# Structural Properties of Urban Street Networks for FTTH deployment

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*Abstract*— **The fixed access network is a major cost element for telecom operators that strongly depends on the underlying street network. In this paper the structural properties of nine urban street networks in Greece, grouped by their corresponding household and building density, are analysed based on Complex Network Theory principles. The Primal approach is used to turn GIS data into spatial graphs and various topological and geographical metrics are observed. This paper intends to demonstrate the importance of the urban morphology complexity on the cost of a telecommunication access network.**

***Keywords- Access network; Fiber-to-the-home (FTTH); Complex Network Theory; Urban street networks; Network planning***

## I. INTRODUCTION

As the Internet market continues its rapid growth, more and more applications are competing for access network bandwidth, and accordingly there are now problems arising from congestion at the network edge. Fiber-to-the-home (FTTH) access network deployments are already present in order to alleviate these local loop bandwidth bottlenecks, but still many telecom operators have not decided their strategy given the high investment costs as indicated by techno-economic studies [1].

A major part of the total capital investment in a telecommunication network is made in the lower part of the network that connects a subscriber by a physical link to its corresponding Central Office (CO) via intermediate network components. In fixed access networks the cables run under pavements in trenches that use the road system as a natural guide to reach the customers. Access network nodes as well as connections strongly depend on the actual geography of the underlying urban street network. An abstraction of the road system of the installation region for calculating the trenching and fiber lengths is already taken into account in the existing geometric models to estimate the OutSide Plant (OSP) cost of urban access networks [2-5]. Typically, the considered abstraction assumes a regular grid-like structure.

However, the spatial structure of the road system appears to be much more complex [6-8]. The urban morphology of an area, in terms of street network topology and geography, may depend on the history, the social processes, the economic activities, the climate, the scale of analysis or more factors that form the overall shape and properties very diverse from area to area [6]. A typology of urban layout classes has already been drawn up: grid-like or Manhattan-like, star-like, medieval, modernist, baroque, lollipop, hippodamian, organic, radio-concentric, self-organized, single-planned, etc. [6, 7].

It is then of great importance for the civil engineering part of the telecommunication network to be able to explicitly take into account the urban street network in the process of FTTH analysis or planning. A reliable and fast methodology that would include the analysis of the street network details could contribute remarkably to the cost feasibility study of the project. Quantities such as the trenching and fiber lengths are fundamental inputs for telecommunications techno-economic models that until now have been over- or under- estimated using the simple geometric models [9]. Bearing also in mind the fact that node locations, node capacities and connection lengths are sensitive to the geometry of the implementation and to the regional specificities, there exists an effect for the quality of service and the overall technical feasibility of the solution.

In this paper nine cases of urban street networks in Greece are studied combining GIS and Complex Network Theory, and therefore a novel approach towards the topological analysis of spatial networks is presented. The street networks are grouped based on the household and building density of the corresponding municipal departments. The Primal approach is used to convert street networks into graphs, where streets are considered as edges and street intersections are considered as nodes. After making realistic assumptions for the distribution part of the FTTH network, the trenching and fiber lengths along the streets are estimated. Variations in the measurements between areas with the same household and building density are explored, which the traditional geometric models would pass by. Also, possible correlations between the estimated lengths and the basic topological metrics are examined.

The rest of the paper is organized as follows. Section 2 refers to the related work and briefly introduces geometric modelling, the Primal approach and Complex Network Theory principles. Section 3 describes the proposed methodology for the structural representation and measurement of the street networks, while Section 4 presents the dataset. Section 5 illustrates the results, and finally conclusions are drawn in Section 6.

## II. RELATED WORK

### A. Geometric Modeling

A major obstacle to the deployment of telecommunication networks is the cost, mostly related to civil works. For an early evaluation of the feasibility of a network installation a detailed GIS-based analysis is rarely an option since it requires substantial time and resources. The use of geometric models is optional for the techno-economic evaluation but of vital contribution to analyze the deployment area, estimate the OSP cost and compare results between areas, technology solutions and architectures.

Geometric models for telecommunication access networks make an abstraction of the installation region under consideration. They are used to design the telecommunication infrastructure based on a set of parameters such as the household (subscriber) density, the building density, the average distance between end users and CO, the network topology, etc. and include an algorithmic or mathematical approach for calculating key geometry-dependent quantities for the cost analysis, e.g., trenching and fiber length in the case of fixed access networks.

