joining the currently scanned entry terminal to the next available exit terminal that does not cause the density to exceed $\Phi$. (An available exit terminal is one that has not yet been assigned to a $p_i$.) If the assigning strategy terminates with failure then one of the two following situations must have occurred.

A. An entry terminal $p_{n-i}$ cannot be joined to $q_{m-i}$ and $q_{m-i} < p_{n-i}$. Note that even if the assigning strategy joins $p_{n-i}$ to an exit terminal to the right of $q_{m-i}$, we eventually run out of exit terminals.

B. Some $p_k$ cannot be joined to the next available exit terminal $q_s$, and $p_k < q_s$.

From now on, we assume that the assigning strategy stops with failure as soon as either situation A or B occurs. We claim that situation A or B cannot occur; i.e., we succeed in joining every entry terminal to an exit terminal without exceeding density $\Phi$. We prove the claim by contradiction. We obtain the desired contradiction by examining in detail what prevented us from joining $p_{n-i}$ to $q_{m-i}$ in situation A, and what prevented us from joining $p_k$ to $q_s$ in situation B.

**Situation A.** In this situation we were unable to join $p_{n-i}$ to $q_{m-i}$ because there are $\Phi$ entry terminals between $q_{m-i}$ and $p_{n-i}$, all of which were joined to exit terminals to the left of $q_{m-i}$. But then, we have $\text{out}(q_{m-i} + 1, \text{M}) = \Phi + i + 1 - i = \Phi + 1$, a contradiction. See Figure 2.1.

**Situation B.** We distinguish two cases.

**Case I:** There are no available exit terminals to the left of $q_s$. See Figure 2.2.
In this case we were unable to join $p_k$ to $q_z$ because there are $\Phi$ exit terminals between $p_k$ and $q_z$, all of which were joined to entry terminals to the left of $p_k$. But then, $\text{out}(1,p_k) = \Phi + 1$, a contradiction.

**Case 2:** There is (one or more) available terminal(s) to the left of $q_z$. See Figure 2.3. Let $q_j$ be the rightmost available exit terminal that is to the left of $q_z$. Note that $q_j$ is to the left of $p_k$ (because of the left-compressed property). Then there are $\Phi$ entry terminals immediately to the right of $q_j$, all of which were joined to exit terminals to the left of $q_j$ (otherwise $q_j$ would not be available). But then, we have $\text{out}(q_j+1,p_k) = 2\Phi + 1$, which in turn implies that

$$\left\lfloor \text{out}(q_j+1,p_k)/2 \right\rfloor = \Phi + 1,$$

another contradiction. □

We are now ready to state the main result of this Section.

**Theorem 2.7** The one-to-any problem can be solved in time $O(n + m)$.

**Proof:** The algorithm and its correctness follow from the preceding discussion. □

3. The One-to-Any Problem With Fixed Nets

In this Section we consider the one-to-any problem as defined in Section 2 when, in addition to the $p_i$'s and $q_i$'s, we have $h$ fixed nets. A fixed net consists of an entry and an exit terminal that are already joined. The fixed nets are given as a list of $h$ entry terminals $v_1, \ldots, v_h$, $v_1 < \cdots < v_h$, a list of $h$ exit terminals $w_1, \ldots, w_h$, $w_1 < \cdots < w_h$, and an $h$-element permutation $g$ such that every $(v_i, w_{g(i)})$ is a net, $1 \leq i \leq h$. The problem is to assign $n$ of the $q_i$'s to the $p_i$'s so that the resulting CRP has minimum density. The resulting CRP now consists of the nets $(p_i, q_{g(i)})$, $1 \leq i \leq n$, and the fixed nets $(v_i, w_{g(i)})$, $1 \leq i \leq h$. See Figure 3.0 for an example. We first show how to compute the
optimal density of a one-to-any problem with \( h \) fixed nets in time \( O(n+m+h) \).

As in Section 2, there exists a solution of minimum density in which \( q_f (1) < \cdots < q_f (n) \), and the problem is again that of selecting \( n \) of the \( m \) exit terminals that will be joined to the \( p_i \)'s. We define \( u_p (x,y) \) (\( d_{ow} (x,y) \)) as the number of \( p_i \)'s (\( q_i \)'s) that are \( \geq x \) and \( \leq y \), and let \( o_{uw} (x,y) \) denote the quantity \( u_p (x,y) - d_{ow} (x,y) \). Note that the functions \( u_p \), \( d_{ow} \) and \( o_{uw} \) do not depend on the fixed nets. The contribution of the fixed nets to the density of column \( x \) is expressed in \( c_{ross} (x) \), which equals the number of fixed nets crossing column \( x \). Recall that a net \( (v_i, w_{g(i)}) \) crosses column \( x \) if and only if \( v_i \leq x < w_{g(i)} \) or \( w_{g(i)} \leq x < v_i \). We now define a quantity \( \Psi \) which we will later show to be equal to the optimal density \( \hat{d} \).

**Definition 3.1** Let \( \Psi \) be defined as follows:

\[
\Psi = \max \left\{ \max_{x,y} \left[ \frac{(c_{ross}(x-1) + c_{ross}(y) + o_{uw}(x,y))}{2} \right], \max_{x} \left[ c_{ross}(x) + o_{uw}(1,x) \right], \max_{x} \left[ c_{ross}(x-1) + o_{uw}(x,M) \right] \right\}
\]

**Lemma 3.2** \( \hat{d} \geq \Psi \).

**Proof:** The proof is along the lines of that of Lemma 2.3 and is omitted.

**Lemma 3.3** \( \Psi \) can be computed in time \( O(m+n+h) \).

**Proof:** The proof is along the lines of that of Lemma 2.5, and is therefore omitted.

**Lemma 3.4** \( \hat{d} = \Psi \).

**Proof:** Lemma 3.2 implies that it suffices to show that \( \hat{d} \leq \Psi \); i.e., density \( \Psi \) can be achieved. We use the same assigning strategy as in the proof of Lemma 2.6, except that now \( \Psi \) plays the role of \( \Phi \). The observations made about the assigning strategy at the beginning of the proof of Lemma 2.6 still hold. We obtain contradictions by examining why we could not join \( p_{n-1} \) to
In situation A, or \( p_k \) to \( q_s \) in situation B.

