A Broadband Convergence Access Network Design Problem

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Abstract

In this paper, we deal with an access network design problem arising from the deployment of broadband convergence network (BcN). The problem can be conceptualized as a three-level hierarchical location-allocation problem with quality of service (QoS) constraints. The nonlinear mixed integer model of the problem seeks to minimize the total cost while guaranteeing QoS constraints. We explore a disjunctive cut generation algorithm for finding the optimal solution of the problem. And we also develop a tabu search algorithm that finds a good feasible solution within reasonable time bound. Promising computational results are presented.

Key words: *BcN, access network design, three-level hierarchical location-allocation, mixed integer programming, disjunctive cut generation*

1. Introduction

We consider a three-level hierarchical location-allocation problem arising from the deployment of broadband convergence network (BcN). BcN, the next generation network (NGN) in Korea, is a QoS guaranteed multimedia network that provides communication, Internet, and broadcasting. This paper addresses a physical access network design problem for deploying BcN. The network architecture of BcN is the Ethernet-over-fiber technology for its functionality, scalability and widespread understanding. We call this Ethernet-over-fiber based access network as a broadband convergence access network (BCAN).

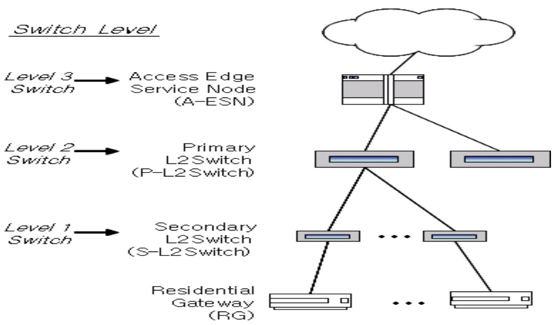

Figure 1: Proposed BCAN Architecture

To focus on the optimization aspect of deploying a BCAN architecture in real telecommunication networks, let us briefly describe the relevant background. As depicted in Figure 1, the BCAN consists of residential gateways (RGs) and hierarchical switches that provide connectivity from central office (CO) to subscribers. Traffics generated by various home appliances are carried to L2 domain Ethernet switches (S-L2 and P-L2) through a RG. The access-edge service node (A-ESN) intermediates traffics between BCAN and the IP transport network. For the design of BCAN, we determine the location of switches and the allocation of demands on an underlying tree structured network while providing QoS. Hence, this problem can be conceptualized as a three-level hierarchical location-allocation problem. Recently, there are several studies about network design (facility location and customer allocation to facilities) of hierarchical systems. Sahin and Sural [6] studied a hierarchical facility location models using mixed integer programming models, and Boffey *et al.* [1] also studied hierarchical location-allocation problem as a nonlinear model. However, these studies did not consider QoS constraints in their model.

To consider the QoS provisioning mechanism of BCAN, we review recent several studies for multi-service IP network dimensioning problem with QoS provisioning mechanism. Based on the IntServ, which is IETF's QoS provisioning framework, Riedl *et al.* [5] classified the traffics generated by various applications into two types: elastic and stream. Zhao *et* *al.* [8] proposed a network dimensioning method of the residential multi-service IP-based access networks over Ethernet, which is known as a broadband residential Ethernet-based access network. They proposed to implement DiffServ framework, which is also IETF's QoS provisioning scheme. Marianov and Serra [3] studied hierarchical location-allocation models with probabilistic congested environment. They formulated a mixed integer programming model by using linearized QoS constraints and proposed a heuristic algorithm. Kim [2] proposed the solution procedure of the BCAN design problem using mixed integer programming with nonlinear QoS constraints. He also developed the relaxation method for a lower bound of the BCAN design problem. Yun [7] presented a tabu search algorithm for solving the BCAN design problem. These research efforts addressed a framework for hierarchical location-allocation model with probabilistic QoS constraints. However, these studies assume that traffic from the RG can be split. Moreover, these studies only provide heuristic algorithms for small-size problems. On the other hand, this paper deals with an exact optimization algorithm and a new heuristic algorithm for large-scale problems, where demand is not allowed to be split.

