Medium Voltage Overhead Power-line Broadband Communications; Transmission Capacity and Electromagnetic Interference

P. Amirshahi and M. Kavehrad (FIEEE)
The Pennsylvania State University,
Department of Electrical Engineering,
Center for Information & Communications Technology Research (CICTR)
University Park, PA 16802
E-mail: mkavehrad@psu.edu

Abstract - *A channel model suitable for multi-wire overhead medium-voltage lines is proposed. This model is then employed in order to evaluate the multipath channel impulse response and the associated transmission capacity limit in actual overhead medium-voltage power distribution networks for broadband power-line communications applications. Electromagnetic interference limitations of such systems are discussed, as well.*

Keywords: Channel model, impulse response, power-line communications, medium voltage, capacity, EMC.

I. Introduction

Broadband power-line (BPL) communications systems have the potential of providing higher data rates compared to old power-line communications (PLC) systems; due to progress in PLC modem technology, mainly owed to advances in signal processing and communications theory.

Last-mile access using Medium Voltage (MV) overhead power lines is being considered in US, Korea and many other countries. Although for nearly a century some elementary transmission models of these lines have been available, no serious attempt has gone into a comprehensive BPL channel modeling describing characteristics of overhead MV lines in terms of magnitude and phase responses or as an impulse response. Recently, new modeling of multi-conductor wave propagation in overhead lines, considering transient effects, has been made available [1]. In this paper, we present a new transmission channel model suitable for multi-wire overhead MV power networks. The proposed model incorporates realistic ground admittance, appropriate for higher frequencies used by broadband power-line communications. The suggested model is more appropriate for higher frequencies than predicted by the model in [2]. The proposed model is further used to evaluate the channel impulse response and transmission capacity in an actual power distribution network. Interference issue is discussed and remedies are suggested.

II. Analysis of MTL

Analysis of multi-conductor transmission lines (MTL) consisting of multiple parallel conductors is a well-understood topic [3]. For example, in a case involving 3 conductors and a ground return, we can define 3 modes as shown in Fig.-1 [4]. Using these independent modes, we can decompose currents I_1 through I_3 as a linear combination of 3 modal currents. Common mode (also called ground mode) is characterized by the highest attenuation among the modes, and is propagation through 3 phases and a return via the earth. Involving signal propagation and return only through wires, differential modes (also called aerial modes) 1 and 2 show a somewhat lower attenuation than the common mode. While the common mode current I_c is the same in magnitude and in direction for 3 lines, the differential mode currents I_{D1} and I_{D2} are the same in magnitude but differ in direction for 3 lines. Common mode currents are much smaller in magnitude than differential mode currents, but yet significant. Generally, these modes are not orthogonal unless the wavelength of electromagnetic wave inside the conductors is a small fraction of the height of wires and the spacing between the wires is a small fraction of wavelength [5]. This condition is satisfied for practical MV power-line systems up to 100 MHz. Beyond this frequency, the discrete modes lose orthogonality and continuous modes start to appear. While the radiated E-field from the differential mode currents subtract, those from common mode currents tend to add [3]. This is an important issue in terms of Electromagnetic Compatibility (EMC) of BPL systems and potential interference into existing local communications systems in the shared bands. In PLC, depending on the way signal is coupled to the lines, either wire-to-wire (WTW) or wire-to-ground (WTG) injection is feasible. For WTW injections, differential modes are mostly excited. For a WTG injection, in the case of coupling to the middle phase, common mode and differential mode 2 are excited. Any transmission line is characterized by its propagation constant. Frequency response of each transmission line at a distance *l* from the source is expressed as:

$$V(l) = H(f)V(0) \qquad (1)$$

$$H(f) = e^{-\gamma(f)l} = e^{-\alpha(f)l}e^{-j\beta(f)l} \qquad (2)$$

in which *v(0)* is the voltage at the source and γ is the propagation constant, α, the real part of the propagation constant, is called attenuation constant and β, the imaginary part of the propagation constant, is called phase constant.