**Situation A.** In this situation we cannot join \( p_{n-i} \) to \( q_{m-i} \) because there exists a column \( x \), \( q_{m-i} \leq x < p_{n-i} \), in which the density is already \( \Psi \). Then there are \( \alpha = \Psi - \text{cross}(x) \) \( p_j \)'s at positions \( > x \) and \( < p_{n-i} \) that are joined to \( q_j \)'s that are \( < q_{m-i} \). This implies that

\[
\text{cross}(x) + \text{out}(x + 1, M) = \text{cross}(x) + \alpha + 1 - i = \Psi + 1, \quad \text{a contradiction.}
\]

**Situation B.** We distinguish two cases.

**Case 1:** There are no available exit terminals to the left of \( q_s \). In this case we cannot join \( p_k \) to \( q_s \) because there exists a column \( x \), \( p_k \leq x < q_s \), in which the density is already \( \Psi \). Then there are \( \alpha = \Psi - \text{cross}(x) \) \( q_j \)'s at positions \( > x \) and \( < q_s \) that are joined to entry terminals to the left of \( p_k \). But then, we have

\[
\text{cross}(x) + \text{out}(1, x) = \text{cross}(x) + \alpha + 1 = \Psi + 1, \quad \text{a contradiction.}
\]

**Case 2:** There is (one or more) available terminal(s) to the left of \( q_s \). Let \( q_j \) be the rightmost available exit terminal that is to the left of \( q_s \). See Figure 3.1. Note that \( q_j \) is to the left of \( p_k \) because of the left-compressed property. Then the following holds:

(i) There exists a column \( y \), \( p_k \leq y < q_s \), such that column \( y \) has currently density \( \Psi \). Then there are \( \Psi - \text{cross}(y) \) \( q_r \)'s at positions \( > y \) and \( < q_s \) that are joined to \( p_r \)'s to the left of \( p_k \). This follows from the fact that we are unable to join \( p_k \) to \( q_s \).

(ii) There exists a column \( x \), \( q_j \leq x < p_k \), in which the density is \( \Psi \). Then \( \Psi - \text{cross}(x) \) \( p_r \)'s at positions \( > x \) are joined to exit terminals to the left of \( q_j \). If such an \( x \) did not exist, then \( q_j \) would not be available.

Then (i) and (ii) imply that
\[(\text{out}(x+1, y) + \text{cross}(x) + \text{cross}(y))/2\] \geq \left[(\Psi + \Psi + 1)/2\right] = \Psi + 1,

a contradiction. \(\square\)

**Theorem 3.5** The optimal density of a one-to-any problem with \(h\) fixed nets can be computed in time \(O(n + m + h)\).

**Proof:** Follows from the last two Lemmas. \(\square\)

We next consider the implementation of the algorithm that produces the assignment achieving density \(\Psi\). The idea of the algorithm is the same as in Section 2: Scan the list of the \(p_i\)'s and that of the \(q_j\)'s from left to right and assign \(p_i\) to \(q_j\) if density \(\Psi\) is not exceeded. When no fixed nets were present, only one column had to be checked in order to determine whether or not the density is exceeded. Now that fixed nets are present, density \(\Psi\) could be exceeded in any column between \(p_i\) and \(q_j\). We outline an algorithm that produces the assignment in time \(O((n + m + h)\log(n + h))\).

During the scan of the lists of entry and exit terminals we use a modified 2-3 tree structure \(T\) in which the leaves contain entry and exit terminal positions in ascending order. Initially, only the entry and exit terminals of the fixed nets are stored in \(T\). The nodes of \(T\) have additional entries that allow us to compute the current maximum density between two positions in the channel in \(O(\log(n + h))\) time. Assume we are at \(p_i\) and \(q_j\) in the scan. We then use \(T\) to determine the current maximum density between \(p_i\) and \(q_j\). If it is less than \(\Psi\), we insert the net \((\text{Max}(p_i, q_j), \text{Min}(p_i, q_j))\) into \(T\), and continue with \(p_{i+1}\) and \(q_{j+1}\). If joining \(p_i\) to \(q_j\) exceeds density \(\Psi\), we continue with \(p_i\) and \(q_{j+1}\). Inserting a net into \(T\) and recording its contribution to the density in the columns between \(p_i\) and \(q_j\) can also be done in \(O(\log(n + h))\) time. The implementation details of the assignment algorithm outlined above are left to the reader. The rebalancing procedure for the tree structure is similar to the one described in [AHU].
Theorem 3.6 An assignment to the one-to-any problem with \( h \) fixed nets achieving density \( \Psi \) can be obtained in \( O((n+m+h)\log(n+h)) \) time.

Proof: The optimal density \( \Psi \) can be computed in \( O(n+m+h) \) time by Theorem 3.5. The tree structure \( T \) described above allows us to obtain the \( n \) exit terminals to be assigned to the \( n \) entry terminals in time \( O((n+m+h)\log(n+h)) \). \( \square \)

4. Ranges and Fixed Nets

A more general version of the one-to-any problem with (or without) fixed nets is the ordered range problem with (or without) fixed nets. In the ordered range problem we are given for every entry terminal \( p_i \) two positions \( l_i \) and \( r_i \) with \( l_i \leq r_i \), \( 1 \leq i \leq n \), and we have \( l_1 \leq l_2 \leq \cdots \leq l_n \) and \( r_1 \leq r_2 \leq \cdots \leq r_n \). Each \( p_i \) has to be assigned to an exit terminal \( q_f(i) \) that is in the range \([l_i,r_i]\); i.e., \( l_i \leq q_f(i) \leq r_i \). We say that \( q_f \) is in the range of \( p_i \) if and only if \( l_i \leq q_f \leq r_i \).