Several geometric models have been developed to estimate the deployment cost of a telecommunication access network [2-5]. Typically the abstraction assumes a regular grid-like structure where all lines have equal length and the same number of junctions. The different analytical models assume highly symmetric graphical models of a uniform customer distribution over a squared area or polygon based area with a recursive structure. However, in FTTH installation the trenching and fibers typically run in the pavements along the streets with various constraints and non-regular street structure. In practice, the traditional geometric models may suffer from inaccuracy problems and have already been criticised for this [9].

Other studies use the mathematical framework of stochastic geometry [10] to derive analytical formulas for distributions of connection lengths. The Stochastic Subscriber Line Model (SSLM) [11] is a stochastic–geometric model for fixed access networks. The choice of random models and parameters allows representing the road system with the desired statistical information but the estimation success still depends on the fitting of optimal tessellations to the considered road system.

### B. The Primal Approach

Other types of abstraction can be used to simplify and analyze a given street network but still retain the complex details of the network thanks to some mathematical tools from Graph Theory. Data from GIS vector maps, that use geometrical segments such as points and lines (coordinate pairs or series of coordinate pairs) to represent objects, can rapidly be transformed into graphs. Between the new techniques that have arisen such as the angular-segment maps [12] and the continuity maps [13], there are two principal modeling approaches that can be applied to represent the street network as a graph, the Primal approach [14] and the Dual Approach [15].

In the Primal approach, the streets are turned into spatial, undirected, weighted, primal graphs, where street intersections and end points are represented as nodes and street segments between successive intersections are represented as edges. The Dual approach is the opposite, where named streets are represented as nodes and the intersections between the streets are represented as graph edges.

In recent studies [6] as well as in this paper, the analysis of the street networks is based on the production of Primal graphs that encapsulate both topological and geometrical properties of urban networks. The advantage of the Primal approach is that it preserves the geometry of the urban space, while the Dual approach preserves only the topological properties with the geometric ones disappearing. In the Dual method a street is one node no matter its real length while metric distance is a key ingredient of spatial networks. Indeed, recent studies have pointed out a number of inconsistencies in the Dual approach. In particular, the use of straight lines is oversensitive to small deformations in the grid, which leads to noticeably different graphs for systems that should have similar configurational properties [16].

### C. Complex Network Theory

Complex Network Theory is widely used in the study of social, biological, communication, transportation and other relational networks [17], but so far fairly little in the spatial analysis of street networks. Despite their inherent differences, most of the real networks are characterized by similar topological properties, as for instance relatively small geodesic path lengths and high clustering coefficients, the so called "small-world" property, "scale-free" degree distributions, and the presence of motifs and community structures.

Though, as increasing amounts of pervasive geographic data are becoming available, new approaches are suggested [6-8] that make use of the Complex Network Theory to characterize and compare the topology of urban street networks. Furthermore, in most cases, the street topologies possess a complex structure and deviate from simple regular patterns such as square-grids. The common traits of such topologies are largely unknown and their quantitative description is lacking. Moreover, the GIS packages by themselves do not provide tools beyond the few standard ones, such as searching for the shortest path or the nearest facility.

Street networks are spatial, which is a special class of complex networks whose nodes are embedded in a two (or three) dimensional Euclidean space and whose edges do not define relations in an abstract space, but are real physical connections [6]. Such a street network can be represented as a graph $G(V, E)$, which consists of a finite set of nodes $V$ and a finite set of edges $E$. The graph nodes have precise position on the planar map $\{x_i, y_i\}_{i=1,\ldots,N}$, while the links follow the footprints of real streets and are associated a set of real positive numbers representing the street lengths, $\{l_\alpha\}_{\alpha=1,\ldots,K}$. In the following, the graph representing an area is described by the adjacency $N\times N$ matrix $A$, whose entry $a_{ij}$ is equal to 1 when there is an edge between $i$ and $j$ and 0 otherwise, and by a $N\times N$ matrix $L$, whose entry $l_{ij}$ is the weight (physical length) associated to the edge connecting $i$ and $j$. In this way both the topology and the geography metric distances are taken into account.

Apart from the number of nodes and edges and other quantities that are defined in Section 3, the basic statistical metrics are presented here; the mean degree, the density, the diameter, the average clustering coefficient, the average shortest path and the degree distribution.

