Balancing Inter-Ring Loads on SONET Dual-Ring without Demand Splitting

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Abstract

In the survivability and simplicity aspect, SONET Self-healing Ring(SHR) is one of the most important schemes for the high-speed telecommunication networks. Since the ring capacity requirement is defined by the largest STS-1 cross-section in the ring, load balancing is the key issue in the design of SONET SHR. Recently, most of the research on load balancing problem have been concentrated on the SONET single-ring case. However, in certain applications, multiple-ring configuration is necessary because of the geographical limitations or the need for extra bandwidth.

In this paper, the load balancing problem for SONET dual-ring is considered by assuming symmetric inter-ring demands. We present a linear programming based formulation of the problem. Initial solution and improvement procedures are presented, which solves the routing and interconnection between the two rings for each demand. Computational experiments are performed on various size of networks with randomly generated demand sets. Results show that the proposed algorithm is excellent in both the solution quality and the computational time requirement. The average error bound of the solutions obtained is 0.26% of the optimum.

1. Introduction

As the link capacity of modern telecommunication networks increases with the introduction of optical fibers, the impact of cable cuts or central office failures is getting more significant. Survivability thus has become the key issue in planning networks, especially for data transmissions. Among many network structural alternatives, Self-Healing Ring (SHR) provides high restoration capability for a single cable cut or equipment failure. A SHR is a ring network that provides redundant bandwidth in which disrupted services can be automatically restored from network failures. In the past, however, the ring architecture was restricted from applications because metallic, low-capacity systems made the ring uneconomical and difficult to adapt to the rapidly growing traffics. Even with optical fiber, the ring has been used only in LANs not in interoffice networks, due to its low speed and complex control scheme. However, standardized SONET (Synchronous Optical Network) technology and associated flexible high-speed add-drop multiplexing technology have made SHR architecture practical [8]. SONET which is the standard for optical transmissions has played an important role for increased survivability and fast restoration in modern optical telecommunication networks.

Among the many challenging problems in network planning that SONET ring gives rise to, the most immediate is that of determining a cost effective, survivable network design using SONET ring components. Since the cost of a SONET ring is dependent on its capacity, to find the routing for all demands in the ring is an important task to accommodate the traffic with as small capacity as possible [1]. Previous works [1], [3], [4], [5], [6], and [7] have focused on the load balancing in single ring either with or without demand splitting. However, two or more rings may be necessary to interconnect geographically separated networks with proper link capacities. In such a case, the link capacity limit may exclude the single ring application. Smith and Yackle [2], as an example, examined a 16-node network with two different traffic demands. The experimental results show that three and four-ring configurations are the least cost alternatives for centralized and mesh demands, respectively.

In this paper, balancing loads in SONET dual-ring is considered. In the dual-ring, to decide the routes of the inter-ring demands is the core of the load balancing problem. For each demand it is to decide the routing direction in each ring and the access node between the two rings. Two objectives can be considered: to minimize the maximum load in the dual-ring, and to minimize the weighted sum of maximum loads in the two rings. In this paper we consider the weighted sum of maximum loads which takes into account the numbers of nodes in the two rings. Note that the latter objective accommodates traffic demands with reduced ring facilities.

2. Formulation of the problem

Although there are a number of design alternatives for multiple ring networks, we in this paper consider dual-ring network with two access nodes. We also assume symmetric inter-ring demands through the paper. Figure 1 shows an example of the dual-ring networks. In the

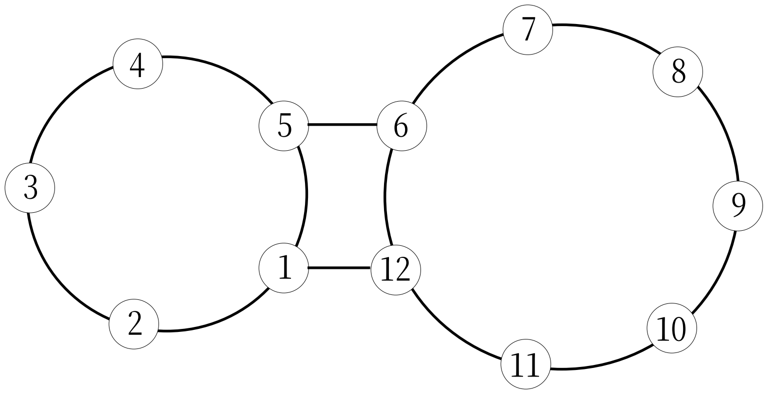

Figure 1: An Example of Dual-Ring Networks

figure each node is equipped with ADM (Add-Drop Multiplexer) facility which is a multiplexing device used to add and drop local channels and to pass through transit channels. In general, the number of ADM nodes are proportional to the amount of traffic in each ring.

