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Evaluation Model for Equipment Estimation of Broadband Access Network Over Medium Voltage Power Lines

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Abstract: This study deals with the problem of providing access of broadband services to a given geographic area by altering the medium voltage power grid. An evaluation model for Broadband over Power Lines (BPL) emerging technology is proposed, applied to the medium voltage distribution network considered as an access telecommunications network, as seen by the Network Access Provider point of view. The model is based on, a detailed grid structure and topology information data stored in a multi-layered geographic information system. The performed application estimates all costs associated with each type of BPL equipment necessary in order to tranceive the broadband signal from the injection point to the end user, by the means of fixed wireless access points and determines the overall investment required for providing broadband access to the geographic area under service. Finally, in order to present a real-case scenario the proposed model was applied and tested to the electric grid of the Prefecture of Laconia/Greece.

Key words: Broadband over power lines, power line communications, extractor, injector, repeater, medium voltage line

INTRODUCTION

The liberalization of telecommunications and the deregulation of electricity utilities have added new dimensions to the potential applications of the electricity infrastructure for the efficient use of the local loop. Furthermore, the birth and growth of the Internet accelerate the demand for digital telecommunications services to almost every premise (Pavlidou *et al*., 2003).

However, the 'broadband for all' concept is not achieved. The main bottleneck in providing such services to reach the users is to have proper access networks to reach their premises. The urban areas are well covered by copper wires from the incumbent operators, whereas the semi-urban and rural areas are not well covered. In this context, the utilities and electricity supply networks have unique features of its ubiquity in reaching almost, 100% of the population in developed and most of the developing countries (Held, 2006).

Broadband over Power Lines (BPL) is the usage of electrical power supply networks for broadband communication purposes. In this case, electrical distribution grids are additionally used as a transmission medium for the transfer of various telecommunications services. The main idea behind BPL is the reduction of cost and expenditure in the realization of new telecommunications networks (Hrasnica *et al*., 2004).

BPL has received tremendous attention in recent years as an alternative and cost-effective last-mile-access technology. It is easy, to install BPL networks cost-effectively since power lines already exist everywhere. Thus, power lines are frequently regarded as the preferred medium for providing a broadband connection to rural or remote areas where telephone and cable connections do not exist. BPL can provide data services, such as broadband Internet service, VoIP service and a variety of value-added services, such as remote metering, street light control, home security, home appliance control and many more. A number of BPL systems have been installed worldwide for various kinds of field trials to demonstrate its feasibility and effectiveness (Lee *et al*., 2006).

The usage of the power grid for control, maintenance and charging purposes by the utility commodities has a long history. For many years, power companies have had the ambition to use electrical distribution networks for communications and data transfer. However, a realistic technology for providing high-speed, two-way communications has just recently become a reality. The

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utilities' existing infrastructure of stout copper lines and long-distance cables has the potential to become a ubiquitous broadband communications platform. Only appropriate system level developments have to be done to carry communication signals on this infrastructure to reach the customers around the country, independent of their location. The major advantage to power networks is that they are ubiquitous, the largest capital outlay for any communications network being the network. Thus, a truly universal information superhighway might be realized, with the capability of providing interconnection to every home, factory, office and organization (Dhir, 2001).

The proposed model can be used as a network evaluation tool helping the Network Access Provider to estimate the overall economic effort necessary for the provision of broadband services to a given geographic area by altering the medium voltage power-grid. The model estimates the required network BPL equipment for the implementation of a hybrid access BPL solution. In this option, only the Medium Voltage (MV) power-grid is used and the interconnection with the end users is provided via wireless connections created by a fixed wireless network. Repeaters and extractors along the line boost the signal and provide customer access via the wireless WiFi technology. Finally, the model calculates all costs associated with each type of BPL equipment necessary in order to, propagate the broadband signal from the injection point to the end user, by the means of fixed wireless access points and determines the overall investment required for providing broadband access to the geographic area under consideration. The model is based on updated and detailed grid structure and topology information data already stored in a Geographic Information System (GIS).

OVERVIEW OF BPL NETWORK TECHNOLOGY

BPL technology enables utility companies to deploy a communications network over existing power line infrastructures by transmitting data signals through the same power cables that transmit electricity. This technology, however, uses a different frequency from the power cable. BPL can be used for various network services such as broadband Internet access, telephony, remote metering and home networking services. There are largely 2 types of BPL networks depending on the area they cover: access BPL and in-home BPL. In its earlier stages, this technology was also referred to as Power Line Communications (PLC). Recent advances in modulation techniques and technology have led to significant increases in the throughput of power line carriers. This new class of high data rate power line carriers is commonly referred to as BPL (Hofstra, 2006; Sakai, 2003).

