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CHARACTERIZATION OF TWISTED PAIR TELEPHONE CABLE FOR BROADBAND TELECOMMUNICATION SERVICES

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Abstract: *Characterization of the existing telephone subscriber loops infrastructure used by the modern broadband telecommmunication services such as xDSL has been presented in the paper. As loop transmission medium quality is one of key requirements for performance capabilities of these services, a method for modelling and simulation of subscriber loops infrastructure in the frequency domain is described. This method is based on ABCD transmission parameters matrix and the appropriate twisted pair cable model representation to account for frequency dependence of its primary per-unit length parameters. It is used to obtain some important subscriber loop characteristics over the service operating frequency band and to analyse quality of cable transmission from the aspect of Heaviside criterion fulfillment.*

Keywords: *Twisted pair, xDSL service, transfer characteristics, insertion loss.*

1. Introduction

In recent years, internet and its multimedia contents, video service, consumer services and many others become the main source of high-speed data communication demands. Such high data-rate demands exceed the bandwidth of now mature high speed voice band modems (up to 56 kbps). The first higher-speed alternative with access speed at 128 kbps, the Integrated Services Digital Network (ISDN), did not achieve wide popularity due to its high installation cost, some incompatibility with the existing telephone service (POTS - Plain Old Telephone Service), and lack of standardization throughout the industry. Therefore, several broadband access technologies, one of which is Digital Subscriber Line (DSL) technology, offering faster data rates while avoiding the drawbacks of ISDN have emerged. These new services have been gaining popularity rapidly in data communication over the past several years.

A broadband telecommunication network is capable of transporting voice, data, and multimedia content in a single converged communication network. While such a unified network is not yet realized, largely due to the already existing independent infrastructure for each service, several broadband access technologies capable of broadband communication are already available today. They are classified into three basic categories: copper-loop, cable (both fiber and coaxial), and wireless access technologies. Many varieties of DSL technology (such as Asymmetric DSL and Very High Speed DSL) collectively referred to as xDSL, equivalent to the copper-loop access technology, has been developed by the telecommunications industry to utilize its largest asset, millions of kilometers of installed twisted-pairs, beyond the existing POTS. At the present time, xDSL technology has shown many advantages over other alternative broadband access solutions.

DSL technology gains much of its advantage over its peer technologies by utilizing, and sometimes even sharing with POTS, telephony subscriber lines (also referred to as local loops) to provide an affordable data access solution. However, because of the narrowband nature (voice band up to 4 kHz) of POTS, the local loops and high-speed access are not always conditioned for broadband xDSL access. This is mainly because of the usage of loading coils to facilitate telephone service over long distances (> 4.5 km), according to Heaviside's electrical circuit theory [1]. With the long distance loop, the twisted pair loses its flat voice band frequency response, which is essential for voice communication, due to effects of attenuation and dispersion. Based on theoretical work of Heaviside, Serbian scientist Mihajlo Pupin, had suggested in 1899 to periodically load telephone cables with inductive coils [2-4] in order to fulfill Heaviside criterion ($R'C'=L'G'$) for ideal audio signal transmission. Today, these loading (Pupin) coils still exist in local and trunk telephone lines and are installed at intervals of about 1 km apart, significantly reducing the attenuation within the voice band and equalizing the frequency response. However, inclusion of coils results in a low-pass characteristics and limited bandwidth of loops [5,6]. This obviously has a negative impact on xDSL, whose operating frequency band is much higher than that of POTS, and therefore there is a requirement that all coils have to be removed.

Various types of DSL technology have evolved over the past years depending on application and standardization. One of the most popular is Asymmetrical DSL (ADSL) which is characterized by different data rates downstream (from central telephone exchange or so-called Central Office to subscriber) as compared to upstream (Subscriber to CO). Downstream data rates for ADSL can be as fast as 8 Mbps depending on the infrastructure length and quality; however, upstream rates are usually ten percent of this speed. An end-to-end system diagram of a typical ADSL system is shown in Fig.1.

