Complex patterns in telecommunications network planning

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Abstract. This thesis discusses a series of related issues raised towards the efficient telecommunications network planning, taking into account the existence of complexity. Three aspects of the associated complexity are examined, focusing on both the telecommunications networks per se, and the underlying street networks: (i) the observation of complexity, (ii) its effects and (iii) its utilization. More specifically, the empirical findings which demonstrate the existence of complex connection patterns are initially described. By collecting novel datasets of network data and graph-theoretically analyzing them, specific patterns of complex connectivity are identified. Next, the impact of complexity in the network efficiency is examined. The comparison of both synthetic and real-world topologies in terms of availability, congestion and cost, shows significant differences and indicates the criticality of specific topological properties. Especially, concerning the traffic congestion, the inclusion of topologies based on the gravity model reveals their superiority. Subsequently, a novel methodology is proposed, using synthetic complex graphs for the preliminary design of fiber-to-the-x telecommunications access networks. In particular, the utilization of planar proximity Gabriel graphs to represent the underlying layer in an urban environment is proved to be superior to the conventional geometric dimensioning models.

Keywords: complex networks, statistical network analysis, optical access networks, street networks, network planning

1 Dissertation Summary

1.1 Introduction

We live in an increasingly interconnected world in which infrastructures composed of different technological layers are interoperating. These infrastructures have progressively become crucial to our human society, as their connectivity has risen over time,

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and their emerging structure has been a hot research field to understand and handle. Examples are provided by the World Wide Web, the Internet, telecommunications networks, electrical power grids and street infrastructures as well.

Especially for telecommunications, it becomes of vital importance to study their features and incorporate the findings into better design and performance solutions. The ever increasing demands for communication and high bandwidth, caused by the introduction of new services and applications, as well as the growing number of users and devices connected to the Internet, pose new challenges for the telecom operators. A possible delay in the provision of telecommunications services (due to economic infeasibility) or uncertain disturbances of a telecommunications network constituent parts (due to failures or attacks) may affect a sizable proportion of the population and the economy, thus the recent focus on the telecommunications connection patterns can be well explained [1].

Most times these infrastructures can be considered as networks. A network, also called a graph in the mathematical literature, is in its simplest form, a collection of interacting constituents joined together in pairs by lines [2]. In the jargon of the field, the constituents are referred to as nodes or vertices and the lines are referred to as edges or links. However, most of the network properties cannot be understood by solely studying the properties of the individual components (nodes) or interactions (edges). Emergent features are coming out from the underlying *pattern of connections*. The appearance of patterns, that are hard to derive from the knowledge of the network elements exclusively, could be described by the term *complexity*. This term implies that the connection patterns may not be straightforwardly predictable; they could be neither purely regular nor purely random, but complex.

It should not be considered as a surprise that a particular pattern of connections, shaping the structure or topology of such networks, can strongly affect the behavior of the network functions. For instance, the pattern of connections between routers on the Internet, does affect the routes that data take over the network and the efficiency with which the network transports those data. Understanding, predicting and eventually utilizing or controlling the networks' non-trivial features is becoming a major intellectual and scientific challenge [3].

Comprehending how these *complex networks* organize and operate is mainly achieved by making use of the Graph Theory nomenclature and tools. Dealing with networks as graphs, and in order to characterize their connectivity, specific topological measurements are used [4]. In particular, the average node degree, the node degree distribution, the average path length, the diameter, the density, the clustering coefficient, and lastly the centrality measurements are the most basic metrics to express the relevant topological features. Of course, more advanced metrics can be used to support more sophisticated features, e.g., the assortativity, the algebraic connectivity, the entropy, the symmetry ratio, etc.