In Figure 1, node 1 and node 12 are located in the same node called Access-1, and node 5 and node 6 are located in Access-2. We assume that two nodes in an access node are connected via optical links, which is one of the three different nodal configurations presented in [8].

To model the Load Balancing problem in Dual-ring (LBDR) the following node and arc sets need to be considered.

$$N_1 = \{1, 2, \cdots, n_1\},$$
$$N_2 = \{n_1+1, \cdots, n_1+n_2\},$$
$$A_1 = \{(1,2), (2,3), \cdots, (n_1-1, n_1), (n_1, 1)\},$$
$$A_2 = \{(n_1+1, n_1+2), (n_1+2, n_1+3), \cdots, (n_1+n_2-1, n_1+n_2), (n_1+n_2, n_1+1)\}, \text{ and}$$
$$A_I = \{(1, n_1+n_2), (n_1, n_1+1)\}.$$

Let R_1=(N_1,A_1) and R_2=(N_2,A_2) be two rings called Ring-1 and Ring-2 respectively. Two rings are interconnected by an arc set A_I. Let (1,n_1+n_2) be Access-1 and (n_1,n_1+1) be Access-2. Then the dual-ring is defined by R=(N_1N_2, $A_1A_2A_I$).

In LBDR we need to decide the route of each inter-ring demand. In other words, we have to decide whether a particular demand is routed in clockwise or counter-clockwise direction in each ring and which access link to use for the interconnection. Therefore, the complete evaluation would imply solving routing problems with 2^{3D} variables, where D represents the number of demands. Now, we introduce the following variables to formulate the load balancing problem.

$$x_k = \begin{cases} 1 & \text{if demand } k \text{ is routed clockwise in Ring - 1,} \\ 0 & \text{otherwise,} \end{cases}$$

$$y_k = \begin{cases} 1 & \text{if demand } k \text{ is routed clockwise in Ring - 2,} \\ 0 & \text{otherwise,} \end{cases}$$

$$w_k = \begin{cases} 1 & \text{if demand } k \text{ is routed via Access - 1,} \\ 0 & \text{if demand } k \text{ is routed via Access - 2.} \end{cases}$$

The load balancing in a single ring [3,4] is to minimize the maximum load which occurs in an arc of the ring. We call this maximum load as maximum arc load. The same objective may be employed in the dual-ring case. However, in a dual-ring network, to minimize the maximum arc load is not an appropriate measure for the objective function. This is mainly because of the different number of nodes in the two rings. In general, as the number of nodes in a ring increases, the maximum arc load also increases. More specifically, the increase of one unit load in a ring calls for the capacity increase of all ADM nodes in the ring. Thus, to obtain a balanced load with appropriate ADM node capacity in each ring we are interested in minimizing the weighted average of the loads in the two rings. The number of nodes in each ring is used for the weight. Based on the above discussion we now formulate the LBDR as follows:

minimize $n_1 z_1 + n_2 z_2$

subject to

$$z_1 \geq \sum_{k \in K_1(l)} d_k x_k + \sum_{k \in K_2(l)} d_k (1 - x_k), \qquad l = 1, \cdots, n_1 - 1, \tag{1}$$

$$z_2 \geq \sum_{k \in K_3(l)} d_k y_k + \sum_{k \in K_4(l)} d_k (1 - y_k), \qquad l = n_1 + 1, \cdots, n_1 + n_2 - 1, \tag{2}$$

$$z_1 \geq \sum_{k=1}^{D} d_k x_k w_k + \sum_{k=1}^{D} d_k (1 - x_k)(1 - w_k), \tag{3}$$

$$z_2 \geq \sum_{k=1}^{D} d_k y_k w_k + \sum_{k=1}^{D} d_k (1 - y_k)(1 - w_k), \tag{4}$$

$$x_k, y_k, w_k \in \{0,1\},$$

where $K_1(l) = \{k \mid i_k \leq l\}, K_2(l) = \{k \mid i_k \geq l+1\}, K_3(l) = \{k \mid j_k \geq l+1\},$ and $K_4(l) = \{k \mid j_k \leq l\}$.

