FIBER OPTICAL NETWORK DESIGN PROBLEMS: CASE FOR TURKEY

A THESIS
SUBMITTED TO THE DEPARTMENT OF INDUSTRIAL ENGINEERING
AND THE GRADUATE SCHOOL OF ENGINEERING AND SCIENCE
OF BILKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

by
Başak Yazar
July, 2013

I certify that I have read this thesis and that in my opinion it is full adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

Assoc. Prof. Bahar Y. Kara (Advisor)

I certify that I have read this thesis and that in my opinion it is full adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

Assoc. Prof. Oya Ekin Karaşan (Co – Advisor)

I certify that I have read this thesis and that in my opinion it is full adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

Assoc. Prof. Hande Yaman

I certify that I have read this thesis and that in my opinion it is full adequate, in scope and in quality, as a dissertation for the degree of Master of Science.

Asst. Prof. Ayşegül Altın Kayhan

Approved for the Graduate School of Engineering and Science

Prof. Dr. Levent Onural
Director of the Graduate School of Engineering and Science

ABSTRACT

FIBER OPTICAL NETWORK DESIGN PROBLEMS: CASE FOR TURKEY

Başak Yazar
M.S. in Industrial Engineering
Supervisor: Assoc. Prof. Bahar Y. Kara
Co-Supervisor: Assoc. Prof. Oya Ekin Karaşan
July 2013

The problems within scope of this thesis are based on an application arising from one of the largest Internet service providers operating in Turkey. There are mainly two different problems: the green field design and copper field re-design. In the green field design problem, the aim is to design a least cost fiber optical network from scratch that will provide high bandwidth Internet access from a given central station to a set of aggregated demand nodes. Such an access can be provided either directly by installing fibers or indirectly by utilizing passive splitters. Insertion loss, bandwidth level and distance limitations should simultaneously be considered in order to provide a least cost design to enable the required service level. On the other hand, in the re-design of the copper field application, the aim is to improve the current service level by augmenting the network through fiber optical wires. Copper rings in the existing infrastructure are augmented with cabinets and direct fiber links from cabinets to demand nodes provide the required coverage to distant nodes. Mathematical models are constructed for both problem specifications. Extensive computational results based on real data from Kartal (45 points) and Bakırköy (74 points) districts in Istanbul show that the proposed models are viable exact solution methodologies for moderate dimensions.

Keywords: Fiber optic, telecommunication network, hub-location, hierarchical design

ÖZET

FİBER OPTİK AĞ TASARIMI PROBLEMİ: TÜRKİYE UYGULAMASI

Başak Yazar
Endüstri Mühendisliği Yüksek Lisans
Tez Yöneticisi: Doç Dr. Bahar Y. Kara
Tez Eş - Yöneticisi: Doç. Dr. Oya Ekin Karaşan
Temmuz 2013

Gelişen teknoloji, fiber optik kablolar ile internet erişimini arttırmaktadır. Bu şekilde daha hızlı, güvenli ve geniş bantlı olarak sağlanmaktadır. Bu tezin konusu, Türkiye'nin en büyük servis sağlayıcısının gerçek bir probleminden ortaya çıkmıştır. Problem, şirketin ilk kez altyapı sağlayacağı bölge ve halihazırda metalik kablolar ile internet hizmeti verdiği bölge olarak iki bağımsız alt problemden oluşmaktadır. Problemler sırasıyla yeşil bölge ağ tasarımı problemi ve bakır bölge ağının yeniden tasarımı problemi olarak adlandırılmaktadır. Yeşil bölge ağ tasarımı probleminde, tek bir merkezi santraldan çıkan fiber optik ağların bütünleşik talep noktalarına, en az maliyetle servis vermesi amaçlanmaktadır. Bu servis, doğrudan merkezi santralden veya pasif bölücü ile dolaylı olarak sağlanabilmektedir. İletim hattı boyunca eklenen kayıp, bant genişliği ve mesafe kısıtları bütünsel olarak düşünülmüştür. Diğer problemde ise, fiber optik kabloların ağdaki varlığı arttırılarak servis seviyesinin iyileştirilmesi amaçlanmaktadır. Bakır döngülere telekomünikasyon dolaplarının yerleştirilmesi, dolap - talep noktası fiber linklerinin kurularak dolaba uzak olan talep noktalarına fiber internet hizmeti verilmesi çalışılmıştır. Her iki alt problem için matematiksel modeller oluşturulmuş ve İstanbul ili Kartal ilçesi (45 nokta) ile Bakırköy ilçesinde (74 nokta) denenmiştir. Makul boyutlardaki problemlerler tam olarak çözülmüştür.

Anahtar Kelimeler: Fiber optik, telekomünikasyon ağı, ana dağıtım üssü, hiyerarşik tasarım

ACKNOWLEDGEMENT

I would like to express my gratitude to Assoc. Prof. Bahar Yetiş Kara and Assoc. Prof. Oya Ekin Karaşan for their supervision and encouragement throughout this study. Their deepest patience to my endless questions improved our work. It is a great pleasure to work with them, listen to them and learn from. I am grateful to Assoc. Prof. Hande Yaman and Asst. Prof. Ayşegül Altın Kayhan for their attention in reading the material and their encouraging comments on my thesis.

Also, I would like to express my sincere appreciation to my mother Zeliha Yazar, my deepest gratitude to my father Tarık Yazar and all my best wishes to my lovely sister Elif Yazar for their infinite love, guidance, encouragement, and moral support. I am always proud to be a member of this perfect family.

My special thanks to Orkun Tunçel for his kind moral support, sincere friendship and all inspirations that he gave me throughout this study. I am also happy to point out my appreciation to Lale Tüzün, İrfan Mahmutoğulları and Fırat Kılcı for their time, help and contribution. Their kind interest improve this work.

For all enjoyable time and long conversations, I would like to thank to my precious classmates Gizem Özbaygın, Bengisu Sert, Halenur Şahin, Nur Timurlenk, Meltem Peker, and Haşim Özlü. Last but not least, I need to express my gratefulness to my friends Feyza Şahinyazan, Kumru Ada, Bilgesu Çetinkaya, Ece Demirci, Hatice Çalık and Görkem Özdemir. Without the love and support of all the above mentioned people, the completion of this degree would not be such brilliant. Thank you.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Communication is a technological development and a human need for expanding knowledge. Communication may include primitive but permanent information sharing tools such as face-to-face speaking, writing a letter, phone calling, conference calls, e-mails, SMS, MMS etc, or may be tools relatively new but will be permanent in very near future, such as video calls or using Internet in high speed technologies. For this accessibility, people need high speed Internet connections in order to be online everywhere via safe, secure and fast connections. To this end, technology development is a huge market in terms of telecommunication equipment manufacturers, service providers, telecommunication network builders, related third parties etc. All shareholders wish to be present in this market by not only providing these services in high quality, but also doing it in a cost effective way. The scope of this thesis is data communication via telecommunication networks.

The latest data communication tool is the high bandwidth Internet access via fiber optical wires and we motivate our problem definition from a real world application installed by Turkish largest service provider. We introduce two different problem definitions into the literature which are the design of fiber optical network for two different fields: green field and copper field.

First field, namely green field, is the area that the corresponding company has not had any data infrastructure so far. The fiber optical network design problem in the green field aims to reach every customer point starting from a central station. This central station is assumed to have a direct link to upper level networks and reach world-wide Internet access. Along reaching the customer points green field network design problem uses different number and type of passive splitter which is a telecommunication equipment to split incoming fiber optical wire. Due to the application dynamics of the problem, the service quality is measured in terms of bandwidth and insertion loss.

Second field is constituted to address improvement in the area that the company has already served via copper cables. Both fully fiber optical wire usage and hybrid usage of fiber – copper wire improve speed of Internet at demand point. Getting closer to the customer point via fiber optical wires provides better outcome by using both fiber and copper wires. For the rest of demand nodes that cannot be served via hybrid usage and for specialized customers that are preliminarily willing to use fully fiber optical wires, the copper field re-design problem provides a cost-effective network.

Application dynamics are derived for both problems embedded in the proposed mathematical models. Although telecommunication network design is a hot topic in operations research, the realistic problem requirements differentiate problems and our models from the ones proposed in the literature.

The rest of this thesis is planned as follows; in the next chapter, the general network design approach in telecommunication is discussed. Also, details of green field and copper field re-design problems are examined with specific requirements of the problem nature.

In Chapter 3, the literature on telecommunication network design problems, namely i) local access network design, ii) backbone network design, and iii) multi-level network design problems and contributions to this study are discussed.

In Chapter 4, the mathematical models for both problems are developed. The mixed integer mathematical model in the green field that selects the location and type of passive splitters decides the fiber link between demand nodes by considering insertion loss and bandwidth requirements. On the other hand, the mixed integer mathematical model for copper field re-design problem aims to find location of telecommunication equipments that bring fiber optical network closer to customer points, assignment and fiber links for the rest of the customers.

The following two Chapters 5 and 6 include the computational study for green field and copper field re-design problems. The Kartal district with 45 nodes and Bakırköy district with 74 nodes are used for computational analyses and performances of experimental results are discussed.

In Chapter 7, the extension model in the green field is posed. In this model, the effect of distance on the network is observed. A preliminary computational analysis is conducted over the network with 45 nodes and some results are discussed. This thesis is concluded in Chapter 8 with final remarks.

Chapter 2

Problem Definition

Modern telecommunication networks are categorized according to their service location or area capacities. Although it varies a lot, the general infrastructure is as follows: The Wide Area Network (WAN) is the biggest one, which usually covers intercontinental distances, countries, cities or large scale geographical areas. It can alternatively be referred as the Global Network. Another type is the Metropolitan Area Network (MAN) and it usually spans over a city. Since this is a regional coverage, it is called the "Macro Cell". The Local Area Network (LAN) connects computers or devices for relatively smaller areas such as houses, schools, buildings, etc. In these local areas, the network level is called the "Micro Cell". Also, there are home area networks, personal area networks, storage area networks, enterprise private networks, and virtual private networks. These are "Pico Cell"s in home/office environments [1]. In this thesis, we will be dealing with a LAN design. Hierarchically and structurally, the equipment and technology used in the network depend on what level the network spans, but in general we can distinguish the upper level and the lower level of the hierarchy. In the rest of the thesis, “backbone network” will refer to the connection to higher level networks and “access/tributary network” to the rest, which will be detailed later.

Although service type, quality, aim and equipment may vary a lot, the working principles of all telecommunication networks are similar. Basic components start with terminals which are the starting or ending points of the network. Then, data is converted from digital to analog or visa versa via telecommunication processors. Finally, signals come to the customer point. The transmission is done via telecommunication channels, which may be copper wires, coaxial cables or fiber cables. The end terminal is generally a point which is closer to the end-customer (user). This terminal may be the user’s computer, home, base of the building, entrance of the living complex, near the street junction, or could be far beyond. High data transmission rate or broadband is desirable and is achieved with the proximity of fiber connection to the user. The upload/download speed of the Internet refers to the bandwidth.

Since the end-point (end-terminal) of the fiber network varies, different structures have specific names. It is generally called, fiber-to-the-X. This “X” changes according to the end point of the fiber wire as shown in Figure 2-1.

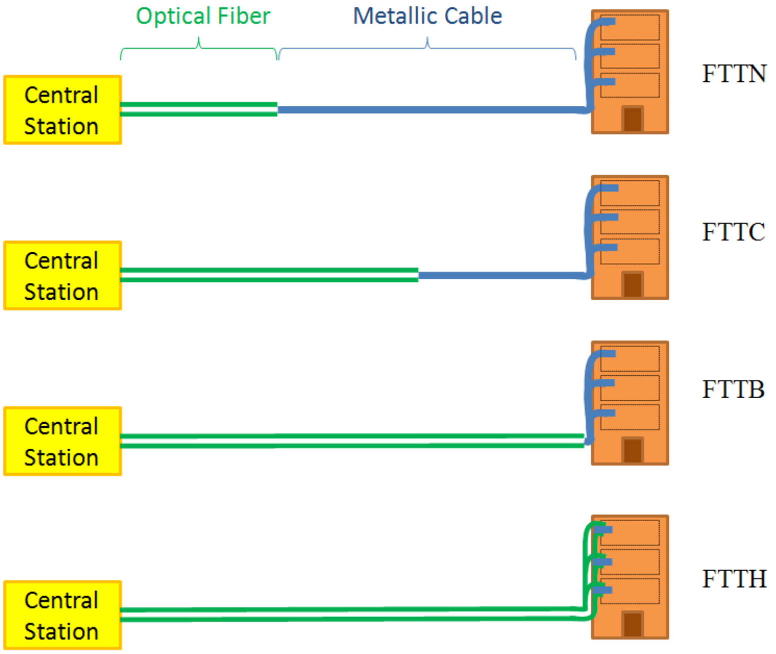

Figure 2-1. Illustration of Fiber-to-the-X

If the fiber ends in the street cabinet, which is another telecommunication equipment including function-specific parts and acting as a central station, it is called fiber-to-the-node or –neighborhood (FTTN). On the other hand, if the cabinet is closer to the user's premises; this is fiber-to-the-cabinet or –curb (FTTC). Although FTTN and FTTC are similar to each other, the distance to the premise node is much smaller in the FTTC. Typically, there is a 300 m-distance between a cabinet and the customer premise in FTTC. This distance is greater in FTTN. Fiber-to-the-building, -business, -basement (FTTB) is used for fiber connection up to the basement of a building. Full fiber Internet access exists in the fiber-to-the-home and fiber-to-the-desktop [2].

In telecommunication networks, the problem could be to design the network from scratch or to improve the existing network in terms of capacity or speed. Our problem is motivated from a real-world application of Turkish largest service provider. Due to the competitive environment in the telecommunication market and privatization of big companies, a highly qualified, efficient and cost effective service in data communication is extremely important. The practice of the market leader is critical for today's market share and will determine near future's market positioning. Although in Turkey competitors are far behind the market leader in terms of data communication infrastructure, the investments show that market competitiveness will be more and more aggressive. Follower companies begin to work for their own infrastructure for small but potentially high return (profit) areas. Therefore, we specify our problem for both designing from scratch and for improvement in the existing network of the service provider. In our service provider application, there are two main categories for design: green field and copper field.

2.1. Green Field Problem Description

Green field refers to an area where the company has no infrastructure at all. In other words, there has been nothing constructed in terms of data wires so far in the region under consideration. This region will be served by the same service provider in terms of voice/phone services but nothing else. Hence, this region is convenient for making a design from scratch. Demands are assumed as known in advance and aggregated into demand points. Our aim is to provide high-speed Internet access in the demand nodes.

In the green field, we consider building only an all fiber optical network due to the regulation of Information and Communication Technologies Authority in Turkey. According to the regulation, when a service provider enters a new region, it should serve all of its customers in the area with a fiber Internet access. This rule is to ensure that the given network will have the possibility to carry future demand and the capability for fiber expansion that may be encountered in the future. The aim is to construct the cost minimizing network so that all demand points receive service with required level.

In fiber optic networks, especially in LANs, specific structures; i.e, splitters, are widely used. Usage of splitters allows carrying data in bulk up to a certain point of the “splitting” according to destination. In particular, passive splitters copy whatever data enters to the outgoing links. Hence, in all layers the same data transects. Also, passive splitters have a capacity of splitting. To this end, the aim of green field problem is to find the location of passive splitters, splitting numbers according to their capacities and interconnection of customers to passive splitters to reach the central station and the Internet at the end. Figure 2-2 is an illustration of a green field problem application.

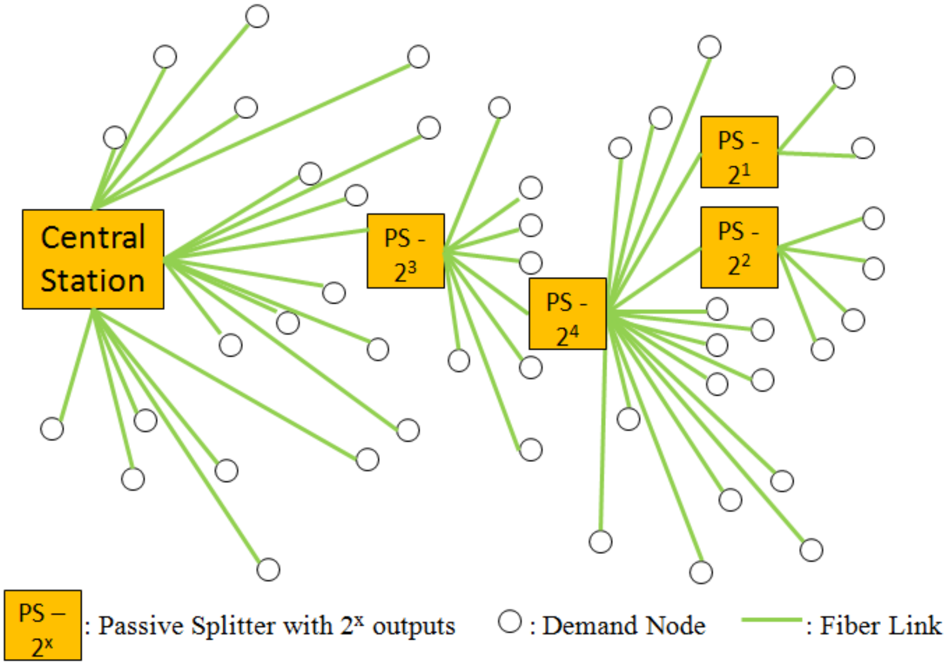

Figure 2-2. Green Field Network Design Problem Illustration

In the particular setting under consideration, there is a central station at a fixed location. This central station serves both for voice communication and the Internet access. Each customer (as an aggregated unit) in the field needs to be connected to this central station with fiber links. The quality of the service is measured in terms of decibels (dB). The company wants to offer services to all its customers guaranteeing a fixed level of dB service quality. Depending on the length of the fiber wire, dB decreases a fixed amount per km while reaching/getting closer to the customer. Direct connections to each customer from the central station will be too costly and thus, certain splitters are used. The company prefers to use passive splitters. The splitters have many types mainly depending on the available number of ports. The utilization of passive splitters also results in extra loss of dB. For example, in a passive splitter with 2^4 = 16 divisions, where the multiple of insertion loss in the port is taken as 3 dB, the total insertion loss in this particular passive splitter is calculated as 3 x 4 = 12 dB.

Another service quality criterion is the speed of the Internet access. The company under consideration wants to serve all customers with at least 100 Mb/sec bandwidth. The service provider determines this target value and specifies its central station’s output capacity as 2.5 Gb/sec. This power splits into fiber wires according to the splitting number of the passive splitter. For example, within a passive splitter with 16 outputs (2^4=16), the power is divided into 16 wires; i.e., 2500/16=625 Mb/sec. As expected, more splitting causes more decrease in the bandwidth value.

Thus, in the network design part of the fiber optic network design problem for this company, the problem is deciding on the location of passive splitters while obeying the dB requirements and bandwidth target values. The passive splitter type selection is another challenging decision to be made involving the tradeoff between the cost of the splitter, the splitting number, the insertion loss and the division in the bandwidth. More splitting increases reachability, but results in high losses. In addition to these insertion losses, we aim to serve all customers in a cost effective way. Hence, the objective is to minimize both fiber optical wiring cost and passive splitter costs.

As a result, the green field problem includes the selection of passive splitter locations, their splitting numbers and fiber links between demand nodes and passive splitters including the central station. While minimizing the total cost function, the insertion loss requirement and bandwidth target value should be considered. Each passive splitter has a different number of outputs that it splits incoming fiber wire. The insertion loss depends on the passive splitter splitting number and the distance traveled beginning from the central station.

2.2. Copper Field Re-design Problem Description

The second problem type is about improving the existing telecommunication service in a region where we call “copper field”. The copper field is composed of some copper wires which are used for data transmission such as Internet access. These wires are copper or related types that allow normal speed Internet access. In order to improve the Internet access bandwidth, fiber wires could be used completely from the central station to the end-user or to a certain point closer to the end-user. Hence, data transmission is done with both fiber and copper wires. When we compare the fully copper networks, with the hybrid usage of fiber/copper usage, we see that the combination gives a quicker, safer Internet access and performs better. We wire fiber cables starting from the central station up to some point in the network and the remaining transmission is done via existing copper cables. Since data travels a smaller distance on the copper wires, the transmission speeds up, relatively.

In this setting, we aim to modify an existing network as shown in Figure 2-3.

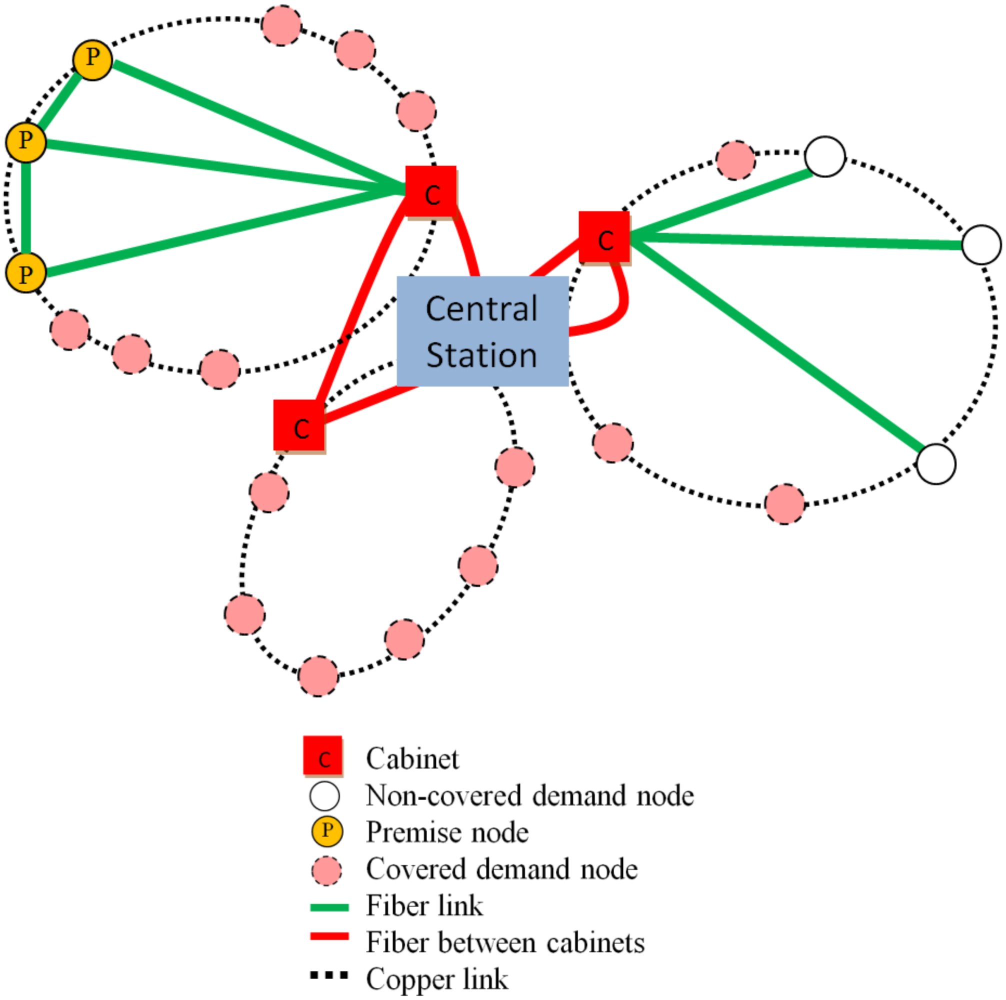

Figure 2-3. Illustration of Copper Field Re-design Problem

There is a central station which is already in use for Internet access via copper wires. The existing network consists of copper cables that make loops around the central station. There might be one or more copper cable rings around a central station depending on the geographical span of the region. Fiber wiring should start from central station and touch the copper loop(s) at some point(s) to improve the bandwidth. The point of touch of fiber wiring to the copper loop needs special equipment called “cabinet”. The cabinet acts as a central station and it is assumed that a cabinet provides the same quality of service as central station does. It is also required that each cabinet is connected to the central station via two arc disjoint paths. This property comes out as a loop structure between cabinets including central station that is shown as the red line in Figure 2-3. In this manner, the central station can also be considered as a cabinet. In this way, we make sure that backbone network, which is the ring consisting of the central station and cabinets, can not be harmed.