Although the study of complex networks has only recently become a major research issue, its origins can be traced back to the pioneering work on random graphs by Erdős and Rényi [5]. Modifying the Erdős-Rényi (ER) random graph model by using a rewiring procedure, almost 40 years later, Watts and Strogatz suggested a more realistic network formation model that produced graphs with *small-world* properties, i.e., high clustering coefficient [6]. Subsequently, the suggestion of the *scale-free* networks, using the new concepts of *growth* and *preferential attachment*, emerged as the most popular formation model, also known as the Barabási-Albert (BA) model [7]. More recently, in 2007, Jackson and Rogers modeled another growing network in which new nodes chose their connections partly based on random choices and partly based on maximizing their utility function [8], also called the Jackson-Rogers (JR) model. Another network model that has lately experienced a resurgence of interest is the gravity model, rooted in Newton's gravitational law [9]. Beyond the deluge of formation models, a plethora of studies have been conducted to assist the understanding of dynamic behavior of real networks, which implies the processes running on top of network topologies [10]. Such studies attempt to uncover the principles behind many network kinds, including telecommunications, social, biological or street networks. Especially for the latter, the strong dependence of infrastructure network elements as well as their connections on the actual geography of the underlying street networks makes it of great importance for the engineering part of the infrastructure (e.g., telecommunications) to be aware of the street networks properties.

Nevertheless, there is plenty of space left for further advancement in the field, as the complex networks literature continuously provides contemporary insights. On top of that, exploiting ways in which the telecommunications networks knowledge and the features of the underlying street networks can jointly improve the telecommunications planning are still lacking.

The aim of this thesis is to discuss a series of related issues raised towards the efficient telecommunications network planning, taking into account the existence of complexity. Focus is set on both the telecommunications infrastructures per se, and the underlying street infrastructures. The ability to handle both infrastructures with graph-theoretic and complex network principles provides an ideal setting for observing and evaluating the impact of their complex patterns. In addition, this thesis contributes to the utilization of the complex characteristics of street networks in a telecommunications dimensioning problem. Explicitly, three facets of the associated complexity are discriminated and discussed, which consider both the infrastructure of telecommunications networks and the infrastructure of the underlying street networks: (i) the complexity observations, (ii) the complexity effects and (iii) the complexity utilization.

1.2 Complexity Observations

With regard to the technological networks and specifically the telecommunications networks, despite the engineer's dominant role in the case of the topology, unexpected and complex topological characteristics can appear. Empirical evidence [2, 4, 7], based on snapshots from the Internet and other telecommunications networks, has demonstrated the presence of power-laws and high robustness to random failures, though increased vulnerability to targeted attacks. In addition, it is not surprising that their topology is strongly constrained by their geographical embedding. Specifically, the distance dependence can soften the power-laws and increase the clustering coefficient, pointing to resemblance with small-world networks. Even though the telecommunications networks and the underlying street networks have not been jointly explored in the literature, there have been various studies empirically analyzing a series of street samples using the Primal approach [11]. What has been found is that street networks also possess a complex structure with a wide range of patterns [12-14], from tree-like to meshed connectivity. Universal properties have been observed among street networks, such as the values of the average node degree, the small average path length and the high clustering coefficient. Though, power-law node degree distributions in such planar networks have not been displayed, since the node degree is limited by the spatial embedding.

The current thesis set its focus on both the telecommunications networks per se, and the underlying street networks. Having a closer look, taking into consideration the empirical observation of telecommunications networks, a wide variety of measures, was examined over time, mostly related to the topological robustness [15]. As a result, it was found that only half of the considered measures have changed over time, even though the network order and size have tripled on average during that time period. As far as the measures that do change are concerned, nonetheless, not all of them are pointing in the same direction. For instance, the average clustering coefficient, the assortativity coefficient, the vulnerability and the natural connectivity, all exhibit improvement, while many other measures appear to worsen over time. Besides, towards understanding the complex structure of street networks, empirical observation was based on urban street networks and explored topological and geometric properties [16]. The outcome was that the number of edges, the topological efficiency and the total length are all correlated to the number of nodes, fitting well a power-law. Additionally, it was presented that the urban street networks of high population density tend to be relatively more "cost effective" compared to the low population density networks. In general, the street networks of a specific population density appear to have a perceptibly different behavior compared to those of different population density. Specifically, it is the number of nodes, the number of edges and the street length per person which have the strongest dependence on the population density. Moreover, several of the real-street properties were shown to display a satisfactory fit to planar proximity graphs, especially the β-skeleton graphs, thus providing a proficient technique to reproduce realistic street network properties [17].