The reader can easily verify that in the ordered range problem there exists an optimal solution with \( q_f(1) < \cdots < q_f(n) \). Fixed nets are represented as in Section 3; i.e., the net \((v_i,w\theta(i)), 1 \leq i \leq h \), is a fixed net. We first show that the optimal density of the ordered range problem can again be computed in \( O(n+m+h) \) time.

We assume for the time being that the \( l_i \)'s (resp. \( r_i \)'s) are distinct. We will later show that any problem for which this assumption is not satisfied can be reduced to an equivalent problem where it is satisfied. We furthermore assume that every \( l_i \) (resp. \( r_i \)) coincides with a \( q_j \), and that every \( q_j \) is in the range of a \( p_i \). (If it is not, it is useless and can be removed.)

In addition to the functions \( \text{out, up, down, and cross} \) defined in Section 3, we define two new functions, \( \text{inl} \) and \( \text{inr} \): \( \text{inl}(x) \) (resp. \( \text{inr}(x) \)) is the number of non-fixed nets that have to cross column \( x \) because their \( p_i \) is \( \leq x \) (resp. \( >x \)) while their \( l_i > x \) (resp. \( r_i \leq x \)). Observe that in the ordered range
Definition 4.1 Let A be defined as follows:

\[ A = \max \left\{ \max_{x,y} \left( (\text{cross}(x-1) + \text{cross}(y) + \text{out}(x,y))/2 \right), \right. \\
\left. \max_{x} \left( \text{cross}(x) + \text{inl}(x) + \text{inr}(x) \right) \right\} \]

Note that in the quantities \( \Phi \) and \( \Psi \) defined in Sections 2 and 3, respectively, the second and third term were not combined for the sake of clarity. If \( \hat{d} \) denotes the optimum density we have the following Lemma.

Lemma 4.2 \( \hat{d} \geq A \).

Proof: Once it is observed that \( \text{inl}(x) \text{inr}(x) = 0 \), the proof becomes similar to that of Lemma 3.2, and is therefore omitted. \( \square \)

Lemma 4.3 A can be computed in time \( O(m+n+h) \).

Proof: The proof is along the lines of that of Lemma 2.5, and is therefore omitted. \( \square \)

Lemma 4.4 \( \hat{d} = A \).

Proof: Lemma 4.2 implies that it suffices to show that density \( A \) can be achieved. We modify the assigning strategy described in the proof of Lemma 2.6 to take care of the fact that \( p_i \) cannot be joined to any \( q_j \) that is not in its range. The assigning strategy stops with failure if some \( p_i \) cannot be joined to an exit terminal in its range. We now prove that this assigning strategy must succeed. Suppose that, to the contrary, we fail to join \( p_i \) to any of the \( q_j \)'s in its range. We distinguish two cases.

Case 1: We were unable to join \( p_i \) to \( r_i, r_i < p_i \). Note that \( r_i \) must be available because it is not in the range of any of the \( p_j \)'s that are to the left of \( p_i \) (recall that we are temporarily assuming that the \( r_j \)'s are distinct). In this case there must be some \( x, r_i \leq x < p_i \), such that there are \( \Lambda-\text{cross}(x) \) \( p_j \)'s that are \( \geq x \) and \( < p_i \) and are joined to \( q_j \)'s that are \( < r_i \). (If there were no such \( x \) then we would be able to
join $p_i$ and $r_i$.) Those $\Lambda-cross(x)$ $p_j$'s are to the left of $p_i$ and hence their $r_j$'s are $< r_i$. This implies that $inr(x) \geq \Lambda-cross(x)+1$, and therefore $inr(x)+cross(x) \geq \Lambda+1$, a contradiction.

Case 2: We were unable to join $p_i$ to $r_i$, $r_i > p_i$. Let $q_\alpha$ be the position of the leftmost available exit terminal that is in the range of $p_i$ with $q_\alpha > p_i$ (possibly, $q_\alpha = r_i$). Then there must exist some $y$, $p_i \leq y < q_\alpha$, such that there are $\Lambda-cross(y)$ unavailable $q_j$'s that are $> y$ and $< q_\alpha$ (otherwise $p_i$ would have been joined to $q_\alpha$). Those $\Lambda-cross(y)$ $q_j$'s are joined to the $\Lambda-cross(y)$ $p_k$'s that are immediately to the left of $p_i$.

Now, we distinguish two sub-cases.

Sub-case A: All the $q_j$'s to the left of $q_\alpha$ are unavailable. In this case $q_\alpha = l_i$ and every $p_k$ to the left of $p_i$ is joined to its $l_k$. But then, $inl(y) = \Lambda-cross(y)+1$, which implies that $inl(y)+cross(y) \geq \Lambda+1$, a contradiction.