The degree of a node (here, intersection) is the number of edges (here, road segments) connected directly to that node. The mean degree of a network is the average degree over all nodes and is defined as $z = \frac{2K}{N}$, where $K$ denotes the number of edges, and $N$ the number of nodes.

The network density measures the ratio of the number of edges to the maximum number of possible edges. For undirected networks, the density is defined as $q = \frac{2K}{N(N-1)}$, where $K$ denotes the number of edges, and $N$ the number of nodes.

The diameter, $r$, of a network is the length (in number of edges) of the longest shortest path between any two nodes in the network.

The average shortest path, $p$, or average geodesic path length is defined as the average number of steps along the shortest paths for all possible pairs of network nodes.

The average clustering coefficient is defined as in [17], $CC = \frac{1}{N}\sum_i C_i$, where the local clustering coefficient is $C_i = \frac{number\ of\ triangles\ connected\ to\ node\ i}{number\ of\ triples\ centered\ on\ node\ i}$.

Node degree data can also be characterized by the degree distribution, or more accurately the complementary cumulative distribution function (CCDF) which is the probability that the degree is greater than or equal to $k$ [17]. The degree distribution in real world networks is usually a “scale free” distribution which shows up as a straight line in a log-log plot. It is not expected to find “scale-free” degree distributions in planar street networks because the node degree is limited by the spatial embedding [8]. In particular, it is very unprobable to find an intersection with more than 5 or 6 streets [6] due to the scarce availability of physical space. Thus no degree distributions are studied in the present work.

Other Complex Network concepts, such as network centralities which are mathematical methods of quantifying the importance of each node in a graph, can show very helpful. For example, they can contribute in identifying the optimal nodes for locating elements in the network, e.g., flexibility points, or may help to identify local clusters. Especially the Closeness centrality measures to which extent a node $i$ is near to all the other nodes along the shortest paths, and is defined as [18] $C_i^C = \frac{N-1}{\sum_{i \neq j} d_{ij}}$, where $N$ is the number of nodes and $d_{ij}$ is the shortest path length between $i$ and $j$, defined in a weighted graph as the smallest sum of the edges length throughout all the possible paths in the graph between $i$ and $j$.

The basic statistical properties of interest can reveal similarities and differences between the considered networks. Despite the peculiar historical, cultural and socio-economic mechanisms that have shaped distinct urban networks in different ways recent empirical studies have shown that, at least at a coarse-grained level, unexpected quantitative similarities exist. For example, studies [8, 15] have found that urban street networks can be classified as “small-world” networks with small average path length and high degree of clustering. Also, the average degree metric shows a range of values 2.10-3.38 as reported in [6, 7]. Similar properties are common at least between cities of the same class, e.g., grid-iron or medieval [6].

## III. METHODOLOGY

The proposed approach in contrast to the existing geometric models captures the complex details of the underlying urban street network in order to accurately estimate the key quantities for a techno-economic evaluation of FTTH networks.

The considered FTTH architecture is presented in Fig. 1. The model consists of a CO where all the optical line terminals are located, the feeder part of network connecting the CO with flexibility points (FP), and the distribution part from FP to the end-users. The FP (or splitting point, or remote node, or aggregation node, or cabinet) plays a concentration role, allowing the merging of customer cables. There are two popular technologies used with FTTH. The Point to Point (P2P) technology which uses all active components throughout the chain and Point to Multi-Point (P2M) / Passive Optical Network (PON) technology which uses passive optical splitters at the aggregation layer. In either case, the distribution part of the access network, between the last FP and the customer, consists of trenches and point-to-point fibers that follow the street network. Connections between the FP nodes and the CO nodes (feeder network) and above layers ensured by the core network are not considered here. Also, a greenfield deployment