1.3 Complexity Effects

Yet, the complex structure of networks does not come without effects. Apart from the inherent graph-theoretic interest, it is crucial to comprehend the behavior of the different complex topologies on which simulation or analytic studies are based. However, evaluating the impact of different topologies is not a new problem. In particular, a limited number of distinct network generation methods have been considered in previous studies in the context of network dynamics evaluation [10]. It has been deducted that the generation method indisputably has a significant effect on both the performance and the cost in each examined issue. With reference to the street networks, the effects of complexity have not been captured in the telecommunications planning related studies, since the long-used geometric models typically assume a regular grid-like structure.

This thesis contributed to this direction through exploring the effects which non-trivial synthetic or real topologies have on related indicators, e.g., network availability, congestion and cost. Particularly, the comparison of topologies such as those based on the scale-free, the random, the gravity, and proximity graph models, under specific simulation settings made plausible the comprehension of differences among models and offered constructive design implications. Indeed, it was verified that the non-trivial structure of both telecommunications and street networks, influence the functionality of processes running over the topologies. More specifically, valuable knowledge was obtained on the way in which different complex networks can affect the optical network availability [18], mainly concluding that the average path length and the diameter have the most critical effect. Subsequently, it was discovered that the topologies created on the basis of the gravity model suffer less from congestion than the random, the scale-free or the JR ones, under either random or gravity traffic patterns [19]. Actually, the congestion level was found to be approximately correlated with the network clustering coefficient in the case of random traffic, whereas in the case of gravity traffic such a correlation is not a trivial one. Other basic network properties, such as the average path length and the diameter, were seen to correlate fairly well with the congestion level. In addition, a comparison among different gravity-based networks, as those have derived from different population distributions, revealed different cost behavior [20], i.e., from linear up to exponential. As well, the urban street complexity impact on the fiber-to-the-home (FTTH) cost was investigated [21] and striking differences among areas were found, which on the contrary the traditional geometric models would typically pass by.

1.4 Complexity Utilization

Beyond observing the complex characteristics and the influential effects of the related networks, a compelling challenge is to be able to utilize the derived knowledge towards more efficient communications [3]. Studies so far have insisted upon the importance of identifying successful resilience and survivability strategies. Basically, this has been possible by using the centrality measures to rank the importance of components which consist a complex network infrastructure. Furthermore, a number of mechanisms for topology control and improvement of network performance have been recently proposed, for instance, the socially inspired ones.

The contribution of the current thesis to the related literature was the suggestion of an innovative approach utilizing synthetic complex graphs in order to assist the telecommunications network planning [22]. Since it can be quite risky to rely on the conventional geometric models which regard the spatial structure of the road system simplified and regular, the idea of using a proper graph-based model which can incorporate the street complexity was supported. Since telecommunications networks are built on top of physically interconnected streets, it is plausible why the complex interactions of the underlying street level should be taken into account including application-specific requirements. Specifically, the use of the Gabriel graph model [23] as a synthetic street network generator indicated its apparent sufficiency for the representation of realistic street structures. In addition, it was justified that the Gabriel model demonstrates a clearly distinct better fitting compared to the existing geometric models [24] on the fiber-to-the-x (FTTx) dimensioning and particularly on the early estimation of the main FTTx cost component – the trenching length. Besides, the conventional geometric models were verified to suffer from inaccuracy problems and thus could lead to wrong conclusion of the early techno-economic assessment. Especially in dense urban service areas, there were found striking differences between estimations and real-street calculations.

2 Results and Discussion

In this section, the two key contributions [19, 22] are described in more detail. Specifically, these are the congestion analysis of complex networks and the utilization of the Gabriel graph model for the FTTx dimensioning.

2.1 Network congestion analysis of gravity generated models

In relation to network congestion, most of the networks examined in existing studies were random (ER algorithm) or scale-free (BA algorithm) and the traffic flows have been assumed to be homogeneous between randomly selected source and destination nodes, with barely a few exceptions. However, in real networks, especially on the spatial ones, the topology can deviate from those derived from the ER or the BA models [25] and traffic is more likely to be generated/received unevenly at some nodes than at others, according to their characteristics [9].

Therefore, in the contribution [19], gravity topologies are introduced as they have been found to share statistical properties with real-world networks while allowing for optimal traffic exchange. Their behavior under congestion is compared to the behavior of random, scale-free and JR topologies. In addition, network congestion is studied taking into consideration traffic flows obeying the more realistic gravity-based flow patterns. The main purpose of this study is to examine the relationship between the complexity structure of different topologies and congestion factors under realistic traffic flows.