Readers who are interested in the NP-Completeness of the above problem are recommended to refer to Cosares and Saniee [1], who proved the NP-completeness of the load balancing problem in single ring. In the formulation i_k and j_k respectively represent the origin and destination of demand k. Constraints set (1) and (2) respectively assure that z_1 and z_2 are at least as large as the maximum of the arc loads in the corresponding ring. Constraints (3) and (4) are concerned with the capacity of the Access-1 and Access-2, respectively. Note that (3) and (4) are nonlinear. However, the first nonlinear term $x_k w_k$ of (3) can be converted into a variable u_k with the addition of the following linear constraints:

$$u_k \leq x_k ,$$
$$u_k \leq w_k ,$$
$$u_k \geq x_k + w_k - 1, \text{ and}$$
$$u_k \geq 0.$$

The above transform is justified due to the zero and one integer valued variables of x_k and w_k. Similarly, $(1\text{-}x_k)(1\text{-}w_k)$, $y_k w_k$, and $(1\text{-}y_k)(1\text{-}w_k)$ can respectively be transformed into linear terms v_k, s_k, and t_k with corresponding linear constraints.

3. The Algorithm

In this section we first present the initial routing algorithm with an illustrative example. Improvement algorithm is then provided which iteratively improves the solution by rerouting demands.

3.1. Getting An Initial Solution

Given an inter-ring demand (i_k,j_k) such that $1<i_k<n_1$ and $n_1+1<j_k<n_1+n_2$, the path can be divided into two intra-ring paths (i_k,a) and (a',j_k). Node a and a' are a pair of nodes in either Access-1 or Access-2.

To determine the values of the decision variables x_k, y_k, and w_k is equivalent to determine a path for a demand k. Any path from a node in Ring-1 to a node in Ring-2 has three characteristics:

- A path traverses either node 1 or node n_1.
- A path traverses either node n_1+1 or node n_1+n_2.
- If the link $(1,n_1)$ is contained in a path, it can be replaced with the link (n_1+1,n_1+n_2), and *vice versa*.

The third characteristic is clear from that nodes 1 and n_1+n_2 are in one access node and nodes n_1 and n_1+1 in another access node. From the above it is clear that the maximum load in Ring-1 can be reduced by taking link (n_1+1,n_1+n_2) instead of link (1,n_1). Replacing link (1,n_1) with link (n_1+1,n_1+n_2) may decrease the maximum load of Ring-1 and increase that of Ring-2. Thus, to decide the access node the algorithm compares the maximum arc load in Ring-1 and the load in the link (1,n_1). Let Diff-1 be the difference between the load of link (1,n_1) and the maximum arc load in Ring-1. In the same way, Diff-2 can be defined in Ring-2. Now, since Diff-1 and Diff-2 respectively represent the spare capacity of link (1,n_1) and link (n_1+1,n_1+n_2) the one with more spare capacity will be chosen as a link in the path of demand k under consideration. In the selection, the weighted spare capacity is considered which is computed by dividing each spare capacity with the number of nodes in the corresponding ring.

The initial solution procedure first determines the routing directions x_k and y_k of each demand k such that a particular link is not overloaded with the assignments. Then it decides the access link w_k.

Initial Solution Algorithm for LBDR

Step 1 List the demands in non-increasing order of the amount d_k.

Step 2 For each demand k in the order in the list of **Step 1**:

Step 2-1 Let the weight of two paths {i_k,i_k+1,...,n_1} and {i_k,i_k-1,...,1} be respectively the sum of corresponding arc loads.

Step 2-2 Compare the weights of the two paths and select the one with the smaller weight.

Step 2-3 For Ring-2, repeat steps **Step 2-1** and **Step 2-2**.

Step 2-4 If selected path is either

{i_k, i_k+1, ..., n_1} on Ring-1 and {n_1+1, n_1+2, ..., j_k} on Ring-2 or

{i_k, i_k-1, ..., 1} on Ring-1 and {n_1+n_2, n_1+n_2-1, ..., j_k} on Ring-2,

then go to **Step 2-5**.