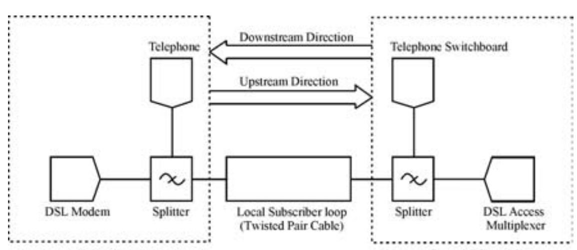


Figure 1. *Typical ADSL system diagram*

The subscriber end requires a telephone splitter to channel the voice and data information to their respected devices in the downstream direction, and combine the two classes of information in the upstream direction. The DSL modem can consist of an external modem, a network interface card, or a router. Connection between the subscriber and Central Office consists of twisted pair cable that generally has a maximum length of around 5 km in ASDL applications. At the Central Office, a splitter is again needed to combine or split the data and voice information. The voice data is routed to a telephone-switching center and the data is integrated into a DSL Access Multiplexer.

The primary motivation behind the development of xDSL technology is the exploitation of existing local telephone subscriber loops. Thus, an investigation of performance capabilities of the twisted pair cable on a physical layer, as a key transmission component of subscriber loops, is critical to assess the applicability and access rate of xDSL technology on the loop. The first step in that direction, from authors of this paper, was made in [7,8] where characteristics of periodically loaded telephone cable with inductive coils were analysed from the aspect of Heaviside criterion fulfillment, over wider frequency range than voice band. The similar analysis is performed in this paper too but now in the operating frequency band of xDSL service and including frequency dependence of twisted pair cable primary per-unit length parameters. Some of the most important loop characteristics when discussing the performances of different DSL technologies, such as voltage transfer function and insertion loss, have been considered. For that purpose, a modeling and simulation of the telephone subscriber loop is performed by the use of transmission line theory and twisted pair cable model based on its physical and electrical properties. *ABCD* transmission parameters matrix has been applied to characterize each twisted pair cable segment as a two-port network as it allows easy evaluation of loop due to its chain-type nature and it can be easily extended to account for different discontinuities along the cable.

2. Twisted pair model and its physical and electrical properties

A twisted pair cable is simply made up of two cables twisted around one another that are electrically driven and sensed differentially to reduce the effects of outside influences such as crosstalk from other cables within the bundle or other outside interferences. Because the wires are physically close and symmetrical to one another, any outside interference will be subtracted out when the wires are driven using a differential mode. Many different types and qualities of twisted pair cable make up the existing telephone industry's cabling infrastructure. Twisted pair cables are usually bundled together in a cable sheath with 25 to 100 twisted pairs of cables in each bundle. Each wire is also coated with some type of insulating material such as a paper-based (PULP) or, more often in recent years, a plastic-based (PIC) material. The bundle of cables contains an outer shield that is grounded at the terminating blocks of the system to reduce the electromagnetic interference (EMI) from outside sources. The rate of twisting (usually in the range of 12 to 40 turns per meter) also varies among the pairs within each bundle to further reduce crosstalk between the cables. In addition to the insulation material, twisted pair cables are also characterized by the diameter of the copper wire of the cable.

The subscriber loop transmission medium or the twisted pair segment can be modeled within the context of transmission line theory. This model incorporates a set of four primary parameters per unit length, including a series inductance and resistance and a shunt capacitance and conductance. The series inductance represents the total self-inductance of the two conductors, and the shunt capacitance is due to the close proximity of the two conductors. The series resistance is due to the finite conductivity of the conductors, and the shunt conductance is due to the dielectric loss in the material between the two conductors. Graphic representation of a twisted pair segment is given in Fig.2.

There are several twisted pair models presently used to simulate the performance of xDSL technology. The model described in [4,9] is generally valid for high frequencies and gives the following primary per-unit length parameters:

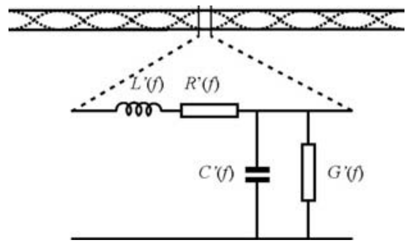


Figure 2. *Transmission line model of twisted pair cable segment*

$$\underline{Capacitance}:\ C'(f) = \frac{\pi\varepsilon_0\varepsilon_r'}{\ln(2D/d)} \quad \text{(F/m)} \tag{1}$$

where ε_r' is the real part of complex relative permittivity of the insulating dielectric material, D is the center spacing between wires, and d is the diameter of the conductor.