A simple model is applied, which considers traffic flows rather than packets, similar to that introduced in [26]. In that traffic model it is assumed that at each time step, unit traffic flow is generated between any two nodes belonging to the same connected component and capacities are randomly assigned on the links. Every origin-destination node pair i, j demands Q_{ij} traffic flows, presumably following different paths in the network. The capacity U_{ij} on the link (i, j) is randomly assigned in the range [20-60], which shows the maximum possible crossing flows on that link. Costs are also put as weights on the links using a special cost function, the US Bureau of Public Roads formula. The link cost is not a constant or a random value, but a function of the flows with congestion effects. Units of flows accumulate on the shortest path, and time step after time step congestion develops on it. Then, for subsequent flows another path becomes the shortest in terms of travel cost, which again would become congested, and so on. Since all traffic flows in each time step are to be assigned simultaneously, a game is developed among traffic flows for the selection of the feasible paths with minimum cost (user equilibrium - UE conditions).

In addition to the standard paradigm of traffic exchange, the approach followed in that paper is again based on the gravity model perspective which allows for a realistic traffic generation for the entire network. Specifically, gravity-based traffic flows are generated in each time step, in the sense that every unit traffic flow is exchanged between node pairs, origin and destination, with probability defined by the gravity equation.

The random, the scale-free and the JR networks are separately considered with random node positions and with positions assigned by the Kamada-Kawai (KK) spring algorithm [27] in order to perform legitimate comparisons and alleviate potential concerns about the networks' equity against spatial advantages.

The congestion factor J is defined as the percentage of congested links out of the total links, as introduced in [26]. Obviously, J=0 corresponds to uncongested traffic on the network, and J=1 indicates the worst case of network congestion. The total network cost *TNC* includes the link length as a cost parameter, which is important in the case of spatial traffic networks. Specifically, it is defined as the summation of all links of the product of the three variables link flow, link cost and link length.

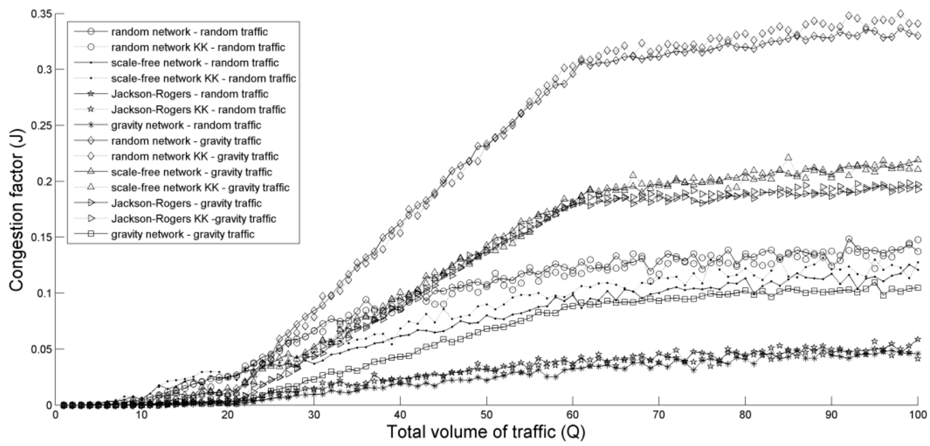

Fig. 1. Congestion factor as a function of total volume of traffic for random, random KK, scale-free, scale-free KK, JR, JR KK and gravity networks for both random and gravity-based traffic patterns[1]

[1] Each curve corresponds to an average over 20 independent realizations of the networks with 100 nodes and average node degree equal to 6. It is assumed for all networks' fitness distribution: γ=1, for the construction of gravity networks: ϕ=1, and for the gravity-based traffic flows: ϕ=1.

Both the standard paradigm of uniform traffic volumes between randomly interacting node pairs (random traffic) and the more realistic gravity-based interactions (gravity traffic) are depicted in Figure 1. In this figure, the parameter ϕ is a constant representing the distance sensitivity and the parameter γ is another constant, for which the higher its value is, the more uniform in fitness the nodes are.