The remainder of this paper is organized as follows. In Section 2, we present a nonlinear mixed integer formulation for designing BCAN. In Section 3, we describe a linear mixed integer programming relaxation to get a lower bound of the problem and develop some valid inequalities. In Section 4, we explore a solution procedure using a cut generation scheme. In Section 5, we propose a heuristic procedure for finding a good feasible solution within reasonable time bound. Computational results and conclusion are presented in Section 6.

2. Problem Formulation

In this section, we develop a nonlinear mixed integer model for the BCAN problem. Suppose that we have an access network of a tree topology rooted at a central office (CO) and several demand nodes. Also, we have intermediate nodes in the path from demand nodes to CO. S-L2 switches and P-L2 switches can be placed at every node and an A-ESN is placed at CO.

For a given tree graph, G (N, E), with node set N and edge set E, let M ($\subseteq$N) be the set of demand nodes in G (N, E). cs_{ij} denotes the cable cost arising when connecting a RG at node $i \in$ M with a S-L2 switch at node $j \in$ M, and cp_{jk} the cable cost for connecting a S-L2 switch at node j with a P-L2 switch at node k. ca_k is the cable cost for connecting a P-L2 switch at node k with an A-ESN switch at the access node. Let fs_j, fp_k, and fa be the fixed costs to install a S-L2 switch at node j, a P-L2 switch at node k, and an A-ESN switch at the access node, respectively. Let us denote CS, CP, and CA as the capacities of an S-L2 switch, a P-L2 switch, and an A-ESN switch, respectively. Each level switch has a number of ports. We denote α, β, and γ as the numbers of ports of a S-L2 switch, a P-L2 switch, and an A-ESN switch. Let us ns_j, np_k, and na be the limit of the number of S-L2 switches, P-L2 switches, and A-ESN switches that can be placed at node j, k, and the access node, respectively. Finally, we denote d_i as the number of subscribers at node $i \in$ M.

We define decision variables x_{ijk}, where $x_{ijk} = 1$ if the number of subscribers of node $i \in$ M that is served by S-L2 switch at node $j \in$ N is connected to P-L2 switch at node $k \in$ N and 0 otherwise. And let $y_{jk} = 1$ if the S-L2 switches at node j is connected to the P-L2 switches at node k and 0 otherwise. We also define zs_{jk}, where zs_{jk} represents the number of S-L2 switches of node $j \in$ N connected to P-L2 switches at node $k \in$ N. Let us define zp_k, where zp_{klq} represents the number of P-L2 switches of node $k \in$ N. And let za be the number of A-ESN switches at the access node. We assume that we have end-to-end QoS functions F_s for stream services and G_s for elastic services for a given network topology and service traffic. Given QoS upper bounds ε_s for $s \in S_{stream}$ and δ_s for $s \in S_{elastic}$, the end-to-end QoS requirement for each service class is expressed as follows.

$$F_s(x_{ijk}, y_{jk}, zs_{jk}, zp_k, za) \le \varepsilon_s, \qquad \forall s \in S_{stream}$$

and

$$G_s(x_{ijk}, y_{jk}, zs_{jk}, zp_k, za) \le \delta_s, \qquad \forall s \in S_{elastic}.$$

Then we formulate the BCAN design problem, denoted by BCNP, as follows.

BCNP:

Minimize $$\sum_{i\in M}\sum_{j\in p_i}\sum_{k\in p_j} d_i cs_{ij} x_{ijk} + \sum_{j\in N}\sum_{k\in p_j}\left(fs_j + cp_{jk}\right) zs_{jk} + \sum_{k\in N}\left(fp_k + ca_k\right) zp_k + fa\cdot za$$

Subject to $$\sum_{j\in p_i}\sum_{k\in p_j} x_{ijk} = 1, \qquad \forall i \in M, \tag{1}$$

$$\sum_{i\in p_j \cap p_k} d_i x_{ijk} \le \alpha \cdot zs_{jk}, \qquad \forall k \in p_j,\ j \in N, \tag{2}$$

$$\sum_{j\in p_k} zs_{jk} \le \beta \cdot zp_k, \qquad \forall k \in N, \tag{3}$$

$$\sum_{k\in N} zp_k \le \gamma \cdot za, \tag{4}$$

$$\sum_{k\in N} y_{jk} \le 1, \qquad \forall j \in N, \tag{5}$$

$$zs_{jk} \le ns_j \cdot y_{jk}, \qquad \forall k \in p_j,\ j \in N, \tag{6}$$

$$G_s\left(x_{ijp}, zs_{jkpq}, zp_{kql}, za_l\right) \le \delta_s, \qquad \forall s \in S_{elastic}, \tag{7}$$