$$\underline{Inductance}:\ L'(f) = \frac{\mu}{\pi}\ln(2D/d) + \frac{R_s}{2\pi^2 fd}\frac{1}{\sqrt{1-(d/D)^2}} \quad \text{(H/m)} \tag{2}$$

where μ is the permeability of air (assuming μ_r is unity) and f is the frequency. R_s is the surface resistance given as:

$$R_s(f) = \sqrt{2\pi f\mu/(2\sigma)} \tag{3}$$

where σ is the conductivity of the conductors used in twisted pair. The first term in Eq.(2) represents the external inductance due to the magnetic field outside the conductors which is independant of frequency, while the second term represents the internal inductance due to magnetic field within the material of the conductors, which decreases as the frequency increases because of the skin effects and tends to zero at high frequencies.

$$\underline{Resistance}:\ R'(f) = \sqrt{\frac{\mu f}{\pi\sigma}}\frac{1}{d\sqrt{1-(d/D)^2}} \quad (\Omega/\text{m}) \tag{4}$$

$$\underline{Conductance}:\ G'(f) = \frac{2\pi^2 f\varepsilon_0\varepsilon_r'\tan\delta}{\ln(2D/d)} \quad \text{(S/m)} \tag{5}$$

where $\tan\delta$ is the loss tangent of the insulating dielectric material.

In terms of the primary per-unit length parameters, the secondary line parameters, complex characteristic impedance $Z_c(f)$ and complex propagation constant $\gamma(f)$, are given by two relations [4]:

$$Z_c(f) = \sqrt{[R'(f) + j2\pi fL'(f)]/[G'(f) + j2\pi fC'(f)]} \tag{6}$$

$$\gamma(f) = \alpha(f) + j\beta(f) = \sqrt{[R'(f) + j2\pi fL'(f)]\,[G'(f) + j2\pi fC'(f)]} \tag{7}$$

These secondary line parameters will be used in the next sections to model the twisted pair cable when the performance analysis of the subscriber loops is done.

3. Subscriber loop modelling

Subscriber loops consist of sections of twisted pair cables usually of different gauges spanning from the Central Office to each subscriber. The subscriber loop structure is divided up into three main portions: the feeder cables, the distribution cables, and the drop wires. The feeder cables have the highest concentration (up to 2500 pairs) of twisted pairs within each bundle that connect the Central Office to the distribution cabinets. From these cabinets, the distribution cables connect the Central Office with current and potential customers. The drop wire is the final section of cable and connects the distribution cables to the subscriber. The connection of two or more sections of cables within each loop is referred to as a splice. A third cable spliced off of the main loop is called a bridge tap. The purpose of the bridge tap is to leave flexibility in the location of future subscribers on any given subscriber loop and is usually open circuited. The bridge tap length is limited to minimize adverse effects on the transmission characteristics of the loop.

Given that the twisted pair cables can be characterized in terms of a two-port system, the transfer function and insertion loss are the important characteristics of any subscriber loop and will be discussed in this section. The two-port parameters that are most convenient in characterizing twisted pair cables are the *ABCD* transmission parameters. These parameters mathematically relate the voltage and current of the input port to the voltage and current of the output port. A cascade connection of two or more two-port networks can be found by simply multiplying the *ABCD* matrices of each individual two-port network; this aspect of the *ABCD* parameters allows easy evaluation of subscriber loops due to the chain-type nature of the topologies.

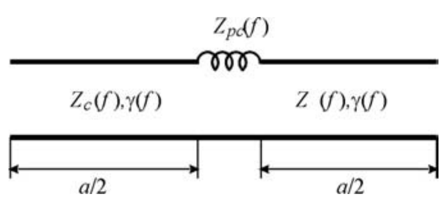


Figure 3. *Twisted pair cable segment with loading coil*

The *ABCD* matrix of a twisted pair cable segment, that in general can contain loading inductive coil to boost voice signals and reduce signal loss (See Fig.3), can be represented as a product of three matrices:

$$[ABCD_a] = [ABCD_{a/2}][ABCD_{pc}][ABCD_{a/2}] \tag{8}$$

where

$$[ABCD_{a/2}] = \begin{bmatrix} \cosh(\gamma(f)a/2) & Z_c(f)\sinh(\gamma(f)a/2) \\ \sinh(\gamma(f)a/2)/Z_c(f) & \cosh(\gamma(f)a/2) \end{bmatrix} \tag{9}$$

and

$$[ABCD_{pc}] = \begin{bmatrix} 1 & Z_{pc}(f) \\ 0 & 1 \end{bmatrix} \tag{10}$$

where $Z_{pc}(f)$ is the impedance of loading inductive coil, $Z_{pc}(f)=R_{pc}+j2\pi f L_{pc}$.