If any demand node is in close proximity (say at most γ meters) to a cabinet over the copper wiring, the particular demand node is accepted as receiving fiber access service. In other words, each cabinet can serve its ring's nodes if and only if the distance between the cabinet and demand node does not exceed γ value on its copper ring. Hence, demand nodes in γ neighborhood over the copper ring to the cabinet are assumed to have fiber service, which is called "covered demand node" in Figure 2-3. If a node is located further than γ value away from a cabinet, it is not considered as served by the cabinet; a direct fiber cable from the cabinet to this node is required. The green lines in Figure 2-3 represent such cases.

In the network design problem over an existing copper network, some customers may require additional services. Such customers are referred as "premise customers" by the company under consideration and they require a fully fiber path from a central station up to their building. In addition, premise nodes also require having a direct connection to at least one other premise node.

In the copper field network re-design problem; there is also a distance limit of the fiber access measured from the central station up to the end-user. This distance is a threshold for wiring fiber cable.

Our aim is to service all nodes with fiber connectivity by installing a minimum cost fiber network over the existing ones.

Chapter 3

Telecommunication Basics & Related Literature

3.1. Telecommunication History & Basics

Communication is an essential need of humanity. Every society communicates with each other. Long distance communication was first tried in ancient Greek society [3]. Due to the lack of technical knowledge about electricity and light, they used human force. Optical telegraph was invented by Claude Chappe in France in 1793, and by Abraham Edelcrantz in Sweden in 1794. The optical telegraph working principle is sending light signals using series of equipment which act like mirror. After a few years, the optical telegraph became a nation wide used communication technology tool in Sweden and in France. The forthcoming discovery was electrical telegraph invented by Samuel Morse in 1831. With the advent of electrical telegraph, the need for human force disappeared. Also, Samuel Morse is the father of simple encoding of its time's alphabet by short, long and dot lines. Finally, Alexander Graham Bell invented the telephone in 1876, which allows voice transfer via electrical signal translations. These telephone networks are the preliminary forms of today's telecommunication networks. In 1897, Marconi's invention was another fundamental milestone in telecommunication network history. He invented wireless telegraphy by using electromagnetic waves. Another technological development was the transmission methodology changes. In 1960s, analog transmission left its place to digital signal transmission. This technology leads forward todays Internet. In 1980s, wireless telephone networks were a more and more used methodology. Then in 1990s, maybe the most important invention was made, namely, the optical transmission usage instead of electrical equipment. These introduced larger bandwidths, fast and secure Internet connections into modern life. A brief history of telecommunication networks is presented in [3].

For designing the infrastructure of telecommunication networks, many disciplines including operations research, computer science and electrical electronics engineering examine the problem within their own perspectives. Within the context of operations research, a telecommunication network consists of a set of nodes and links between some of them [4]. These nodes are demand points that send/receive messages or information such as voice, data, and video. The transmission is done via communication links [4]. The communication links can be copper cables (coaxial cable or twisted pair) fiber ones or both.

The telecommunication network structures are examined according to their levels. It is similar to the structure in the geographical classification; LAN connects some local nodes to an upper level which are nodes in the MAN and MAN is in fact a special detailed area in the WAN. Similarly, every multi-level network structure has an upper and a lower layer. Without loss of generality, we can define every network as/in terms of backbone and access networks. The upper level is the backbone and the lower level is the access network. Any two consecutive layers in the hierarchy can be viewed as backbone and access networks.

When we look at this backbone/access network differentiation in terms of hub location, a telecommunication network consists of “tributary” and “backbone” networks. Hubs are switching points of the telecommunication traffic. Tributary networks (local access networks) connect demand nodes to hubs and backbone networks interconnect the hubs. In this definition, tributary networks can be “local” or “access” networks and backbone networks can be “hub-level” networks. Hubs are telecommunication elements such as switches, gates, concentrators, control points, or access points [4]. Some of the different electronic equipment may be exemplified as multiplexers, concentrators, or switches. The multiplexer collects incoming signals and composites the outgoing signal with higher frequency. Concentrators are like multiplexers, they compress incoming traffic and combine the outgoing signals. On the other hand, switching centers are points that remote switches have local switching functions to interconnect all users [5]. Even though the devices maybe different in each layer, we can view the system in terms of supplier – customer perspective in both backbone and access networks. Hence, suppliers are in the backbone network and customers are in the access one, even though the capacity, geographical area, and spanning region vary.

In general, the multi-level network structures include multiple levels which are connected to each other in a hierarchical manner. These levels may have different names in different literatures. In this thesis, we use operational research view and use this hierarchy in only two levels. For more general cases, Figure 3-1 shows the multi-level structure. The very up level is called backbone network. These links have high capacities and high transmission rates. The second level is the local access area. The connection is done via switching centers which are roots in the local access areas. In Figure 3-1, switching-center-6 consists of six service sections and these service sections constitute the primary network. Each local access consists of several service sections. From service-section-4, we move to the third level of the network, which includes multiple terminal sections. The interconnection of these terminal sections defines the secondary network. Finally, each terminal section includes the territory network where the end-users are connected to the Internet [6].

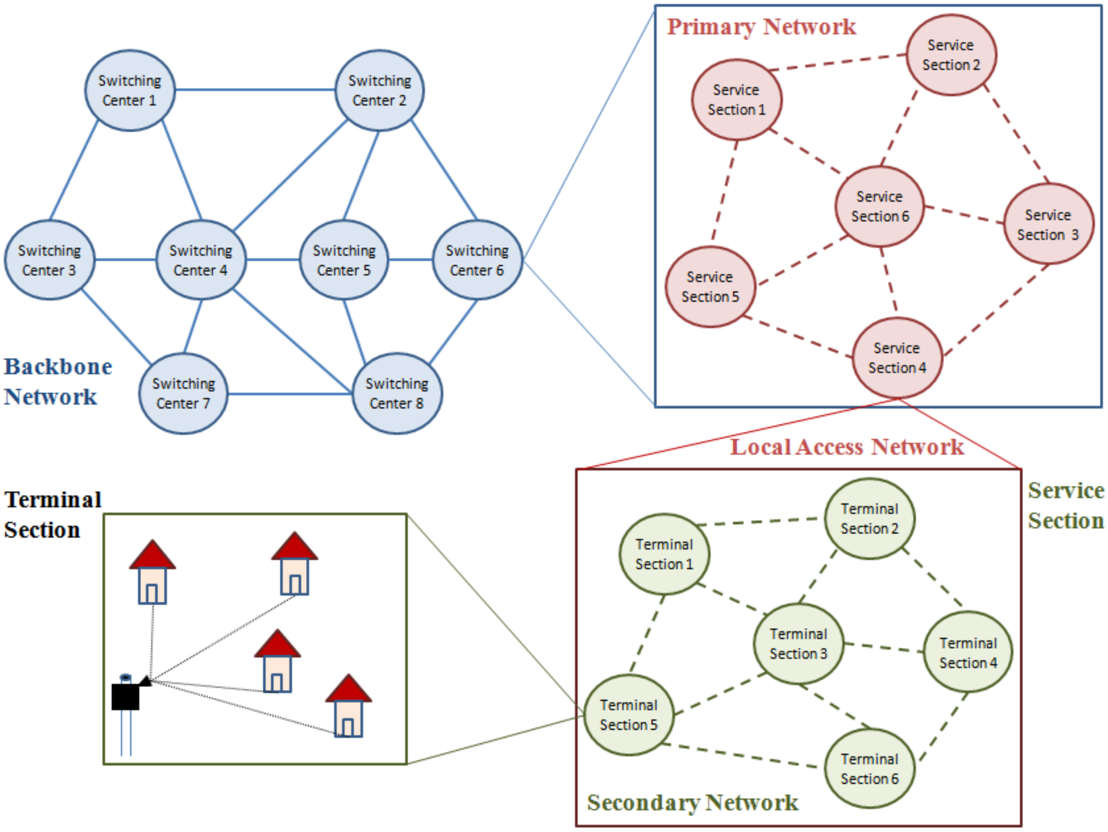

Figure 3-1. Multi-level network

We now give more specific explanations based on Figure 3-2. At the highest level, which is the backbone network, nodes are called gateways. As explained before, the bandwidth between gateways is high and transmission rate in these links is also high. In this figure, gateways have a fully interconnected topology. Gateways are points which spread connection to local access area via switching centers. Switching centers in this figure refer to the service sections in Figure 3-1. Then, the local access network starts. Distribution points can depend on the definition of the network and these might be junction points of highways or entrances of private areas. The network from distribution points to the end-customers is referred as the allocation area [5].

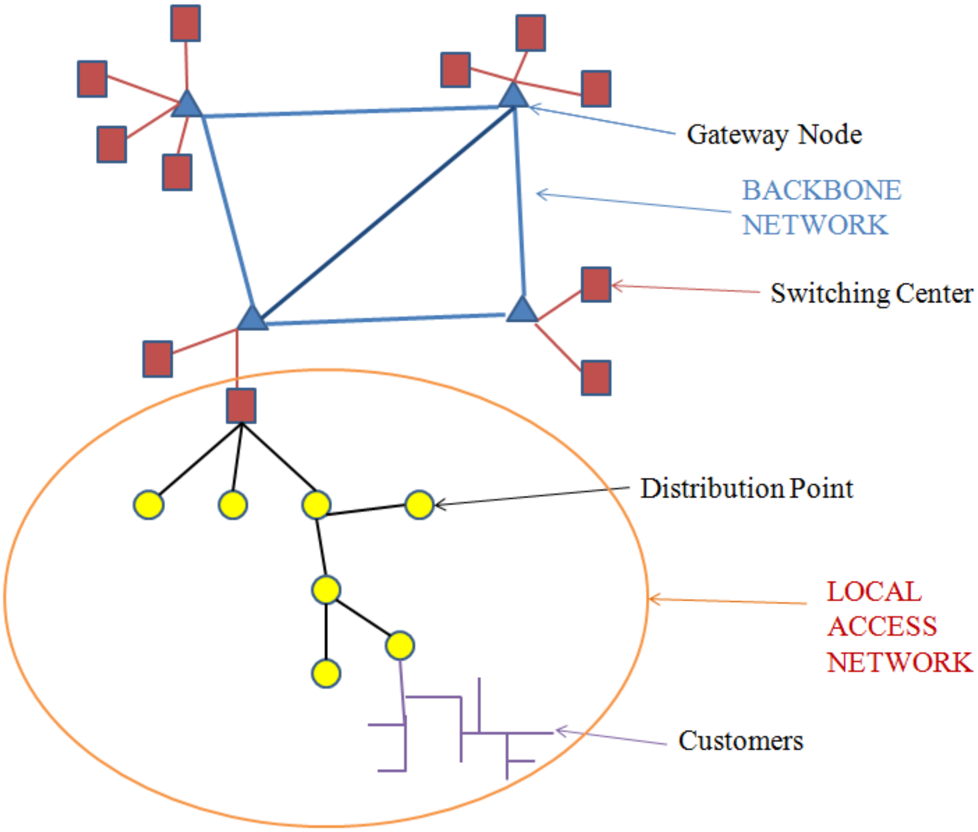

Figure 3-2. Hierarchical Structure of Telecommunication Network

The main difference of a backbone network is the high transmission rate over it. The backbone networks can have complete (fully-interconnected), ring or mesh topology. For fully-interconnected networks, the transmission is faster as expected, since there is a direct link between each other [4]. However, it is not so cost effective. On the other hand, ring structure allows two arc-disjoint paths between two nodes to reach each other. When there is a failure in one of the links, the other path can be used instead. Thus, survivability is achieved in the ring structure [7]. Mesh networks have connected topologies where at least one direct connection is missing [4].

Since our problem definition emerges from an application from Turkey's largest service provider, we will be referring to these switching centers as central stations in their terminology in the rest of this thesis. As explained in Chapter 2, our scope is the local access network including a central station and its corresponding distribution points.

3.2. The Telecommunication Network Design Problem

In the OR literature, the telecommunication networks design problem (TNDP) is defined as finding a suitable configuration of nodes and links, so as to satisfy the traffic demand between nodes [6]. The objective of TNDP may be to minimize the cost or minimize / maximize certain performance measures. Costs include the installation and operation costs of new devices such as concentrators or switches. On the other hand, the performance measure can be reducing network congestion, routing the traffic, and other similar operational decisions [6].

The TNDP can consider either a network design from scratch, i.e. there is nothing in the beginning in terms of communication, or an expansion/improvement over the existing network. If there is no network in the beginning, the overall aim is a network with telecommunication elements in a cost-effective way considering demand points, technical specifications, and equipment capacities. The expansion of the existing network may include capacity expansion by adding new links, by changing the existing technological infrastructure or an improvement of the existing network by restoration of equipments [8].

In both expansion and designing from scratch cases, the resulting networks have many evaluation criteria. These criteria are network cost, capacity, reliability, performance, and demand pattern [4]. The cost of a network includes establishing a link, using a link dependent on the usage volume, establishing a hub, using a hub as in [9]. Usage costs are actually depending on the amount of flow. Capacity of networks contains both link capacities and hub capacities. Performance depends on technical capabilities of telecommunication hardware and software elements. Performance can be evaluated when the amount of traffic in the network arises over time and when the network can handle the increased amount of traffic. Demand pattern may be many-to-many, i.e., any node can have traffic with any other node in the network or many-to-one, i.e., every node will have connectivity to a central location existing in the networks [4]. The survivability is an important issue in telecommunication networks. Especially in backbone networks, any failure in the link may cause critical service problems. The reader can refer to [10, 11, 12, 13, 14] for further details. In the reliability issue, the network may use homing to multiple hubs which allows a node to have a direct link to more than one hub node. If there is only a single hub, the problem is called single homing. Also, alternate routing is used in backbone networks. In this type, there is more than one path between each hub node which has sufficient capacity [4]. Thus, rerouting is possible when a failure occurs. Also, reliable p-hub location problems are developed as p-hub maximum reliability and p-hub mandatory dispersion models in [15].

There are different types of problems that consider (i) solely tributary or (ii) solely backbone networks as well as (iii) joint problems which evaluate backbone and tributary together. Since the telecommunication network problems are complex in general, a typical researcher divides the core problem into subproblems and solve them subsequentially [16]. The subproblems are generally NP-hard [17].

We now provide the relevant literature under each heading, namely local access network design, backbone network design and joint network design separately.

3.2.1. Local Access Network Design Problem

According to [6], there are four main problem types in local access network design. The first is (i) concentrator location problem which decides on the number and location of concentrators. There is a fixed installation cost, assignment cost and capacity of new concentrators. The problem seeks concentrator locations with assignment of terminals to the selected concentrators while minimizing total costs and obeying capacities [18]. The second one is (ii) terminal assignment problem which is about concentrator- terminal matching. The third problem type is (iii) terminal layout problem. In this one, it is assumed that original network has all the available connections and given the terminal-concentrator assignments, the objective is to find the best network topology to connect each concentrator to its assigned terminal. The last one is (iv) Telpak problem, which is about the link capacities. Terminals and end users generate/receive different amounts of traffic according to the distance to the switching center. Even if terminals are identical, closer ones carry higher load than further links. Hence, there is a variety in loading capacity of the links. This problem is about minimizing network link costs while satisfying traffic requirement and selecting link capacities in a tree structure [16]. It is originally discussed in Rothfarb and Goldstein [19] and is known in the literature as the one-terminal Telepak problem. Several heuristics have been developed for the problem by Goldstein [20], Hansler [21], Chandy and Russell [22]. The main characteristics of the problem are explained in [16, 5, 23]. In [5], local access network expansion problem is discussed. The paper is mainly about the capacity expansion of the network and the problem is formulated as a minimum cost multicommodity network flow problem.

In the analyses of telecommunication elements, there are several evaluation criteria. The facility type is one of the important characteristics of a telecommunication network design problem: they might be single facility or multi-facility. Also, the design problem may be for a single representative period, which is referred as the single-period or the problem may include designing within time intervals, which refer the multi-period models. The topology of the problem may be fully-interconnected, ring, star, tree, mesh. The topology issue is a restriction in some cases. Also, flow pattern is important in some networks. If there is more than one origin destination pair in the network, then flow pattern is multi commodity. The capacity of transmission links or hardware characteristics defines the capacitated problems. In the uncapacitated problems, the cost of links and hardwares are considered.

Table 3-1 provides a snapshot of the characteristics of local access network design problems according to the facility type, period, topology if it exists, flow pattern and capacity.

Table 3-1. Local Access Network Design Problem

Local Access Network Design Problem										
	Facility Type		**Period**		**Topology**	**Flow Pattern**		**Capacity**		**Solution Methodology / Notes**
	Single	**Multi**	**Single**	**Multi**		**Single Com.**	**Multi Com.**	**Uncap.**	**Cap.**	
[50] (Bley and Koch, 2002)	√		√		Tree		√		√	Backbone and local access design are formulated separately. Sequential solution procedure is used. Integer linear programming techniques are proposed.
[5] (Balakrishnan, 1991)		√	√		Tree	√			√	Modeled as a minimum cost multicomodity flow with gains problem. It is a capacity expansion problem.
[25] (Chamberland, 2010)		√	√		-	√			√	
[16] (Gavish, 1991)	√		√		Tree-Ring	√			√	Heuristics are proposed.
[24] (Frantzeskakis and Luss, 1999)										Mixed integer model and a heuristic algorithm are proposed.

In the local access network design problem, there are redesign and update problems. Redesign is motivated to reach a desired level of capacity while using existing capacity. An example is in [24], which is local access redesign problem and modeled as mixed integer problem (solved by a heuristic algorithm). In this network redesign problem, the motivation rises from the annually leasing facilities of large telecommunication companies to other carriers in some areas. Although using the existing service system was a cost-effective structure at the beginning, as demand increases over time, the service quality between the source-destination pair in the embedded network may become insufficient. Thus, this problem attempts to find optimal network structure to serve existing and new demands given certain existing facilities, and routing assignments. At the end, some existing facilities may be disconnected or utilized differently and new facilities may be constructed with routing structures for new demands. [24] provides a mixed- integer program (MIP) which is solved via a software package and heuristic algorithm.

On the other hand, network update problem is usually proposed in terms of technological specs of the infrastructure. In Chamberland [25], the update problem is considered to satisfy new demands for existing subscribers. The subscribers may prefer to use/buy new service equipment as technology develops such as high-definition televisions working over the Internet. In order to satisfy this demand, the architectures may need to be changed. A mixed integer programming model is developed and a tabu-based heuristic algorithm is proposed.

For further information about local access networks, the reader can refer to surveys [23, 26]. For earlier works, the reader can refer to [16, 5, 27].

3.2.2. Backbone Network Design Problem

In general, backbone network design problem decides (i) location of backbone nodes, (ii) processor/equipment used in these backbone nodes, (iii) routing and capacity assignments via linking backbone network nodes and building a route between them.

Generally, backbone networks have many-to-many structure. In other words, there are several sources and destination nodes, hence traffic flows from many different sources to many different sink nodes. Therefore, the backbone network problem is generally modeled by using minimum cost multicommodity network flow problem which minimizes a cost function while routing the commodities over a capacitated network. In the telecommunication applications, the model may include time-delay and reliability requirements. The requirements may differentiate according to the priority requirements [28]. Also, if there is a predetermined topology, the topological constraints need to be obeyed.

Some backbone network problems' details are shown in Table 3-2.

Table 3-2. Backbone Network Design Problem

Backbone Network Design Problem										
	Facility Type		**Period**		**Topology**	**Flow Pattern**		**Capacity**		**Solution Methodology / Notes**
	Single	**Multi**	**Single**	**Multi**		**Single Com.**	**Multi Com.**	**Uncap.**	**Cap.**	
[31] (Altınkemer and Yu, 1992)	√			√	-		√		√	Lagrangian relaxation based algorithm is proposed.
[34] (Din, 2008)	√			√	-		√		√	The metaheuristic: simulated annealing is used to find near optimal solutions
[11] (Ho and Cheung, 2007)	√			√	-		√		√	Generalized survivable network is modeled
[12] (Ho et al., 2006)	√			√	-		√		√	Generalized survivable network is modeled
[30] (Kershenbaum et al., 1991)	√			√	Mesh		√		√	Local search heuristic algorithm (MENTOR) is proposed.
[35] (Pierre and Elgibaoui, 1997)	√			√	Mesh		√		√	Delay & reliability of the network is considered. Tabu search which is a metaheuristics is used.

Backbone Network Design Problem										
	Facility Type		**Period**		**Topology**	**Flow Pattern**		**Capacity**		**Solution Methodology / Notes**
	Single	**Multi**	**Single**	**Multi**		**Single Com.**	**Multi Com.**	**Uncap.**	**Cap.**	
[36] (Konak and Smith, 1997)	√			√	Mesh		√		√	Delay & network reliability are considered. Evolutionary algorithm which is a metaheuristic is used.
[29] (Gerla and Kleinrock, 1987)	√			√	Mesh		√		√	Delay & network reliability are considered. Minimum Cost Multicommodity Flow Problem is utilized.
[13] (Alevras et al., 1998)		√	√		-	√			√	A cutting plane algorithm combined with linear programming based heuristics is proposed.
[40] (Chen and Tobagi, 2007)	√		√		Complete		√	√		Heuristics are proposed.

In the backbone network design problems, OR literature shows that there are different types of solution techniques including heuristics, such as branch exchange, concave branch elimination or cut saturation [29, 30, 31]. MENTOR, which is a heuristic method is proposed in [30] and a lagrangian relaxation is used in [31]. However, due to curse of dimensionality, problems may be difficult to solve [32]. Also, other techniques are used as simulated annealing [33, 34], tabu search [35], evolutionary algorithms [36, 37, 38], ant colony optimization [39] and heuristics [40, 32]. For earlier studies about the backbone network design, the reader can refer to [41, 32, 42, 43, 44, 45, 46].

3.2.3. Backbone and Local Access Network Design Problem

The last problem type is on the joint networks which include both backbone and access network at the same time. We refer to this type as hierarchical design as in the cases in [47, 48, 49]. Since two-level hierarchical network design problems include many decisions, it may be divided into some sub- problems. According to [47], these subproblems include (i) hub location problem, (ii) clustering of nodes, (iii) interconnection of nodes in the backbone and cluster networks, (iv) routing in the backbone network and then cluster networks. Note that these subproblems are actually similar to the solely local access or solely backbone network design problems.

The details about some joint network design problems are given in Table 3-3.

Table 3-3. Joint Network Design Problem

Multi-level Network Design Problem										
	Facility Type		**Period**		**Topology**	**Flow Pattern**		**Capacity**		**Solution Methodology / Notes**
	Single	**Multi**	**Single**	**Multi**		**Single Com.**	**Multi Com.**	**Uncap.**	**Cap.**	
[67] (Proestaki and Sinclair, 2000)	√		√		Ring - Ring	√			√	The partition, construct and perturb network design method is used. For small problems, optimal solutions are obtained. For various network, heuristic results are shown.
[66] (Labbe et al., 2004)	√		√		Ring - Star	√			√	Polyhedral-based exact algorithm and branch-and-cut algorithm are proposed. Up to 300 vertices can be solved optimally.
[64] (Petrek and Siedt, 2001)	√		√		Star - Star	√			√	It is used for GSM networks.
[48] (Thomadsen and Stidsen, 2007)	√		√		Mesh		√	√		Models general fixed charge network design problem. Branch and cut and price algorithm is proposed.

Multi-level Network Design Problem										
	Facility Type		**Period**		**Topology**	**Flow Pattern**		**Capacity**		**Solution Methodology / Notes**
	Single	**Multi**	**Single**	**Multi**		**Single Com.**	**Multi Com.**	**Uncap.**	**Cap.**	
[49] (Rosenberg, 2005)	√		√		-	√		√		A dynamic algorithm is proposed.
[68] (Thomadsen and Larsen, 2007)	√		√		Complete - Complete		√	√		Decomposition, column generation and branch-and-price algorithms are used.
[65] (Labbé and Yaman, 2008)	√		√		Star - Star		√	√		Facet-defining inequalities are proposed and branch-and-cut is used. Heuristic based on lagrangean relaxation is also proposed.
[69] (Kramer and Pesavento, 2002)		√	√		Complete - Complete		√		√	Parallel evolutionary algorithm is proposed.
[70] (Yaman and Carello, 2005)	√		√		Complete - Star		√		√	Modular link capacities are used. Both exact and heuristic methods are used.

In hierarchical networks, there are different methods for formulation and solution methodologies. For instance, mixed-integer problem (MIP) formulation, which decides on locations of hubs in the backbone network and routing for each cluster, is used in [48]. According to [48], the hierarchy of the telecommunication network allows us to use the economies of scale methodology in the backbone networks by utilizing the high speed network in the central side. The mesh network topology for the backbone network is used and it includes interconnection of the given clusters. The problem is called generalized fixed-charge network design problem. For the MIP, a branch-cut –and- price algorithm is proposed. On the other hand, in [49], Rosenberg proposes a dynamic programming algorithm for interconnection of a number of nodes.