Sub-case B: There exists at least one available exit terminal to the left of $q_\alpha$. Let $q_\beta$ be the rightmost available exit terminal to the left of $q_\alpha$. There must be some $x$ between $q_\beta$ and $p_i$ such that $\Lambda-cross(x-1)$ $p_k$'s with $p_k \geq x$ are joined to $q_j$'s that are $< x$. Note that such an $x$ must exist both when $q_\beta > l_i$ and when $q_\beta \leq l_i$, since otherwise $q_\beta$ would not be available (because it is in the range of at least one $p_j$). But then, we have

$$[(out(x,y)+cross(x-1)+cross(y))/2] = [(2\Lambda+1)/2] = \Lambda+1,$$

a contradiction. \(\square\)

We now show that an ordered range problem which does not satisfy the assumptions we made earlier can be transformed in $O(n+m)$ time into an equivalent problem which does satisfy these assumptions. Recall that these assumptions were that the $l_i$'s are distinct, the $r_i$'s are distinct, that each $l_i$
and \( r_i \) coincides with a \( q_j \), and that every \( q_j \) is in the range of at least one \( p_i \). First, the problem is modified in an obvious way so that the last two assumptions hold. Then, the \( l_i \)'s are made distinct as follows: If \( p_i \) and \( p_{i+1} \) have \( l_i = l_{i+1} = q_j \), for some \( j \), we change the value of \( l_{i+1} \) to \( q_{j+1} \). Such a change is justified by the facts that (i) no more than one entry terminal can get assigned to position \( l_i \), and (ii) there is an optimal solution without any crossings. The \( r_i \)'s are made distinct in a symmetric manner. We leave it to the reader to verify that the above transformations can be implemented in \( O(n + m) \) time by scanning the list of \( p_i \)'s and that of the \( q_i \)'s first from left to right and then from right to left. This scan is also used to detect whether or not the given range problem has a solution, i.e., whether it is possible at all to assign to every \( p_i \) a \( q_j \) without violating the range constraints.

**Theorem 4.5** The optimal density of an ordered range problem with \( h \) fixed nets can be computed in time \( O(n + m + h) \).

**Proof:** Follows from the above Lemmas.

**Theorem 4.6** An assignment to the ordered range problem achieving density \( \Lambda \) can be obtained in \( O(n + m) \) time when no fixed nets are given.

**Proof:** The algorithm is similar to the assignment algorithm described in Section 2, and details are omitted. \( \square \)

**Theorem 4.7** An assignment to the ordered range problem achieving density \( \Lambda \) can be obtained in time \( O((n + m + h) \log(n + m)) \) when \( h \) fixed nets are given.

**Proof:** Similar to the proof of Theorem 3.6. \( \square \)

5. **Generalizations which are NP-hard**

In this Section we show that two generalizations of the assignment problems discussed in the previous sections are NP-hard. Consider first the
weighted one-to-any problem: Assume a positive weight \( w_i \) is associated with every \( p_i \). The density of column \( x \) is now defined to be the sum of the weights of the nets that cross column \( x \). For example, if the \( w_i \)'s of the CRP shown in Figure 2.0(a) are 15,7,12, then the density is 19.

Theorem 5.1 The weighted version of the one-to-any problem is NP-hard.

Proof: The proof is by a transformation from PARTITION. Let \( a_1, \ldots, a_n \) be an instance of the PARTITION problem [GJ], and create in polynomial time the following instance of the weighted one-to-any problem. Let \( M = 3n + 2 \), and create \( n + 2 \) entry terminals \( p_0, \ldots, p_{n+1} \) such that \( p_i = n + i + 1 \), \( 0 \leq i \leq n + 1 \). Also create \( 2n \) exit terminals \( q_1, \ldots, q_{2n} \) such that \( q_i = i \) if \( 1 \leq i \leq n \), and \( q_i = n + 2 + i \) if \( n + 1 \leq i \leq 2n \). (See Figure 5.1.) In addition, if we let \( w_i \) denote the weight associated with \( p_i \), then set \( w_0 = w_{n+1} = a_1 + \cdots + a_n \), and set \( w_i = a_i \) for \( 1 \leq i \leq n \). The minimum density in the resulting weighted one-to-any problem equals \( 3(a_1 + \cdots + a_n)/2 \) if and only if the PARTITION problem has a solution. □

The second problem shown to be NP-hard is the most general terminal assignment problem, the choice problem. In the choice problem we are given for every entry terminal \( p_i \) a set \( P_i \) of \( m_i \) exit terminals. We have to assign each entry terminal \( p_i \) to one of the exit terminals in \( P_i \) (i.e., \( q_f(i) \in P_i \)) so that the CRP consisting of the nets \( (p_i, q_f(i)) \) has minimum density. The \( P_i \)'s need not be disjoint. We show that the choice problem with every \( m_i = 2 \), called the 2-choice problem, is already NP-hard. The proof is by a transformation from monotone 3-SAT, in which every clause of a boolean formula in conjunctive normal form contains either 3 unnegated or 3 negated variables, [GJ].

Theorem 5.2 The 2-choice problem is NP-hard.

Proof: Let \( C_1, C_2, \ldots, C_k \) be the \( k \) clauses which contain only unnegated
variables, and which we call the positive clauses. Let \(D_1, D_2, \ldots, D_{k_2}\) be the \(k_2\) clauses which contain only negated variables, and which we call the negative clauses. Let \(x_1, x_2, \ldots, x_n\) be the variables used in the \(k_1+k_2\) clauses, and let \(o_i\) (resp. \(s_i\)) be the number of occurrences of \(x_i\) in the positive (resp. negative) clauses. The \(l\)-th leftmost occurrence of the variable \(x_i\) in the positive (resp. negative) clauses is referred to as \(x_{il}\) (resp. \(\bar{x}_{il}\)), \(1 \leq i \leq n\), \(1 \leq l \leq o_i\) (resp. \(1 \leq l \leq s_i\)). We can assume that each variable \(x_i\) occurs in at least one positive clause and in at least one negative clause. If \(x_i\) appears only in positive (resp. negative) clauses we can set \(x_i\) to true (resp. false) and delete all the clauses containing \(x_i\) (resp. \(\bar{x}_i\)).