Total *ABCD* matrix of twisted pair cable, represented as a cascade connection of segments shown in Fig.3 can be obtained as:

$$[ABCD_t] = \begin{bmatrix} A_t & B_t \\ C_t & D_t \end{bmatrix} = \prod_{i=1}^{N-1} [ABCD_a]_i \tag{11}$$

where N is the number of segments, $N=d/a$ (d is the total length of twisted pair cable connecting subscribers to CO).

For analysis of a loop, some information is needed beyond the two-port ABCD parameters of the twisted pair segments. This information includes the source impedance, Z_g that is usually the impedance of the data transmitter used to send information or the measurement equipment if a subscriber loop analysis is in progress and the termination impedance, Z_p (See Fig.4).

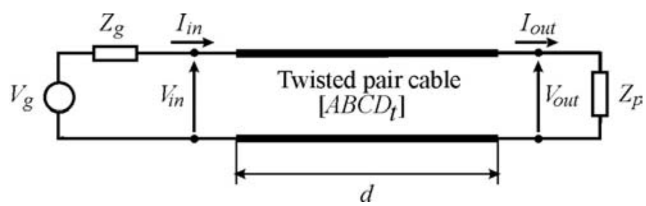


Figure 4. *A generic end-to-end model of a subscriber loop using two-port parameters.*

Input voltage and input current are related to the output voltage and output current by [ABCD$_t$] matrix:

$$\begin{bmatrix} U_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} A_t & B_t \\ C_t & D_t \end{bmatrix} \begin{bmatrix} U_{out} \\ I_{out} \end{bmatrix} \tag{12}$$

In finding the voltage transfer function of the subscriber loop, defined as the ratio of the voltage across the output port of the loop with the voltage placed on the input port, the following relation has to be used for all frequencies:

$$H_U(f) = \frac{V_{out}}{V_g} = \frac{Z_p}{Z_g[C_t Z_p + D_t] + A_t Z_p + B_t} \tag{13}$$

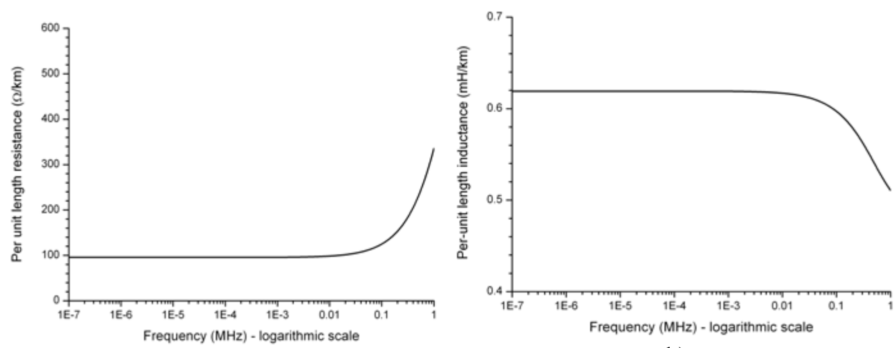
The insertion loss of the loop is defined as the ratio of the power delivered to the load with the power delivered to the load had the loop not been present. This is basically the loss that is inserted between the Central Office and the subscriber due to the loop existence and is given in decibels as:

$$IL(dB) = 10\log\left(\frac{P_{noloop}}{P_{loop}}\right) = 20\log\left(\left|\frac{A_t Z_p + B_t + Z_g[C_t Z_p + D_t]}{Z_g + Z_p}\right|\right) \tag{14}$$

4. Subscriber loop simulation

A subscriber loop, connecting subscribers to Central Office, in reality can consist of several different twisted pair segments connected together in what makes up the telephone industry's cabling infrastructure. However, for simplicity reasons, we will assume that all feeder cables, the distribution cables, and the drop wires are made of twisted pair segments with the same electrical properties and the same length, even the approach suggested in section 3 can be applied on a loop that could be seen in industry as well. Also, it is well known that the bridged taps, which provide greater flexibility in terms of connecting future subscribers, have a negative impact on the insertion loss of a subscriber loop and high-speed connection. Thus, we will carry our loop simulation in the frequency domain assuming that all bridge taps are removed but again approach in section 3 can be extended to model a bridge tap line with an additional *ABCD* parameters matrix relating to shunt impedance [9].