In [50], Bley and Koch study the nation-wide communication network which includes both access and backbone networks. In the backbone network, there are survivability and routing constraints. The model aims to find assignments between nodes and layers by considering node locations, demands, possible connections and some other technical constraints. A MIP is proposed which selects which node should belong to which layer while each node needs to be connected to its layer and to the next layer via a tree structure.

Generally, multi level, which means with more than 2 levels, network design problems are examined as a hub location view in OR literature [51, 52]. More general surveys include [53, 54, 55, 56, 57, 58, 59, 60, 61, 62]. Also [63] Yuan gives an annoted bibliography over telecommunication networks.

Klincewicz [4] studies the two-level hierarchical network in its survey. There might be same or different topologies in each level, examples of which are star - star [64, 65], ring - star [66], ring - ring [67], complete - complete [4, 68, 69], complete - star [70] or mesh -mesh [71].

The joint network of fully interconnected backbone and access network is defined in [4] and called fully interconnected network design problem. In [69], network is designed from scratch and the problem is solved via parallel evolutionary algorithm which uses clustering rather than match hubs with corresponding access networks. In [68], numbers of clusters and the number of nodes in the clusters are predetermined. It is modeled as a mixed integer programming problem and solved via decomposition, column generation and branch-and-price.

Another type of two level hierarchy is as follows: a fully interconnected backbone network with a star topology in access network arises in [70]. This problem is modeled as a capacitated single assignment hub location problem with modular link capacities. Since link capacities are modular, the cost of an edge is not linear but stepwise. Also, another special assumption of [70] is the capacity restrictions on traffics. Here, the capacity of a hub is the amount of traffic transiting through the hub instead of incoming traffic. This model allows only single homing, which means that each node is related to exactly one hub. In [72], the same problem type is modeled as a capacitated single allocation hub location problem. Also, single homing, double homing with free pair and double homing with fixed pair cases are examined. Two level local search approach is used for solution methodology (initial solution, optimization step and post optimization step).

Another possible topology that is considered in the literature is the ring-star structure. In this type, each transit node is connected to one hub node. For example, in [66] ring structure represents the internet and star topology is the intranet (assignments). Here, the problem is solved via a branch-and-cut algorithm.

In the star-star topologies, both backbone and access networks are in the star structure. This topology is similar to a special case of green field model explained in Chapter 2 (with two levels- with single level passive splitter usage). In [65], the problem is modeled as uncapacitated hub location problem. Hubs are directly connected to a central station and each terminal node is directly connected to a hub. In the solution methodology, branch-and-cut is employed. Heuristics based on lagrangean relaxation are developed. Another star-star topological problem is investigated in [64] which simultaneously solves concentrator quantity problem, concentrator location problem and assignment problem. Since even special cases of this problem are NP-hard and can not be solved optimally for the large networks, a high complexity algorithm is proposed.

The ring - ring topology in [67] considers multiple interconnected rings. Total ring length and intra-ring traffic are constraints for the problem. The proposed routing algorithm's objective is to minimize the maximum flow on the rings especially for designed for dual homing structures.

Recall from Chapter 2 that in the green field, designing the network from scratch, the goal is to reach every customer in a cost effective way by utilizing passive splitters. From a given central station node, the model decides the location of passive splitters, their types and assignment of demand nodes to passive splitters while obeying bandwidth and insertion loss requirements. The green field network design problem has a multi –commodity flow pattern. Since passive splitters have a limited outgoing fiber, the problem is capacitated. Similarly, different passive splitter types show the multi-facility type and we design for a single period. For the green field, the network is a rooted tree – star structure due to the fact that there is a single central station. And the connection of passive splitter to this central station results in a tree structure that is rooted from central station. At each passive splitter, demand nodes are connected to the splitter with star topology. Since we do not know in advance the number of level in the embedded tree network, the problem definition differs from the ones in the literature.

Our copper field re-design problem is about an improvement in the network. The infrastructure of given network consists of copper loops that are connected to the central station. In the re-design model we determine the location of cabinets in these copper loops and connect the cabinets with central station in a ring structure. Also, additional fibers installed depend on the γ value coverage threshold. Besides these fiber links, the premise nodes are linked to the nearest ones. Therefore, it seems to have a ring-star structure when γ is zero and have a specialized structure in the other cases. Also, the premise node’s specific requirement differentiates the problem from the existing ones in the literature. Remaining characteristics includes multi-commodity flow pattern and single facility type since all cabinets are homogenous.

Chapter 4

Model Development

The proposed problems consider designing the infrastructure of fiber optical network of the service provider company. In order to find possible solutions to our problems in the green field and the copper field, we formulated mixed integer mathematical models. In both problems, we wish to install fiber optic wires to provide service in a cost effective way. The data specific to each problem is attained after numerous discussion sessions with the service provider.

4.1. Green Field Model Development

In the infrastructure of designing from scratch, we know the central station location in advance. We assume that distribution points are aggregated forecasted demand locations to which high bandwidth Internet access should be served. In this network, we need to find passive splitter locations to diminish fiber optical wire usage. Since we wish to reach each demand node, to put passive splitters in the same location with a demand node decreases surplus usage of wires. Hence, without loss of generality, we assume that demand points are possible passive splitter locations. Let N be demand node set on a network including a central station which is referred as $central$.

Different passive splitter types are considered in the system and so, we use a set for defining these different passive splitters. Let T be the set of passive splitters' types. The first type passive splitter is solely used for the central station and for the remaining ones the output number is a function of parameter $k \in T$, e.g., $k = 3$ is the 3rd type passive splitter with $2^{3-1} = 2^2 = 4$ outputs or $k = 4$ is the passive splitter with $2^{4-1} = 2^3 = 8$ outputs.

In the infrastructure, wiring can be applied in the roads including junction points corresponding to corners of streets or entrance of private areas. Therefore, we use highway and street distances in the system. $\mathrm{L} = [\mathrm{l_{ij}}], \mathrm{i}, \mathrm{j} \in \mathrm{N}$ shows the highway distance from node i to node j. Since we aim to minimize the cost, we include the fiber optical wire cost in the function. Then, $C = [\mathrm{c_{ij}}], \mathrm{i}, \mathrm{j} \in \mathrm{N}$ shows the cost of shortest path from i to j.

Also, the passive splitter usage incurs a cost to the service provider which includes purchasing, setting, operating and maintenance costs. The cost of a passive splitter depends on its type. We let $\mathrm{c_k}$ show the cost of $\mathrm{k^{th}}$ type passive splitter where $k \in T$. As technological developments increase and the specs improve the cost of a passive splitter may vary. To this end, we define a parameter α corresponding to the proportion between the splitter and wiring costs. This proportion allows us to make a comparison for different cost structures of the fiber optical wiring and passive splitters.

As explained in problem definition part, each passive splitter usage causes an insertion loss according to its splitting number. Since the dB loss depends on the passive splitter type, we denote the port number in the splitter by parameter $\mathrm{f}_{\mathrm{k}}, k \in T$. For example, if the model uses a passive splitter with 8 = 2^3 outputs, then the model uses splitter type $\mathrm{k} = 4$, the number of ports is $\mathrm{f}_4 = 3$. The insertion loss in each level of port is specified with parameter $declineps$, which is fixed at 3 dB for each port by the service provider. For example, in a passive splitter with 4 outputs, the insertion loss in the passive splitter is 6 dB, as shown in Figure 4-1.

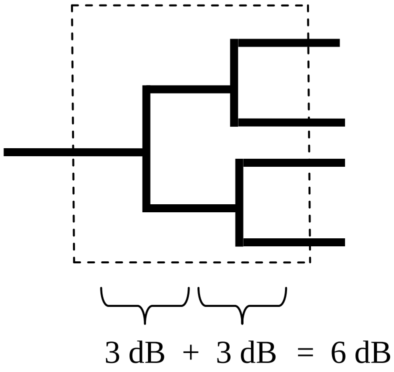

Figure 4-1. Insertion Loss Illustration in 1:2^2 Passive Splitter

Similarly, the insertion loss per km is another power loss in the system, which is given as 0.2 dB/km by the service provider and is defined as parameter $declineway$ in our model. The insertion loss budget is given as 28 dB by the service provider, but in order to generalize the model formulation, we define parameter $dBcapacity$ for threshold value loss. For simplicity, we assume that a signal starts at the central station with zero dB and each fiber optical wire length augments the dB amount. Also, passive splitters make contribution to that amount. Thus, every node need to be in this 28 dB, namely $dBcapacity$, radius.

The speed of Internet can be measured by download/upload speed as seen in the problem definition part. Therefore, we consider the service quality of the company by the download speed measured by Mb/sec. The out power of the central station is determined by $mbcentral$ which is specified as 2.5 Gb/sec in our application. The aim of the service provider is to provide at least 100 Mb/sec download threshold for each distribution point, customer, in our models. This specification is also affected by the number of ports in the passive splitters. More splitting causes more reduction in the speed. This 100 Mb/sec service quality is defined as $mbthreshold$ in the model.

Figure 4-2 visualizes the change in dB and Mb/sec, where the parameters assumed as follows: central station starts with 0 dB and the power of central station is 1000 Mb/sec. The insertion loss during the way is 2 dB/km where the insertion loss multiple in the passive splitter is 3 dB. Additionally, the insertion loss budget is 30 dB.

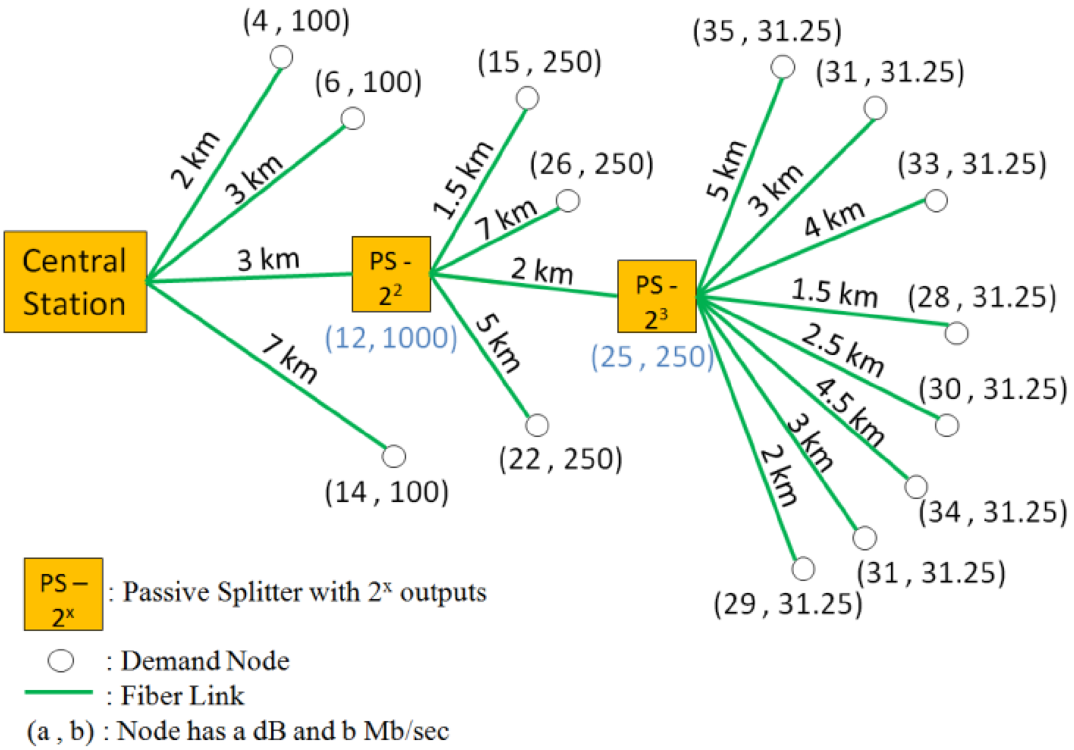

Figure 4-2. Illustration of Green Field Problem

As shown in Figure 4-2, the insertion loss of the passive splitter with 2^2 outputs has both insertion losses during the way and in the passive splitter. Then, insertion loss is *2 (dB/km) x 3(km) = 6 (dB)* during the way and additionally *3 x 2 = 6 dB* in the passive splitter, which results with *6 + 6 = 12 dB*. For the second passive splitter, we add *2 x 2 = 4 dB* during the way and *3 x 3 = 9 dB* in the passive splitter. When we add these *4 dB* and *6 dB* to the previous passive splitter's insertion loss amount, we get *12 + (2 x 2) + (3 x 3) = 25 dB*.

To summarize, sets, matrices and parameters are as follows:

N	Set of demand nodes
T	Set of passive splitter type
$L = [l_{ij}; i, j \in N]$	Shortest distance matrix
$C = [c_{ij}; i, j \in N]$	Cost matrix
f_k , $k \in T$	port number in the passive splitter, $k \in T$
$central$	Central station
α	Proportion between cost of fiber link and cost of passive splitter
$declineway$	Insertion loss through the fiber link
$declineps$	Insertion loss in passive splitter
$dBcapacity$	Insertion loss budget
$mbcentral$	Bandwidth at central station
$mbthreshold$	Required bandwidth at each demand node

The objective function includes both passive splitter usage cost and fiber optical wiring cost. By deciding on the passive splitter location, the splitter number in it and fiber optical wiring pairs, we satisfy the bandwidth requirement and dB loss restriction. So, we need to know pairs of nodes with the fiber optical wire connection and passive splitter's location with its type. Decision variables are as follow:

$$x_{ij} = \begin{cases} 1, & if\ there\ is\ a\ fiber\ link\ between\ node\ i\ and\ node\ j;\ i \neq j, i, j \in N \\ 0, & otherwise \end{cases}$$

$$y_{jk} = \begin{cases} 1, & if\ k^{th}\ type\ of\ passive\ splitter\ is\ located\ in\ node\ j;\ k \in T, j \in N \\ 0, & otherwise \end{cases}$$

m_j : the speed at the node $j \in N$ in terms of Mb/sec

p_j : the dB amount at node $j \in N$

The proposed model is as follows:

$$Min \quad \sum_{i\in N}\sum_{j\in N} c_{ij}x_{ij} + \sum_{i\in N}\sum_{k\in T} \alpha\, c_k\, y_{ik} \qquad (4.1.1)$$

$s.t.$

$$\sum_{k\in T} y_{jk} + \sum_{i\in N|j} x_{ij} \geq 1 \qquad \forall j \in N, j \neq central \qquad (4.1.2)$$

$$\sum_{j\in N|i} x_{ij} \leq \sum_{k\in T} 2^{f_k}\, y_{ik} \qquad \forall i \in N \qquad (4.1.3)$$

$$\sum_{k\in T} y_{ik} \leq \sum_{j\in N} x_{ij} \qquad \forall i \in N \qquad (4.1.4)$$

$$\sum_{k\in T} y_{jk} \leq \sum_{i\in N} x_{ij} \qquad \forall j \in N, j \neq central \qquad (4.1.5)$$

$$p_j \geq p_i + declineway\ l_{ij}\, x_{ij} + \sum_{k\in T} declineps\ f_k\, y_{jk} - M(1 - x_{ij})$$

$$\forall i, j \in N, j \neq central \qquad (4.1.6)$$

$$p_j \leq dBcapacity \sum_{i\in N} x_{ij} \qquad \forall j \in N, j \neq central \qquad (4.1.7)$$

$$x_{ij} + x_{ji} \leq 1 \qquad \forall i, j \in N \qquad (4.1.8)$$

$$p_{central} = 0 \qquad (4.1.9)$$

$$y_{central,1} = 1 \qquad (4.1.10)$$

$$y_{j,1} = 0 \qquad \forall j \in N\ , j \neq central \quad (4.1.11)$$

$$m_{central} = mbcentral \quad (4.1.12)$$

$$m_j \leq \frac{m_i}{2^{f_k}} + mbcentral\ (1 - \ y_{ik}) + \ mbcentral\ (1 - \ x_{ij})$$

$$\forall k \in T, i, j \in N{:}\, i, j \neq central \quad (4.1.13)$$

$$m_j \geq mbcentral\ x_{central,j} \qquad \forall j \in N, j \neq central \quad (4.1.14)$$

$$m_j \leq mbcentral \qquad \forall j \in N \quad (4.1.15)$$

$$m_j \geq mbcap \qquad \forall j \in N \quad (4.1.16)$$

$$x_{ij}, y_{jk} \in \{0,1\} \qquad \forall i, j \in N, k \in T \quad (4.1.17)$$

$$p_j, m_j \geq 0 \qquad \forall j \in N \quad (4.1.18)$$

This model selects the location of the passive splitters, its types and fiber optical connections. In the objective function (4.1.1), the aim is to minimize the total cost of passive splitter and fiber optical wiring costs.

In order to cover all customers, each customer needs to be served by a fiber optical wire access. If a demand node is selected as a passive splitter location, then it will be automatically served. In addition to that, if there is an incoming link to a node, that node is served as shown in the constraint (4.1.2).

Each passive splitter has an output depending on its type. Constraint (4.1.3) ensures the outgoing link number from a node at which a passive splitter is located. The total number of outgoing link from a node is calculated as 2^{f_k}. Also, the constraint guarantees that in order to have an outgoing link from any node, a passive splitter has to be located in there.

The passive splitter and fiber optical link relations are in Constraints (4.1.4) and (4.1.5). The Constraints guarantee that if a passive splitter is located at a node, then there should be an outgoing and an incoming fiber.

To evaluate insertion loss requirements, constraint (4.1.6) and (4.1.7) are used. With constraint (4.1.6), each node's dB amount is calculated. For the simplicity, we calculate dB requirement beginning from central station and we assume that central station has 0 value. Then, dB value of all nodes needs to be within the insertion loss budget. If there is link between two nodes, then dB amount increases from the previous one by length of the fiber. Also, if the specific node is a passive splitter location, it also increases the dB amount depending on its type. Constraint (4.1.7) ensures that every node's dB amount has to be less than dB insertion loss budget if there is an incoming arc. These two constraints are Miller-Tucker-Zemlin type constraints and they also prevent any subtour.

Constraint (4.1.8) ensures that there is a single arc between two nodes. For central station's characteristics, we present Constraints (4.1.9)-(4.1.11) including the zero dB amount in central station, first type passive splitter is located in the central station and any type of passive splitter other than first one cannot be located in the central station. The reason for defining a passive splitter type for the central station is for simplicity in the model. The output number of central station is specified by the service provider company. In the bandwidth calculation, the central station begins with *mbcentral* parameter (Constraint (4.1.12)) and decreases through the splitters. With Constraint (4.1.13), the decrease amount is calculated. If there is a passive splitter in node *i* and if there is a link from node *i* to node *j*, then node *j*'s dB amount depends on to its parent passive splitter. For example, if the passive splitter in node *i* is fourth type with $f_4=3$ ports, then there are $2^3=8$ outputs. Each outgoing arc has $\frac{m_i}{8}$ dB.

Constraint (4.1.13) reduces m_j to $\frac{m_i}{8}$. The dB calculations for nodes that directly connect to central station are calculated with Constraint (4.1.14). The limitations of dB amount are specified in Constraints (4.1.15) and (4.1.16).

Constraints (4.1.17) and (4.1.18) are domain constraints.

In order to improve the performance of the model, we introduced three valid inequalities. They are all data dependent. The first valid inequality excludes the nonfeasible pairs in terms of dB decline. Let *i* and *j* be two demand nodes in N, there is a dB loss between these two nodes if we build a fiber optical wire. From the problem nature, we know that the loss amount between two nodes cannot exceed the capacity, if so, these two pairs cannot be linked to each other.

$$x_{ij} = 0 \qquad \forall i,j \in N\colon l_{ij} declineway > dBcapacity \qquad \text{(VI 1)}$$

The second one is about insertion loss related with central station. In this valid inequality, the pair of nodes one of which is directly connected to the central station is considered.

$$x_{ij} = 0 \qquad \begin{aligned} \forall i,j \in N\colon declineway\ (l_{central,i} + l_{ij}) > dBcapacity, \\ declineway(\ l_{central,j} + l_{ij}) > dBcapacity \end{aligned} \qquad \text{(VI 2)}$$

In Figure 4-3(a), there is a link between central station and node *i*, then between node *i* and node *j*. Suppose that the dB decline from central station until the node *j* exceeds the insertion loss budget. Similarly, from Figure 4-3(b), we observe the reverse of the network, here there is direct connection from central station to node *j* and then link to node *i*. If both insertion loss due to distance from central to node *j* in Figure 4-3(a) and to node *i* in Figure 4-3(b) exceed the insertion loss budget then the pair (*i* , *j*) cannot have a direct connection. Because, even if a single passive splitter is needed to reach demand node from the central station, the insertion loss budget does not suffice.

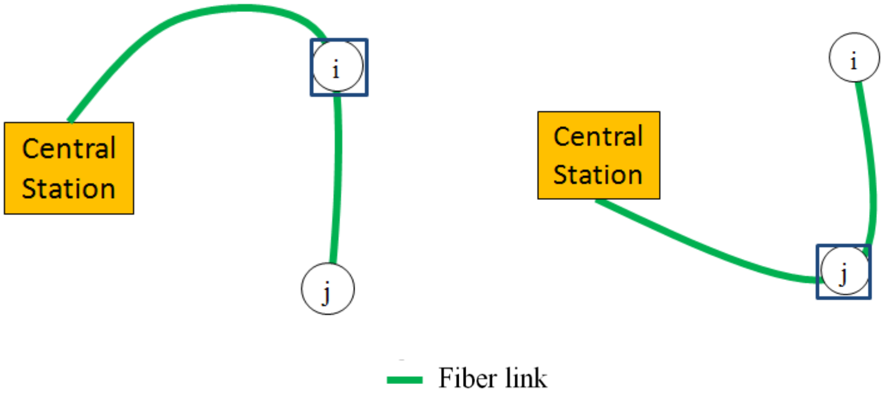

Figure 4-3(a). Illustration 1 for VI 2

Figure 4-3(b). Illustration 2 for VI 2

For the valid inequality (3), we define another parameter, $\min(j) = \text{argmin}_i\{l_{ij}, i \in N\}$ which shows the nearest node for each node $j \in N$. In this valid inequality we find the location then any passive splitter cannot be located and set related binary variable to zero. Similar logic in VI 2 is used here.

$$\sum_{k\in T} y_{ik} = 0 \qquad \forall i \in N: declineway(l_{central,i}+l_{i,\min(i)}) > 28 \qquad \text{(VI 3)}$$

In Figure 4-4, there is link from central station to node i and then nearest node to node i.

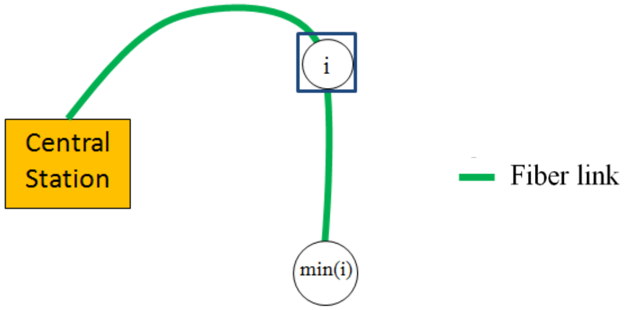

Figure 4-4. Illustration for VI 3

If this link's dB decline value is more than insertion loss budget, node i cannot link to anywhere else. Hence, no passive splitter can be located in node i.

4.2. Copper Field Re-design Model Development

For an improvement in an area that the company has already entered, we propose the copper field re-design model. A mixed integer formulation using the same notation set N, $central$ and $L = [l_{ij}]$ as in the green field model formulation, is proposed. The distance capacity from the central station till the demand node is considered in this model, and the maximum distance is expressed as H. Since cabinets have degree two, the path length at each cabinet should be calculated via both clockwise and counterclockwise. For the rest of the demand nodes, path length from the central station should be considered as the summation of the largest path length of the cabinet and the distance between cabinet and particular node. Therefore, we evaluate the path length at any cabinet from two ways (clockwise / counterclockwise) and consider the largest one for the rest of the calculations. Also, the number of cabinets used in the network is determined by p.