While, the details of electric power grid structures and topologies differ from country to country, a power grid basically consists of power plants or generators, transmission substations, transmission lines, power substations with transformers to change voltage levels and distribution lines that collectively generate and carry the electricity from power plants all the way to wall plugs (Lushbaugh and Safavian, 2007).

Electricity flows over powerlines at a near-steady 50 Hz. If a signal is injected over this network at much higher frequencies, it would present minimal interference with the electricity delivery; somewhat analogous to DSL technologies using different frequency bands for voice and for data over the same copper infrastructure. Utilities have been transmitting communications signals over powerlines for many decades, mainly for control purposes. However, these signals usually operated at kilohertz ranges and offered only modest transmission capacity, sometimes less than a kilobit per second. A relatively new idea has been to transmit broadband signals for communications purposes, i.e., BPL. This has been made possible by advances in communications design and in electronic chips, which can successfully modulate and demodulate information of a carrier signal operating at high-frequency ranges. Most modern BPL systems operate with a carrier frequency range of approximately 1-30 MHz, which, according to Shannon's Theorem (Shannon, 1948), could provide many tens of Mbps of throughput, depending on the Signal-to-Noise Ratio (SNR). However, practical limits on signal levels and noise within the power systems limit the throughput.

The power distribution network was not designed or optimized for information delivery, with numerous bridges, splits, taps, branching, etc., as well as a myriad equipment on route such as capacitor banks and transformers. In addition and according to the heterogeneouity criterion, two systems are not alike.

Considering the utility network for delivering power, distribution typically begins at a substation, which connects upstream into the high-voltage transmission or sub-transmission system. From the substation, electricity traverses multiple kilometres (on average) at MV levels (multiple kilovolts), after which point it goes through a distribution (step-down) transformer (also called a low-voltage, or LV, transformer) to reach the end-users. Most systems have a tree design, where multiple end-users tap off from a shared distribution transformer and distribution transformers themselves branch off from a feeder line coming from the substation. US utilities typically serve on the order of 4-8 end-users per distribution transformer, give or take and thus, are able to use relatively small distribution transformers. In contrast, in Europe and Asia, most distribution transformers feed 100-200 end-users. Of course, different utilities or different consumer mixes can lead to different power network designs. The different power systems and grid designs make BPL standardization and thus, market volume, more difficult, as do the different regulations in different countries (Tongia, 2004).

The 20 kV distribution voltage network that is currently used in Greece was standardized in 1970 for economical harmonization according to the European standards. Until then, the value was 15 kV, with the exception of Athens, where 22 and 6.6 kV was used. The major part of distribution network operates at 20 kV. Equipment operating at the same voltage (20 kV) is being installed in the remainder parts that operate at lower voltage (15 kV) aiming at the progressive upgrade to 20 kV. All medium voltage networks are 3 phase, 3 conductors.

The standardized nominal voltages of operation for the Greek electric network are:

- Transportation network: 400, 150 and 66 kV.
- Medium voltage distribution network: 20 and 15 kV.
- Low voltage distribution network: 380/220 V (400/230 V).

High-Voltage (HV) lines are usually too noisy to transmit broadband communications signals; only MV and LV lines are used for BPL. MV lines are usually less branched than LV lines, making point-to-point connections possible. MV networks allow communication over longer distances because of their weaker signal attenuation and lower noise level (Held, 2006; Lushbaugh and Safavian, 2007).

In general, a Point of Presence (POP) is used to connect the BPL network to a backhaul network so that data from applications such as Internet, VoIP or mobile telephony can enter (or leave) at the substation level, where specialized equipment generates the data signals that are coupled (physically attached) onto the MV wire (Hrasnica *et al.*, 2004). For the backbone network, cable network or fiber optic communication is used since a cost-effective BPL technology for supporting long-haul communication has not yet been developed.

Since, the signal attenuates over the line, with higher losses at higher frequencies and emission limits restrict boosting the transmission signal, the cost of repeaters, used en-route, must be taken into account. LV transformers, secondly, act as a low-pass filter, allowing electricity through with low losses but not higher frequencies. In the specified model, in order to overcome the last issue, the hybrid solution has been adopted.