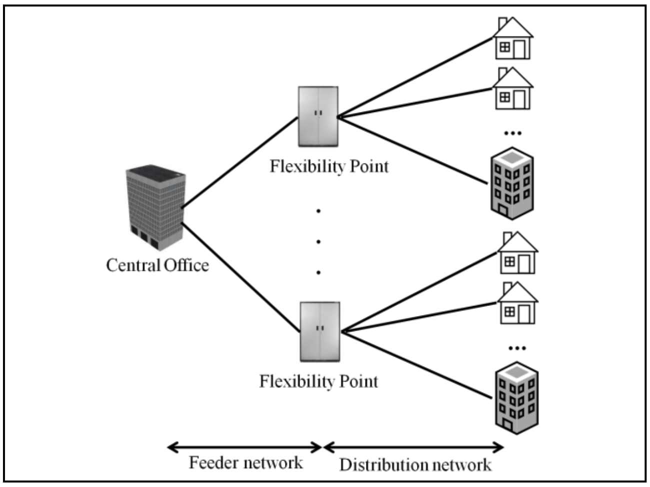

Figure 1. FTTH access network architecture

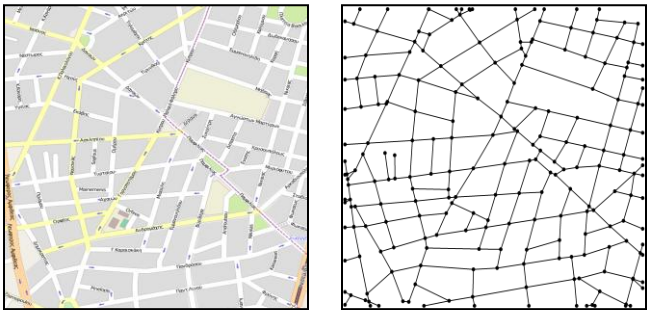

Figure 2. In the left it is the street network of the district sample of M.D. Nea Smirni, while to the right is the corresponding Primal graph

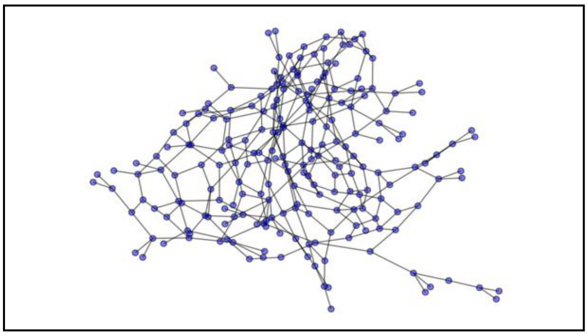

Figure 3. The urban street network of the district sample of M.D. Nea Smirni represented in a non planar way

is assumed and no existing infrastructure is taken into account. The installation closely follows one street and connects all houses from one street-wise cable along the street. The cable can be located at the middle of the street, or at one side of the street as well. All households in the area are connected by the end of the installation.

Here, structural analysis of the urban street network for FTTH deployment takes place in two main parts. First, the topological and geometrical analysis of the road system and second, the study of the extended graphs derived by the splitting into smaller service areas, placement of FPs and adding of customer building nodes and connections between them.

A sample urban area is chosen and GIS data are collected without further GIS processing or analysis. The GIS data are then transformed to a spatial, weighted, undirected graph using the Primal approach where intersections are turned into nodes and streets into edges, as shown in Fig. 2. All nodes of degree $k$=2 that represent curved or sharply bended streets rather than physical intersections of different streets are removed from the database. This leads to an additional decrease in the number of both nodes and links in the network. The network can also be represented in a non planar way, as in Fig. 3, because of the necessary information retained in the edge weights.

Then, various network characteristics may be computed. Also, the trenching length or cost of the wiring [6] is defined as the sum of street lengths $T = \sum a_{ij} l_{ij}$ and measured in kilometers. This metric is chosen instead of calculating the near optimal trenching topology of an extended Steiner tree over the full road-topology, since that could only lead to insignificant differences [19].

Depending on the demographic data and the subscriber (or household) density of the area, a number of FPs is assigned at optimal locations. Each FP can serve a maximum number of households, e.g., 144 or 288, thus the total number of households is divided to this number to produce the required FPs. Then, the considered area needs to be split into serving zones, for example squares of equal size in order to serve approximately the same number of buildings/households (Fig. 4). Each FP is associated with a serving zone such that the inscribed subnetwork that gathers all fiber lines between the FP and the subscribers displays a star structure that follows the underlying street network. The simplest approach to compute the fiber length in the area is to sum up the fiber lengths of all serving zones.