Otherwise, compute the load at each link and find the maximum arc load in each ring. Compute Diff-1/n_1 and Diff-2/n_2. If Diff-1/n_1 > Diff-2/n_2, then arc (n_1, 1) is included to the path. Otherwise, arc (n_1+n_2, n_1+1) is selected.

Step 2-5 Compute the load of each arc. Go to **Step 2**.

We will now demonstrate the initial solution procedure with the following demand patterns in the dual-ring given in Figure 1. The unit of the demand is the number of STS-1s. STS-1 (Synchronous Transport Signal-Level 1) is the basic building block in SONET signal hierarchy the transmission rate of which is 51.84 Mbps.

Among the five demands, since demand 1 has the biggest amount, it is routed first as shown in Figure 2. It is routed along the path that traverses the smallest number of links. Access-2 is selected arbitrarily as an interconnection node.

Table 1: Demand Patterns

k	(i_k, j_k)	d_k
1	(2,7)	9
2	(3,8)	7
3	(3,11)	4
4	(4,9)	8
5	(4,10)	2

Figure 3 shows the paths on each ring for demand 4, which has the second biggest amount. Since the origin of demand 4 is node 4, the weights of path {4,5} and {4,3,2,1} are compared. Path {4,5} with smaller weight is selected in Ring-1. In the same manner, path {12,11,10,9} is selected as a path in Ring-2. As seen in Figure 3, to complete the path the access link has to be decided. For that purpose the two weighted spare capacities are computed to make a choice

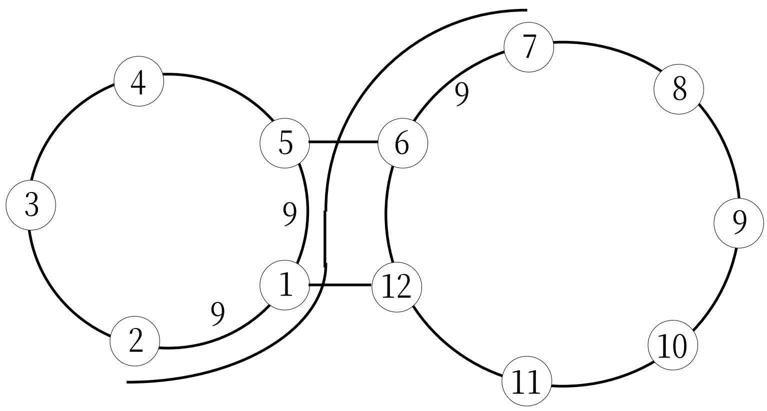

Figure 2: Path for Demand 1

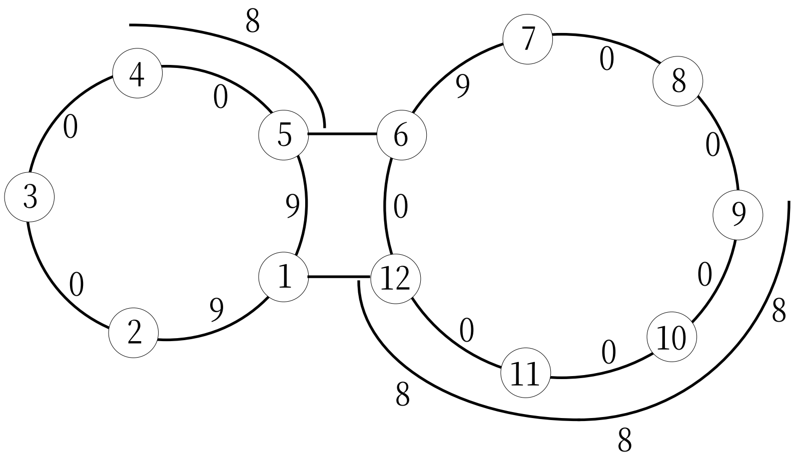

Figure3: Path for Demand 4

Table 2: Initial Solution

k	(i_k,j_k)	d_k	x_k	w_k	y_k
1	(2,7)	9	0	0	1
2	(3,8)	7	1	1	0
3	(3,11)	4	0	1	0
4	(4,9)	8	1	0	0
5	(4,10)	2	0	1	1

between arc (5,1) and (6,12). Since Diff-1/5 = 0/5 and Diff-2/7 = 9/7, arc (6,12) is selected for the route of demand 4. After all demands are routed, the initial solution is obtained as presented in Table 2. Note that the maximum arc load in Ring-1 is 16 at arc (5,6) and that in Ring-2 is 19 at arc (11,12).