Given an instance of the monotone 3-SAT problem we create the following instance of the choice problem on a channel of length \(M = 6(k_1+k_2)+2n\). For each clause we create 6 entry and 6 exit terminals. To the left of the \(6(k_1+k_2)\) terminals associated with the clauses we create \(n\) entry terminals at positions 1, \(\ldots, n\), and to the right we create \(n\) exit terminals at positions \(n+6(k_1+k_2)+1, \ldots, 2n+6(k_1+k_2)\). See Figure 5.2. For each positive clause \(C_r = (x_{il} \lor x_{jl} \lor x_{kl})\) the 6 entry terminals are called \(x_{il}, x_{jl}, x_{kl}, y_{il}, y_{jl},\) and \(y_{kl}\). Below these are 6 exit terminals: \(u_{il}, u_{jl}, u_{kl}, \bar{u}_{il}, \bar{u}_{jl},\) and \(\bar{u}_{kl}\). See Figure 5.3(a). The entry terminal \(x_{il}\) and the exit terminal \(u_{il}\) are at position \(n+6(r-1)+1\). For each negative clause \(D_r = (\bar{x}_{il} \lor \bar{x}_{jl} \lor \bar{x}_{kl})\) the 6 entry terminals are \(\bar{x}_{il}, \bar{x}_{jl}, \bar{x}_{kl}, \bar{y}_{il}, \bar{y}_{jl},\) and \(\bar{y}_{kl}\), and the 6 exit terminals are \(\bar{v}_{il}, \bar{v}_{jl}, \bar{v}_{kl}, v_{il}, v_{jl},\) and \(v_{kl}\). See Figure 5.3(b). Setting \(x_i = \text{true}\) will correspond to joining every \(x_{il}\) to \(u_{il}\), \(1 \leq l \leq o_i\), and to joining every \(\bar{x}_{ik}\) to \(v_{ik}\), \(1 \leq k \leq s_i\). Setting \(x_i = \text{false}\) will correspond to joining every \(x_{il}\) to \(\bar{u}_{il}\), and to joining every \(\bar{x}_{ik}\) to \(\bar{v}_{ik}\).

For every entry terminal \(x_{il}\) (resp. \(\bar{x}_{il}\)) let the set of exit terminals, called the choice set, be \(X_{il} = \{u_{il}, \bar{u}_{il}\}\) (resp. \(\bar{X}_{il} = \{v_{il}, \bar{v}_{il}\}\)). Then the clause
\( x_{i1} \lor x_{i2} \lor x_{i3} \) is satisfied if and only if the density created by the 3 nets corresponding to the \( x \)'s in the clause is less than 3. The \( y \)'s (resp. \( \bar{y} \)'s) are used to make the assignment consistent; i.e., if \( x_i \) is assigned a true-value in one clause, it has to be assigned a true-value in all the other clauses in which it appears. Let the \( n \) leftmost entry terminals be \( x_{i0}, \ldots, x_{in} \), and let the \( n \) rightmost exit terminals be \( y_{1}, \bar{y}_{1}, \ldots, y_{n}, \bar{y}_{n} \). Let the choice sets for the entry terminals be as follows:

- choice set for \( x_{i0} \) is \( X_{i0} = \{ u_{i1}, v_{i1} \} \)
- choice set for \( x_{il} \) is \( X_{il} = \{ u_{il}, \bar{u}_{il} \} \) \( 1 \leq l \leq i \)
- choice set for \( y_{il} \) is \( Y_{il} = \{ u_{il}, \bar{u}_{il+1} \} \) \( 1 \leq l < i \)
- choice set for \( y_{i, \sigma_i} \) is \( Y_{i, \sigma_i} = \{ u_{i, \sigma_i}, v_{i, \sigma_i+1} \} \)
- choice set for \( \bar{x}_{il} \) is \( \bar{X}_{il} = \{ \bar{v}_{il}, v_{il} \} \) \( 1 \leq l \leq \sigma_i \)
- choice set for \( \bar{y}_{il} \) is \( \bar{Y}_{il} = \{ \bar{v}_{il}, v_{i, \sigma_i+1} \} \) \( 1 \leq l \leq \sigma_i \)

This construction links all occurrences of \( x_{il} \) and \( \bar{x}_{ik} \) together, \( 1 \leq l \leq i \), \( 1 \leq k \leq \sigma_i \), so that either every \( x_{il} \) is assigned to \( u_{il} \) and every \( \bar{x}_{ik} \) is assigned to \( v_{ik} \), or every \( x_{il} \) is assigned to \( \bar{u}_{il} \) and every \( \bar{x}_{ik} \) is assigned to \( \bar{v}_{ik} \). Figure 5.4 shows these two possible assignments. It is clear that, given a boolean formula, the 2-choice problem corresponding to the construction described above can be created in polynomial time.

We claim that a given boolean formula is satisfiable if and only if the corresponding 2-choice problem has a solution of density less than \( n + 6 \). Assume that the boolean formula is satisfiable. Assign every \( x_{il} \) to \( u_{il} \) and every \( \bar{x}_{ik} \) to \( v_{ik} \) if \( x_i \) is true in the formula. Assign every \( x_{il} \) to \( \bar{u}_{il} \) and every \( \bar{x}_{ik} \) to \( \bar{v}_{ik} \) if \( x_i \) is false. In each case there remains only one exit terminal to be assigned to each of the \( y \)'s and \( \bar{y} \)'s. The construction created for each variable \( x_i \) adds 1 to the density in the columns between position \( n \) and \( n + 6(k_1 + k_2) \).
Since at least one $x_{ii}$ (resp. $\bar{x}_{ik}$) in each clause is assigned to the exit terminal at the same position (otherwise the formula is not satisfied), the density of the solution to the 2-choice problem obtained in this way is at most $n + 4$.