$$F_s\left(x_{ijp}, zs_{jkpq}, zp_{kql}, za_l\right) \le \varepsilon_s, \qquad \forall s \in S_{stream}, \tag{8}$$

$$x_{ijk} \in \{0,1\}, \qquad \forall i \in M,\ \forall j \in p_i,\ \forall k \in p_j,$$

$$y_{jk} \in \{0,1\}, \qquad \forall k \in p_j,\ j \in N,$$

$$zs_{jk},\ zp_k,\ za \ge 0, \text{ and integer}, \qquad \forall j \in N,\ k \in N.$$

The objective function of BCNP is to minimize the total cost which is the sum of the switch costs and cable costs. Constraint (1) enforces that the demand node should be served by S-L2 switches and P-L2 switches. Constraints (2), (3), and (4) represent the port limit constraints of each level switch. Constraint (5) ensures that a S-L2 switch to be installed on a link should be the only one P-L2 switch to be installed on the same link. And Constraint (6) restricts the number of S-L2 switches allocated to a node to be less than or equal to the maximum number of S-L2 switches.

Now, we consider QoS constraints (7) and (8). Constraint (7) is defined as a function that calculates the end-to-end delay factor for elastic services, whereas constraint (8) is defined as a function that calculates the end-to-end blocking probability for stream services on the S-L2 switch at node $j \in$ N, on the P-L2 switch at node $k \in$ N, and the A-ESN switch at the access node. We define that a delay factor can be modeled from formulas (9) to (15) by the theory of the process sharing with the Erlang C formula (E_C). Let $SL2TI_{js}$, $PL2TI_{ks}$, and $AESNTI_s$ be the traffic intensity of each service class. We define the delay factor of elastic services using formulas (9) to (11) and the number of channels in formulas (12) to (14). Consequently, constraint (15) restricts the end-to-end delay factor to be less than or equal to the maximum requirement of QoS limit among each level switches [2].

$$SL2TI_{js} = \sum_{i\in p_j}\sum_{k\in p_j} d_i x_{ijk} \cdot A_s, \qquad \forall\ j \in N,\ \forall s \in S_{elastic}, \tag{9}$$

$$PL2TI_{ks} = \sum_{i\in p_k}\sum_{j\in p_k} d_i x_{ijk} \cdot A_s, \qquad \forall k \in N,\ \forall s \in S_{elastic}, \tag{10}$$

$$AESNTI_s = \sum_{i\in M}\sum_{j\in p_i}\sum_{k\in p_j} d_i x_{ijk} \cdot A_s, \qquad \forall s \in S_{elastic}, \tag{11}$$

$$DS_{jps} = 1 + \frac{E_C(SL2TI_{js}, \sum_{k\in p_j} CS \cdot us_s \cdot zs_{jkpq} / r_s)}{\sum_{k\in p_j} CS \cdot us_s \cdot zs_{jk} / r_s - SL2TI_{js}}, \qquad \forall\ j \in N,\ \forall s \in S_{elastic}, \tag{12}$$

$$DP_{ks} = 1 + \frac{E_C\left(PL2TI_{ks}, CP \cdot up_s \cdot zp_k / r_s\right)}{CP \cdot up_s \cdot zp_k / r_s - PL2TI_{ks}}, \qquad \forall k \in N,\ \forall s \in S_{elastic}, \tag{13}$$

$$DA_s = 1 + \frac{E_C\left(AESNTI_s, CA \cdot ua_s \cdot za / r_s\right)}{CA \cdot ua_s \cdot za / r_s - AESNTI_s}, \qquad \forall s \in S_{elastic}, \tag{14}$$

$$\max(DS_{js},\ DP_{ks},\ DA_s) \le \delta_s, \qquad \forall j \in N,\ k \in p_j,\ \forall s \in S_{elastic}. \tag{15}$$