In order to make easier that estimation, a spatial, weighted, undirected graph is constructed considering buildings as nodes. Depending on the building density of the area, a new spatial network is made as an extension of the street network, with new nodes placed equidistance from neighbor nodes along the existing edges, so that the total number of nodes is equal to the number of buildings (Fig. 4). The Closeness centrality method is applied to identify the optimal node to place the FP, in terms of total fiber distance to reach all other nodes. Then physical fiber connection is established as the shortest path from the building where the household is located to the corresponding FP following the streets. This appears to be a realistic assumption for the fixed access network. These point-to-point distances are computed as the lengths of shortest paths following the streets using Dijkstra’s algorithm. The total fiber

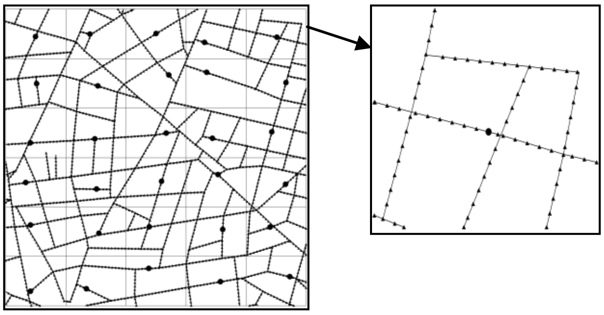

Figure 4. In the left it is the street network of the district sample of M.D. Nea Smirni split into square serving zones with FPs placed in the optimal locations, while to the right is a certain serving area zoomed

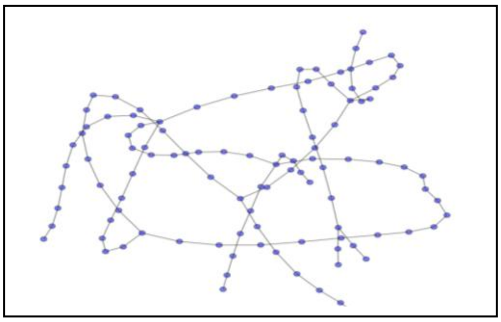

Figure 5. A certain serving area of the district sample of M.D. Nea Smirni represented in a non planar way

length of the area is defined as the sum of the fiber length of all serving zones, $F = \sum_{serv.zones} \sum_{i} d_{ci} h$, where $c$ is the node with the highest Closeness centrality in that particular serving zone and $h$ is the average number of households per building. The quantity $F$ is measured in kilometers. Again, the subnetwork can be represented in a non planar way (Fig. 5) because the necessary information is retained in the edge weights.

## IV. DATASET

In Greece there are 6126 municipal departments (M.D.) with only a small portion of them able to be considered as urban. When examining the 100 municipal departments with the highest household density, the highest is 9464 households/km$^2$ and the lowest is 382 households/km$^2$ [20] (Fig. 6).

Here, three groups of municipal departments are formed, the Dense-Urban, the Urban and the Semi-Urban (Table 1), each with three municipal departments that have almost identical household and building density. Totally, nine municipal departments in Greece are selected, namely: Nea Smirni, Ampelokipi, Athens, Ilioupoli, Eleftherio, Amarousio, Chalkida, Corinth and Nafplion (Fig. 7, Fig. 8 and Fig. 9).

TABLE I. MUNICIPAL DEPARTMENTS TYPE CHARACTERISTICS

| **Group Type** | ***Household Density (households/km$^2$)*** | ***Building Density (buildings/km$^2$)*** | ***Samples*** |
|---|---|---|---|
| Dense-Urban | 8000 | 1700 | Nea Smirni<br>Ampelokipi<br>Athens |
| Urban | 2000 | 800 | Ilioupoli<br>Eleftherio<br>Amarousio |
| Semi-Urban | 500 | 400 | Chalkida<br>Corinth<br>Nafplion |

The data are obtained from the collaborative project OpenStreetMap [21] and the Hellenic Statistical Authority [20]. The constructed dataset consists of nine 1-square-kilometer samples of the abovementioned municipal departments. Their data are imported in a GIS environment and are turned into spatial, weighted, undirected graphs using the Primal approach. The properties of the derived graphs, $N$, $K$, $z$, $q$, $r$, $p$, $CC$, are evaluated and the trenching length, $T$, is estimated in Section 5.