Now assume that the 2-choice problem has a solution with a density less that $n + 6$. Observe that as soon as one $x_{ii}$, $\gamma_{ii}$, $\bar{x}_{ik}$, or $\bar{\gamma}_{ik}$ chooses its exit terminal, the exit terminals to be chosen by the remaining entry terminals with $i$ as first subscript have been determined. This corresponds to a consistent true/false assignment to $x_i$ in the boolean formula. Furthermore, setting every $x_i$ to true if $x_{i1}$ is joined to $\omega_{i1}$ and to false if $x_{i1}$ is joined to $\bar{\omega}_{i1}$ results in a true/false assignment to the $n$ variables that satisfies the boolean formula. This is seen as follows. If one positive clause is not true, then the 3 exit terminals corresponding to the $x$'s in this clause are assigned to the $\omega$'s, which then implies that the 3 $y$'s are assigned to the $\bar{\omega}$'s. Hence, density $n + 6$ is achieved in column $x_{ki}$, a contradiction. A similar argument holds when a negative clause is not true. This concludes the proof of the Theorem. □

6. The One-Sided Range Problem

We next consider the version of the range problem in which every $l_i = 1$. We show how to solve this one-sided range problem in $O(n \log n)$ time when every position on the lower row of the channel contains an exit terminal; i.e., $q_i = i$ for $1 \leq i \leq M$. The input now consists of a list $L$ containing $n$ entry terminals and their right bounds $(p_1, r_1), \cdots, (p_n, r_n)$ with $1 \leq p_1 < \cdots < p_n \leq M$ and $1 \leq r_i \leq M$. The solution is a CRP of minimum density consisting of the nets $(p_i, q_f(i))$ with $1 \leq q_f(i) \leq r_i$. See Figure 6.0(a) and (d). In this section we call a net $(p_i, q_f(i))$ a right net if $p_i < q_f(i)$, a left net if $p_i > q_f(i)$, and a trivial net if $p_i = q_f(i)$. We call an entry $(p_i, r_i)$ with $p_i \leq r_i$ a right entry (since the net $(p_i, q_f(i))$ can be a right net), and we call an entry $(p_i, r_i)$ with $p_i > r_i$ a left entry (since the net $(p_i, q_f(i))$ has to be a left net).
The technique used to determine the optimal assignment in the one-sided range problem is somewhat different from the one used in the previous sections. Instead of computing the optimal density and then using an assignment algorithm, we describe an algorithm that achieves the optimal density in time $O(n \log n)$ without pre-computing. Our algorithm is preceded by two preprocessing steps. In the first one we generate a list $L_2$ containing the entries $(r_{i_1}, p_{i_1}), \ldots, (r_{i_n}, p_{i_n})$ sorted lexicographically in increasing order. We also determine the position of each $p_i$ in $L_2$ and the position of each $r_{ij}$ in $L_1$. This information can be generated in $O(n \log n)$ time.

In the second preprocessing step we transform the problem into an equivalent one with distinct $r_i$'s. The tie-breaking rules for making the $r_i$'s distinct are as follows. If a left and a right entry have the same $r_i$, we change the right bound of the right entry to $r_i-1$. If two left entries, respectively two right entries, have the same $r_i$, we change the right bound of the entry with the smaller $p_i$ to $r_i-1$. See Figure 6.0(b). The justification for these rules is as in Section 4.

We make the $r_i$'s distinct by scanning list $L_2$ from right to left. We apply the tie-breaking rule at all positions in the channel that contain two or more right bounds initially, and at positions that received two or more right bounds as a result of applying the tie-breaking rule to positions to the right. We use a heap to store the entries encountered during the scan of $L_2$ and whose right bounds have not yet been changed to their final value. Assume that we are at position $x$, and that there are $k$ entries with $r_i=x$. Insert the $k$ entries in the heap, and delete the entry with the largest $p_i$ value. The final right bound of the deleted entry is $x$. (Note that we did not need a heap in Section 4 because the $l_i$'s and $r_i$'s were ordered.) It can easily be shown that this procedure changes the right ranges correctly and that it can be implemented in $O(n \log n)$ time. We thus have the following Lemma.
Lemma 6.1 Every one-sided range problem can be transformed in \( O(n \log n) \) time into an equivalent problem in which all \( r_i \)'s are distinct.

Proof: Follows from the above discussion. □

From now on we assume that all the \( r_i \)'s are distinct. Let \( \text{inr}(x) \) be the number of left entries \((p_i, r_i)\) with \( p_i > x \) and \( r_i \leq x \). These entries need an exit terminal \( q_f \leq x \) and thus cross column \( x \) coming from the right. Since \( \text{inr}(x) \) exit terminals are needed by entries passing through column \( x \) from the right, right entries with \( p_i \leq x \) and \( r_i > x \) may have to get assigned to an exit terminal \( > x \) and thus pass through column \( x \) coming from the left. As an example, see the entry \((p_2, r_2)\) in Figure 6.0(a). Let \( \text{inl}(x) \) be the number of right entries that have to pass through column \( x \) from the left. If we define \( \sigma(x) \) to be equal to \( x \) if \( x \geq 0 \) and to equal 0 otherwise, then \( \text{inl}(x) = \sigma(\text{inr}(x) + \text{up}(1,x) - x) \). Recall that now \( \text{down}(1,x) = x \). We now define a quantity \( \Gamma \), which we will show to be the best achievable density.

Definition 6.2: Let \( \Gamma \) be defined as follows:

\[
\Gamma = \max_x \{ \text{inr}(x) + \text{inl}(x) \}
\]

Lemma 6.3 \( \tilde{d} \geq \Gamma \).