Recall from Chapter 2 that, a cabinet can also "cover" some nodes. A covered node means that a cabinet is close enough to it, so the node has an Internet service better than before but not necessarily as fast as fully fiber optical Internet access. For this purpose, for each node we define a set PL_i which holds potential cabinet locations which can cover i node within via γ value copper cable, e.g., $PL_i = \{j: d_{ij} \leq \gamma, i, j \in N\}$. Observe here that a cabinet can cover a node only if the node is in its copper. Thus, we need another distance matrix $D = [d_{ij}]$ which shows distance of all nodes on the same copper ring, e.g., if two nodes, say a and b, are on different copper rings, d_{ab} gives an infinite value. The γ value is the distance for covering of a demand node by a cabinet via copper cable. Note that we assume central station is a cabinet and so cover some demand nodes.

In the copper field network re-design problem, we need to differentiate some of the customers. The premise nodes are the customers that may wish to have a full fiber Internet access (i.e., refuse the coverage access). Set P shows the premise node set. Since we know premise nodes in advance, we aim to connect a premise node, to the nearest premise node. We assume that a single premise node has two terminal points and without loss of generality it is assumed that these are two different demand nodes. Therefore, there can not be a single excluded node in the area. In order to connect to nearest premise node, we need to keep closest premise node for each premise node. Let the parameter $R(i)$ denote the closest premise node to the premise node $i \in P$, defined as $R(i) = argmin_j \{l_{ij}, j \in P, i \neq j\}$.

We use w_{ij} decision variable for links between cabinets and x_{ij} for links from/to cabinets. Decision variables are as follows;

$$w_{ij} = \begin{cases} 1, & if\ we\ build\ a\ fiber\ wire\ between\ two\ cabinets\ i\ and\ j;\ i \neq j, i, j \in N \\ 0, & otherwise \end{cases}$$

$$x_{ij} = \begin{cases} 1, & if\ there\ is\ \ fiber\ link\ from\ cabinet\ i\ to\ node\ j;\ i \neq j, i, j \in N \\ 0, & otherwise \end{cases}$$

$$z_j = \begin{cases} 1, & if\ demand\ node\ j\ is\ selected\ as\ cabinet;\ j \in N \\ 0, & otherwise \end{cases}$$

$$y_j = \begin{cases} 1, & \text{if demand node j is served by a cabinet via copper wire; j} \in \text{N} \\ 0, & otherwise \end{cases}$$

u_i : the path length at node $i \in N$ (MTZ variable for w’s)

$\hat{u}_i$: the reverse path length at node $i \in N$ (reverse MTZ variable for w’s)

$\bar{u}_i$: the longest path length at node $i \in N$

q_i : the path length at node $i \in N$ (MTZ variable for x’s)

The mathematical model is as follows;

Min $$\sum_{i\in N}\sum_{\substack{j\in N\\ j\neq i}} l_{ij}(x_{ij}+w_{ij})+\sum_{i\in P}\frac{1}{2}l_{i,R(i)} \qquad (4.2.1)$$

s.t.

$$z_i+y_i+\sum_{\substack{j\in N\\ j\neq i}} x_{ji}\geq 1 \qquad \forall i\in N \quad (4.2.2)$$

$$\sum_{\substack{j\in N\\ j\neq i}} w_{ij}+\sum_{\substack{j\in N\\ j\neq i}} w_{ji}\geq 2z_i \qquad \forall i\in N \quad (4.2.3)$$

$$\sum_{j\in PL_i} z_j\geq y_i \qquad \forall i\in N \quad (4.2.4)$$

$$z_{central}=1 \qquad (4.2.5)$$

$$\sum_{k\in N} z_k=p+1 \qquad (4.2.6)$$

$$w_{ij}+w_{ji}\leq 1 \qquad \forall i,j\in N, i\neq j \quad (4.2.7)$$

$$\sum_{\substack{j\in N\\ j\neq i}} w_{ij}=z_i \qquad \forall i\in N, i\neq central \quad (4.2.8)$$

$$\sum_{\substack{j\in N\\ j\neq i}} w_{ji}=z_i \qquad \forall i\in N, i\neq central \quad (4.2.9)$$

$$\sum_{\substack{i\in N\\ i\neq central}} w_{i,central}=\sum_{\substack{k\in N\\ k\neq central}} w_{central,k} \qquad (4.2.10)$$

$$\sum_{\substack{j\in N\\ j\neq central}} x_{central,j}+\sum_{\substack{j\in N\\ j\neq central}} x_{j,central}=0 \qquad (4.2.11)$$

$$\sum_{\substack{j\in N\\ j\neq i}} x_{ij} \leq M\, z_i \qquad \forall i \in N \quad (4.2.12)$$

$$\sum_{\substack{i\in N\\ i\neq j}} x_{ij} = 1 \qquad \forall j \in P \quad (4.2.13)$$

$$u_{central} = 0 \qquad (4.2.14)$$

$$u_i - u_j + H\, w_{ij} \;\leq H - w_{ij} l_{ij}$$

$$\forall i,j \in N, j \neq central, j \neq i \quad (4.2.15)$$

$$\bar{u}_j - \bar{u}_i + H\, w_{ij} \leq H - w_{ij} l_{ij}$$

$$\forall i,j \in N, i \neq central, j \neq i \quad (4.2.16)$$

$$\hat{u}_i \geq \bar{u}_i \qquad \forall i \in N \quad (4.2.17)$$

$$\hat{u}_i \geq u_i \qquad \forall i \in N \quad (4.2.18)$$

$$\hat{u}_i \leq H \qquad \forall i \in N \quad (4.2.19)$$

$$q_j \geq \left(x_{ij} - 1\right)M + \hat{u}_i + l_{ij} \qquad \forall i,j \in N, j \neq i \quad (4.2.20)$$

$$q_{R(i)} + l_{R(i),i} \leq H \qquad \forall i \in P \quad (4.2.21)$$

$$q_j \leq H \qquad \forall j \in N \quad (4.2.22)$$

$$w_{ij}, x_{ij}, z_j, y_j \in \{0,1\} \qquad \forall i,j \in N, j \neq i \quad (4.2.23)$$

$$u_j, \bar{u}_j, \hat{u}_j, q_j \geq 0 \qquad \forall j \in N \quad (4.2.24)$$

In the copper field design problem the aim is to minimize the fiber optical wiring in the network. The first part of the objective function is related to the fiber decision of the model. If there is a link between cabinets or link from a cabinet to a node, then these are included in the objective function. The second part of the objective function is about the premise nodes. Since each premise node and its nearest premise node are known in advance, the link is directly added to the objective function value. The division by 2 is to avoid double counting.

The demand satisfaction of every node is via Constraint (4.2.2). The demand satisfaction can be accomplished via three different ways: (i) A cabinet can be located at a demand node, then the demand node is automatically satisfied via this cabinet, (ii) a node can be covered via a cabinet node in γ threshold distance, and (iii) is linking from cabinet to demand node.

The loop structure among cabinets is satisfied via the Constraint (4.2.3). A demand node should have degree 2 if the node is a cabinet node. The coverage of demand nodes within γ distance is considered via Constraint (4.2.4). If there is a cabinet within γ distance of a node, then the demand node is considered as covered. The central station is assumed to act like a cabinet via Constraint (4.2.5). Therefore, the total number of required cabinets is cabinet number plus 1, as in Constraint (4.2.6).

Constraint (4.2.7) – (4.2.9) are to assign w values only between two cabinets and allows the usage of the fiber in one direction only. There could be more than one ring connected to central station, and thus the flow balance for central station is given via Constraint (4.2.10).

For the cabinet-node links, we use x binary variable. We assume that any node can not be linked to the central station, which is satisfied via Constraint (4.2.11), since the central station can only be connected to the other cabinets. And if there is no cabinet in a node *i*, there cannot be an outgoing x link from that particular node (Constraint (4.2.12)).

For the premise nodes, there has to be exactly one incoming link from any cabinet and that is presented in Constraint (4.2.13).

The path length value in the demand nodes is calculated via Miller-Tucker-Zemlin type constraints. In Constraint (4.2.14), the path length of central station is fixed to zero. Then in Constraint (4.2.15) and (4.2.16), the path length in each cabinet node is calculated. The path length variable u_i and $\bar{u}_i$is the clockwise and counter clock wise variables of node *i* which is selected as a cabinet node. Since we wish to determine a threshold value to every demand node, we need to calculate the longest distance. Therefore, we take the maximum of these two distance calculation. The $\hat{u}_i$ is the longest length from central station to cabinet *i*, in Constraints (4.2.17) and (4.2.18). Any distance from central station to a cabinet node cannot exceed distance threshold value, expressed in Constraint (4.2.19).

For the nodes that are linked to cabinets, the distance from central station is calculated via adding cabinet-node link length to the cabinet path length. We take the longest path length at the cabinet and add cabinet-node link length (Constraint 4.2.20). If this is a premise node, its longest distance from central station includes premise-node-link as well. Then, the longest distance (q) is the path length in nearest node path length plus the length between the particular node and its nearest point. It is calculated in Constraint (4.2.21). As in the path length variable in cabinet, the path length variable for demand nodes cannot exceed the distance threshold value and it is shown in Constraint (4.2.22).

The rest of the constraints (4.2.23-24) are the domain constraints.

Chapter 5

Computational Results for the Green Field

5.1. Data

To test the behavior of the mathematical models, computational studies were performed. In these studies, two distinct data sets are used. The first data based on Kartal district, İstanbul, Turkey, is relatively small, and the second one based on Bakırköy district, İstanbul, Turkey, is larger.

Kartal district has 45 nodes, which includes private areas, business centers, shopping malls and public offices. The nodes are chosen from the locations which need high bandwidth Internet access. Real shortest highway distances attained from ArcGIS roadmap [73] are utilized. The location of each aggregated demand node is obtained with the help of Google Maps. The locations of the demand nodes can be seen in Figure 5- 1.

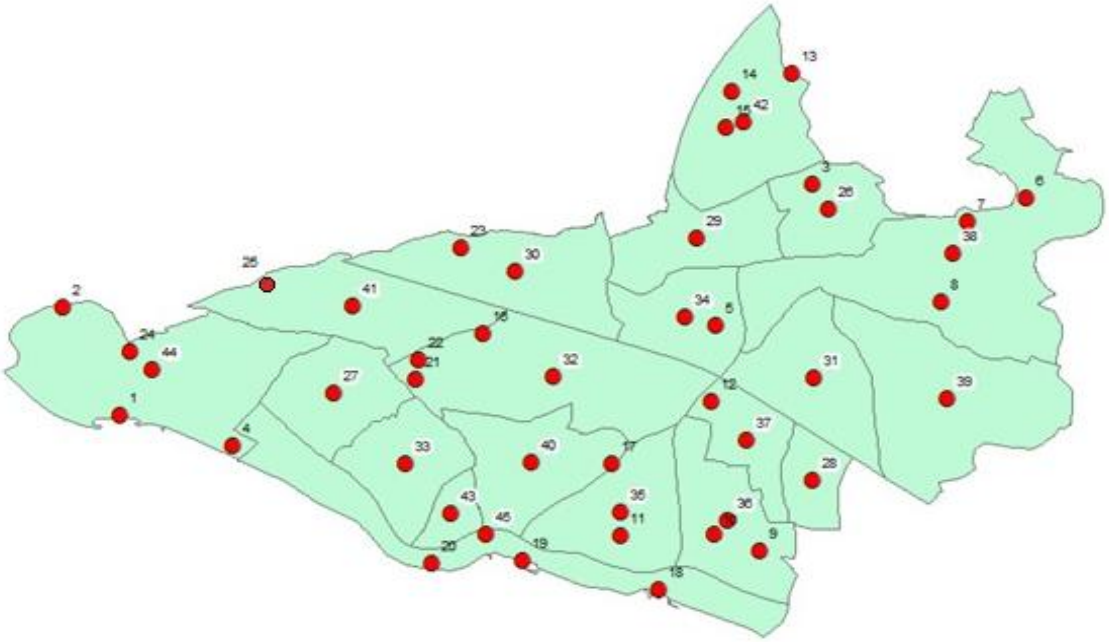

Figure 5-1. The Map of Kartal Data Set

To generate the distance data, ArcGIS is used. Given a road network of Kartal, in order to obtain the distance between the points representing demand locations, an Origin – Destination Matrix problem was defined by using the Network Analyst extension [73]. Recall that the green field network design problem needs a predefined central station. We assume that the point 32 is the central station due to its geographical centrality in Kartal district.

On the other hand, the larger data set includes 74 nodes which are attained through a similar prioritization demand point selection criteria. The aggregated demand points can be seen in Figure 5-2. The central station is taken as the 74th point.

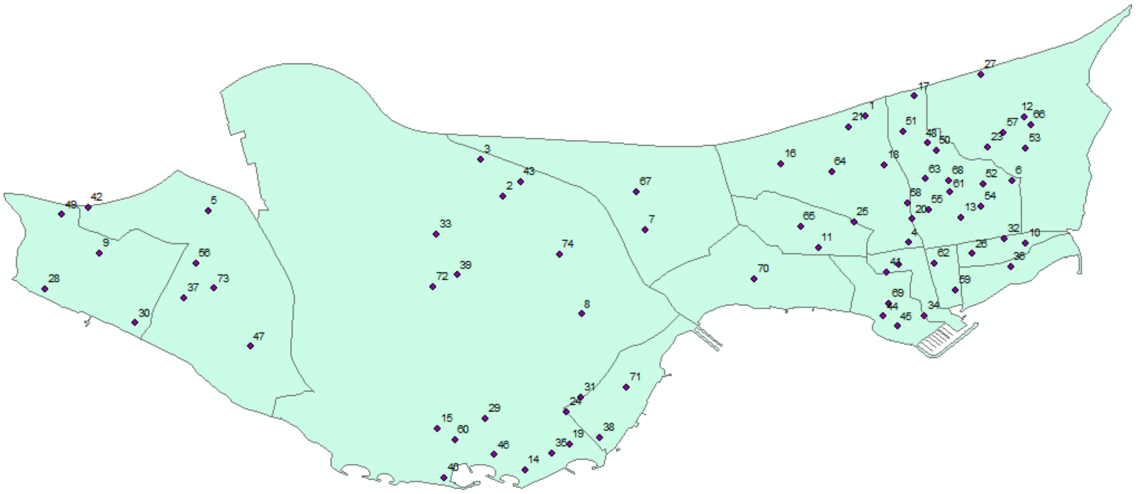

Figure 5-2. Bakırköy Data Set Map

All computational results are taken on a Linux environment with 4x AMD Opteron Interlagos 16C 6282SE 2.6G 16M 6400MT RAM 96GB 12x8GB DDR3-1600 ECC REG RoH.

In order to evaluate the run results, we try two different software packages for a set of instances; namely Gurobi 5.0.2 and Cplex 12.4. Table 5-1 shows the CPU performances of the two solver programs for the Kartal data set with the same parameters. In these analyses we do not use any valid inequalities. The first column of Table 5-1 shows the instance numbers, "GKx" refers the xth instance of green field problem. Alpha is the input parameter of the model. Objective function value and CPU performances of Cplex and Gurobi are shown in the consecutive columns.

Table 5-1. Comparison of Gurobi vs. Cplex Solver

#	**CPU (sec)**	
	Cplex	**Gurobi**
GK14	16.67	137.67
GK15	64.15	280.53
GK16	426.44	549.24
GK17	583.43	1365.21
GK18	918.07	1931.39
GK19	1555.85	2531.78
GK20	1903.58	3297.71

Obviously the performance of the model with Cplex solver outperforms that with Gurobi. Therefore, we decided to continue with Cplex solver for the remaining computations.

5.2. Green Field Model Results for Kartal Data Set

In the green field version of our problem, we aim to conduct a fiber optical network by using passive splitters. Since splitter types and capacities change, the insertion loss and bandwidth requirements have to be fulfilled accordingly. All passive splitters have different costs depending on their capacity. Besides there is a fiber optical wiring cost including its purchase, operation, wiring…etc. In the analyses of the model, we moderately alter the proportion between costs, namely, the alpha value. When alpha value is 1, it means that the model uses given passive splitter costs and fiber optical wiring cost. These costs are settled according to the data such as $c_{ij} = 1, \forall i, j \in N$ and $c_k = \{0, 12.5, 15, 20, 25\}$. The first type of passive splitter is specified for central station, hence the cost is zero. As the alpha value increases, the cost of a passive splitter becomes much more than the fiber optical wiring cost. Similarly, a decrease in the alpha value results in similar costs to each other. In other words, for very small alpha values, we are indifferent between using a passive splitter or wiring a fiber cable.

In order to evaluate the performances of the three valid inequalities, we compare some instances with and without valid equalities as sown in Table 5-2.

Table 5-2. Effect of Valid Inequalities in Green Field Problem

		No V.I.	**(1)**	**(2)**	**(3)**	**(1) , (2)**	**(1) , (3)**	**(2) , (3)**	**(1) , (2) , (3)**
GK13	**Best Bound**	71.76	71.76	71.76	71.76	71.76	71.76	71.76	71.76
α = 0.5	**CPU (sec)**	16.93	18.26	17.30	17.16	16.90	16.51	17.52	17.38
GK14	**Best Bound**	68.79	68.79	68.79	68.79	68.79	68.79	68.79	68.79
α = 0.45	**CPU (sec)**	77.56	81.74	74.13	76.24	79.25	75.58	79.47	77.40
GK15	**Best Bound**	65.83	65.83	65.83	65.83	65.83	65.83	65.83	65.83
α = 0.4	**CPU (sec)**	294.08	279.61	264.89	282.17	270.59	267.08	272.52	267.09
GK16	**Best Bound**	62.83	62.83	62.83	62.83	62.83	62.83	62.83	62.83
α = 0.35	**CPU (sec)**	1272.82	1102.63	1170.08	1381.16	1120.65	1148.26	1239.41	1248.27
GK17	**Best Bound**	59.79	59.79	59.79	59.79	59.79	59.79	59.79	59.79
α = 0.3	**CPU (sec)**	1669.68	1673.40	1748.00	1536.23	1601.35	1446.55	1472.25	1582.88
GK18	**Best Bound**	56.76	56.76	56.76	56.76	56.76	56.76	56.76	56.76
α = 0.25	**CPU (sec)**	1049.43	1202.82	977.18	1057.90	1049.55	952.07	1006.77	912.32
GK19	**Best Bound**	53.72	53.72	53.72	53.72	53.72	53.72	53.72	53.72
α = 0.2	**CPU (sec)**	3057.79	2650.60	2728.04	3186.08	2872.51	2776.08	3387.64	2723.43

”Best bound” shows the best bound in the root node.

In Table 5-2, it is shown that valid inequalities do not change the CPU in relatively simple instances such as GK13, GK14, and GK15. However, in more difficult cases, such as GK17, GK18, GK19, GK20 where the choice between locating a passive splitter or wiring fiber is harder, models with valid inequalities perform better in terms of CPU times. Note that the best bound in the root nodes are the same for the same parameters. Therefore, we include all valid inequalities in the remaining analyses.

Table 5-3 shows the green field model results for Kartal data set. The first column shows the instance number and the second one depicts the alpha parameter value of the model. The column “Level Number” refers to the number of layers of the resulting network. If there is only 1 level, it means that central station directly connects to every demand node. If it is 2, fiber optical wires reach some of the demand nodes over passive splitters. When the level number is 3, some fiber optical connection starts from central station and visits two passive splitters before reaching some of the demand nodes. In other words, level number shows the number of times that fiber optical wires need to pass over passive splitters and reach the demand point. The fourth column is the detail of the passive splitter used in the system. The representation “a:b” shows that a^{th} type passive splitter is used b times in the network. Objective function value is represented in the next column and lastly CPU performance can be seen in the terms of seconds.

Table 5-3. Green Field Results for Kartal Data Set

#	**α**	**Level Number**	**Passive Splitter Usage**	**Objective Function**	**CPU (sec)**
GK1	5	1	0	178.89	2.38
GK2	1.5	2	4:1	159.54	1.89
GK3	1.25	2	4:1	153.29	2.26
GK4	1	2	4:1	147.04	3.01
GK5	0.95	2	4:1	145.79	3.28
GK6	0.9	2	4:1	144.54	3.98
GK7	0.85	2	2:1, 4:1	143.25	4.56
GK8	0.8	2	2:1, 4:1	141.25	5.67
GK9	0.75	2	2:1, 4:1	139.25	6.94
GK10	0.7	2	2:1, 3:1, 4:1	137.11	9.7
GK11	0.65	2	2:1, 3:1, 4:1	134.11	12.34
GK12	0.6	2	2:1, 3:1, 4:1	131.11	9.89
GK13	0.55	2	2:1, 3:1, 4:1	128.11	10.82
GK14	0.5	2	2:1, 3:1, 4:1	125.11	16.75
GK15	0.45	2	2:2, 3:1, 4:1	121.80	62.22
GK16	0.4	2	2:2, 3:1, 4:1	118.05	444.6
GK17	0.35	3	1:2, 2:2, 3:3	113.39	625.05
GK18	0.3	3	1:2, 2:6, 3:1	106.96	946.74
GK19	0.25	4	1:3, 2:6, 3:1	99.99	1411.65
GK20	0.2	4	1:3, 2:6, 3:1	92.62	1647.33
GK21	0.15	(4)	(1:4, 2:6, 3:1)	(85.16)	Gap After 2 hours 0.93%
GK22	0.1	(4)	(1:5, 2:6, 3:1)	(76.89)	Gap After 1 Hour 4.57%
GK23	0.05	(4)	(1:11, 2:5)	(67.24)	Gap After 2 Hours 6.68%
GK24	0	(5)	(1:23, 2:1)	(53.11)	Gap After 2 Hours 7.96%

As shown in Table 5-3, the CPU performances vary a lot. The minimum CPU time is 1.89 sec, but there are unsolvable instances in 2 hours. In the detailed analyses of Kartal data set for the Green field, we first aim to find the alpha value for which no passive splitters are established. Instance GK1 (where α is 5) shows the result when there are fiber optical wires from central station to all demand nodes with a star structure as shown in Figure 5-3.

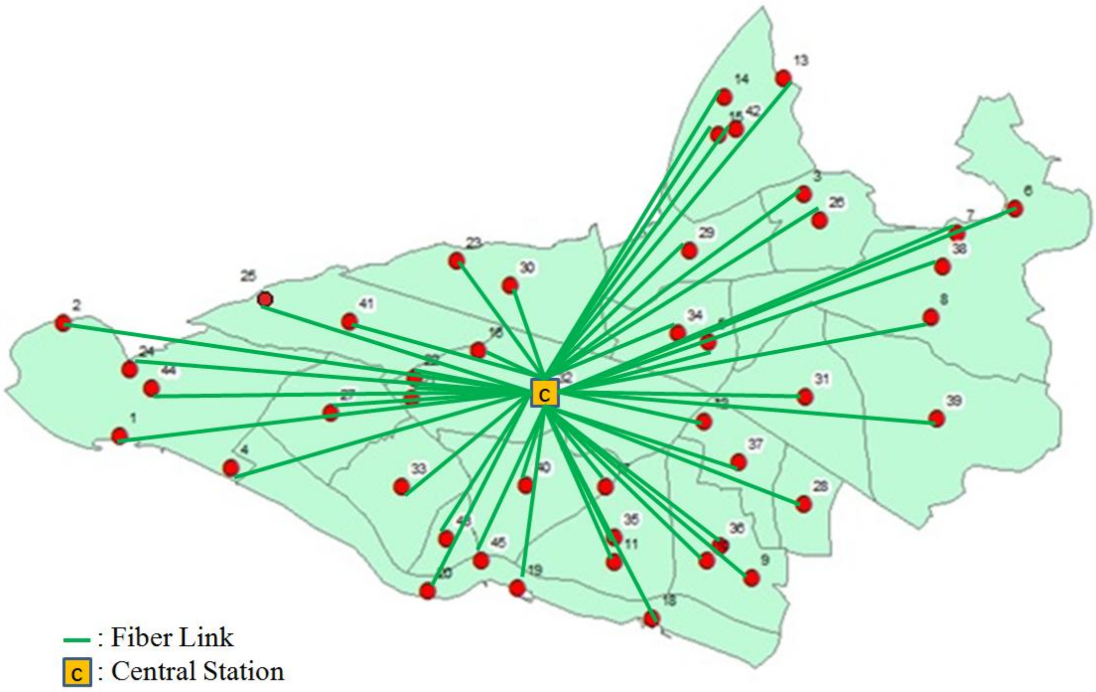

Figure 5-3. Illustration of GK 1

In this instance, passive splitter usage costs are so high that the model chooses not to use any passive splitters. The objective function value for this instance is 467.67. However, in much smaller α values, such as Instance GK4 where alpha is 1, wiring cost and passive splitter cost are relatively close to each other and the model utilizes passive splitters; as shown in Figure 5-4.