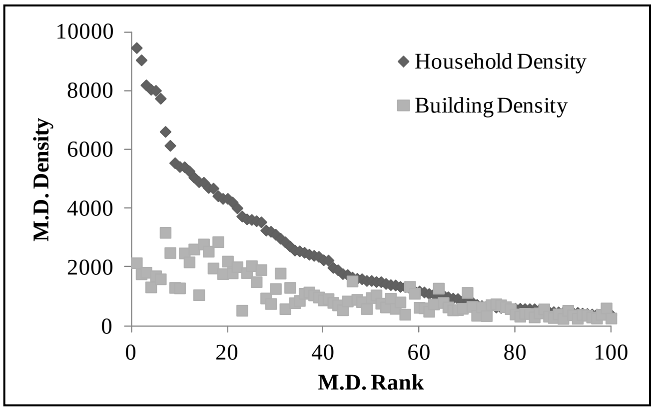

Figure 6. The 100 municipal departments of Greece with the highest household density together with their building density

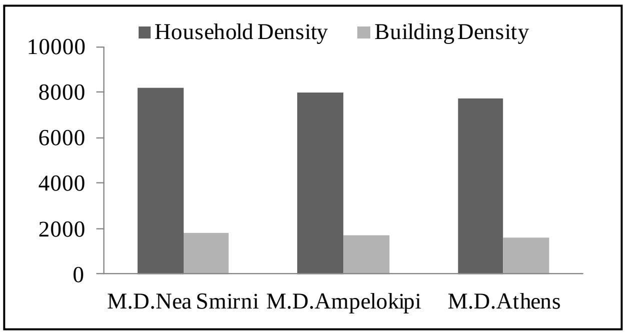

Figure 7. Selected Dense-Urban municipal departments with approximately identical characteristics

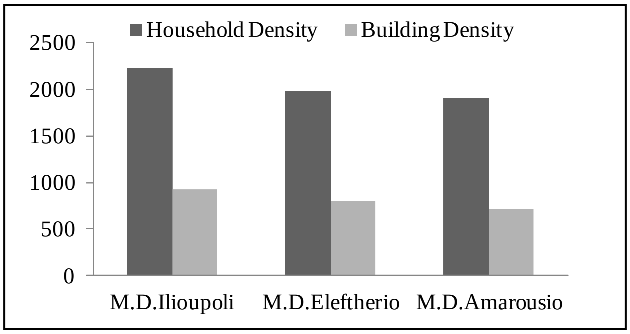

Figure 8. Selected Urban municipal departments with approximately identical charactristics

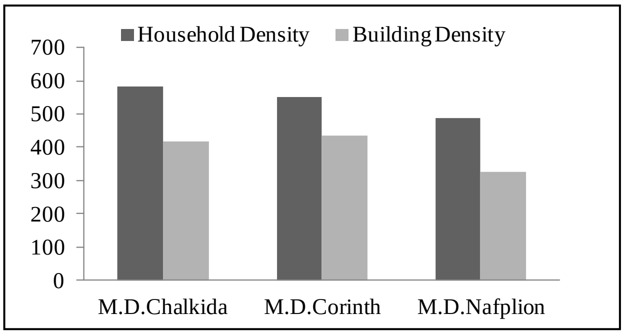

Figure 9. Selected Semi-Urban municipal departments with approximately identical characteristics

To find the number of FPs (cabinets) per sample M.D. it is assumed that each FP can serve up to 288 households. The total household number of each sample M.D. is divided by 288 and the result is rounded up to the nearest even integer. This gives 1-square-kilometer samples: M.D. Nea Smirni 30 FPs, M.D. Ampelokipi 28 FPs, M.D. Athens 28 FPs, M.D. Ilioupoli 8 FPs, M.D. Eleftherio 8 FPs, M.D. Amarousio 8 FPs, M.D. Chalkida 4 FPs, M.D. Corinth 2 FPs and M.D. Nafplion 2 FPs. Then, the fiber length, $F$, is estimated for each FP serving zone and the total fiber length arises.