It is shown that depending on the traffic pattern, the networks have different tolerance to congestion, with the gravity traffic causing more severe congestion to all networks. Moreover, the study demonstrates that the topologies created on the basis of the gravity model suffer less from congestion than the random, the scale-free or the JR ones, plus at a lower cost. Furthermore, the congestion level is found to be approximately correlated with the network clustering coefficient in the case of random traffic, whereas in the case of gravity traffic such a correlation is not a trivial one. Other basic network properties such as the average path length and the diameter are seen to correlate fairly well with the congestion level. Further investigation on the adjustment of the gravity model parameters indicates particular sensitivity to the traffic congestion, whereas only minor sensitivity to the total network cost.

These findings may be explained by the structural properties of the gravity networks; they are neither uniform, nor power-law distributed. Although gravity networks can reproduce a scale-free behavior under particular circumstances, on the other hand the spatial constraints can make the network more homogeneous. Particularly, the distance factor can shape the node degree distribution to deviate from the power-law form [9, 25], allowing for a more distributed flow exchange. This is additionally confirmed by the statistical properties of gravity topologies indicating small average path length, small diameter and high clustering coefficient, respectively.

2.2 Incorporating Gabriel graph model for FTTx dimensioning

The study [22] supports the idea that using of a graph-based model, a better alternative street layout could be succeeded, in comparison with the imprecise geometric models and the costly area-specific Geographic Information System (GIS) solutions. Particularly, the utilization of Gabriel graphs [23], shown to incorporate the complexity of real street networks, is suggested as a novel credible abstract approach that conjointly meets accuracy, simplicity and generality.

Especially, these graphs are useful in modeling graphs with geographic connectivity that resemble grids, but additionally incorporate more complex traits. They have already been suggested as capable to capture the structure of telecommunications networks in the physical backbone level. Nevertheless, it is quite intriguing to examine whether the Gabriel graph can capture the structure of the urban street network – the basis of a telecommunications access network.

In the Gabriel connection scheme, two nodes are directly connected if and only if there are no other nodes falling inside the circle associated with the diameter that has the two nodes as endpoints. Mathematically, two nodes i and j, from a set of V nodes, are connected if the square of the distance between them is less than the sum of the squared distance between each of these points and any other point k. An undirected graph is constructed by adding edges between nodes i and j if for all nodes k, $k \neq i, j$, where d expresses the Euclidean distance:

$$d(i, j)^2 \leq d(i,k)^2 + d(j,k)^2 \tag{1}$$

Based on the Gabriel graph, the network installation would follow all streets and connect buildings (subscribers) which are all assumed to be distributed along the streets (graph edges) for simplicity reasons. The total length can be derived from simulations which only require the parameter $|V|$. It is thus necessary for the length estimation to be able to calculate the number of intersections $|V|$ i.e., counting road intersections on the map.

Towards the analysis of the structural properties of Gabriel graphs, several properties are observed and compared to real-street datasets from various countries. More specifically, the dataset (100 Greek cities) and the procedure described in [16] are followed; however, three additional datasets – provided in related empirical studies – are supplementary taken into account [12-14]. Their samples are collected from diverse areas around the world (20 world cities, 118 US urban areas and 21 German cities, respectively) and correspond to large surface areas. For comparison reasons, all calculations refer to data represented using the Primal approach [11] and normalized (scaled down) to correspond to 1-square-kilometer area.

Moreover, by making use of the Mean Absolute Percentage Error (MAPE) statistic, it is demonstrated that the Gabriel graph model is able to produce synthetic networks quite similar to the considered real-street networks. In particular, the derived MAPE, for all the datasets and the basic statistical properties, is up to the level of 25%-30%.

Regarding the crucial property of the total length, it appears to take values as a function of the number of nodes (intersections) $|V|$, in all real-street datasets, as well as in the synthetic Gabriel graphs. Despite the fact that the examined real-street samples represent very diverse geographic cases, the relation between the total length and the number of nodes can fit well a power-law, i.e., $\sim |V|^p$. In the case of the synthetic Gabriel graphs, this particular equation, estimating the total length using solely the number of nodes, is:

$$W = 1.212 \cdot |V|^{0.572} \tag{2}$$

With respect to the estimation of the trenching length, a case study is presented concerning the fiber-to-the-building (FTTB) or FTTH deployment in the selected dataset of 100 urban areas in Greece, for which all required data are readily available (e.g., building density per sample area). Particularly, five traditional geometric models along with the Gabriel graph model are applied in order to estimate the required trenching length of the network installation and then compare results with the real-street lengths.