Constraints (16) to (22) represent blocking probabilities for each level switch by applying the Erlang B formula (E_B). Formulas (16) to (18) represent the traffic intensities by each level switch. We define the blocking probabilities of stream services using the formulas (16) to (18) and the number of channels in formulas (19) to (21). Especially, constraint (22) enforces the end-to-end blocking probability to be less than or equal to the requirement of QoS limit.

$$SL2TI_{js} = \sum_{i\in p_j}\sum_{k\in p_j} d_i x_{ijk} \cdot A_s, \qquad \forall\ j \in N,\ \forall s \in S_{stream}, \tag{16}$$

$$PL2TI_{ks} = \sum_{i \in p_k} \sum_{j \in p_k} d_i x_{ijk} \cdot \left(1 - BS_{js}\right) A_s, \qquad \forall k \in N,\ \forall s \in S_{stream}, \qquad (17)$$

$$AESNTI_s = \sum_{i \in M} \sum_{j \in p_i} \sum_{k \in p_j} d_i x_{ijk} \cdot \left(1 - BP_{kqs}\right) A_s, \qquad \forall s \in S_{stream}, \qquad (18)$$

$$BS_{js} = E_B(SL2TI_{js}, \sum_{k \in p_j} CS \cdot us_s \cdot zs_{jk} / r_s), \qquad \forall j \in N,\ \forall s \in S_{stream}, \qquad (19)$$

$$BP_{ks} = E_B\left(PL2TI_{ks}, CP \cdot up_s \cdot zp_k / r_s\right), \qquad \forall k \in N,\ \forall s \in S_{stream}, \qquad (20)$$

$$BA_s = E_B\left(AESNTI_s, CA \cdot ua_s \cdot za / r_s\right), \qquad \forall s \in S_{stream}, \qquad (21)$$

$$1 - \left(1 - BS_{js}\right)\left(1 - BP_{ks}\right)\left(1 - BA_s\right) \le \varepsilon_s, \qquad \forall j \in N, ,\ k \in N,\ \ \forall s \in S_{stream}. \qquad (22)$$

Remark 1. The problem BCNP is NP-complete (see Kim [2])

3. Relaxation and Valid Inequalities

In this section, we propose the relaxation problems by linearizing the QoS constraints. Observe that the end-to-end QoS constraints presented in section 2 are the nonlinear inequality formulas. We develop the relaxation problems by dropping nonlinear relationship of the QoS measures among switches as described in Kim [2]. We express the QoS region and its relaxed region as shown in Figure 2, and replace the nonlinear formula (22) into one as follows:

$$BS_{js} \le \varepsilon_s,\ BP_{ks} \le \varepsilon_s,\ BA_s \le \varepsilon_s, \qquad \forall j \in N, ,\ k \in N,\ \ \forall s \in S_{stream}.$$

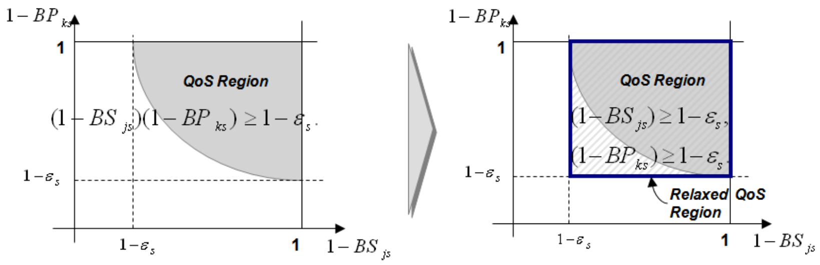

Figure 2. An illustration of QoS area and its relaxation

QoS requirement can be expressed as a bandwidth requirement since the minimum bandwidth required for guaranteeing QoS monotonically increasing according to the increase of traffic intensity. In this problem, we assume the switch stacking technology that provides the network expansion. In other words, if two or more switches are installed at certain node, the number of subscribers connected to switches at that node is increased exponentially. Hence, we transform these nonlinear inequalities into linear inequalities. Toward this, we define binary variables zzs_{jkp}, where $zzs_{jkp} = 1$ if the p number of S-L2 switches are installed at node $j \in$ N is connected to P-L2 switch at node $k \in$ N and 0 otherwise. And we define binary variables zzp_{kq}, where $zzp_{kq} = 1$ if the q number of P-L2 switches are installed at node $k \in$ N and 0 otherwise. Let $zza_l = 1$ if the l number of A-ESN switches are installed at *CO* and 0 otherwise. Let us define ns_j, np_k, and na as the maximum number of S-L2, P-L2, and A-ESN switches that can be installed at node $j \in$ N, node $k \in$ N, and an access node, respectively. Then, inequalities (15) and (22) are expressed as follows:

$$\sum_{p=0}^{ns_j} zzs_{jkp} \le 1, \qquad zs_{jk} = \sum_{p=0}^{ns_j} p \cdot zzs_{jkp}, \qquad \forall j \in N,\ \forall k \in N, \qquad (23)$$

$$\sum_{q=0}^{np_k} zzp_{kq} \le 1, \qquad zp_k = \sum_{q=0}^{np_k} q \cdot zzp_{kq}, \qquad \forall k \in N, \qquad (24)$$

$$\sum_{l=0}^{na} zza_l \le 1, \qquad za = \sum_{l=0}^{na} l \cdot zza_l. \qquad (25)$$

Now, we develop some classes of valid inequalities in order to tighten the formulation BCNP. We develop the valid inequalities calculating the minimum number of each level switch for using the switch port number and maximum subscribers connected to S-L2 switch. Let us define *MS*, where *MS* represents the maximum subscribers connected to S-L2 switch.

$$\sum_{j \in N} \sum_{k \in p_j} zs_{jk} \geq \left\lceil \frac{\sum_{i \in p_j} d_i}{\max(\alpha, MS)} \right\rceil, \tag{26}$$

$$\sum_{k \in N} zp_k \geq \left\lceil \frac{\sum_{i \in p_j} d_i}{\max(\alpha, MS)} \right\rceil / \beta, \tag{27}$$

$$za \geq \left\lceil \frac{\sum_{i \in p_j} d_i}{\max(\alpha, MS)} \right\rceil / \beta / \gamma, \tag{28}$$

4. Exact Optimization Algorithm

In this section, we propose a solution procedure of the BCNP using cut generation scheme. We obtain a lower bound from relaxation described in previous section. Note that if the relaxed solution satisfies the original QoS constraints, then the solution is optimal. Otherwise, we explore a disjunctive cut generation algorithm to get an optimal solution. Observe that blocking probabilities and delay factors of the end-to-end QoS constraints are monotonically increased according to the increase of the connected number of subscribers on each level of switch. The current solution should be infeasible when the connected number of subscribers to each level of switches are greater than or equal to the maximum number of subscribers on each level of switch. Hence we generate disjunctive cuts using the connected number of subscribers on each switch of infeasible route. We define *SL2_INF_NS*, *PL2_INF_NS* and *AESN_INF_NS* are the number of the connected subscribers to S-L2 switch, P-L2 switch, and A-ESN switch at infeasible route. We define that D is the total number of subscribers in the access network. Let *P* be the set of (*j*, *k*, *p*), which is the set of *j*, *k* path installed *p* number of S-L2 switches unsatisfied end-to-end QoS. And let *Q* be the set of (*j*, *k*, *q*), which is the set of *j*, *k* path installed *q* number of P-L2 switches unsatisfied end-to-end QoS. Also let *R* be the set of (*j*, *k*, *l*), which is the set of *j*, *k* path installed *l* number of A-ESN switches unsatisfied end-to-end QoS. Generated disjunction cuts are given as follows.

$$\sum_{i \in p_j} d_i x_{ijk} \leq (SL2\_INF\_NS - 1) \cdot zzs_{jkp} + D(1 - zzs_{jkp}) \qquad \forall (j,k,p) \in P, \tag{29}$$

or

$$\sum_{i \in p_j} d_i x_{ijk} \leq (PL2\_INF\_NS - 1) \cdot zzp_{kq} + D(1 - zzp_{kq}), \qquad \forall (j,k,q) \in Q, \tag{30}$$

or

$$\sum_{i \in p_j} d_i x_{ijk} \leq (AESN\_INF\_NS - 1) \cdot za_l + D(1 - za_l), \qquad \forall (j,k,l) \in R. \tag{31}$$

5. Heuristic Algorithm

In this section, we describe an effective tabu heuristic procedure for generating a feasible solution for problem BCNP. In essence, this procedure searches optimal switch allocation nodes at each iteration.