In this option, typically only the MV lines are used and a fixed wireless network replaces the LV lines and in-house BPL. In hybrid BPL, the extractor does not couple the broadband signal to/from the LV line but converts it to/from a wireless format and delivers it to the wireless Access Point (AP) also located on the pole. The interconnection with end users is provided via wireless connections at the transformer. It must be a WiFi connection at 2 points: At a service injection point for medium voltage (20 kV) line and at the customer drop. Repeaters and extractors along the line boost the signal and provide customer access via WiFi. Line-mounted extractors can be powered through induction (requires >70A line) and have an internal WiFi antenna. Pole-mounted and enclosure-mounted (for areas with underground wires) installations require a transformer and external antenna, or an antenna hidden inside a light pole. The solution uses off-the-shelf WiFi equipment as CPE. BPL is able to transport data, voice and video at broadband speeds for end-user customer connections. This model saves on some of the costs of the transformer bypass and can potentially allow greater sharing of access in the final drop (Chowdhury, 2005).

The last issue is that the system is based on shared bandwidth, in part due to the tree design of the infrastructure. While, an opportunity in terms of sharing capital equipment costs across users, shared infrastructures also lead to congestion, multiplexing, interference and security concerns. To overcome these issues, BPL solutions rely on sophisticated signal processing and encoding. Typically, the physical layer and coding is based on Orthogonal Frequency Division Multiplexing (OFDM) and sometimes on spread-spectrum techniques. OFDM offers not only spectral efficiency, but also robustness against interference, a major concern in noisy electrical networks (Tongia, 2004).

USING GIS FOR BPL NETWORK DESIGN

From the application point of view, a GIS is ideally suited for network planning and development. The ability to layer information onto the earth's surface, complete with attribute data, allows telecom engineers the unique ability to model and assess a network from the office. This saves valuable time and reduces the number of trips, if any, that the engineer must make to the field. Furthermore, the powerful automation capabilities offered by a GIS increase the speed and accuracy of the network design process and can help reduce and even eliminate, the downstream impacts of design-phase errors on cost and schedule during the network deployment phase. Rule-based features found in a GIS can also offer network designers the ability to produce better products, optimized for cost, shortest routing distances, or other user-defined metrics. The skill level and design time involved in hand-producing comparable designs would be significantly higher (Lucas, 2007).

The design and implementation of a BPL access network requires excellent knowledge of the power-grid infrastructure in order to achieve optimal economic exploitation and rapid installation and setup process. The electric networks are being constantly extended due to the continuous addition of new loads and substations, rendering network follow-up with informed and distinct maps indispensable. Using conventional methods, this process involves the constant creation of new imprintings (traditional maps or sketches) in study that require large operational costs, waste great amounts of time and effort and cause delays in the briefings and deceleration of investments due to delayed customer service. Obviously, this problem is intensified in regions where the network growth is rapid because of the increasing number of connections of new distributed generation plants.

Comprehensively, a GIS is comprised of the following entities (http://www.mapinfo.com):

- Database of the involved geographic data.
- Map creation: These systems offer dynamic mapping creation and provide functions that can determine the relations among the various elements on the surface of the ground.
- Model creation: Using individually adapted tools, they can provide geographic information management and conclusion exporting.

Moreover, various GIS systems provide an array of different functions that can be adapted to the individual needs of each user.

THE PROPOSED EVALUATION MODEL

The objective of the proposed model is to estimate the overall cost of introducing BPL technology in a given power supply grid. For this reason, an application was used that fulfils the requirements of creating a complete system that can both record a medium voltage supply network for simple mapping production and at the same time perform complex calculations of network parameters necessary for the deployment of BPL technology equipment (Lazarou and Pyrgioti, 2007). The design of the application was made with the intention of being able to apply the model in every generic medium voltage network. This application is then used for the estimation of the type and number of equipment required for the introduction of BPL technology to a medium voltage supply grid.

NETWORK DIGITALIZATION

Network digitalization is essential for recording all the necessary electric elements. The procedure is based on the recording of 2 kinds of entities, the nodes and the two-port network elements. The reporting of all elements is made in relation to the nodes, which are classified with a unique serial number. Between 2 nodes it can be one or more two-port network elements.

As a two-port network we consider every non specific point of the power-grid, such as: Line segments and transformers. The representation of all the 2-port network elements is made by the standard 2-port network model, which in every case is adapted to the particular element under consideration.

The nodes have a unique serial number and represent the primary database key for data indexing. The first node entered in the system is recorded as node 1, the second as node 2, etc. Between 2 nodes, a two-port network element is placed (line segment, cable and transformer) and this is how the entire BPL network is structured.