Specifically, the five most well-established geometric models for abstracting the fixed access network deployment area are the Simplified Street Length (SSL), the Street Length (SL), the Double Street Length (DSL), the SYNTHESYS, and finally the

TITAN/OPTIMUM models [24]. In practice, they are used as a starting point to design the fixed street-based (buried) telecommunications infrastructure connectivity. They are commonly based on a set of parameters such as the customer and building density, the area size, as well as the average distance between end-users and the Central Office (CO).

Table 1. Models' fitting to the real-street trenching length

	SSL	SL	DSL	SYNTHESYS	TITAN/ OPTIMUM	Gabriel graph
MAPE	0.415	0.429	0.562	1.326	0.389	0.201

After this process, remarkable variances among the results of the simple geometric models can be clearly observed, which in turn lead to errors higher than 38.9%, as seen in Table 1. The numerical results indicate that the Gabriel model solution outperforms the existing solutions by the conventional geometric ones. Even more significant is the observation that the proposed Gabriel model leads to an approximately 20% error, that is to say at least 48% better accuracy (up to 85%) than any of the geometric models. Hence, the models may be ranked from the best to the worst as follows concerning the estimation of the trenching length: Gabriel graph, TITAN/OPTIMUM, SSL, SL, DSL, SYNTHESYS.

In addition, it is achievable to quantify the inaccuracy of the considered models, caused by the irregular street connectivity, discriminated in different area types: Semi-Urban (250-500 buildings/km^2), Urban (500-1,000 buildings/km^2), and Dense-Urban (more than 1,000 buildings/km^2). Once again, it is easily apparent that the Gabriel approach offers much higher accuracy than geometric models do, especially in highly populated areas, where the existing models diverge even more from the real data (see Figure 2).

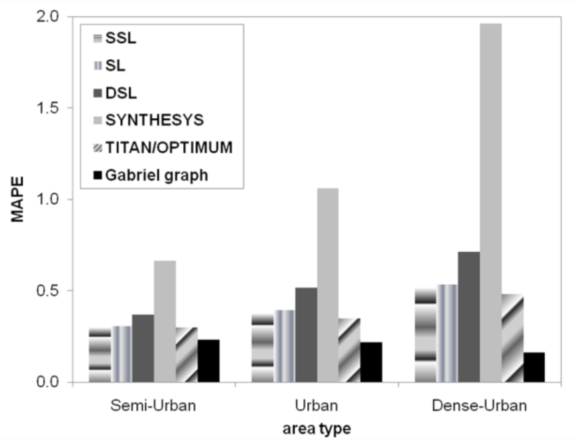

Fig. 2. MAPE behavior under different area types: Semi-Urban (250-500 buildings/km^2), Urban (500-1,000 buildings/km^2), and Dense-Urban (more than 1,000 buildings/km^2)

3 Conclusions

Complex patterns of connections (i.e., power-laws and scale-free structure) have recently emerged in the network analysis studies, forcing researchers to finally depart from the assumption of random or regular topologies.

Particularly, this thesis contributed on the complex networks analysis and modeling, on the investigation of the emergent complexity effects, and on the development of methodologies to utilize complexity towards more efficient telecommunications network planning. Specifically, the introduction of time was proved essential in the complex network analysis, the coupling between street network complexity and population density was displayed and the β-skeleton graphs' sufficiency to reproduce real-street properties was shown. As well, the impact of different complex topologies to availability, congestion and cost was presented, the superiority of gravity topologies on congestion and cost was revealed, and finally the use of Gabriel graphs was proposed, indicating a departure from the conventional geometric models.

Although the above contributions provide significant new insights into the complexity met in both the telecommunications and the underlying streets, future research is needed in order to investigate more in depth aspects which were not included in the present thesis. In particular, the consideration of functional network characteristics would be the most relevant and practical supplement from the telecommunications services perspective. Besides, a more exhaustive observation of the gravity network statistical properties would unveil the explanation for their dominance under congestion. With regard to the Gabriel graph-based approach for the preliminary FTTx dimensioning, there still remains space for exclusively ascribing the topological and geometric metrics to engineering metrics and the calculation of the rest of the FTTx cost factors, i.e., fiber length, number of splitters and so on.

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