Proof: The proof is along the lines of that of Lemma 4.2 and is omitted. □

First, observe that there exists an optimal solution in which every right entry \((p_i, r_i)\) is assigned to an exit terminal at a position \( \geq p_i \) (since all the \( r_i \)'s are distinct). A right entry \((p_i, r_i)\) that is assigned to the exit terminal at position \( p_i \) does not add to the density. Hence, each right entry initially claims the exit terminal at \( p_i \) as the one it is assigned to. However, we may not be able to assign every right entry to the exit terminal in position \( p_i \). If a left entry \((p_j, r_j)\) does not find an unclaimed exit terminal (i.e., an exit terminal not claimed by a right entry) at a position \( \leq r_j \), a right entry \((p_i, r_i)\) with \( p_i \leq r_j \) has to give up its claim on the exit terminal at position \( p_i \) and take one
at a position \( p_i \). Hence, a right entry will be assigned to an exit terminal so that the resulting net is either a trivial or a right net, but never a left net. This leads to an algorithm for the one-sided range problem that consists of 4 phases. Each phase can be implemented in \( O(n) \) time.

**Phase 1.** Tentative trivial net assignment: all right entries \((p_i, r_i)\) claim the exit terminal \( p_i \).

**Phase 2.** Determine the right entries whose claimed exit terminals are needed for left entries.

**Phase 3.** Assignment of the left entries.

**Phase 4.** Assignment of the remaining right entries.

Phase 1 can easily be implemented in \( O(n) \) time. In Phase 2 we scan list \( L_2 \) from left to right. Assume we determine at position \( x \) that an additional exit terminal at a position \( \leq x \) is needed. Then the rightmost right entry \((p_i, r_i)\) with \( p_i \leq x \) and \( r_i > x \) that was tentatively assigned as a trivial net gives up its claim on the exit terminal at position \( p_i \). We say that the right entry \((p_i, r_i)\) is taken out. Note that the taken out right entry \((p_i, r_i)\) will always encounter a free exit terminal between position \( x+1 \) and \( r_i \). This follows from the fact that the \( r_i \)'s are distinct. In order to implement Phase 2 in \( O(n) \) time we use an auxiliary list that allows us to find the next right entry to be taken out in constant time. The auxiliary list contains initially all right entries of list \( L_2 \), and we delete entries that are taken out or that have \( r_i \leq x \). Note that for achieving density \( \Gamma \) it is not crucial that the right entry closest to column \( x \) is taken out. This is a convention used by the algorithm that enables us to determine the entry that can be taken out efficiently.

In Phase 3 we scan the list \( L_2 \) from right to left and assign each left entry \((p_i, r_i)\) to the first exit terminal \( x \leq r_i \) that is not used in a trivial net. The left entry \((p_i, r_i)\) has precedence over other left entries \((p_j, r_j)\) with \( r_j < r_i \). We record in list \( L_1 \) and \( L_2 \) the exit terminal assigned to each left entry. Thus, Phase 3 can be implemented in \( O(n) \) time.
In Phase 4 we assign the remaining right entries. Recall that each taken out right entry \((p_i, r_i)\) gets assigned to an exit terminal at a position \(> p_i\). We scan list \(L2\) from right to left. A list of length \(O(n)\) containing information about the positions of the free exit terminals is initially obtained from \(L2\), and is scanned simultaneously. Assume we are at position \(x\) where \(x = r_i\) and \((p_i, r_i)\) is a taken out right entry. We then assign \(p_i\) to the rightmost free exit terminal at a position \(\leq x\). This exit terminal can be determined in \(O(1)\) time.

It is possible that two taken out right entries are assigned to exit terminals so that the corresponding nets cross each other when they don't have to. But the contribution to the density of two crossing right nets is identical to the contribution to the density of the two uncrossed nets. The list containing the information about the free exit terminals can be handled so that the total amount of time needed to assign the taken out right nets in \(O(n)\).

**Theorem 6.4** The one-sided range problem can be solved in time \(O(n \log n)\) by an algorithm that achieves density \(\Gamma\).

**Proof:** The correctness and the \(O(n \log n)\) time bound follow from the above discussion. Note that only the preprocessing steps require \(O(n \log n)\) time. It remains to show that the algorithm achieves density \(\Gamma\). Figure 6.1 shows the 10 configurations that can occur at any position \(x\), \(1 \leq x \leq M\). In the CRPs generated by the algorithm configurations 6.1(e) and (i) cannot occur since a right entry is only taken out when its exit terminal is needed by a left entry.

Let \(d_x\) be the density in column \(x\). We will now show that for every \(x\), \(d_x \leq \Gamma\). Suppose there exists a column \(x\) with \(d_x > \Gamma\). Choose \(x\) so that column \(x+1\) has a smaller density; i.e., \(d_{x+1} < d_x\). The density in column \(x\) is created by \(d_{r_x}\) right nets and \(d_{l_x}\) left nets where \(d_{r_x} + d_{l_x} = d_x\). From the algorithm it follows that \(d_{r_x} \leq d_{l_x}\). In column \(x+1\) the situation 6.1(b), (c), or (f) has to occur. (All other situations are density increasing or density preserving.) The exit terminal at position \(x+1\) is taken by a right net in
situation 6.1(b) and (f) and is empty in situation 6.1(c). In both cases no left entry could take this exit terminal in Phase 3, and hence, $dl_x = inr(x)$. If $dr_x = 0$, then $inr(x) \geq \Gamma$, a contradiction. If $dr_x > 0$, the $dr_x$ right entries crossing column $x$ have been forced out by left entries. The number of forced out right entries is $inr(x) + up(1, x) - x$. Hence, $inr(x) + ini(x) = dl_x + dr_x > \Gamma$, a contradiction, and the Theorem follows. □

7. Choosing Fewer Than $n$ Nets

Consider the one-to-any problem with the following modification: Instead of choosing $n$ nets, we want to choose $s$ nets, $s < n$, such that the resulting CRP has minimum density. In other words, we must select $s$ of the $n$ entry terminals, $s$ of the $m$ exit terminals, and then assign the $j^{th}$ selected entry terminal to the $j^{th}$ selected exit terminal, $1 \leq j \leq s$. We show that this problem can be solved in time $O((n + m)\log \hat{d})$, where $\hat{d}$ is the optimal density. First we give a verification algorithm which, given an integer $k$, decides in time $O(m + n)$ whether $\hat{d} \leq k$. The claimed result follows by using such a verification algorithm to compute $\hat{d}$ in a binary search manner.