The application was developed in MapInfo using MapBasic, which is an optimized language for geographical information data entry. A specific database was created, containing the following tables:

- PointTab.TAB: Node entry table.
- SegmentTab.TAB: Two-port network entry table.
- PointTypeTab.TAB: Node type entry table.
- LineTypeTab.TAB: Line type entry table.
- RegionTab.TAB: Region entry table.
- CompanyTab.TAB: Company entry table.

During the digitalization process every entity, node or two port network element, imported by the user is recorded in the PointTab or in the SegmentTab table. These are the 2 main database's tables.

According to, the database structure the PointTab table acquires the data on the available node types from the PointTypeTab table and the geographic area of the digitalization from the RegionTab table. The SegmentTab table acquires the essential line segment type additional data from the Line Type Tab table and the information regarding the equipment owner from the CompanyTab table.

As a node we consider every point of the electric network, where a discontinuity in the transport line is presented. In particular, as nodes are considered the points where there are:

- Change in the power line type.
- Power line branch.

- Power line redirection.
- Power line termination point.
- Substation or a transformer.

According to, the above stated cases, the following node types are considered, respectively:

- Power line type change node.
- Power line branch node.
- Power line redirection node.
- Power line termination node.
- Substation or transformer node.

Thus, for the node type entry table PointTypeTab we need only 2 columns, the first one containing the name of the node type and the second one with additional explanatory information for the end user. Table 1 depicts the form of the PointTypeTab table.

The information to be recorded, during the data entry process, related to every node consists of the following entities:

- The serial number (assigned automatically by the application).
- The type (imported by the node type table).
- The name (or the exact location).
- The region in which is located (imported by the region table).
- The code number, as it is registered in the power company's records.
- The nominal voltage.
- The insulation level.
- VARIOUS comments (maintenance history log, damage reports, etc.).

Therefore, Table 2, the form of the records of the PointTab table, is depicted.

The MV distribution line characteristics included in the application are the following:

- Name of the line type (which will be selected during the 2 port network entry phase of the digitalization process).
- Material.
- Diameter.
- Insulation level.
- Resistance, the inductance and the capacitance per kilometer.
- Weight per kilometer.

Thus, the records of LineTypeTab table will have the following form Table 3.

Table 1: PointTypeTab-Node type entry table

Point_Type_Name	Comments
Change	Power line type change node
Branch	Power line branch node
Direction	Power line redirection node
Termination	Power line termination node
Substation	Substation or transformer node

Table 2: Records in the PointTab table

Field name	Description
Code	Node's serial number
Type	Type (from table)
Region	Region (from table)
Place	Name or location
CodeE	Company code
V	Nominal voltage
Insulation	Insulation level
Comments	Various information

Table 3: Records in the lineTypeTab table

Field name	Description
Line_Type_Name	Type name
Material	Material
D	Diameter
Insulation	Insulation level
Resistance	per km
Inductance	per km
Capacitance	per km
Weight	Weight per km
Comments	Various information

The data entry in the SegmentTab table is based on the two-port network model. An initial distinction has to be made between a distribution line segment and a transformer. A primary key is needed for the differentiation between the 2 entities. At the distribution line segment is attributed the value 1 and at the transformer is attributed the value 2. In the case of the distribution line segment the type of line has to be given from the LineTypeTab table. The additional data that need to be recorded are as follows:

- Departure node and the arrival node in the power grid.
- Line length as it is provided by the cable's owner company records and as it is measured by the GIS application.
- Owner company (from the CompanyTab table).
- Protection elements installed at the extremes of the Two-port network element (if there are any).
- Circuit number, in the case, which there are various two-port network elements connected in parallel between the 2 nodes. Usually the circuit number value is equal to 1.
- Various comments.

The records of the SegmentTab table have the following form Table 4.

Table 4: Records in the SegmentTab table

Field name	Description
Line/Trns	Option: 1-line, 2-transformer
Type	Two-port network type
Circuit_no	Circuit number
From	Departure node
To	Arrival node
Len	Length according to the company
Len_gis	Length according to the GIS
Status	In use or not
Owner	Company (from table)
Prot_from	Protection element departure
Prot_from_stat	In use or not
Prot_to	Protection element arrival
Prot_to_stat	In use or not
Comments	Various information

Table 5: Records in the RegionTab table

Field name	Description
Region_name	Location's name
Comments	Various information

Table 6: Records in the CompanyTab table

Field name	Description
Company_name	Company's name
Comments	Various information

The RegionTab and the CompanyTab tables need only to include the information regarding the geographical areas under consideration and the names of the existing companies. Thus, the records of the RegionTab table and of the CompanyTab table will have the following forms, respectively (Table 5 and 6).