The conductors of twisted pair cable are assumed to be insulated by plastic material whose real part of complex relative permittivity is $\varepsilon_r' \approx 2$ [4]. The distance between the conductors is about 1.5 times their diameter ($2D/d=3$). Diameter of the conductor is $d=0.4$ mm and conductivity of the used conductors is $\sigma = 5.65e7$ S/m. The per-unit length resistance and inductance variation with frequency is shown in Fig.5 [4].



a) b)

Figure.5. *Variation with frequency of the a) resistance and b) inductance of twisted pair cable*

The per-unit length resistance of this twisted pair cable has the same value at low frequencies as it has for steady currents and it is around 100 Ω/km. Above 100 KHz, it increase as the square root of the frequency (See Eq.(4)) because of the skin effect. The per-unit length inductance reaches the value of 0.44mH/km, only at high frequencies (> 1 MHz – not shown in Fig.5b). The first term in Eq.2 highly contribute to this value because, as already mentioned, the second term associated to internal inductance tends to be zero as high frequencies. However, as the frequency falls, per-unit length inductance increases and reaches a value sligthly above 0.6 mH/km due to the addition of the internal inductance. The per-unit length capacitance, from Eq.(1) is 0.051 μF/km, while per-unit length conductivity is very small at all frequencies so typical value of 1e-7 S/km is used.

It is obvious that twisted pair cable with such primary per-unit length parameters is far away from satisfying Heaviside Criterion, $R'C' = L'G'$, for the ideal voice signal transmission. This is a reason why telephone companies have installed small amplifiers known as loading coils which boost voice signals and reduce signal loss. Unfortunately, these loading coils can not amplify xDSL frequencies and actually prevent them from passing through the voice network. Therefore, if a user is far enough from the Central Office to require a loading coil in the local loop, xDSL may not be an option. In order to illustrate this, the voltage transfer function of unloaded and loaded subscriber loop of length d=5 km, obtained by using Eq.(13), is shown in Fig.6. For the case of loaded subscriber loop, inductive coils of inductance L_{pc}=123.7 mH (coil losses are neglected, R_{pc}=0 Ω) were inserted every one kilometer, which gives N=5 sections.

It is clear from Fig.6 why unloaded loop is not suitable for baseband audio signal transmission. In addition, transfer characteristics of real cable, obtained by using twisted pair cable model that takes into account frequency dependence of its primary per-unit length parameters, (bold solid line) is even worse at higher frequencies than from the simplified case when this dependence is neglected assuming that per-unit length parameters values in voice band can be used at DSL frequencies (solid line in Fig.6). The same loop with loading coils inserted in each kilometer to modify cable primary parameters to partly satisfy Heaviside criterion, improves significantly the low frequency response (dashed line).

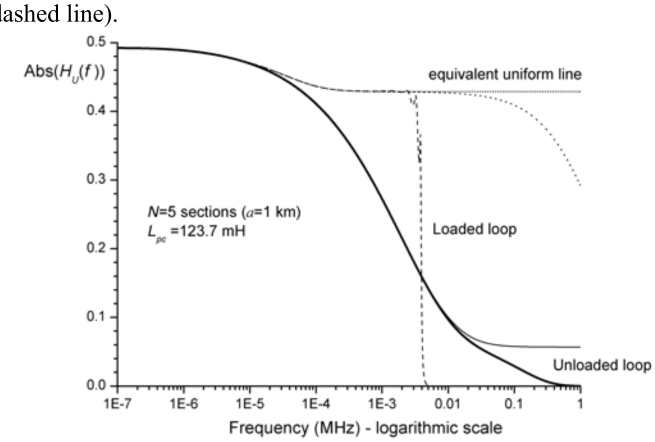


Figure 6. *Voltage transfer characteristics of unloaded (bold solid line) and loaded (dashed line) subscriber loop*