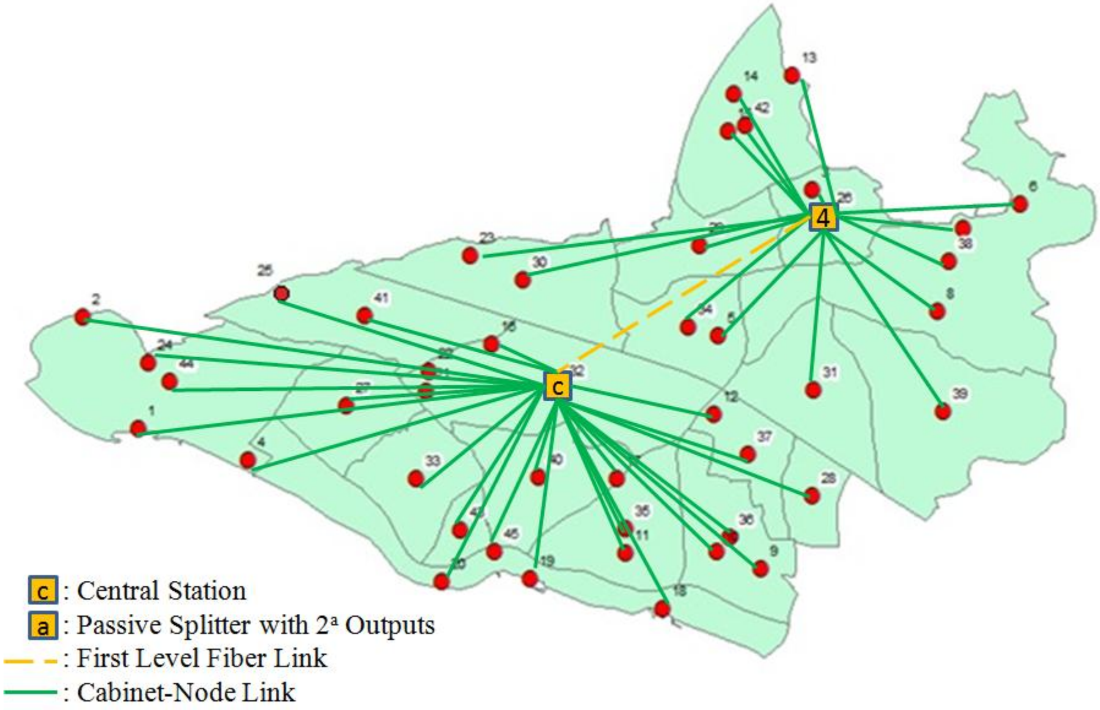

Figure 5-4. Illustration of Instance GK 4

Instead of making a star structure from supply to all demand nodes, using a distribution point becomes more desirable. For this Instance GK 4, a single passive splitter with 2^4 outputs is used. This time, the objective function value decreases to 147.03. In other words, using a single fiber wire up to a certain point and then splitting fibers to the 16 demand nodes gives smaller cost.

Also, we observe that as we decrease α value, the number of passive splitters that are used in the network increases as can be seen in Instances GK6, GK8, GK10. In GK6, there is only a single 4th type of passive splitter, whereas in GK8, 2nd type is added and 3rd type is also used in GK10.

Interestingly, between Instances GK14 and GK15, although the α value decreases by only 0.05, one more 2^{nd} type passive splitter is used in Instance GK15. This shows that small changes in α value may have significant impact in the solution.

Similarly, from Instance GK 18 (Figure 5-5) to Instance GK 19 (Figure 5-6), the α value decreases by only 0.05. But in these instances, not only the number of passive splitter number increases but also the number of levels increase.

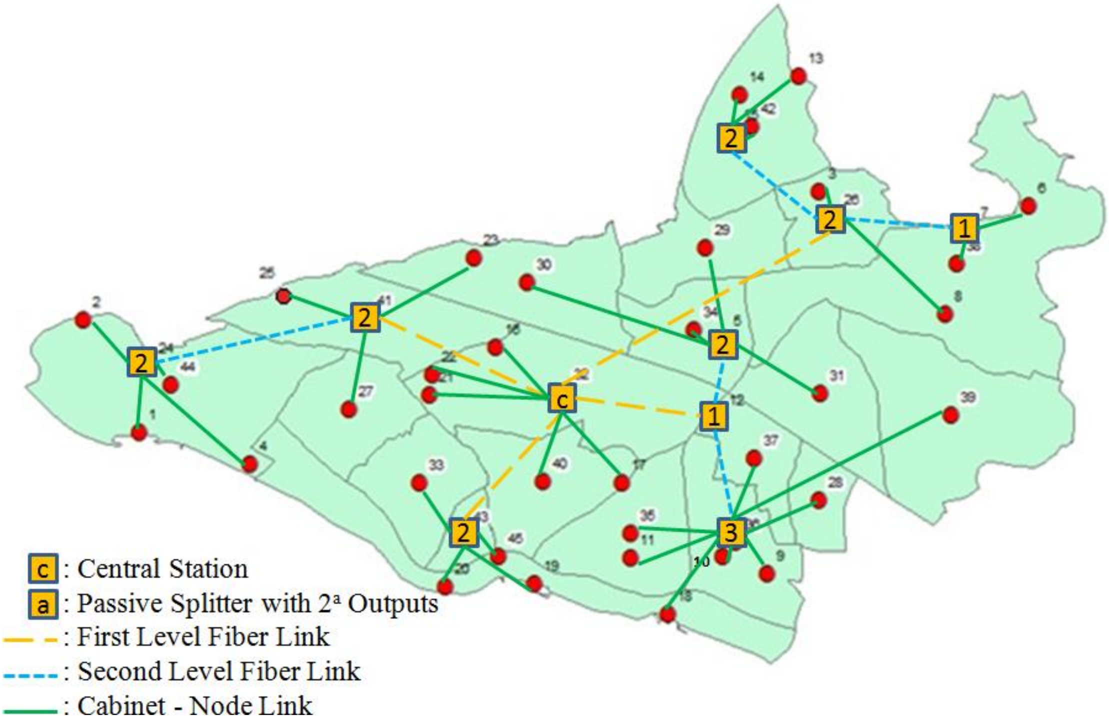

Figure 5-5. Illustration of Instance GK 18

Until Instance GK 19, there are at most 3 levels (hops) from the central station. In other words, from any demand node, the central station can be reached via 3 different fiber optical wires. At each level, there are passive splitters. Hence, at most 2 passive splitter stops are enough to reach a demand point from the central station. However, in Instance GK 19, some of the demand nodes need to visit 3 passive splitters to access higher bandwidth Internet access.

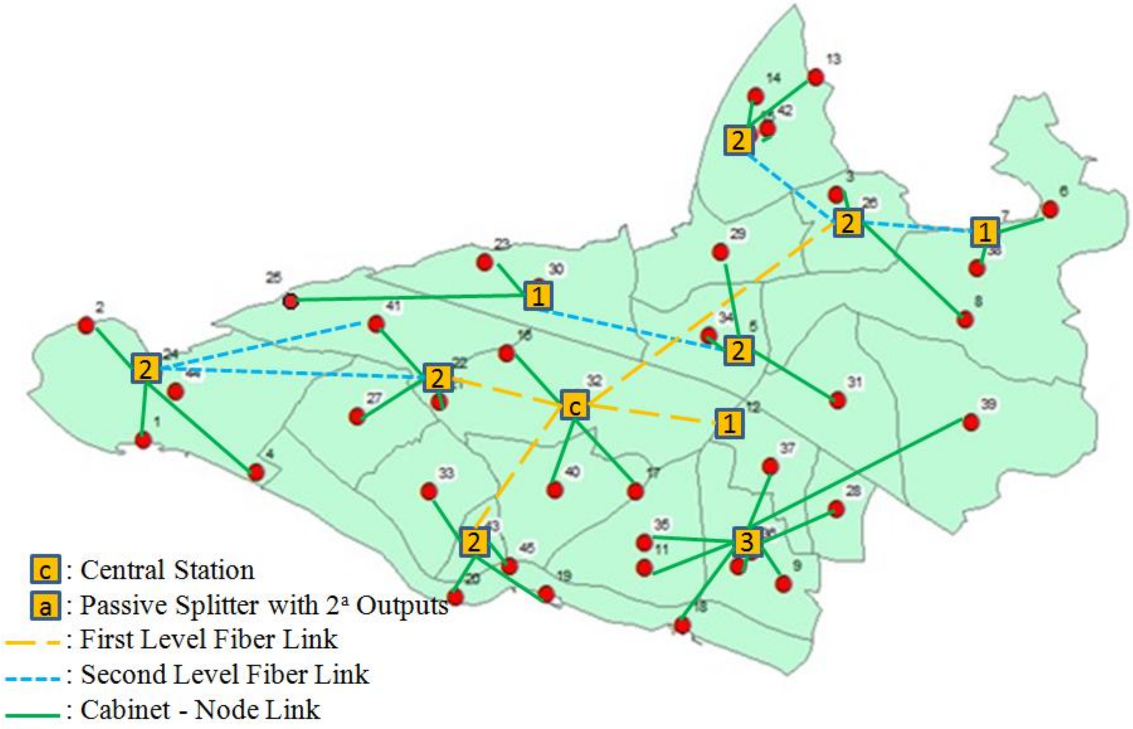

Figure 5-6. Illustration of Instance GK 19

Another interesting observation is between Instances GK 17 and GK 18. Although both network designs have 3 levels, their structures are totally different. In Instance 17, there are seven passive splitters; two 1st type, two 2nd type and three 3rd type, as shown in Figure 5-7.

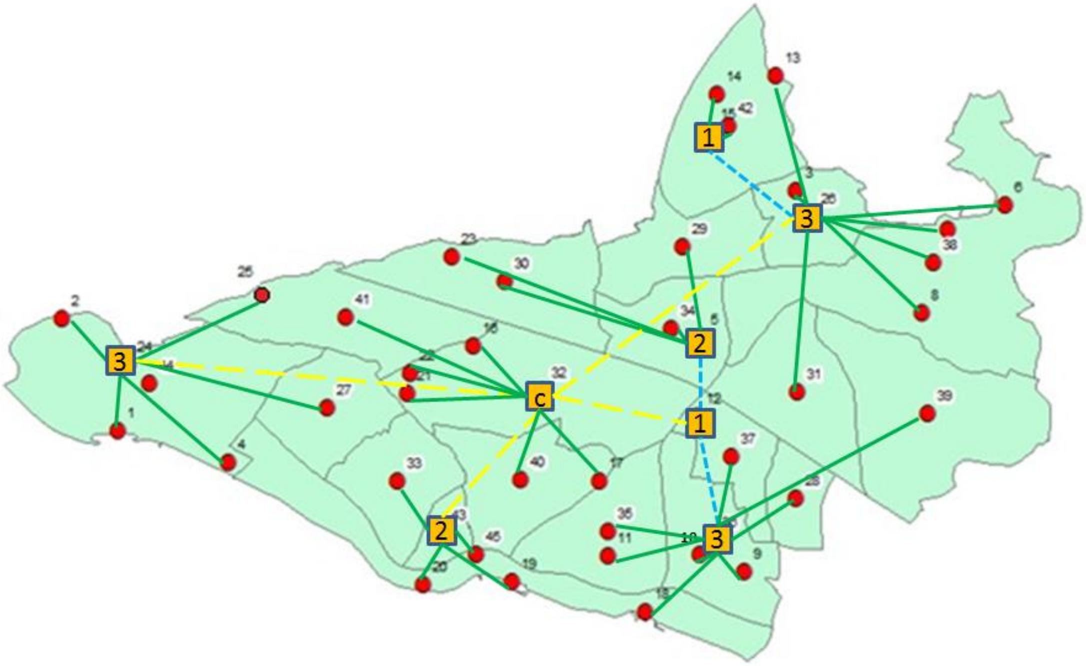

Figure 5-7. Illustration of GK 17

Similarly, there are only two 1st type passive splitters used in Instance GK 18. However, instead of using three 3rd type passive splitters, there is only one in Instance GK18. Since each 3rd type refers to $2^3=8$ outputs, these 16 outputs are provided via 2nd type passive splitters. In GK 18, there are four more 2nd type passive splitters. This allows $4 \times 2^2 = 16$ outputs to be used via second type passive splitters. This again illustrates the fact that very small changes in α value may affect the structure of the designed network drastically.

5.3. Green Field Model Results for Bakırköy Data Set

In order to observe the performance of the model developed for the green field network design problem for larger data sets, we performed similar computational analyses over a larger network; Bakırköy data set. Similar to the Kartal data set example, we first aim to find the range for the α parameter. This range begins by using only fiber optical wires and ends in the point that there is no cost for passive splitter usage. Table 5-4 depicts the run results for different α values. For the cost structure of fiber optical wires and passive splitters, we use the same costs as in the Kartal data set. However, for this data set, in order to attain applicable results, α value needs to be taken bigger than the corresponding value of the Kartal data set. The α value starts from 0 (Instance GB1) in order to analyse when passive splitters have no cost and increases up to 5 where there is no passive splitter usage (Instance GB11).

Table 5-4. Green Field Results for Bakırköy Data Set

#	**α**	**Stage Number**	**Passive Splitter Usage**	**Objective Function Value**	**CPU (sec)**
GB1	0	(2)	(3:2 , 4:3)	(233.63)	Gap After 1 Hour 8.54%
GB2	0.5	(2)	(4:4)	(176.22)	Gap After 1 Hour 12.69%
GB3	1	(2)	(3:2 , 4:3)	(233.64)	Gap After 1 Hour 8.54%
GB4	1.5	(2)	(3:2 , 4:2)	(289.40)	Gap After 1 Hour 6.35%
GB5	2	(2)	(3:1 , 4:2)	(335.64)	Gap After 2 Hours 4.53%
GB6	2.5	2	4:2	369.51	635.02
GB7	3	2	4:2	394.51	221.65
GB8	3.5	2	4:2	419.51	50.01
GB9	4	2	4:2	444.51	48.49
GB10	4.5	2	4:1	457.89	16.67
GB11	5	1	0	467.67	6.31

Beginning from alpha value 0 until alpha is 2, the model can not be solved exactly in 2 hours as shown in Instances GB1-GB5. However, it should be noted that, the time to get the exact solution for the rest of the table is less than 11 minutes.

In Instance GB6, there are only two passive splitters and both are of type 4. These two passive splitters split incoming fiber optical wire into 16 different cables. Therefore, only visiting at most a single passive splitter is enough to reach each demand node. This shows that although Bakırköy data set has more demand nodes than Kartal data set, it can be served in two stages. One reason for that is the geographical span of the Bakırköy data set. Bakırköy is a more narrow area, hence its demand nodes are closer to each other. The second reason is the insertion loss and bandwidth requirements. Since there are more demand nodes in closer distances, the solutions use less passive splitters with more splitting capabilities and splits in near to demand nodes. As can be seen from Bakırköy map in Figure 5-2, demand nodes are located as clusters. When splitter is close to one of these clusters and then splits to various nodes, the length of the aggregated fiber wire gets longer. Hence, it gives a much smaller cost than that of having fiber optical wiring to each demand node.

For the instances GB6-9, the model gives same network structure as the solution. Since their alpha values are different, the multiples of passive splitters changes. Hence, although fiber optical wire costs are the same in all instances, the passive splitter usage cost differs due to alpha value. Therefore, GB6, GB7, GB8 and GB9 have different objective function values.

When we make a 0.5 increment in alpha value in Instance GB10, the passive splitter usage becomes too expensive. Therefore, in the solution only one of the passive splitters is utilized and there is a direct connection from central station to the rest of the demand nodes.

Another extreme case is Instance GB11. In this instance, the passive splitter usage is so expensive that all nodes are directly connected to the central station corresponding to the high cost value of 467.67.

5.4. Further Trials on the Model

For further analysis of the green field network design model, consider constraints (4.1.2), (4.1.4) and (4.1.5). (4.1.2) satisfies the customer satisfaction, where x is the binary fiber link and y is the location decision of passive splitter. Since the demand satisfaction can be provided with fiber link to each demand node, the first part of the (4.1.2) can be omitted and the constraint (4.1.2) can be replaced with (4.1.2’).

$$\sum_{i\in N|j} x_{ij} \geq 1 \qquad \forall j \in N, j \neq central \quad (4.1.2’)$$

(4.1.2’) ensures that ever demand node needs to have an incoming fiber link. Since (4.1.2’) ensures the reachability of each demand node, the necessity of flow balance constraints (4.1.4) and (4.1.5) can be discussed. Due to minimization aim in the objective function, the passive splitter is only located for splitting wires and reaching more demand points. To make comparison and understand the effect of each constraint, Table 5-5 is conducted.

Table 5-5. Comparison of Trials

	Constraints	**Model Formulation**				
	(4.1.2')	**Original Model Results**	**Yes**	**Yes**	**Yes**	**Yes**
	(4.1.4)		**Yes**	**No**	**Yes**	**No**
	(4.1.5)		**Yes**	**No**	**No**	**Yes**
GK15	**Best Bound**	444.6	527.07	247.37	270.28	309.89
α = 0.4	**CPU (sec)**	65.8268	69.8289	69.8289	69.8289	69.8289
GK16	**Best Bound**	625.05	939.46	1418.73	677.83	1308.35
α = 0.35	**CPU (sec)**	62.8247	66.7039	66.7039	66.7039	66.7039
GK17	**Best Bound**	946.74	907.23	1113.11	815.99	1496.09
α = 0.3	**CPU (sec)**	59.7924	63.5350	63.5350	63.5350	63.5350
GK18	**Best Bound**	1411.65	1396.1	1277.05	1126.89	1521.32
α = 0.25	**CPU (sec)**	56.7601	60.3319	60.3319	60.3319	60.3319
GK19	**Best Bound**	1647.33	2125.11	2076.42	1636.38	3503.42
α = 0.2	**CPU (sec)**	53.7209	57.1288	57.1288	57.1288	57.1288

According to Table 5-5, although the best LP bound at the root node does improve in further model variations, there is no particular gain in the CPU performances.

Also, note that when we use (4.1.2) without (4.1.4) or (4.1.5), the model assumes the demand satisfaction can be handled by putting passive splitters without necessity of connection to the rest of the fiber wires. Therefore, using (4.1.2) and omitting (4.1.4) or (4.1.5) or both, will give wrong results.

Chapter 6

Computational Results for the Copper Field

Recall that in the network re-design problem of the copper field, we assume there is a copper wired network which spans all demand nodes over the copper loops. Thus, for computational analyses, we need to construct the existing copper loops for both of the data sets.

6.1. Copper Field Re-design Model Results for Kartal

In order to create a pre-built copper ring infrastructure, we used a nearest neighbor based greedy clustering algorithm. We fix a particular distance capacity as the maximum length of a copper ring. The algorithm starts with an arbitrary node and keeps visiting neighbors in a nearest neighbor fashion as long as the tour length does not exceed the specified distance capacity. When the threshold is exceeded, another ring infrastructure is constructed. Kartal region necessitated 4 copper loops with distance capacity of 20 km. Note that none of the copper loops include the central station. For simplicity we differentiate each node in the same copper loop by painting same color as shown in Figure 6-1.

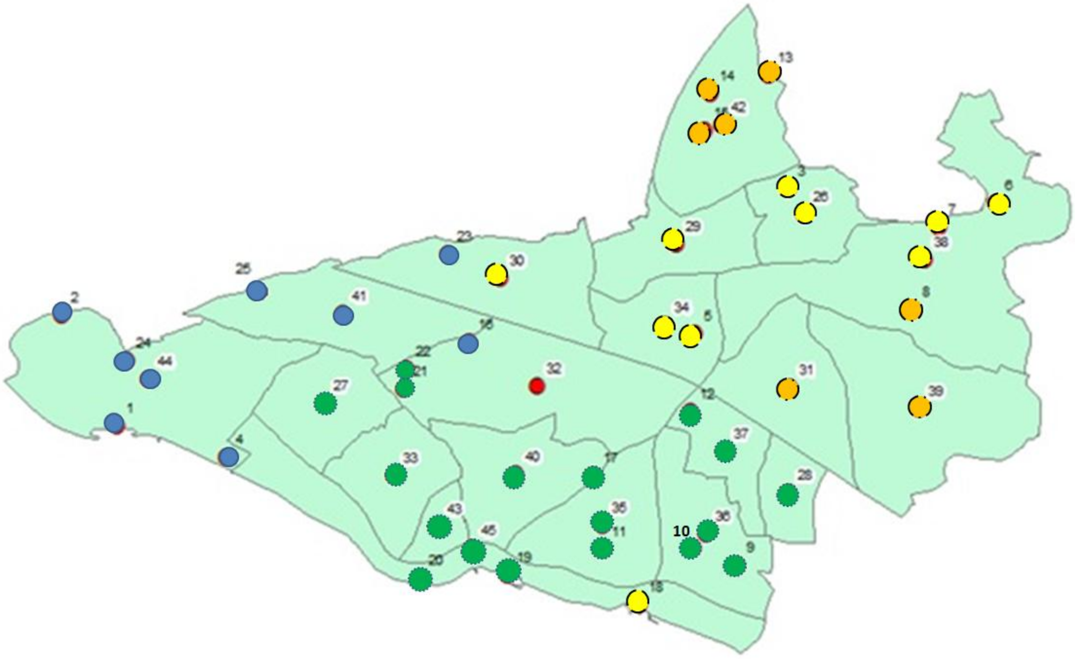

Figure 6-1. Illustration of Copper Loops

Since the algorithm starts with an arbitrary node and augments with the nearest neighboring strategy, the last loop is constructed from the right over nodes. In our algorithm, the last copper loop is the orange one. Therefore, it seems like divided into two and far from each other.

As explained previously, we aim to find the locations of cabinets and the additional cabinet-node link(s) to cover all customers. These coverages depend on three main parameters, namely, γ value, number of cabinets (*p*) and distance threshold (*H*). When a cabinet is located within the threshold value distance to a demand node, that node is assumed to have faster Internet access; as having a Fiber-to-the-Cabinet service. As explained in Chapter 4, the γ value shows the coverage distance of a cabinet over a copper loop. When a demand node can not be covered in this γ value, then a cabinet-node fiber link is built from the closest cabinet. The number of cabinets (*p*) is another input parameter which decides the cabinet number in the network. Finally, each demand node needs to be within a distance of threshold length from the central station. In Sections 6.1.1 – 3, we look for a meaningful range for these input parameters: γ, p and H as coverage distance, number of cabinets and distance threshold value.

6.1.1. Effect of the γ Value

In order to evaluate the effect of the γ value over the network design for the Kartal data, we evaluate the value in the range as shown in Table 6-1. The first column shows the instance number such that "CK x" shows xth instance of copper field re-design problem of Kartal data set. The second column is the value of γ where the third one corresponds to the total cabinet number in the network. The distance threshold value is the maximum allowance of the distance from central station to any demand node, which is provided in the fourth column. The fifth column presents the number of fiber optical wire links between a cabinet and a node in the solution. The objective function value and CPU performances are depicted in the last two columns.

Table 6-1. Effect of γ Value

#	**Parameters**			**Results**		
	γ	***p***	***H***	**# of Cabinet-Node Link**	**Objective Function Value**	**CPU (sec)**
CK 61	0	4	50	40	92.169	6.98
CK 62	1	4	50	37	89.392	7.7
CK 63	2	4	50	30	80.099	9.39
CK 64	3	4	50	24	72.257	9.09
CK 65	4	4	50	19	62.839	10.82
CK 66	5	4	50	14	51.779	9.77
CK 67	6	4	50	12	44.131	10.5
CK 68	7	4	50	8	35.4	10.77
CK 69	8	4	50	5	27.494	11.62
CK 70	9	4	50	1	16.062	5.95
CK 71	10	4	50	0	14.404	3.9

As mentioned earlier, there are 45 nodes in the network including the central station. If the γ value is zero, it means that no demand node can be considered as covered via the cabinet. Since one of them is the central station, there are 44 demand nodes and we expect 44 cabinet-node links. We select 4 cabinets in our analysis in order to locate a single cabinet for each copper ring. Also, the distance threshold value is selected as a very large value corresponding to practically the uncapacitated case. Thus, for Instance CK 61, our model installs 40 cabinet-node links as expected.