The digitalization procedure is completed when all the essential entities of the power grid have been recorded in the database.

The proposed model achieves minimum renewal times of digital maps and at the same time records all the essential information in order to perform network studies (http://www.mapinfo.com). It can be applied to any kind of medium voltage supply network.

BPL equipment estimation: The detailed and well organized knowledge of the information digitalized according to the above procedure is indispensable for the exact calculation of all the BPL equipment necessary for the provision of broadband services in the area under investigation. In particular, the calculation of the precise number of repeaters depends on the length of the power lines. The exact evaluation of the distance between repeaters should be based on numerical techniques or analytical methods that use the primary parameters of the power cable, as well as on the repeaters' manufacturer's technical specifications (Galanis *et al*., 2007; Biglieri, 1998). The correct estimation of the required head-ends and extractors depends on the number of substations, MV power lines and transformers. The model based on the above information, included in the database and on the BPL equipment cost, given as input by the user, estimates the overall investment necessary for the introduction of access BPL technology.

Cost estimation in our model was based on a number of realistic assumptions. According to the hybrid solution described in the study, the connection to a backhaul network is made through a Base Station (BS) coupled to a MV distribution line, usually located next to a power substation where multiple MV lines are connected. The BS is typically a bidirectional device that converts data formats, aggregates and concentrates uplink data streams, provides routing functionality, helps allocate bandwidth and resources, generates billing and charging data and provides various backhaul Ethernet interfaces to fiber optic or wireless connections.

Since, a distribution transformer serves 100-200 end users, as stated in study, WiFi Access Point can be collocated in order to provide broadband access at a neighbourhood level.

The aforementioned assumptions are summarized as following:

- The major components of equipment required to introduce BPL technology in an existing MV powerlines infrastructure are: base stations, head-ends, extractors, repeaters and WiFi Access Points.
- A head-end is connected to each MV line at the substation level.
- The base station is attached to each head-end as described above.
- Each WiFi Access Point is attached to an extractor.
- An extractor is inserted at each transformer site.

These assumptions are used to estimate the total number of required components for the implementation of a BPL hybrid solution, as the one described above.

The next section presents a real time application of the proposed evaluation model.

EVALUATION MODEL'S REAL TIME APPLICATION

The power grid of the Prefecture of Laconia (Fig. 1) in the south part of Peloponnese in Greece was chosen, mainly because of the particular geographical physiognomy of the terrain and of its size (1200 nodes). It represents a typical electrical distribution network of the Hellenic rural area. The total line length is 360,016 m and it comprises 4 medium voltage power lines.

The application prompts the user to provide additional inputs such as: The distance between two repeaters on the same power line in order to boost the signal and the cost of the equipment (Fig. 2).

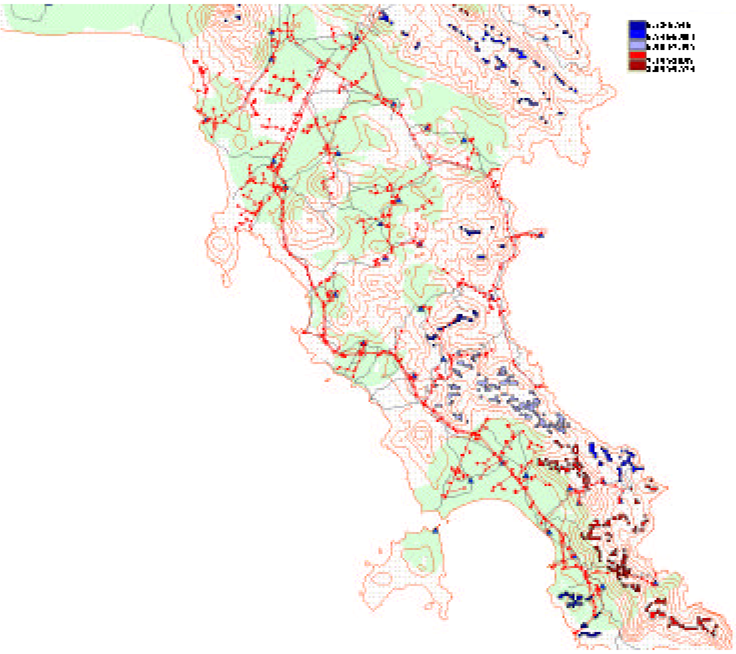

Fig. 1: GIS map and medium voltage (20 kV) distribution lines in the prefecture of Laconia, Greece