3.2. Improving The Initial Solution

The initial solution obtained in Section 3.1 can be improved by examining a demand which is routed through heavily loaded arcs. The demand is routed in the direction which is opposite to the previous one, if it improves the objective function value. The access node is determined in the same way as in the initial solution procedure. This process is continued as far as rerouting a demand improves the solution.

Improving Algorithm for LBDR

Step 1 Let S={1,2,...,D} be the candidate set of demands.

Step 2 For each demand in the set S, determine the sum of the loads of arcs in its path.

Select the demand k whose sum is the maximum.

Step 3 Reroute the demand k selected in **Step 2** by the following procedure:

Step 3-1 Remove the demand k from the network and compute the load of each arc.

Step 3-2 Determine the maximum arc load in path $\{i_k, i_k+1, ..., n_1\}$ and that in path $\{i_k, i_k-1, ..., 1\}$.

Step 3-3 Select the path which has the smaller maximum arc load as the path of demand k in Ring-1. The ties are broken by replacing the maximum arc load by the second to the maximum, third to the maximum, and so forth.

Sep 3-4 Repeat **Step 3-2** and **Step 3-3** for Ring-2.

Step 3-5 If selected paths are

$\{i_k, i_k+1, ..., n_1\}$ in Ring-1 and $\{n_1+1, n_1+2, ..., j_k\}$ in Ring-2 or

$\{i_k, i_k-1, ..., 1\}$ in Ring-1 and $\{n_1+n_2, n_1+n_2-1, ..., j_k\}$ in Ring-2,

then go to **Step 3-6.**

Otherwise, compute the load of each arc and find the maximum load in each ring. Compute Diff-1/n_1 and Diff-2/n_2. If Diff-1/n_1 > Diff-2/n_2, then arc (n_1, 1) is included to the path. Otherwise, arc (n_1+n_2, n_1+1) is selected.

Step 3-6 Compute the load of each arc.

Step 4 If the objective function value is not decreased, let S=S-{k}. If the set S is empty, stop. Otherwise go to **Step 2.**

Table 3 shows the result of the above improving algorithm applied to the initial solution obtained in Table 2. From the result of the initial solution as shown in Figure 4(a), the five demands are sorted as 5,1,2,3, and 4 which is the non-increasing order of the sum of arc loads. Note that the first two demands, i.e., demands 5 and 1 failed to decrease the objective function value, when they are rerouted. Figure 4(b) shows that the objective function value is decreased