Fig.6 also shows that at frequencies for which wavelength is significantly greater than the spacing between coils ($\lambda >> \pi a$ [4]), loading loop is behaved as an equivalent uniform line with inductance, $L' + L_{pc}/a$, increased continuously along the line (dotted line when frequency dependence of equivalent primary parameters is taken into account and short dotted line when this dependence is neglected). However, inclusion of coils changes transmission line structure and introduces periodic reflections resulting in a low pass characteristics and rejection of xDSL frequencies. From the filter theory, cut-of frequency is estimated as:

$$f_{cut} \approx 1/\left(a\pi\sqrt{[L'(f)+L_{pc}/a]C'(f)}\right) \tag{15}$$

and in this case is f_{cut}= 4 KHz. It should be pointed out that we based our transfer function calculation on assumption that unloaded and loaded loop were terminated at both ends with their characteristic impedances, i.e. for unloaded loop, Z_g=Z_p=$Z_c(f)$ and for loaded loop:

$$Z_g = Z_p = \sqrt{[R'(f) + j2\pi f(L'(f) + L_{pc}/a)]/[G'(f) + j2\pi fC'(f)]} \tag{16}$$

It is worthwhile to show that keeping the same inductance per kilometer but distribute it evenly along the loop, would extend the subscriber loop bandwidth but unfortunately not enough to pass the whole operating frequency band of xDSL service. The voltage transfer function of loaded subscriber loop for three different distances between loading coils (a=1, 0.5 and 0.25 km) is shown in Fig.7. It is obvious that ingenious Pupin's approach of Heaviside criterion fulfillment in the form of discrete inductive coils placed regularly along the cable can not work at xDSL frequencies, partly because it is even harder to fulfill this criterion with significant change in per-unit length parameters with frequency. How transfer characteristics considerably depends on electrical properties, one of possible solution for providing quality service over twisted pair is to try to achieve Heaviside criterion or at least to approach to equivalent uniform line characteristics. This could be done, for an example, in manufacturing stage changing primary parameters of cable via its physical properties.

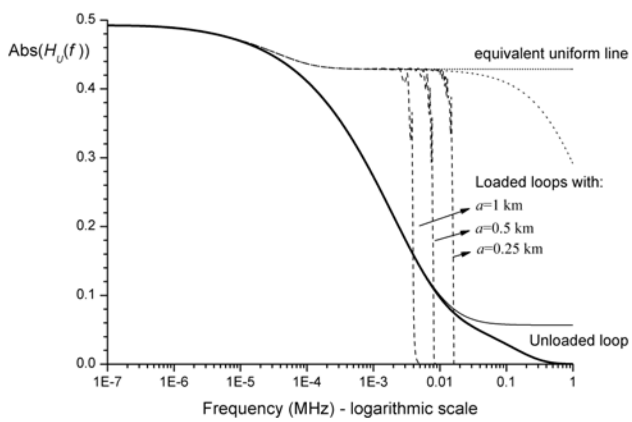


Figure 7. *Voltage transfer characteristics of loaded loops for three different distances between loading coils*

Finally, insertion loss, as one of the most important loop characteristics when discussing the performance capabilities of different DSL technologies, is shown in Fig.8, for unloaded subscriber loop when frequency dependence of primary parameters is neglected (solid line) or taken into account through twisted pair model (bold solid line). Model of twisted pair cable, describing more accurately its electrical properties in frequency domain, gives a much higher insertion loss at DSL frequencies.

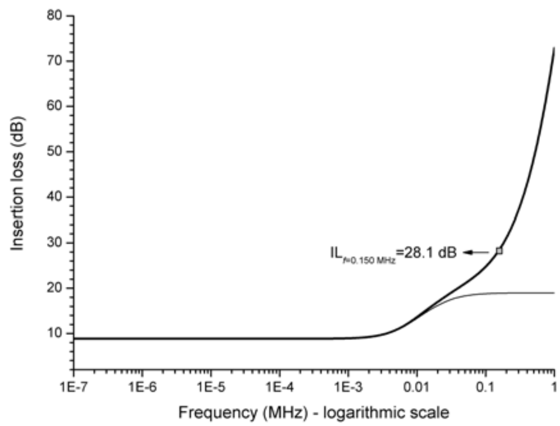


Figure 8. *Insertion loss of unloaded subscriber loop*

It is common practice to specify, as typical characteristics, insertion loss in dB/km, measured at 0.150 MHz with 135 Ω resistive source and load. So in calculating insertion loss from Eq.(14), it is used that Z_g=Z_p=135 Ω. At 0.150 MHz insertion loss is around 28.1 dB which, for loop of length *d*=5 km, gives IL@0.150 MHz=5.62 dB/km.