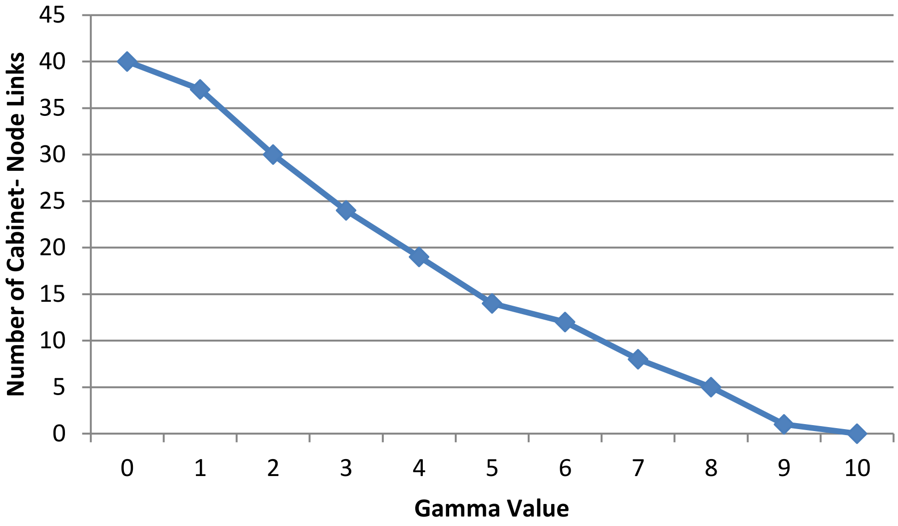

Figure 6-2. Effect of γ Value

We increase the γ value with equal intervals up to the point where with the γ coverage, all demand nodes are served without any additional fiber links. This value is 10 for the Kartal data set. Note that for the corresponding instance, namely Instance CK 71, the number of cabinet-node links is zero. Therefore, the γ value begins with 0 and increases up to 10. There is no need to increase the γ value beyond 10 since the objective function value will not change. Figure 6-2 depicts the inverse relation between the γ value and the cabinet-node links (and consequently the objective function value).

6.1.2. Effect of Number of Cabinets (*p*)

The solution of the copper field re-design problem also depends on the number of cabinets that needs to be installed as shown in Table 6-2.

Table 6-2. Effect of Number of Cabinets

#	**Parameters**			**Results**		
	γ	***P***	***H***	**# of Cabinet-Node Link**	**Objective Function**	**CPU (sec)**
CK 72	5	1	50	infeasible		
CK 73	5	2	50	29	9.3722	11.75
CK 74	5	3	50	20	6.7133	12.94
CK 75	5	4	50	14	5.1779	10.24
CK 76	5	5	50	10	4.0623	10.35
CK 77	5	6	50	6	3.3791	60.95
CK 78	5	7	50	1	2.6767	14.78
CK 79	5	8	50	0	2.5303	75.87

In our experimentations, we increase the number of cabinets one by one. When we put a single cabinet into the system, there is no solution. When we add 8 cabinets into the Kartal data, all nodes can be covered without any cabinet-node links (for $\gamma=5$). For analysis, we used a γ value of 5,59 which is the mid value of the previous analysis. The distance threshold value is again taken as 50, which corresponds to a practically uncapacitated case.

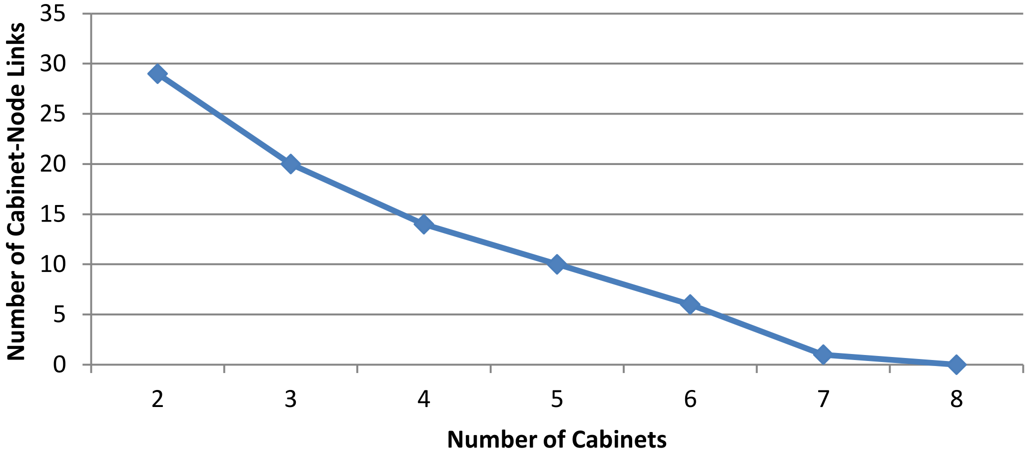

Figure 6-3. Effect of Number of Cabinets

Figure 6-3 shows the decrement in the number of cabinet-node links, as the number of cabinets increases. When there are 8 cabinets, there is no need for any fiber links in this data set.

6.1.3. Effect of Distance Threshold (*H*)

The results are also sensitive to the distance threshold value. In this analysis, we again use γ value as 5. Distance threshold values are taken as 10, 20 and 30 for the Kartal region. Beyond 30, there is no change in the objective function value. As long as the threshold decreases, the infrastructure of the network changes. The results are depicted in Table 6-3 for $\gamma = 5$, $p = \{2, 4, 6, 8\}$ and $H = \{10, 20, 30, 40, 50\}$.

Table 6-3. Effect of Distance Threshold

#	Parameters			Results	
	Gamma Value	# of Cabinets	Distance Threshold	Objective Function Value	CPU (sec)
CK 1	5	2	10	115.19	0.07
CK 2			20	93.72	9.25
CK 3			30	93.72	11.31
CK 4			40	93.72	9.77
CK 5			50	93.72	10.51
CK 6		4	10	60.62	92.6
CK 7			20	51.78	11.76
CK 8			30	51.78	9.64
CK 9			40	51.78	10.93
CK 10			50	51.78	9.19
CK 11		6	10	41.52	719.26
CK 12			20	35.51	88.19
CK 13			30	33.79	19.23
CK 14			40	33.79	66.17
CK 15			50	33.79	50.94
CK 16		8	10	(36.78)	Gap After 2 Hours is 16.61%
CK 17			20	28.59	305.08
CK 18			30	25.30	53.52
CK 19			40	25.30	57.11
CK 20			50	25.30	55.57

6.1.4. Detailed Computational Analysis for Kartal Data Set

For the analysis of different γ values, we ranged γ as 1, 3, 5, 7 and 10. Table 6-4 depicts the results. We omit the instances after break points of the corresponding distance threshold values beyond which the objective value remains the same; i.e., *H* after 20 for p=2, 4 and after *H* after 30 for p=6 ,8 where γ = 1, 3; similarly, *H* after 20 remains same where γ is 7 and 10.

Table 6-4 (a). Copper Field Results for Kartal Data Set

#	Parameters			Results	
	Gamma Value	# of Cabinets	Distance Threshold	Objective Function Value	CPU (sec)
CK 21	1	2	10	136.79	0.15
CK 22			20	119.49	6.21
CK 23			30	119.49	5.54
CK 24		4	10	96.98	70.65
CK 25			20	89.39	9.79
CK 26			30	89.39	8.86
CK 27		6	10	87.49	5519.15
CK 28			20	78.43	131.73
CK 29			30	76.14	14.24
CK 30		8	10	(81.28)	Gap After 1 Hour 14.54%
CK 31			20	69.99	581.13
CK 32			30	67.54	265.41
CK 33	3	2	10	125.85	0.05
CK 34			20	107.17	6.26
CK 35			30	107.17	7.29
CK 36		4	10	79.61	14.85
CK 37			20	72.26	10.91
CK 38			30	72.26	9.15
CK 39		6	10	62.55	636.77
CK 40			20	55.50	61.74
CK 41			30	52.77	19.27
CK 42		8	10	(55.05)	Gap After 1 Hour 17.72%
CK 43			20	42.01	62.36
CK 44			30	39.28	9.7

Table 6-4 (b). Copper Field Results for Kartal Data Set

#	Parameters			Results	
	Gamma Value	# of Cabinets	Distance Threshold	Objective Function Value	CPU (sec)
CK 45	7	2	10	109.57	0.07
CK 46			20	80.22	9.71
CK 47		4	10	39.46	12.37
CK 48			20	35.40	11.97
CK 49		6	10	27.19	330.67
CK 50			20	22.89	96.57
CK 51		8	10	(27.20)	Gap After 2 Hours 9.90%
CK 52			20	19.72	168.34
CK 53	10	2	10	76.91	0.03
CK 54			20	55.50	4.72
CK 55		4	10	17.75	5.01
CK 56			20	14.40	3.4
CK 57		6	10	17.81	61.37
CK 58			20	14.99	27.45
CK 59		8	10	19.94	455.12
CK 60			20	16.05	199.06

Observe from Table 6-4 that, when we increase γ, for fixed p and H, the objective function value, which is directly related with fiber link, decreases. For example; when we compare Instance CK 21 and CK 33, the cabinets can cover more demand nodes due to increase in the cover threshold. Since the coverage increases, the cabinet-node links decrease. Hence, the objective function value decreases. Similarly, the objective function value decreases from Instance CK 25 to CK 37.

The effect of the number of cabinets can be observed at Instances CK 3, CK 8, CK 13 and CK 1 of Table 6-3. For fixed $\gamma = 5$ and $H = 30$, the increase in the number of cabinets provides more coverage from the cabinets. Hence, the objective function value decreases.

Although the model can solve the Kartal data in moderate times, challenging parameter combinations exist. In particular, when γ value is 7 and there are 8 cabinets in the system, the *H* value of 10 can not be solved in 2 hours as shown in Instance CK 51.

Another observation is about the sensitivity of the objective function value to the number of cabinets. When the γ value is 10, and distance threshold value is 10, the objective function value changes for different number of cabinets. When the number of cabinets is 2, the objective function value is 76.91, in Instance CK 53 as shown in Figure 6-4. The model chooses the two cabinets at blue and green loops (one for each). Observe here that even though there are many other nodes which are still close enough (within γ) to the cabinets, they still need a fiber access since they do not have a copper link to the opened cabinets.

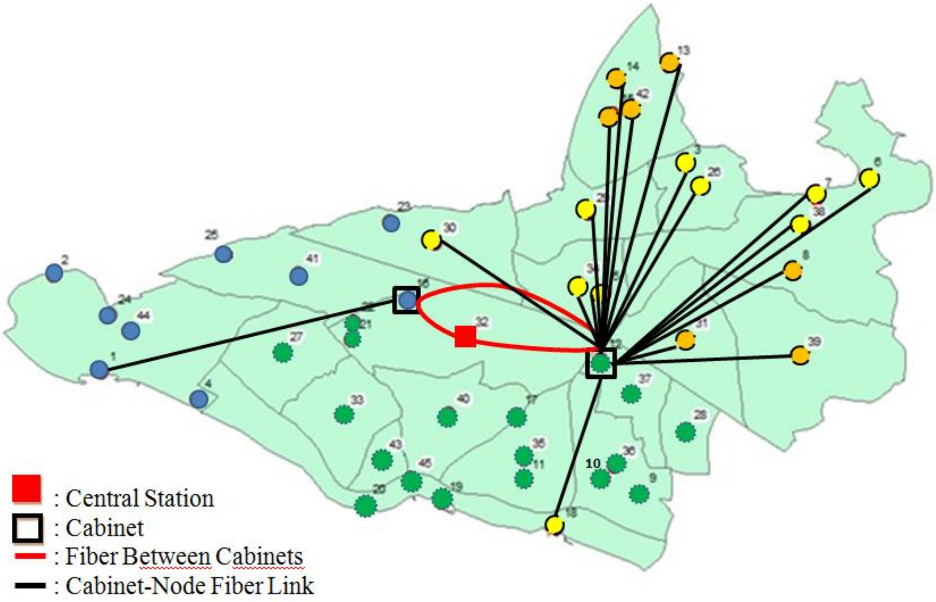

Figure 6-4. Illustration of Instance CK 53

However, for 4 cabinets, this value decreases to 17.75 (Instance CK 55) since 4 cabinets can cover all nodes without the need for any fiber cabinet-node link, as shown in Figure 6-5.

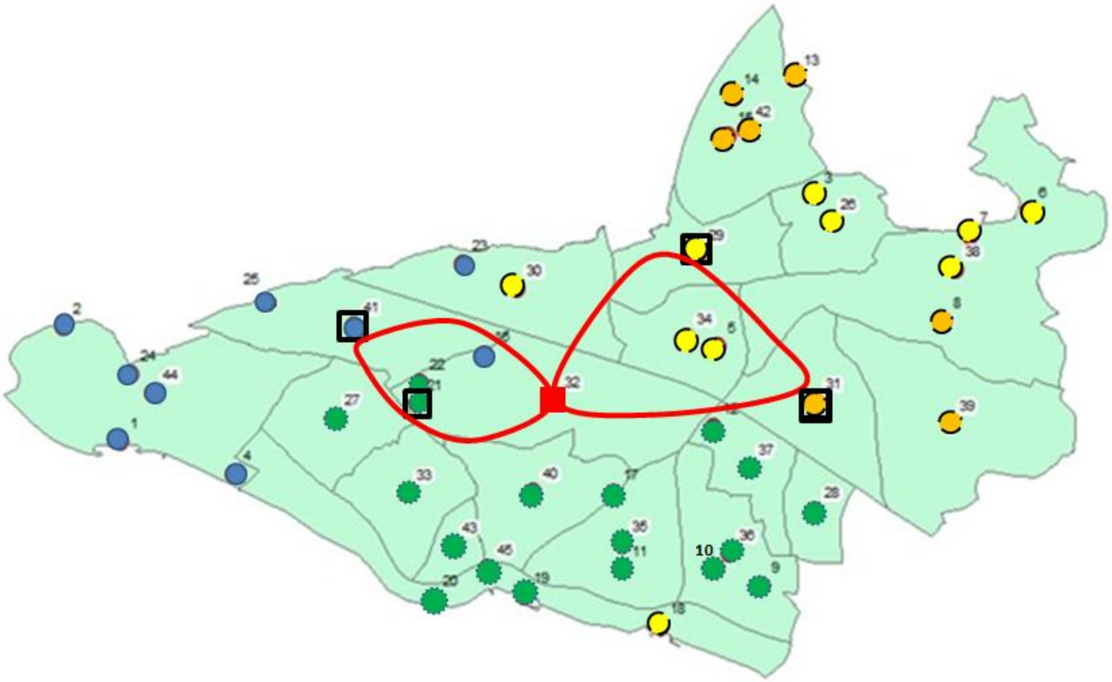

Figure 6-5. Illustration of Instance CK 55

Interestingly, when we continue to increase the number of cabinets, the objective function starts to increase. From Instance CK 55 to Instance CK 57, the number of cabinets increases by 2. In Instance CK 57, there are 6 cabinets and the loop around cabinets needs more usage of fiber optical wire which causes additional cost in the objective function value (Figure 6-6).

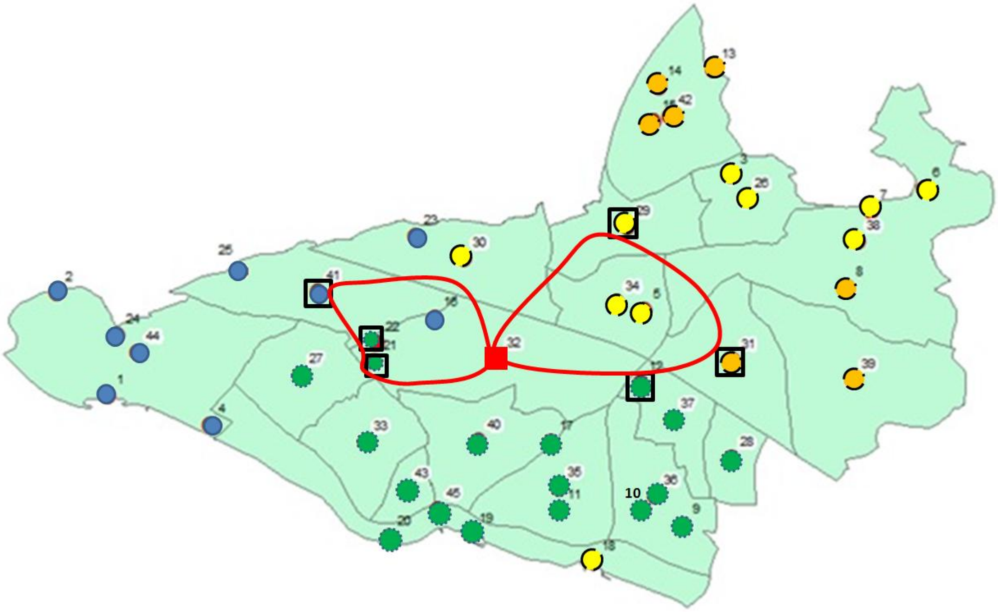

Figure 6-6. Illustration of Instance CK 57

Finally, when we add 2 more cabinets in the Instance CK 59, the objective function value rises to 19.94, as shown in Figure 6-7. This increase in the objective function value shows that the network does not need as that much of cabinets.

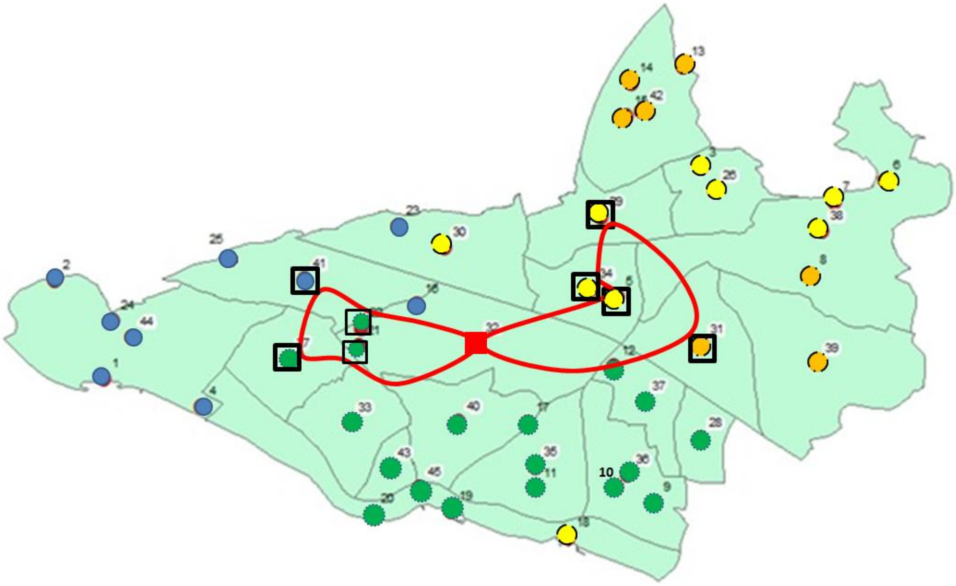

Figure 6-7. Illustration of Instance CK 59

6.1.5. Computational Results with Premise Nodes in Kartal Data Set

As explained in Chapters 2 and 4, premise nodes are special customer nodes that need to connect each other with fiber optical wire. Up until now, we analyzed the performance of the models when there are no premise nodes in the data set (i.e., $= \emptyset$). We now provide some results when data set does include premise nodes. For this analyses, we select three clusters of premise nodes: first one is {7, 38}, second one is {7, 9, 10, 36, 38} and last one is {1, 2, 7, 9, 10, 24, 36, 38, 44}. For the computational analyses, we test them for three different γ, p and H values. Our findings are summarized in Table 6-5.

Table 6-5. Copper Field with Premise Nodes for Kartal Data Set

#	Parameters				Results	
	γ	**p**	**H**	**Premise Nodes**	**Objective Function**	**CPU (sec)**
CKP 1	0	4	50	7,38	92.39	7.91
CKP 2			50	7,9,10,36,38	93.12	6.78
CKP 3			50	1,2,7,9,10,24,36,38,44	95.56	7.24
CKP 4	5	6	30	7,38	34.68	14.11
CKP 5			30	7,9,10,36,38	40.79	16.84
CKP 6			30	1,2,7,9,10,24,36,38,44	48.69	14.05
CKP 7	10	8	10	7,38	22.71	1500.92
CKP 8			10	7,9,10,36,38	29.14	4644.87
CKP 9			10	1,2,7,9,10,24,36,38,44	41.37	6173.74

The first observation is about the objective function value. As the number of premise nodes increases, the number of fiber link between premise nodes increases. For example, Instance CKP 4 has two premise nodes. The objective value is 34.68. When we add three more premise nodes (Instance CKP 5), the objective function value rises to 40.79. For the final one where premise nodes are {1, 2, 7, 9, 10, 24, 36, 38, 44} in Instance CKP 6, the objective function value increases to 48.69.

Similar observation about the increase in the γ value and cabinets can be seen in these instances with premise nodes. From Instance CKP 2 to Instance CKP 5, both γ value and number of cabinets increases whereas premise nodes remain same. Although premise nodes exist, as the γ value and number of cabinets increase from 0 to 5 and 4 to 6, sequentially, more demand nodes can be covered. Hence, the need for cabinet-node links and objective function value decrease.

For comparison purpose, we refer to Figure 6-7 where γ value is 10, *p* is 8 and *H* is 10. When we add two premise nodes, as node 7 and node 38, the objective function value augments from 19.94 (Instance CK 59) to 22.712 (Instance CKP 7). This augment is due to the fiber link between premise nodes as shown in Figure 6-8.

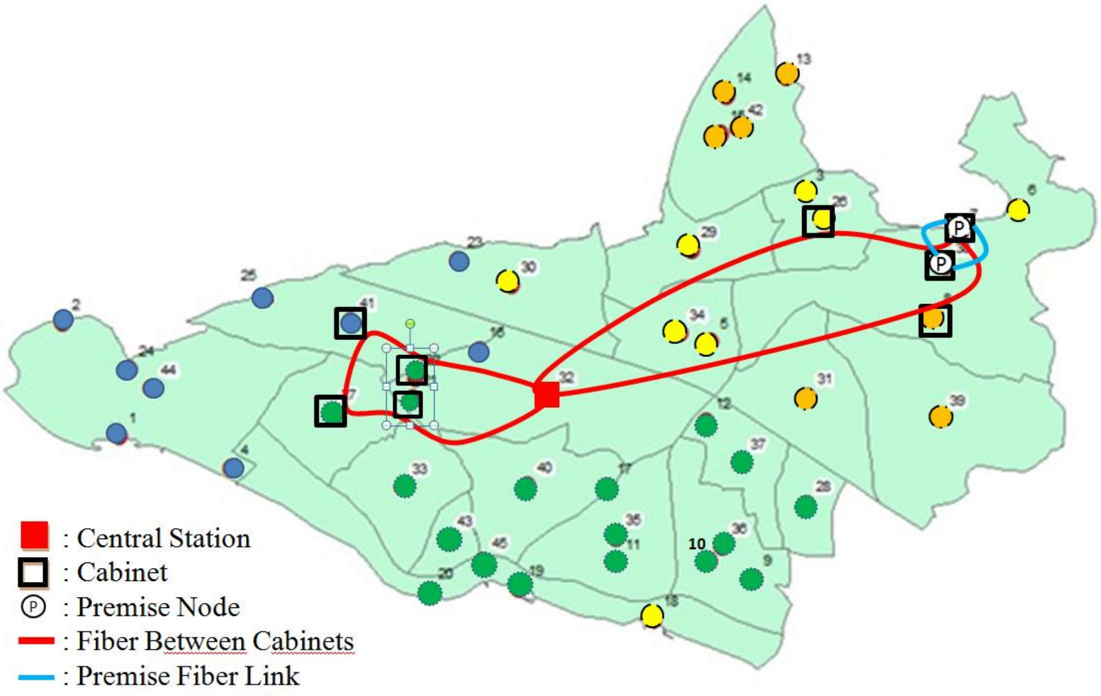

Figure 6-8. Illustration of Instance CKP 7

Interestingly, in addition to node 7 and 38, when we add nodes 9, 10, 36 to the premise node set, the cabinet locations change to minimize the total fiber length (Figure 6-9).