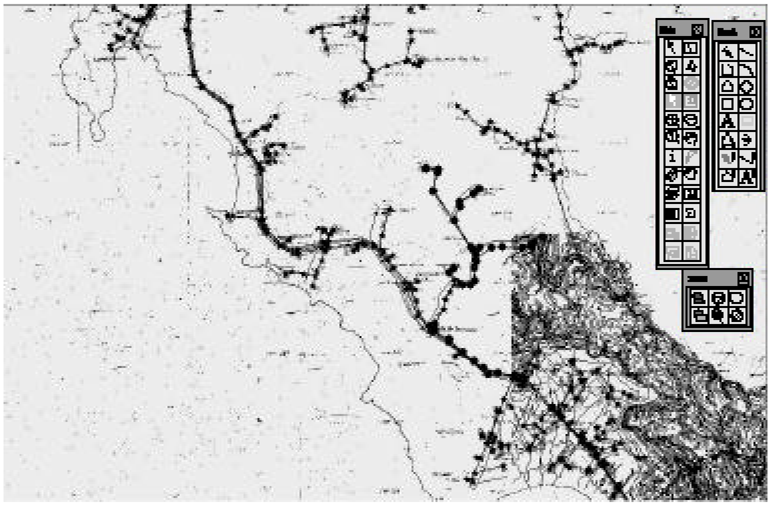

Fig. 2: Input of BPL equipment cost

The model determines the total number of repeaters, extractors and head-ends devices. The results presented in Table 7 are based on a maximum distance of 500 m between any pair of successive repeaters.

From the Table 7, it is obvious that the total cost is heavily dependent on the cost and the number of the repeaters. The number of repeaters derives from the distance of their installation. As previously mentioned, the exact distance between 2 repeaters necessitates the accurate evaluation of the cable parameters. For the network of the Prefecture of Laconia, Greece, Fig. 3 and

Table 7: Model output (case A)

	BPL network equipment		
Type	Number	Cost (€)	Type cost (€)
Base station	1	10,000	10,000
Head-end	4	2,000	8,000
Extractor	231	1,700	392,700
WiFi access point	231	800	184,800
Repeater	727	1,500	1,090,500
Total cost			€ 1,686,000

Equation 1 give the number of repeaters N with respect to their distance l.

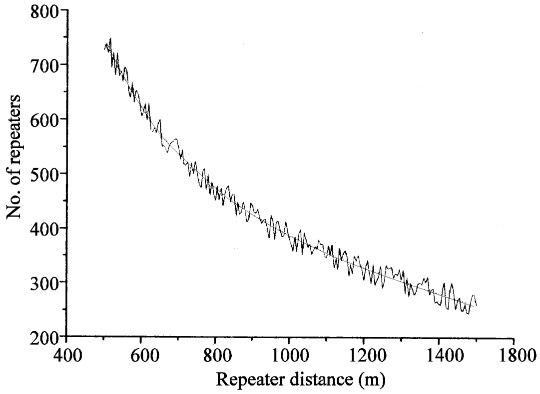

Fig. 3: Number of repeaters

$$N(l) = 1345.53e^{\left(-\frac{1}{219.83}\right)} + 1263.01e^{\left(-\frac{1}{224.08}\right)} + 1523.58e^{\left(-\frac{1}{5984.39}\right)} - 929.89 \qquad (1)$$

Equation 1 is the curve fitted solution of Fig. 3.

CONCLUSION AND FUTURE WORK

An evaluation model for the design and implementation of a BPL access network for the provision of broadband services in a predefined geographic area was presented. The model based 0on accurate data information stored in a GIS application, regarding the infrastructure of the medium voltage power-grid, estimates the overall investment required for the introduction of BPL technology in the area under consideration. The model was tested in the Prefecture of Laconia, Greece and the results proved the validity of the model.

An improvement of the proposed model could be the optimization of the introduction of broadband internet service in an existing MV supply network, by the means of a techno-economical algorithm. The algorithm should determine the optimal timing of introduction of BPL technology to an electric network. The implementation strategy should be determined on the basis of the maximization of the total income while, keeping capital expenditures, including ongoing expenses such as operation and maintenance during a given time horizon, under a given budget. Costs and Incomes would be predicted based on current prices of both charging rates and broadband equipment.

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