Initialization. Allocate the S-L2 switches at three or more degree node that is closest to the demand node.

Step 1. Short term memory phase: define tabu list, two kinds of move, and evaluation function.

1.1. Tabu list: Switch location and number of switch. We define tabu tenure as a N/2.

1.2. Move: Switch-down & -up and edge transfer.

1.3. Evaluation function: Evaluate the neighborhood calculating the total cost

Step 2. Long term memory phase: intensification and diversification

2.1. Intensification: Re-allocate the demand node to S-L2 switch among cost effective and QoS unsatisfied solutions.

2.2. Diversification: Random initial solution start

6. Computational Results and Conclusion

We test our proposed solution approach for randomly generated test problems. We use the service classification and the parameters concerning the traffic characteristics. There are three stream service classes; *speech*, *high interactive*, *multimedia*, and two elastic service classes; *messaging*, *switched data*. In particular, we generate the problems by varying the number of ports of each level switch to see the effects of the ports on the performances of the proposed solution procedure. Algorithms are coded in C and all runs were made on a Pentium IV 2.6GHz PC with CPLEX version 11.0 as the MIP solver. All computational times were measured in seconds, and one-hour (3,600 seconds) time limit was applied on the computation time. We report the computational results of 12 test problem instances in Table 1, 2. *Z_EA* denotes the objective function value of the optimal solution obtained by solving the problem BCNP. *Z_TS* denotes the objective function value of the tabu heuristic procedure. Gap means the gap between the exact solution and the heuristic solution, measured by (*Z_TS -Z_EA*) / *Z_EA* * 100%.

Table 1: Computational results ($\alpha = 16, \beta = 4, \gamma = 2$)

Problem	# of Node	Z_EA	Z_TS	Gap	T_EA	T_TS
N50_R1	50	9421.6	9615.0	2.1%	75.5	1.0
N50_R2	50	10057.8	10064.2	0.1%	16.0	0.7
N50_R3	50	8828.2	8843.3	0.2%	18.1	0.8
N50_R4	50	9010.5	9034.8	0.3%	432.0	1.0
N60_R1	60	13084.5	13341.4	2.0%	11.9	1.1
N60_R2	60	13174.1	13244.6	0.5%	4.2	1.2
N60_R3	60	8666.9	8786.8	1.4%	3600+	1.4
N60_R4	60	13837.7	14251.5	3.0%	388.2	2.3
N70_R1	70	15565.2	15565.2	0.0%	11.2	1.7
N70_R2	70	15272.4	15587.6	2.1%	0.3	1.8
N70_R3	70	9526.8	9526.8	0.0%	2.7	1.2
N70_R4	70	7181.3	7209.1	0.4%	337.4	2.7

Table 2: Computational results ($\alpha = 24, \beta = 8, \gamma = 4$)

Problem	# of Node	Z_EA	Z_TS	Gap	T_EA	T_TS
N50_R1	50	6233.8	6856.5	10.0%	140.3	1.7
N50_R2	50	6792.1	6926.7	2.0%	1.9	1.8
N50_R3	50	5285.0	5364.1	1.5%	1.6	2.0
N50_R4	50	5703.2	5960.6	4.5%	3600+	1.5
N60_R1	60	8547.1	8745.8	2.3%	483.3	1.3
N60_R2	60	9039.4	9274.4	2.6%	28.6	1.5
N60_R3	60	5320.6	5761.2	8.3%	673.8	2.1
N60_R4	60	8843.5	8916.4	0.8%	2975.2	3.8
N70_R1	70	11048.1	11296.6	2.2%	183.1	2.0
N70_R2	70	10163.1	10245.3	0.8%	5.0	1.2
N70_R3	70	6115.5	6115.5	0.0%	21.6	2.9
N70_R4	70	5047.6	5176.1	2.5%	44.7	1.2

From Table 1 and 2, our proposed solution procedure finds optimal solutions within reasonable time bound. However, as the number of each level switch ports increases, the time of finding the optimal solutions (*T_EA*) is increased and the gap between *Z_EA* and *Z_TA* is increased. By way of on-going research, we are investigating a dynamic cut (column) generation procedure. Also, we are examining the polyhedral structure and preprocessing rules of model BCNP that can be exploited for tightening the lower bound for problem BCNP.

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