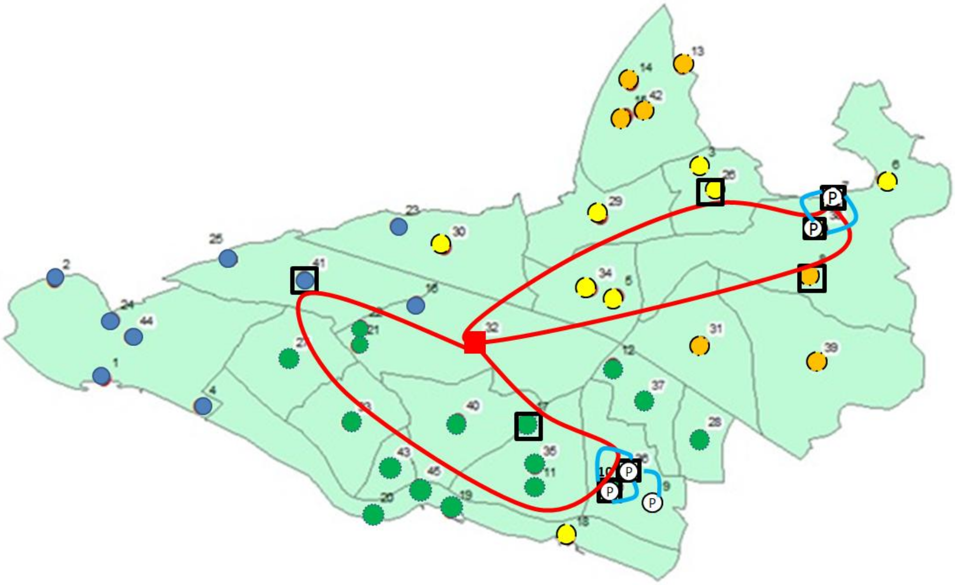

Figure 6-9. Illustration of Instance CKP 8

From Instance CKP 8 to CKP 9, we only change the premise node set by adding nodes 1, 2, 24, and 44. For this instance, two of the cabinet locations change. Also, new fiber links between premise nodes are added as shown in Figure 6-10.

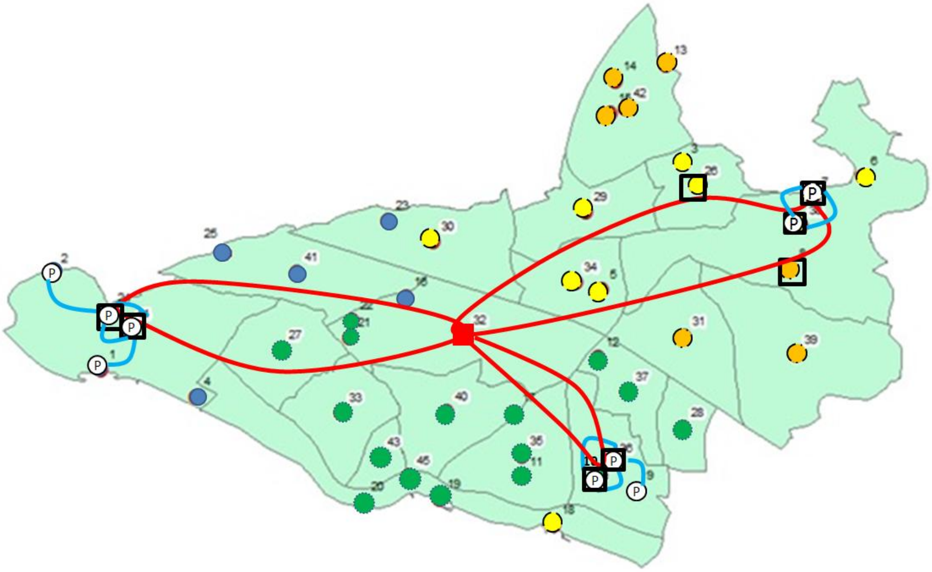

Figure 6-10. Illustration of Instance CKP 9

6.2. Copper Field Model Results for Bakırköy Data Set

For the construction of copper loops, we use the same approach as explained in Section 6.1. Since the Bakırköy data set is dense, its maximum length is smaller than that in the Kartal data set and the maximum length of a copper ring is 15 km. The algorithm results in 6 copper loops.

For this data set, we varied p (number of cabinets) as 3 and 6. The γ value is selected from {0, 1, 5, 10}. The *H* (distance threshold) values are larger when compared to Kartal data. Also, due to the structure of the demand node locations, the length of the loop between cabinets needs to be longer. The run results are summarized in Table 6-6, below. The first column, where "CB x" shows the xth instance of the copper field network re-design problem in Bakırköy data set.

Table 6-6(a). Copper Field for Bakırköy Data Set

#	**Parameters**			**Results**	
	γ	***p***	***H***	**Obj. Func.**	**CPU (sec)**
CB 1	0	3	15	235.33	1885.49
CB 2			20	143.45	49.61
CB 3			25	141.21	37.69
CB 4			50	141.21	48.04
CB 5		6	15	(109.75)	Gap After 1 hour 10.61%
CB 6			20	(103.88)	Gap after 1 hour 4.47%
CB 7			25	(101.69)	Gap After 1 Hour 0.92%
CB 8			50	97.96	320.34
CB 9	1	3	15	233.27	1371.65
CB 10			20	140.64	67.54
CB 11			25	137.31	59.71
CB 12			50	137.31	56.78
CB 13		6	15	(101.28)	Gap After 1 hour 12.59%
CB 14			20	(95.56)	Gap After 1 hour 8.63%
CB 15			25	(93.26)	Gap After 1 hour 4.71%
CB 16			50	89.85	1138.95

Table 6-6(b). Copper Field for Bakırköy Data Set

#	Parameters			Results	
	γ	***p***	***H***	**Obj. Func.**	**CPU (sec)**
CB 17	5	3	15	(215.69)	Gap After 1 hour 42.66%
CB 18			20	99.67	55.11
CB 19			25	98.87	58.69
CB 20			50	98.07	67.01
CB 21		6	15	(43.86)	Gap After 1 hour 20.16%
CB 22			20	(42.24)	Gap After 1 hour 17.11%
CB 23			25	36.35	756.17
CB 24			50	36.32	1547.02
CB 25	10	3	15	(201.37)	Gap After 1 hour 38.49%
CB 26			20	74.32	70.43
CB 27			25	74.32	65.32
CB 28			50	74.32	61.32
CB 29		6	15	(29.08)	Gap After 1 hour 36.87%
CB 30			20	(23.34)	Gap After 1 hour 17.66%
CB 31			25	(23.25)	Gap after 1 hour 17.61%
CB 32			50	(23.25)	Gap after 2 hours 15.35%

The observations in the Kartal data set such as number of cabinet-node link decrease as γ value increase, coverage increase as p increase for fixed γ and H, objective function value sensitivity to the p after a certain value are also valid in the Bakırköy data set. Therefore, for this data set, we discuss some additional observations.

The objective function value depends on the γ value, as expected. In Instance CB 1, there are 3 cabinets and the distance threshold is 20 where none of the demand nodes is covered via the corresponding γ value. In this instance 70 cabinet-node links are needed. Cabinets are in points 8, 29, and 70. When we allow γ value to be 1, in Instance CB 9, the locations of cabinets are the same. However, this time there are only 66 cabinet-node links and the remaining 4 demand nodes are covered via a cabinet.

Also, the number of cabinets has a strong effect on the structure of networks. For example, as the cabinet number increases for the same γ and distance threshold values, the objective function value decreases. From Instance CB 19, where there are 3 cabinets to Instance CB 23, where there are 6, the objective function value decreases from 98.87 to 36.35. This difference is due to the less cabinet-node link installations in the network.

Also, the same number of cabinets may result for totally different parameter settings. In Instance CB 2, where the γ value is 0, the number of cabinets is 3 and the distance threshold is 20, the cabinets are located in points 31, 37 and 58, as shown in Figure 6-11.

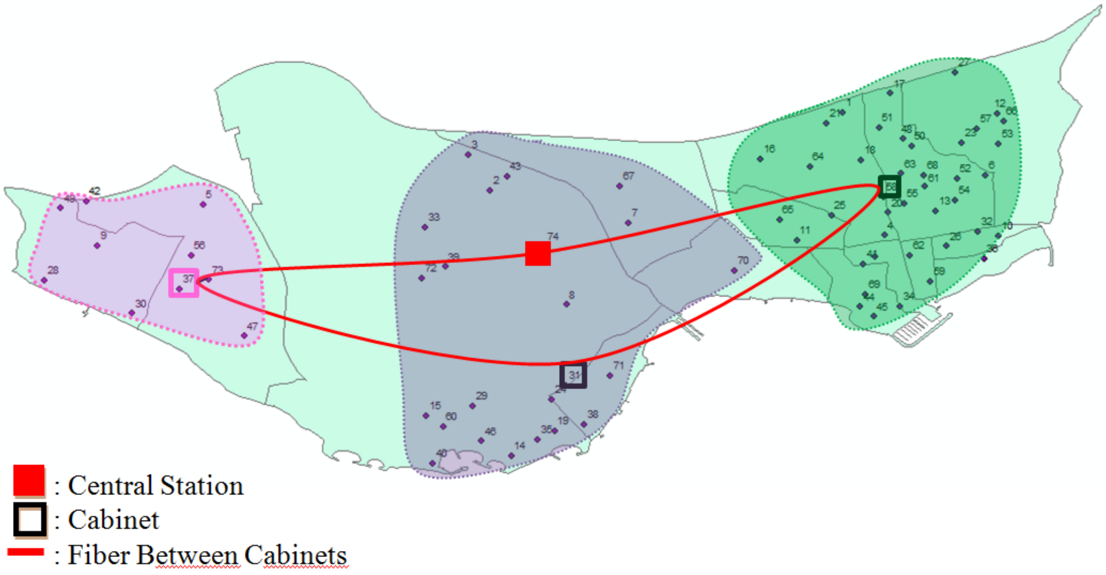

Figure 6-11. Illustration of Instance CB 2

In the figure each cloud corresponds to a cabinet and every demand node in the cloud is connected to its cabinet in the cloud with star topology. When we increase the γ value to 1, in Instance CB 10, the same nodes are selected as cabinets. However, in Instance EB 2, there are 70 cabinet-node links, whereas in Instance CB 10, there are only 64. Six nodes are covered via cabinets. This shows the effect of the γ value. The Instance CB 10 is shown in Figure 6-12.

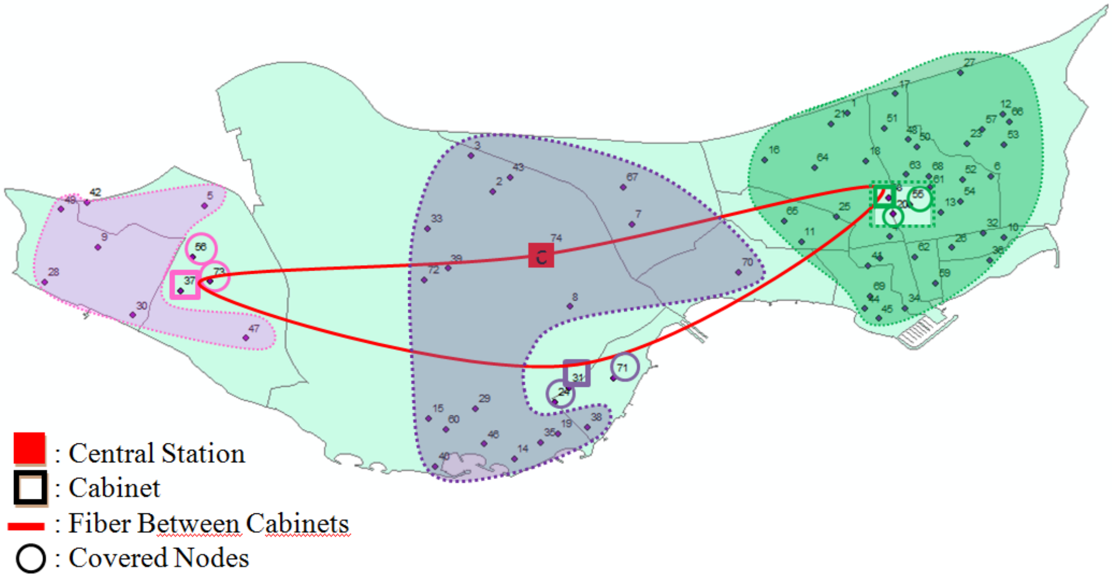

Figure 6-12. Illustration of Instance CB 10

Another interesting observation arises from the comparison of Instances CB 2 and CB 3. In Instance CB 2, nodes numbered 31, 37 and 58 are cabinets and 70 cabinet-node links are required. When we only change the distance threshold value by 5 km, in Instance CB 3, node 55 becomes a cabinet instead of node 58, as shown in Figure 6-13.

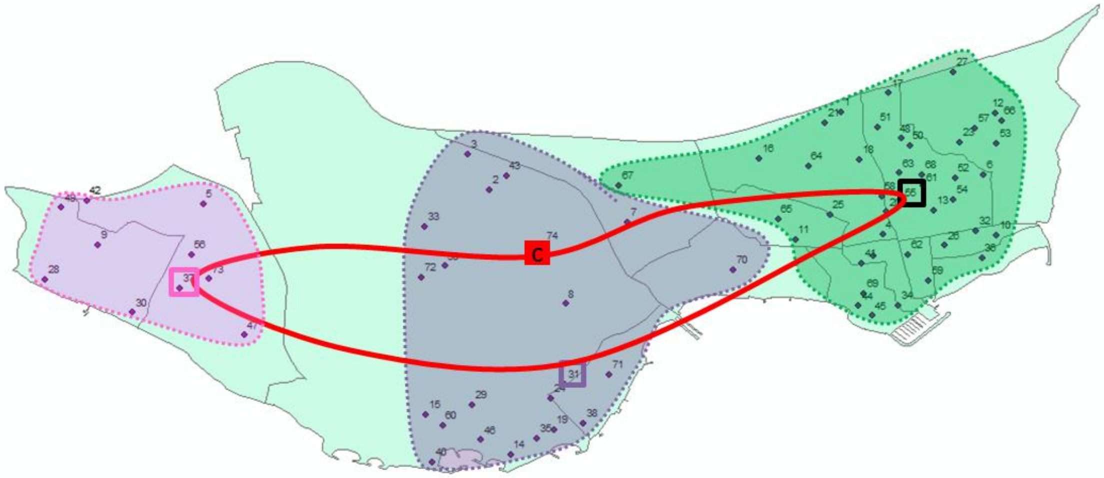

Figure 6-13. Illustration of Instance CB 3

Similarly, there are 70 cabinet-node links in the solution of Instance CB 3. All nodes that are connected to cabinet 58 are now linked to node 55. But, since the distance threshold value increases, demand node 67, which is connected to cabinet 31 changes its allocation. In Instance CB 3, node 67 is connected to cabinet 55.

Also, the model can solve many instances in moderate times, some challenging instances exist. Especially, when γ is 10 for 3 and 6 cabinets, H values can not be solved within 2 hours as Instances CB 25, 29-32.

Chapter 7

Model Variation: A Specific Green Field Extension

7.1. Motivation of the Problem

In this chapter, we propose a specific variation of the green field problem. The main motivation under the variation is to analyze the effect of wiring distance on the output network configuration. Thus, for this variation we set related parameters to certain values so that the network configuration will only be affected by the wiring distance. The following table depicts the parameter settings.

Table 7-1. Comparison of Problem Settings for the Green Field and the Variation

Characteristic	Green Field Problem	Variation
Passive Splitter Type	4	1
Number of Passive Splitters	Variable	Fix
Insertion Loss Multiplier		
Along the Way	0.2	1
In the Passive Splitter	3	0
Bandwidth Splitting in the Passive Splitter	Variable	0

Since the passive splitter type and the corresponding splitting capacity change the insertion loss, we assume that we use a single type of passive splitter with a predetermined output capacity. In addition, to observe the distance effect clearly, we aim to omit the insertion loss along the way. Thus, instead of taking the insertion loss value as 0.2 dB/km, we take it as 1 and we assume there is no loss within the passive splitter. Since we only consider the distance effect with multiplier 1, we automatically measure the length from the central station to each demand node. Since the dB amount is only changed according to distance, the multiplier, which is taken as 1, converts the dB calculation to a distance function. Therefore, we use a limitation in length calculated from the central station.

In this variation, we also want to understand the effect of having premise nodes in the green field application, recall that premise nodes problem features are used in the copper field re-design problem. Thus, in addition to the demand nodes, we add premise nodes to the problem definition. For the premise nodes, we would like to link each other in order to have at least two arc disjoint paths from the passive splitter to any one of them. By this way, connection to premise nodes becomes more survivable. To observe premise nodes' effect clearly, we do not allow putting a passive splitter over a premise node.

7.2. Model Development

In this model, the demand node set N, the shortest path between two nodes $L = [l_{ij}]$ and central station, namely $central$ are the same as in the green field problem (Section 2.1). There is a single passive splitter type, we add p such passive splitters, each with the same predetermined output capacity, referred to $output\_number$ in the mathematical model.

Let P be the set of premise nodes corresponding to customers that require a more survivable connection. The parameter a_i indexesthe premise nodes as follows;

$$a_i = \begin{cases} 1, & if\ i \in P \\ 0, & otherwise \end{cases}$$

Also, as explained earlier, the dB capacity in the green field problem means a distance threshold value referred to as $threshold$. This value is used for limiting the path length of each demand node from the central station.

In this extension, a mixed integer mathematical model is proposed to find location of passive splitters and the fiber links between demand nodes while obeying distance threshold value. Additionally, the model depicts two arc disjoint paths from nearest passive splitter to the premise nodes.

Decision variables are as follows;

$$x_{ij} = \begin{cases} 1, & if\ there\ is\ a\ fiber\ link\ between\ node\ i\ and\ node\ j;\ i \neq j, i, j \in N \\ 0, & otherwise \end{cases}$$

$$y_j = \begin{cases} 1, & if\ a\ passive\ splitter\ is\ located\ to\ node\ j;\ j \in N \\ 0, & otherwise \end{cases}$$

p_i is the path length up to node $i \in N$

The fiber link and path length decision variables are the same as those of the green field network design model. Since there is a single type of passive splitter in this problem, we omit the index referring to the type of the location variable.

The mathematical model is as follows;

Min $$\sum_{i \in N} \sum_{j \in N} l_{ij} x_{ij} \tag{7.1}$$

s.t.

$$y_i + \sum_{\substack{j \in N \\ j \neq i}} x_{ji} \geq 1 \qquad \forall i \in N, i \neq central \tag{7.2}$$

$$\sum_{\substack{j \in N \\ j \neq i}} x_{ij} \leq output\_number\ y_i + M(1 - y_i) \qquad \forall i \in N, i \neq central \tag{7.3}$$

$$y_i \leq \sum_{\substack{j \in N \\ j \neq i}} x_{ji} \qquad \forall i \in N, i \neq central \tag{7.4}$$

$$y_{central} = 1 \tag{7.5}$$

$$\sum_{k \in N} y_k = p + 1 \tag{7.6}$$

$$\sum_{\substack{j \in N \\ j \neq i}} x_{ij} + \sum_{\substack{m \in N \\ m \neq i}} x_{mi} \geq 2\, a_i \qquad \forall i \in A, i \neq central \tag{7.7}$$

$$x_{ij} \leq y_i + a_i a_j \qquad \forall i, j \in N, i \neq j \tag{7.8}$$

$$\sum_{i \in N \setminus P} x_{ij} = 1 \qquad \forall j \in P \tag{7.9}$$

$$y_i = 0 \qquad \forall i \in P \tag{7.10}$$

$$p_i - p_j + threshold\ x_{ij} \leq threshold\ - x_{ij} l_{ij} \qquad \forall i, j \in N \setminus A, i \neq j \tag{7.11}$$

$$p_i +\ l_{ij} x_{ij} \leq threshold \qquad \forall i \in N, j \in A, i \neq j \tag{7.12}$$

$$p_{central} = 0 \tag{4.1.9}$$

$$x_{ij} + x_{ji} \leq 1 \qquad \forall i, j \in N, i \neq j \tag{4.1.8}$$

$$x_{ij}, y_j \in \{0,1\} \qquad \forall i, j \in N \tag{7.13}$$

$$p_i \geq 0 \qquad \forall i \in N \tag{7.14}$$

The objective function minimizes the total fiber link length in the network similar to the objective function of the proposed model for the green field network design problem. Since we consider different passive splitters in the green field model, we include different cost structures of the passive splitters in the objective function as well. However, for the extension model, we only consider fiber link length whereas cost of wiring per km is the same. Then, we reduce our objective function to l_{ij} multiplier instead of $c_{ij}, i, j \in N, i \neq j$.

The demand satisfaction is ensured in Constraint (7.2). Similar to the green field problem, a node can be selected as a passive splitter location and if there is a passive splitter in a node, then the demand is automatically satisfied. Additionally via an incoming link to a node will be served. This constraint is the same as in the (4.1.2), except the index for passive splitter type.

In Constraint (7.3), the number of outputs from a passive splitter is limited to the outbound capacity similar to the Constraint (4.1.3). The difference is as follows; due to the premise nodes, Constraint (7.3) does not prevent an outgoing link unless the node is a passive splitter location. Thus, if there is no passive splitter, the constraint is redundant.

Constraint (7.4) relates fiber links and passive splitters. Unless there is a fiber incoming link to a node, passive splitter cannot be located in this particular node. When we omit index for passive splitters, Constraint (4.1.5) reduces to Constraint (7.4).

Since the central station is assumed as passive splitter in Constraint (7.5), the number of passive splitter in the network has a surplus as shown in Constraint (7.6).

For premise nodes, constraints (7.7) - (7.10) are proposed. Constraint (7.7) ensures that the degree of a premise node is at least two. To associate this extra link between premise nodes, Constraint (7.8) is used. An outgoing link can be built, if the source is a passive splitter location or two endpoints of the link are premise nodes, as shown in Constraint (7.8). On the other hand, Constraint (7.9) deals with passive splitter – premise node link. In order to ensure that each premise node has a link with a passive splitter, total number of incoming links to a premise node from all non-premise nodes has to be one. As assumed by the definition of the problem, any premise node cannot be a passive splitter location, as shown in Constraint (7.10).

The Miller-Tucker-Zemlin type subtour elimination for path lengths (Constraints (7.11) and (7.12)) are used in the model. These constraints are similar to (4.1.6) and (4.1.7) in the green field model..

The Constraints (4.1.8) and (4.1.9) are used in this model as well by assumption that a single link is enough to upload/download and path length of central station is zero. The rest of the constraint (7.13) and (7.14) are the domain constraints.

7.3. Computational Analyses

To test of the mathematical model, we use Kartal data set which is explained in Section 5.1. Since we propose this model to observe the distance traveled in the green field, we select distance threshold value as 20 that has no effect on the infrastructure. Beyond this value, results are the same.

The following tables show the preliminary results of the model variation. The first column shows the instance number whereas GEKx shows x^{th} instance of green field extension model for Kartal data set. The remaining parameters, namely passive splitter type and input parameter p are in the second and the third columns, respectively. The objective function value and CPU performances are shown in the last two columns. Table 7-2 shows the preliminary results when there is no premise node for 3^{rd} and 4^{th} passive splitter types.

Table 7-2. Preliminary Results of Extension Model without Premise Nodes

#	Parameters		Results	
	Passive Splitter Type	p	Objective Function	CPU (sec)
GEK1	3	1	155.2413	1.08
GEK2	3	2	135.0812	0.5
GEK3	3	3	119.9441	1.92
GEK4	4	1	140.4366	0.74
GEK5	4	2	115.9587	1.18
GEK6	4	3	101.3618	1.85

Observe from Table 7-2 that as *p* value, which is the number of passive splitter, increases, the objective function value decreases. This is due to the fact that more passive splitter usage allows combining more fiber links. Then, model splits the combined fiber link into distinct wires in an area much more closer to the demand nodes. By this way, the link usage decreases and the objective function value decreases.

Also, the passive splitter type is effective on the objective function value. When we observe Instance GEK2 and GEK5, the only different parameter is the change in the passive splitter type. As the output number in the passive splitter increases, more fiber link can be combined. Therefore, less fiber link is needed and the objective function value decreases from 135.0812 to 115.9587.

To compare the green field problem and its extension we observe an example from Chapter 5, namely Instance GK4. This instance has a single 4th type passive splitter. In order to make a comparison we use the result of the green field network design problem as an input to the extension model. Hence, passive splitter type is 5 and the number of passive splitters is 1, namely Instance GEK7.