TABLE II. URBAN STREET NETWORKS BASIC METRICS

| **Municipal Departments (1-square-km samples)** | ***Nodes*** | ***Edges*** | ***Density*** | ***Average Degree*** | ***Diameter (hops)*** | ***Average CC*** | ***Average shortest path (hops)*** | ***Average street length (meters)*** |
|---|---|---|---|---|---|---|---|---|
| Dense-Urban | | | | | | | | |
| Nea Smirni | 224 | 316 | 0.0132 | 2.82 | 23 | 0.0116 | 9.38 | 62.96 |
| Amplelokipoi | 284 | 401 | 0.0097 | 2.82 | 25 | 0.0094 | 10.81 | 57.85 |
| Athens | 291 | 426 | 0.0105 | 2.93 | 26 | 0.0296 | 10.73 | 55.76 |
| Urban | | | | | | | | |
| Ilioupoli | 160 | 237 | 0.0188 | 2.96 | 25 | 0.0070 | 8.80 | 80.87 |
| Eleytherio | 283 | 406 | 0.0102 | 2.87 | 29 | 0.0243 | 11.21 | 56.91 |
| Amarousio | 154 | 216 | 0.0182 | 2.81 | 18 | 0.0050 | 8.02 | 77.47 |
| Semi-Urban | | | | | | | | |
| Chalkida | 280 | 404 | 0.0108 | 2.89 | 27 | 0.0146 | 10.69 | 58.57 |
| Corinth | 128 | 183 | 0.0225 | 2.86 | 15 | 0.0117 | 7.39 | 84.69 |
| Nafplion | 82 | 117 | 0.0352 | 2.85 | 17 | 0.0000 | 6.62 | 94.27 |

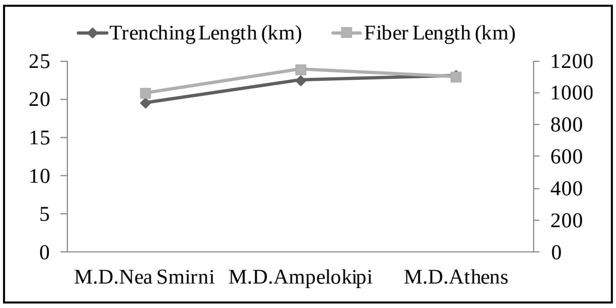

Figure 10. Lengths for the selected Dense-Urban sample M.D.s

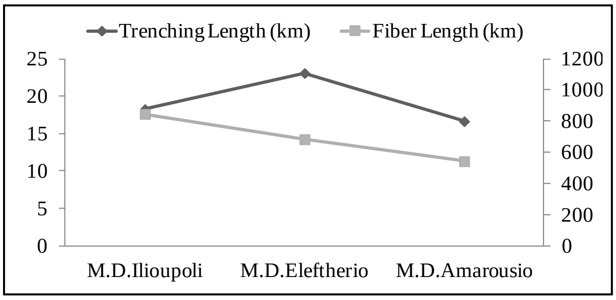

Figure 11. Lengths for the selected Urban sample M.D.s

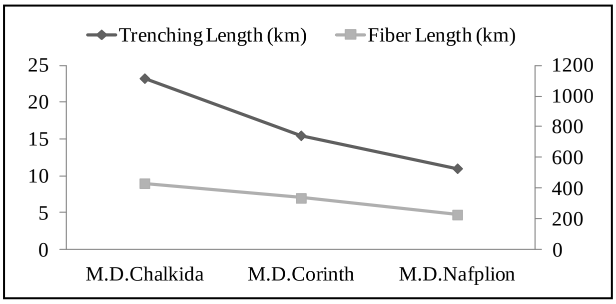

Figure 12. Lenghts for the selected Semi-Urban sample M.D.s

## V. RESULTS

The nine urban street networks are described by their global indicators in Table 2. These indicators provide a general description of the nature of each network and appear to be quite diverse.

The size of the derived networks varies from 82 to 291 nodes and correspondingly edges, from 117 to 426. The average degree values are almost invariable, from 2.81 to 2.96 and are in accordance with the measurements reported in [6, 7] that show a range of values 2.10-3.38. It is worth noting that the average degree is slightly lower than expected because the edges that were cut in the boundaries of the 1-square-kilometer area are still taken into account.

“Small-world” properties are not found to emerge in the networks. As one can remark not so high average clustering coefficients, neither small average shortest paths are present in the studied samples.

The studied networks show a notable variance in the density, the diameter, the average clustering coefficient, the average shortest path and the average street length even between the M.D.s of the same urban class. Concerning the trenching length, it takes values 11 km – 23 km and the fiber length 228 km – 1150 km.

According to the traditional geometric models the urban areas that occupy the same amount of land and have identical household and building density should also have the same trenching and fiber length. However, this is not the case here (Fig. 10, Fig. 11 and Fig. 12). One can observe remarkable variances between the M.D.s of the same group. For example, variance in trenching length is up to 52% (M.D. Chalkida, M.D. Nafplion) and in fiber length is up to 47% (M.D. Chalkida, M.D. Nafplion).