5. Conclusions

Characterization of the telephone industry's subscriber loop infrastructure is presented in this paper. The subscriber loop model is made up of a network of twisted pair cables extending from the Central Office to each subscriber. For simulation purposes, transmission line theory and twisted pair cable model that includes frequency dependence of its primary per-unit length parameters are used. Some loop transmission characteristics such as the transfer function and insertion loss, important to determine performance and feasibility investigations of xDSL technology on the loop topology, are calculated and shown in the frequency domain. Negative impact of loading coils on broadband DSL access is illustrated in the paper as well. It is shown that one of main requirements in providing quality service is to try to extend Heaviside criterion fulfillment of twisted pair cable in service operating frequency band. Future research will be focus to the simulation of real subscriber loops used in industry which means that some other important loop characteristics (e.g. BER) have to be taken into account as well as possible discontinuities along the cable such as cable faults and moisture effects.

References

[1] L.Cohen, *Heaviside's Electrical Circuit Theory*, McGraw Hill Book Co., London, 1928.

[2] M.Pupin, *Art of Reducing Attenuation of Electrical Waves and Apparatus Therefore*, patent No.652230, June 19, 1900, application filed December 1899.

[3] P.Miljanić, *Theory of Periodical Electric Currents* Propagation, Edition of Serbian Academy of Sciences and Arts, Belgrade 2004, in Serbian.

[4] P.F.Combes, *Microwave Transmission for* Telecommunications, John Wiley and Sons, 1991.

[5] A.Marinčić, R.Biljić, "Heaviside Criterion and Cable Bandwidth", *Proceedings of XII Telecommunications Symposium TELFOR* 2004, Belgrade, Serbian and Montenegro, November 2004, in Serbian.

[6] A.Marinčić, "Analysis of Transmission Line with Periodical Inductance Loading", *Microwave Review*, Vol.10, No.2, 2004, pp.43-48.

[7] B. Milovanović, A.Marinčić, N.Dončov, "Introduction of Heaviside Criterion Fulfillment Factor for Transmission Line Analysis", *Proceedings of the 40th International Conference ICEST 2005*, Niš, Serbia and Montenegro, Vol.1, 2005, pp.187-190.

[8] B. Milovanović, A.Marinčić, N.Dončov, "Matrix Analysis of Transmission Line with Inserted Pupin's Coils", *Proceedings of the 7th IEEE International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services TELSIKS 2005*, Niš, Serbia and Montenegro, Vol.1, 2005, pp.287-290.

[9] Jason Jon Yoho, "Physically-Based Realizable Modeling and Network Synthesis of Subscriber Loops Utilized in DSL Technology", PhD Thesis, Faculty of the Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, USA, 2001.

Sadržaj: *Karakterizacija infrastrukture postojećih telefonskih pretplatničkih petlji za potrebe širokopojasnih telekomunikacionih servisa, kao što je xDSL, je prezentovana u ovom radu. Kako je kvalitet prenosnog medijuma petlji jedan od ključnih zahteva za performanse ovih servisa, metod za modelovanje i simulaciju infrastrukture pretplatničkih petlji u frekvencijskom domenu je opisan u radu. Metod se bazira na korišćenju ABCD matrice i modela telefonske parice koji uključuje frekvencijsku zavisnost njenih primarnih podužnih parametara. Ovaj metod je korišćen za dobijanje nekih važnih karakteristika pretplatničke petlje u radnom frekvencijskom opsegu servisa i za analizu kvaliteta prenosa kabla sa stanovišta ispunjenosti Heaviside-ovog kriterijuma.*

Ključne reči: *Telefonska parica, xDSL servis, prenosna karakteristika, unešeni gubici.*

KARAKTERIZACIJA TELEFONSKIH PARICA ZA POTREBE ŠIROKOPOJASNIH TELEKOMUNIKACIONIH SERVISA

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