The algorithm consists of a scan of the list of entry terminals and that of exit terminals. Let $ENT$ (resp. $EX$) be the index of the entry (resp. exit) terminal currently scanned (i.e. if the scan is at $p_i$ and $q_j$ then $ENT = i$ and $EX = j$). Let $COUNT$ contain the number of nets created so far.

Outline of the Verification Algorithm

*Input:* The $p_i$'s, the $q_i$'s, $s$ and an integer $k$.

*Output:* 'Yes' if $\hat{d} \leq k$, 'No' otherwise.

*Step 0:* Set $ENT = 1$, $EX = 1$, $COUNT = 0$.

*Step 1:* Repeat Step 2 until $COUNT = s$ or $EX = m + 1$ or $ENT = n + 1$.

*Step 2:* If joining $p_{ENT}$ to $q_{EX}$ does not cause the density to exceed $k$ then create the net $(p_{ENT}, q_{EX})$ and increment each of $ENT, EX$ and $COUNT$ by one. Otherwise do the following:
Case 1: If $P_{\text{ENT}} < q_{\text{EX}}$ then increment $\text{ENT}$ by one.
Case 2: If $q_{\text{EX}} < P_{\text{ENT}}$ then increment $\text{EX}$ by one.

Step 3: If $\text{COUNT} = s$ then output 'Yes', otherwise output 'No'.
End of Verification Algorithm

To prove correctness of the above algorithm, it suffices to show that there is a solution with density $\leq k$ if and only if the above algorithm answers 'Yes'. If the above algorithm answers 'Yes' then it is clear that the $s$ nets it produced are a solution whose density is $\leq k$. We now show that if there is a solution whose density is $\leq k$ then our algorithm answers 'Yes'. Let $\alpha_1, \ldots, \alpha_l$ be the nets produced by our verification algorithm. To prove that our algorithm answers 'Yes' it suffices to show that $l = s$. Among all valid solutions (i.e. solutions with density $\leq k$), choose the one having as many nets as possible in common with the nets $\alpha_1, \ldots, \alpha_l$. Let $\beta_1, \ldots, \beta_s$ be the nets of this valid solution. We claim that $\alpha_i = \beta_i$ for every $1 \leq i \leq l$. We prove this claim by induction on $i$:

Basis: First, note that $\alpha_1 = (p_1, q_1)$. If $\beta_1 \neq \alpha_1$ then the nets $\alpha_1, \beta_2, \ldots, \beta_s$ constitute another valid solution which has one additional net in common with $\alpha_1, \ldots, \alpha_l$, a contradiction. Hence, $\beta_1 = \alpha_1$.

Induction: Suppose that $\alpha_j = \beta_j$ for all $j < i$ and that $\alpha_i \neq \beta_i$. To get a contradiction, it suffices to show that setting $\beta_i$ equal to $\alpha_i$ yields a valid solution. Let $\alpha_i = (a, b)$ and $\beta_i = (c, d)$. From Step 2 of the algorithm, it follows that $a \leq c$ and $b \leq d$. This implies that if we change $\beta_i$ from $(c, d)$ to $(a, b)$, $\beta_1, \ldots, \beta_s$ still form a valid solution, a contradiction.

This completes the proof of the claim. The claim implies that $l = s$, because if $l < s$ then the algorithm would have selected at least one additional net $\alpha_{i+1}$ (possibly $\alpha_{i+1} = \beta_{i+1}$). This completes the correctness proof of the verification algorithm.
Theorem 7.1 The modified one-to-any problem in which only \( s \) nets are generated, \( s < n \), can be solved in time \( O((m+n)\log d) \).

Proof: It is not hard to see that the verification algorithm can be implemented to run in time \( O(m+n) \). Since \( \log d \) applications of that algorithm produce an optimal solution, it follows that such an optimal solution can be found in time \( O((m+n)\log d) \). \( \Box \)

The above modification for choosing only \( s \) nets can also be applied to the one-to-any problem with fixed nets and to the range problem with/without fixed nets. The details are left to the reader.

8. Conclusions

In this paper we presented efficient solutions to a number of different terminal assignment problems, and we showed that some more general versions of the problems considered are NP-hard. We introduced a new way to characterize the optimal density for the one-to-any and the ordered range problem both with and without fixed nets. Once the best achievable density was known, our assignment strategy produced an optimal assignment of entry to exit terminals. For two other assignment problems different methods were used to obtain the optimal assignment efficiently.

References


Figure 2.0

(a) non-optimal

(b) optimal

Figure 2.1
Situation B when there are no free exit terminals to the left of \( q_s \)

Figure 2.2

Situation B when there are free exit terminals to the left of \( q_s \)

Figure 2.3
One-to-any problem with 3 fixed nets

Figure 3.0

Figure 3.1
Figure 5.1

Organization of the channel

Figure 5.2

(a) Terminals for the clause \((x_{u_1} \lor x_{j_2} \lor x_{k_3})\)  (b) Terminals for the clause \((\overline{x}_{u_1} \lor \overline{x}_{j_2} \lor \overline{x}_{k_3})\)

Figure 5.3
Solid lines show the assignment corresponding to $x_i = true$, dashed lines show the assignment corresponding to $x_i = false$.

Figure 5.4

(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 6.1
(b) after preprocessing

(c) after phase 3

(d) final assignment

Figure 6.0