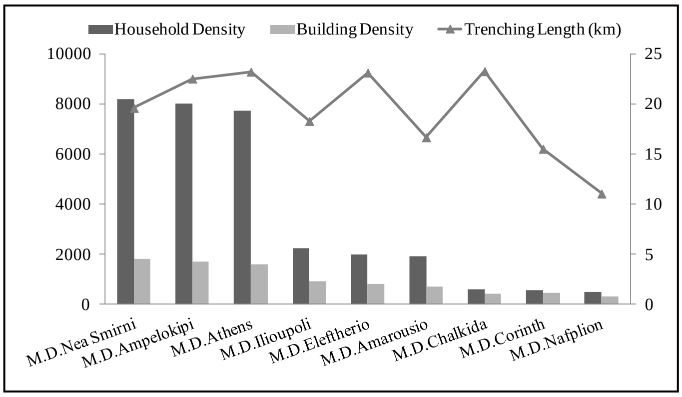

Figure 13. Estimated trenching lengths for the selected municipal departments

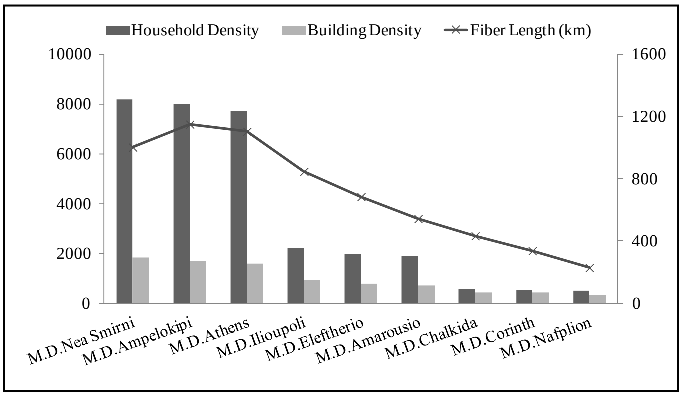

Figure 14. Estimated fiber lengths for the selected municipal departments

The fiber length is found proportional to the household density of the area (Fig. 14), while this is not valid for the trenching length (Fig. 13). If lengths are observed per urban group, there also emerges a trend showing the fiber length to be correlated to the trenching length, except the M.D.s of Athens and Ilioupoli. Particularly in Athens and Ilioupoli the shift in the trend appears to be due to the slight differences in household density between other M.D.s in the group, lower and higher, respectively.

Some correlations are also apparent between topological and geographical measurements. The M.D.s with the lower trenching length (i.e., Ilioupoli, Amarousio, Corinth and Nafplion) appear to have lower node and edge number, higher graph density, smaller average shortest path and higher average street (segment) length.

The results of the structural analysis, based on such a minimum dataset (GIS vector map, household and building density) that could be easily obtained for most urban areas, produce additional information for the network planning and the cost estimation process and support the belief that the urban morphology complexity has great impact on the cost of telecommunication access networks.

## VI. CONCLUSIONS

Here it is discussed the potential of the integration of GIS and Complex Network Theory principles to provide a complementary view of the structure of the road system to the telecommunication access network planner.

The selection of municipal departments (1-square-kilometer samples), identical in terms of household and building density, makes it appropriate to derive topological and geographical information that could be used as a preliminary and exploratory process prior to a full techno-economic evaluation. The approach presented here can also help decrypt the complexity of the urban street networks and find striking differences between areas which the traditional geometric models would pass by. Main OSP cost drivers for the FTTH deployment, such as the trenching and the fiber length are found here to be strongly dependent on the actual geography of the underlying urban street network.

The adoption of the above or similar techniques could assist a telecom operator to early evaluate in a fast, but detailed and reliable way, candidate areas for network deployment. It is also possible to investigate different implementation scenarios (e.g., different splitting ratios) and technologies (e.g., P2P vs PON) and negotiate with regulatory authorities about the network coverage and cost.

In future, the selection of larger surface areas would allow a more complete consideration of the access network including the feeder part. Also, if additional data such as existing infrastructure, pavement types and pavement width, required equipment, exact location of buildings, geomarketing data, etc. are available, the characterization of the urban street networks could be enriched and the overall methodology could be improved.

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