Table 7-3. Comparison of Green Field vs. Extension Models

#	Parameters			Results			
	Alpha	Passive Splitter Type	# of Passive Splitter	Stage Number	Passive Splitter Usage	Objective Function	CPU (sec)
GK4	1	n/a	n/a	2	4:1	147.04	3.01
GEK7	n/a	5	1	2	n/a	122.04	0.22

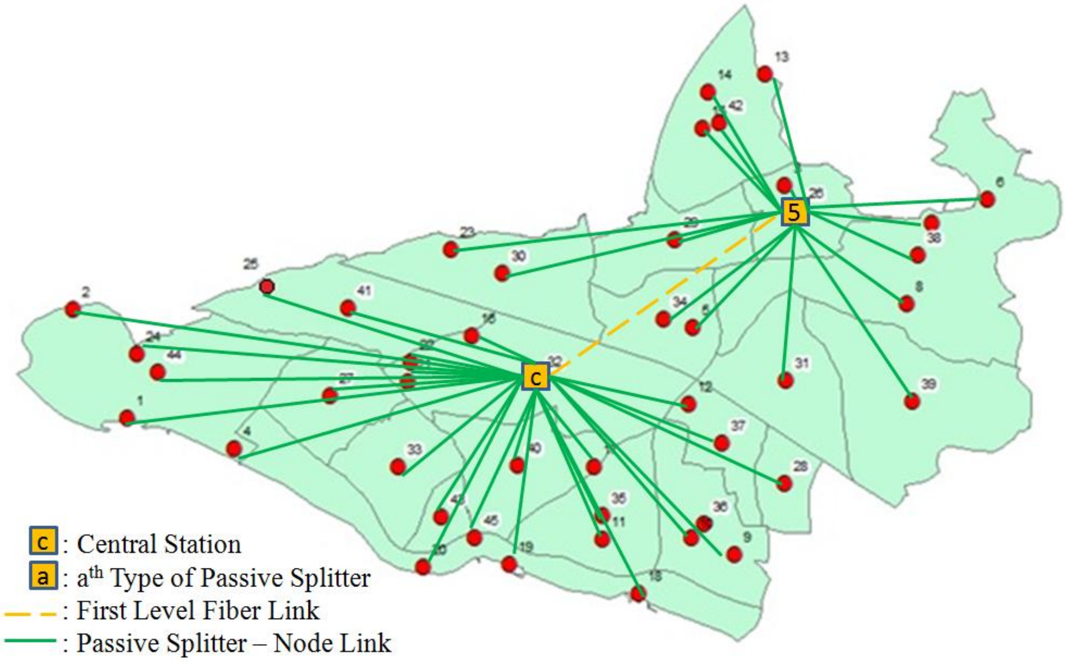

Figure 7-1. Illustration of Instance GEK7

According to the objective function values of Instance GK4 and GEK7, since the green field problem model includes the passive splitter cost in the objective function, the resulting objective function value in GK4 is higher than in Instance GEK7. However, when we compare Figure 7-1 and Figure 5-4, the resulting network is the same, as expected.

Another observation is about the effect of passive splitter type on the objective function value whereas there are premise nodes in the network (Table 7-4).

Table 7-4. Preliminary Results of Extension Model with Premise Nodes (p=2)

#	Parameters			Results	
	Passive Splitter Type	p	Premise Nodes	Objective Function	CPU (sec)
GEK8	2	2	7,9,10,36,38	155.6132	0.87
GEK9	3	2	7,9,10,36,38	137.3867	0.49
GEK10	4	2	7,9,10,36,38	116.9439	1.12

As shown in Table 7-4, passive splitter type also affects the objective function value where there are 5 premise nodes. The Instance GEK8 is shown in Figure 7-2.

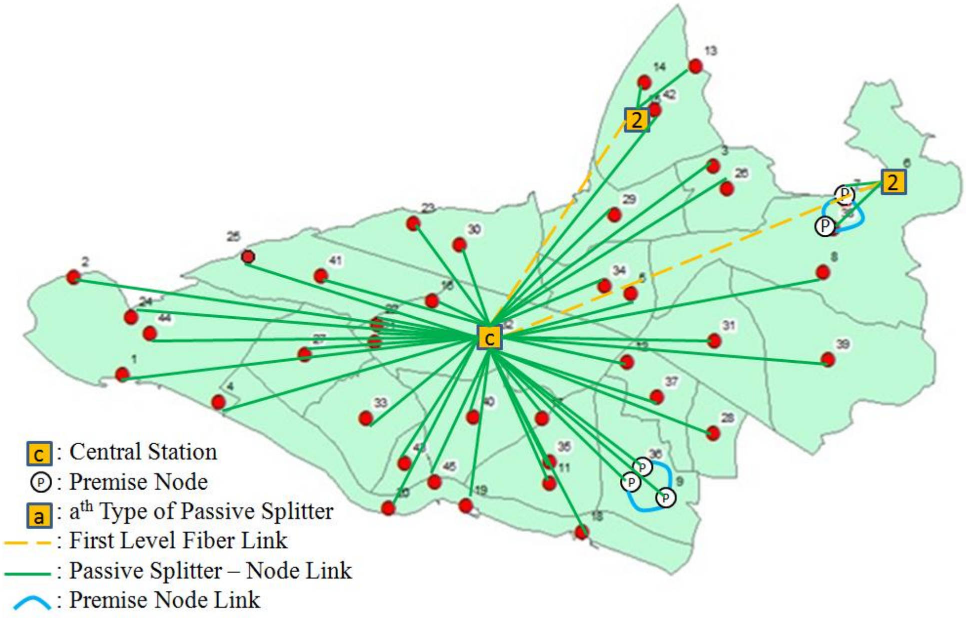

Figure 7-2. Illustration of Instance GEK8

In Instances GEK8, nodes 15 and 6 are selected as passive splitter locations with second type. When the passive splitter type is 4, in Instance GEK10, the location of passive splitters changes.

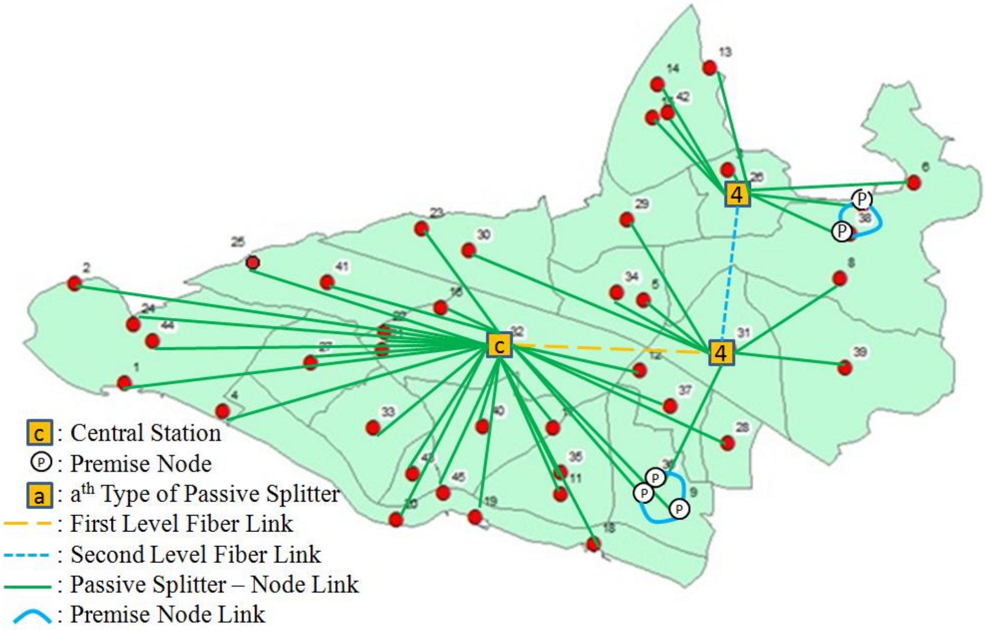

Figure 7-3. Illustration of Instance GEK10

Since passive splitters with more outputs are used in Instance GEK10, the fiber link length decreases and the objective function value decreases as well.

Table 7-5 summarizes findings for different premise node sets.

Table 7-5. Preliminary Results for Extension Model with Alternate Premise Node Sets

#	Parameters			Results	
	P.S. Type	# of P.S.	Premise Nodes	Objective Function	CPU (sec)
GEK11	2	2	-	153.7963	1.65
GEK12	2	2	7,38	154.8473	0.87
GEK8	2	2	7,9,10,36,38	155.6132	0.87
GEK13	2	2	1,2,7,9,10,24,36,38,44	158.0266	0.71
GEK14	2	3	-	142.996	1.33
GEK15	2	3	7,38	144.047	1.41
GEK16	2	3	7,9,10,36,38	144.8129	0.96
GEK17	2	3	1,2,7,9,10,24,36,38,44	147.2263	0.66
GEK18	2	4	-	133.2781	1.82
GEK19	2	4	7,38	134.412	2.15
GEK20	2	4	7,9,10,36,38	135.1779	1.26
GEK21	2	4	1,2,7,9,10,24,36,38,44	137.5913	1.12

When the passive splitter type is fixed, different premise node sets change the objective function value as well. In Instance GEK14, there is no premise node and the objective function value is 142.996. When we add nodes to premise node set in Instance GEK15, premise node 7 and 38 need to be connected to each other. Therefore, number of fiber link increases and the objective function value increases. Similarly, the objective function in Instance GEK16 and GEK17 increases.

Note that the mathematical model can be solved in few seconds for all the instances of our preliminary analysis.

Chapter 8

Conclusion

In this study, the telecommunication network design problem, arising from an application of the largest Internet service provider in Turkey, is addressed. Two main fields, namely green and copper fields are studied. Since real world application dynamics are embedded into both problem definitions and mathematical models, we introduce a new notion to the literature. Due to the special requirements of the problems, characteristics of the models are interesting.

In the green field network design problem, the aim is to conduct a least cost network from scratch. The problem definition includes serving all aggregated demand points from a central station with a predetermined bandwidth service level. Such network requires telecommunication equipment, namely passive splitter. The passive splitter is a data copying equipment which splits the incoming wire into different number of wires according to its type. Although passive splitters decrease the need of fiber link by combining some link up to a point, passive splitter usage causes splitting bandwidth of the central station and insertion loss, which refers to a power loss. This insertion loss depends on the passive splitter type and fiber optical wire length. Since there is limited insertion loss budget and bandwidth threshold refers to a service level, the location of passive splitters and their types include a trade-off.

On the other hand, the copper field application is an improvement in the network that the corresponding company already serves the area with copper wires. The aim is to improve current service level by augmenting fiber optical wires in the network. By adding special telecommunication equipment, namely cabinets, into copper rings, the data communication can utilize both fiber and copper wires. This hybrid usage improves service level. For those demand nodes that are located far from cabinets, direct cabinet-node links are required. Additionally, premise nodes, which are customer points that wish to be served with at least two fiber links from cabinets are considered in the mathematical model.

To test our mixed integer mathematical models, we perform computational analysis on real data from Kartal (45 points) and Bakırköy (74 points) districts in İstanbul, Turkey. According to computational analyses in green field, as the alpha value (proportion between fiber link and passive splitter usage) decreases, there is an indifference between locating a passive splitter or wiring a direct link. As the α value decreases, the stages in the network increases. So, the indifference between locating a passive splitter or wiring a direct link results with more stages in the network. On the other hand, copper field problem shows the effect of γ value, number of cabinets and distance threshold. As the γ value and number of cabinet increase, more demand node can be covered by cabinets, and less cabinet-node link is needed. Also, after a certain number of cabinets, whereas all demand nodes are covered by cabinets, to increase number of cabinet for the same γ value, does not improve the network. Also, it makes negative effect to the objective function value and causes augmentation of the fiber cabinet loop length.

Since real life application dynamics are embedded in the mathematical models, this study has a contribution to the operations research literature. Tree-star and ring-star topologies are used in green and copper fields, sequentially. Although CPU performance varies a lot, extensive computational results show that proposed models are viable exact solution methodologies for moderate dimensions.

As a future research, the inherent challenges leading to high CPU times for some parameter choices could be analysed. To this end, valid inequalities strengthening the models could be developed. Furthermore, a heuristic solution methodology could be implemented for higher dimension problem sizes. In the current version of the problem, service is considered as an on/off decision. The models can be extended to incorporate a balanced service level, when service is treated as a decaying function of distance. The test results can be enhanced by including other data sets.

Bibliography

[1] K. Pahlavan and P. Krishnamurthy, “Principles of Wireless Networks: A Unified Approach 2nd”. John Wiley & Sons, Inc, New York, USA, 2011.

[2] H.J.A. da Silva, “Optical Access Networks”. Technical Report: it, Instituto de Telecomunicações, Pole of Coimbra, Portugal, 2005.

[3] S. Van Hoesel, "Optimization in Telecommunication Networks." Statistica Neerlandica vol. 59(2),pp. 180-205, 2004.

[4] J.G.Klincewicz, "Hub location in backbone/tributary network design: a review," Location Science, vol 6, pp.307-335, 1998.

[5] A.Balakrishnan, T.L.Magnanti, A.Shulman, R.T.Wong, "Models for planning capacity expansion in local access telecommunication networks." Annals of Operations Research, vol. 33, pp. 239-284, 1991.

[6] İ.Y.Ergün, Ö.Kırca, H.Süral, Technical Report: "Network Design Problems in Telecommunication." Middle East Technical University, June 2011.

[7] M. Henningsson, K. Holmberg, D. Yuan, "Ring Network Design." M.G.C. In Resende and P. M. Pardalos (Eds.), Handbook of Optimization in Telecommunications, Springer, 2006.

[8] M. Picavet and P. Demeester, "Long-Term Planning of WDM Networks: A Comparison between Single-Period and Multi-Period Techniques." Photonic Network Communications, vol.1:4, pp. 331-346, 1999.

[9] B. Gavish, " Topological design of computer communication networks-the overall design problem." European Journal of Operational Research, vol. 58, pp.149-172,1992.

[10] M. Grötschel, C. L. Monma, M. Stoer, "Computational Results with a Cutting Plane Algorithm for Designing Communication Networks with Low-Connectivity Constraints." Operations Research, vol. 40(2), pp.309-330, 1992.

[11] K. S. Ho and K.W. Cheung, "Generalized Survivable Network," IEEE/ACM Transactions on Networking, vol. 15(4), pp.750-760, 2007.

[12] K. S. Ho, M. Zhou, K. Cheung, "A New Approach for Designing the Next Generation Survivable Backbone Network." In:12th International Telecommunications Network Strategy and Planning Symposium, IEEE, 2006.

[13] D. Alevras, M. Grotschel, R. Wessaly, "Cost efficient network synthesis from leased lines." Annals of Operations Research, vol.76, pp.1-20, 1998.

[14] C.S. Vadrevu and M. Tornatore, "Survivable IP topology design with re-use of backup wavelength capacity in optical backbone networks," Optical Switching and Networking , vol. 7(4), pp.196-205, 2010.

[15] H. Kim and M. E. O'Kelly, "Reliable p-Hub Location Problems in Telecommunication Networks". Geographical Analysis, vol. 41, pp. 283–306, 2009.

[16] B. Gavish, "Topological Design of Telecommunication Networks- Local Access Design Methods." Annals of Operations Research, vol. 33,pp.17-71, 1991

[17] B. Gavish, C. Li, D. Simchi-levi, "Analysis of heuristics for the design of tree networks." Annals of Operations Research, vol. 36, pp.77-86, 1992.

[18] E. Gourdin, M. Labbe, H. Yaman. "Telecommunication and Location, In Facility Location", Z. Drezner and H. W. Hamacher (Eds.), Springer, 2002.

[19] B. Rothfarb and M.C. Goldstein. “The one-terminal Telepak problem”. Operational Research, vol. 19, pp. 156 -169, 1971.

[20] M.C. Goldstein, “Design of long-distance telecommunication networks - the Telepak problem”. IEEE Transactions Circuit Theory CT vol. 20 pp. 186-192, 1973.

[21] E. Hansler, “A heuristic configuration procedure for cost minimal communication networks”, Technical Report: IBM Research Report RZ-666, 1974.

[22] K.M. Chandy and K.M. Russell, “The design of multipoint linkages in a teleprocessing tree network”. IEEE Trans. Comm. COM col. 21, pp. 1062-1066, 1972.

[23] T. Carpenter and H. Luss. “Telecommunications Access Network Design”. M.G.C. In Resende and P.M. Pardalos, (Eds.), Handbook of Optimization in Telecommunications, Springer, 2006.

[24] L.F. Frantzeskakis and H. Luss, "The Network Redesign Problem for Access Telecommunications Networks." Naval Research Logistics, vol. 46, pp.488-506, 1999.

[25] S. Chamberland, "Global Access Network Evolution." IEEE/ACM Transactions on Networking, vol. 18(1), pp.136-149, 2010.

[26] C.D. Randazzo and H.P. Luna, "A comparison of optimal methods for local access uncapacitated network design." Annals of Operations Research, vol. 106, pp.263-286, 2001.

[27] A. Balakrishnan, T.L. Magnanti, R.T. Wong, R.T., “A decomposition algorithm for local access telecommunications network expansion planning”. Operations Research, vol 43, pp. 58-76, 1995.

[28] K. Holmberg and D. Yuan, "A Multicommodity Network-Flow Problem with Side Constraints on Paths Solved Column Generation." INFORMS Journal on Computing, vol. 15, No.1, pp. 42-57, Winter 2003.

[29] M. Gerla and L. Kleinrock, "On the Topological Design of Distributed Computer Networks." IEEE Transactions on Communications, vol. 25(1), pp.48-60, 1977.

[30] A.Kershenbaum, P.Kermani, G.Grover, "MENTOR: an algorithm for mesh network topological optimization and routing." IEEE Transactions on Communication,vol. 39(4), pp.503-513, 1991.

[31] K. Altinkemer and Z. Yu, "Topological design of wide area communication networks," Annals of Operations Research, vol. 36,pp.365-382, 1992.

[32] X.Ma, S.Kim, K.Harfoush, "Towards realistic physical topology models for Internet backbone networks." 6th International Symposium on High Capacity Optical Networks and Enabling Technologies (HONET), pp.36-42, 2009.

[33] P. Datta, M. Sridharan, A. K. Somani. “A simulated annealing approach for topology planning and evolution of mesh-restorable optical Networks”. In Proc. of Design of Reliable Communication Networks (DRCN) Workshop, Canada, 2003.

[34] D.Din, "Heuristic and Simulated Annealing Algorithms for Wireless ATM Backbone Network Design Problem," Journal of Information Science and Engineering, vol. 24,pp.483-501, 2008.

[35] S. Pierre and A. Elgibaoui, "A Tabu-search Approach For Designing Computer-network Topologies With Unreliable Components," IEEE Transactions On Reliability, vol 46(3), pp.350-359, 1997.

[36] A. Konak and A.E. Smith, "A Hybrid Genetic Algorithm Approach for Backbone Design of Communication Networks." In: Proceedings of the 1999 Congress on Evolutionary Computation CEC, 1999.

[37] B. Al-bassam, A. Alheraish, S.H. Bakry, "A tutorial on using genetic algorithms for the design of network topology." International Journal of Network Management, vol. 16, pp.253-262, 2006.

[38] B. Dengiz, F. Altiparmak, A.E. Smith, S. Member,"Local Search Genetic Algorithm for Optimal Design of Reliable Networks." IEEE Transactions On Evolutionary Computation , vol. 1(3), pp.179-188,1997.

[39] K. Watcharasitthiwat and P. Wardkein, "Reliability optimization of topology communication network design using an improved ant colony optimization." Computers & Electrical Engineering, vol .35(5), pp.730-747, 2009.

[40] B. K. Chen and F. Tobagi, "Network Topology Design to Optimize Link and Switching Costs." 2007 IEEE International Conference on Communications, pp.2450-2456, 2007.

[41] Y.K. Agarwal, “An algorithm for designing survivable networks”. Technical Report: AT&T Technical Journal, vol. 68, pp. 64-76, 1989.

[42] A. Balakrishnan and K. Altinkemer, “Using a hop-constrained model to generate alternative communication network design”. ORSA Journal on Computing, vol. 4, pp. 192-205, 1992.

[43] I. Baybars and R.H. Edahl, “A heuristic method for facility planning in telecommunications networks with multiple alternate routes”. Naval Research Logistics, vol. 35, pp. 503-528, 1988.

[44] I. Baybars and K.O. Kortanek, “Transmission facility planning in telecommunications networks: a heuristic approach”. European Journal of Operational Research, vol. 16, pp. 59-83, 1984.

[45] S.G. Chang and B. Gavish, “Telecommunications network topological design and capacity expansion: formulations and algorithms”. Telecommunications Systems vol. 1, pp. 99-131, 1993.

[46] B. Gavish, K. Altinkemer, "Backbone network design tools with economic tradeos". ORSA Journal on Computing vol. 2, pp. 236-245, 1990.

[47] T. Thomadsen, "Hierarchical Network Design." PhD Thesis, Technical University of Denmark, 2005.

[48] T. Thomadsen and T. Stidsen, "The generalized fixed-charge network design problem." Computers & Operations Research vol. 34, pp.997 – 1007, 2007.

[49] E. Rosenberg, "Hierarchical Topological Network Design." IEEE/ACM Transactions On Networking, vol. 13(6), pp.1402-1409, 2005.

[50] A. Bley and T. Koch, "Integer Programming Approaches to Access and Backbone IP Network Planning.", 2002.

[51] J.F. Campbell, “A survey of network hub location”. Studies in Locational Analysis, vol. 6, pp. 31-49, 1994.

[52] M. E. O'Kelly, H.J. Miller, “The hub network design problem: a review and synthesis”. Journal of Transport Geography, vol 2, pp. 31-40, 1994.

[53] M.L. Brandeau,S.S. Chiu, “An overview of representative problems in location research”. Management Science, vol. 35, pp. 645-674, 1989.

[54] M.S. Daskin, “Network and Discrete Location: Models Algorithms and Applications”. Wiley/ Interscience, New York, 1995.

[55] W. Domschke and G. Krispin, “Location and layout planning: a survey”. OR Spektrum vol. 19, pp. 181-194, 1997.

[56] R. Francis, and P.B. Mirchandani, “Discrete Location Theory”, Wiley/Interscience, New York, 1990.

[57] R. Francis, J. White, "Facility Layout and Location: An Analytic Approach". Prentice-Hall, Englewood Cliffs, NJ, 1974.

[58] G.Y. Handler, P.B. Mirchandani, "Location on Networks: Theory and Algorithms". MIT Press, Cambridge, MA, 1979.

[59] A. Kershenbaum, "Telecommunication Network Design Algorithms". McGraw-Hill, New York, 1993.

[60] T.L. Magnanti, R.T. Wong, "Network design and transportation planning: models and algorithms". Transportation Science vol. 18, pp. 1-55, , 1984.

[61] B.C. Tansel, R.L. Francis, T.J. Lowe, "Location on networks: a Survey, Parts I and II". Management Science vol. 29, pp. 482-511, 1983.

[62] R.T. Wong, , "Location and Network Design", M., O'hEigeartaigh, J.K. Lenstra, A.H.G. Rinnooy Kan, (Eds.), Combinatorial Optimization: Annotated Bibliographies. Wiley, New York, pp. 127-147, 1985.

[63] M. Picavet and P. Demeester, "Long-Term Planning of WDM Networks: A Comparison between Single-Period and Multi-Period Techniques." Photonic Network Communications, vol.1:4, pp. 331-346, 1999.

[64] J. Petrek and V. Siedt, "A large hierarchical network star-star topology design algorithm”. European Transactions on Telecommunications, vol. 12(6), pp. 511-22, 2001.

[65] M. Labbé and H. Yaman, "Solving the Hub Location Problem in a Star–Star Network", NETWORKS, pp. 19-33, 2008.

[66] M. Labbe, G. Laporte, I.R. Martin, J.J. Salazar Gonzalez, "The ring star problem: Polyhedral analysis and exact algorithm," Networks, vol. 43(3),pp. 177-189, 2004.

[67] A. Proestaki and M.C. Sinclair, "Design and dimensioning of dual-homing hierarchical multi-ring networks." IEEE Proceedings-Communications vol. 147(2), pp.96-104, 2000.

[68] T. Thomadsen and J. Larsen, "A hub location problem with fully interconnected backbone and access networks." Computers & Operations Research vol. 34, pp.2520-2531, 2007.

[69] G. Kramer and G. Pesavento, “Ethernet Passive Optical Network (EPON): Building a Next- Generation Optical Access Network”. IEEE Communication Magazine, 2002.

[70] H. Yaman and G. Carello, "Solving the hub location problem with modular link capacities." Computers and Operations Research, vol. 32, Issue 12,pp. 3227-3245, December 2005.

[71] T. Thomadsen, "Hierarchical Network Design." PhD Thesis, Technical University of Denmark, 2005.

[72] G. Carello, F. Della Croce, M. Ghirardi, R. Tadei, “Solving the Hub Location Problem in Telecommunication Network Design: A Local Search Approach”. NETWORKS, pp. 94- 105, 2004.

[73] F. Kılcı, “A decision support system for shelter site selection with gis integration: Case for Turkey”, MSc Thesis, Bilkent University, 2012.