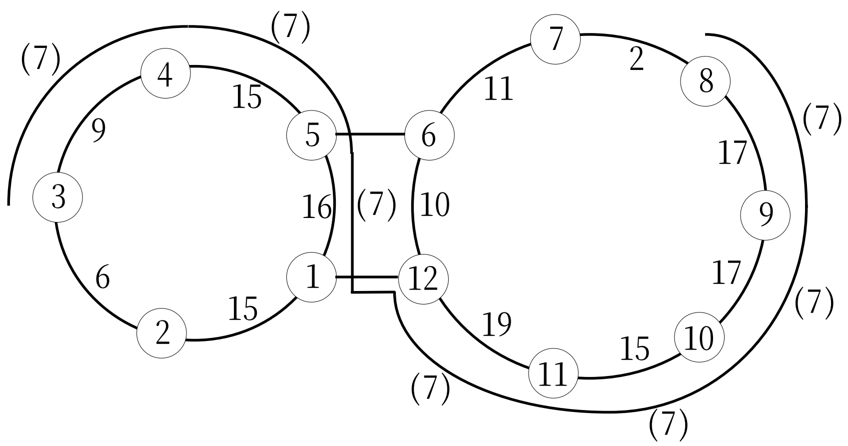

Figure 4(a): Initial Solution and Route of Demand 2

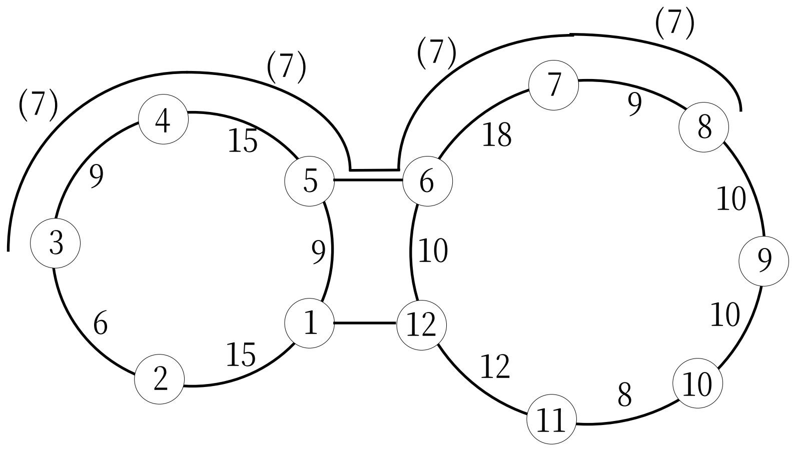

Figure 4(b): Rerouting Demand 2

Table 3: Improved Solution

k	(i_k,j_k)	d_k	x_k	w_k	y_k
1	(2,7)	9	0	0	1
2	(3,8)	7	1	0	1
3	(3,11)	4	0	1	0
4	(4,9)	8	1	0	0
5	(4,10)	2	0	1	0

by rerouting demand 2. Thus, the procedure starts again by sorting all five demands as 5,3,2,4, and 1. Now, the objective function is decreased by rerouting the demand 5. The same procedure is repeated with the sorted demand order 3,2,4,5, and 1. Since no improvement is experienced, the algorithm terminates and the result is shown in Table 3. The maximum arc load in Ring-1 is 15 at arc (1,2) and that in Ring-2 is 16 at arc (6,7).

4. Computational Results

Computational experiments are performed with various size of networks. In each case of the problem demands are generated such that the amount of each demand is uniformly distributed integer over (1,19), which is arbitrarily set solely for comparison purpose. The optimal solutions are obtained using the CPLEX[9]. All experiments are performed at 486-DX33 IBM PC. The average of five instances for each scenario is presented in Table 4. The number represents the relative amount of the solution found by the algorithm, compared with the optimum solution or the lower bound. Of the 95 instances examined, the proposed algorithm generated optimum solutions in 27 cases. Except the instances (5,5,10), all solutions are within 1% of the optimum.

The results shows that the initial solution procedure is excellent enough to make the improvement procedure unnecessary. Improvements are performed only in 12 instances out of 95 experiments.

5. Conclusion

An efficient heuristic algorithm is presented to solve the load balancing problem on SONET dual-rings. A network which consists of two rings connected via two access nodes is considered by assuming symmetric inter-ring demands. The initial solution is obtained by first deciding the routing directions x_k and y_k of each demand k such that a particular link is not overloaded with the assignments. Then it determines the access link w_k. The algorithm iteratively improves the initial solution by re-routing the demand that passes through the arc with the maximum load. The performance of the algorithm is experimented with various size of randomly generated problems. Computational results show that the initial solution is as excellent as the improved solution, while the latter is even closer to optimal solution. The average error bound of the solution is 0.26% of the optimum.

Table 4: Computational Results of the Dual-Ring Load Balancing Problem

Problem size (n_1,n_2,D)	Initial Solution	CPU Seconds	Improved Solution	CPU Seconds
(5,5,9)	102.90	0.00	103.34	0.03
(5,10,20)	100.62	0.02	100.62	0.02
(5,15,30)	100.61	0.05	100.61	0.05
(5,20,40)	100.19	0.16	100.19	0.27
(10,10,30)	101.04	0.09	100.90	0.13
(10,15,40)	100.17	0.16	100.09	0.29
(10,20,50)	100.29	0.23	100.26	0.48
(10,25,60)	100.07	0.48	100.03	0.95
(15,15,50)	100.20	0.33	100.12	0.57
(15,20,60)	100.16	0.53	100.16	0.90
(15,25,70)	100.08	0.71	100.06	1.46

(15,30,80)	100.19	1.04	100.17	1.96
(20,20,70)	100.14	0.75	100.14	1.36
(20,25,80)	100.12	1.05	100.10	1.98
(20,30,90)	100.06	1.45	100.06	2.69
(20,35,100)	100.18	1.79	100.18	3.41
(25,25,90)	100.09	1.32	100.09	2.52
(25,30,100)	100.06	1.82	100.06	3.52
(30,30,110)	100.77	2.34	100.77	4.87

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