The first step in finding the MTL propagation constant is to obtain *per-unit-length* parameters for the conductors. For this, Carson [2] suggested incorporating ground impedance. However, this model, without considering the ground admittance, is only suitable over low frequency values and/or under good conductive ground plane conditions.

As an effort to find a new ground return path model for the higher frequencies and/or under poor ground conductivity conditions, a new procedure was suggested. This methodology by D'Amore et al [1] incorporates *per-unit-length* series-impedance and shunt-admittance matrices, using the curl-Maxwell field equations.

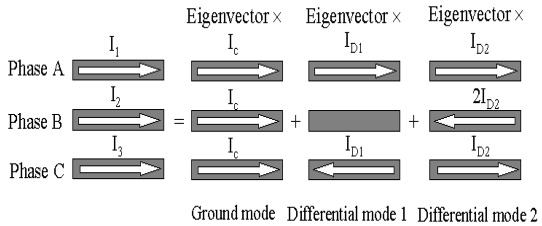


Fig.-1 Modes of three-phase power lines

Following the steps in [1], the real and imaginary parts of the propagation constant for each mode in a system are depicted in Fig.-2. This system is composed of three wires at 1 meter spacing between each pair; so three discrete modes are defined for the configuration. The diameter of each wire is 1 cm and they are placed at 10 meters above the ground level. Earth is characterized by a relative permittivity of ε_g =13 and a conductivity of σ_g =5 mS/m.

The phase constants of the 3 modes agree over almost the entire frequency range. On the contrary, attenuation constants exhibit different behavior and values. Common mode shows higher attenuation over the frequency range and the attenuation factors for the two aerial modes are close to one another. Common mode attenuation factor increases up to some frequency and decays beyond it. This incident is due to a resonance phenomenon in the ground medium, initially inductive and by increasing frequency later it becomes capacitive. A more detailed explanation of this topic is available in [5].

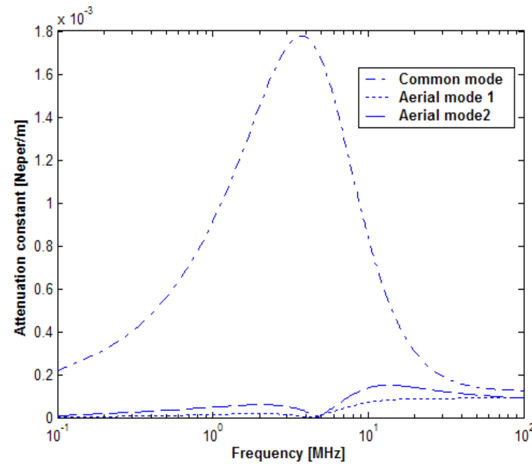
III. Power-line Network Channel Model

Channel transfer function of a matched transmission power-line follows (2). In the case of unmatched junctions, part of a propagating signal reflects back to the transmitter at branch junctions due to impedance mismatch and the remainder travels through [6]. The propagation along a wire follows (2), so one can easily express the multipath network channel model as:

$$H(f) = \sum_{i=1}^{N} g_i e^{-\alpha(f) d_i} e^{-j\beta(f) d_i} \qquad (3)$$

where N is the number of significant arrived paths at the receiver, d_i is the length of i^{th} path and g_i is the weighting factor of the i^{th} path. This formulation is basically similar to what has been mentioned in [7], however, with a model for propagation constant that is appropriate for overhead MV power-lines, rather than underground cables in Europe.

Fig.-3a represents frequency response of a matched transmission channel over a 1 Km span MTL system. As the system is matched, signal does not get reflected at the receiver-end and signal path is one straight point-to-point path. In this case, the only loss comes from MTL path loss. Fig.-3a depicts frequency response for two coupling methods: common mode and differential mode-1. Common mode exhibits more loss than differential mode, especially at low frequencies. As frequency increases, losses of the two configurations become comparable. Also, one may notice that both systems show a very low loss at high frequencies over a 1 Km repeater span.



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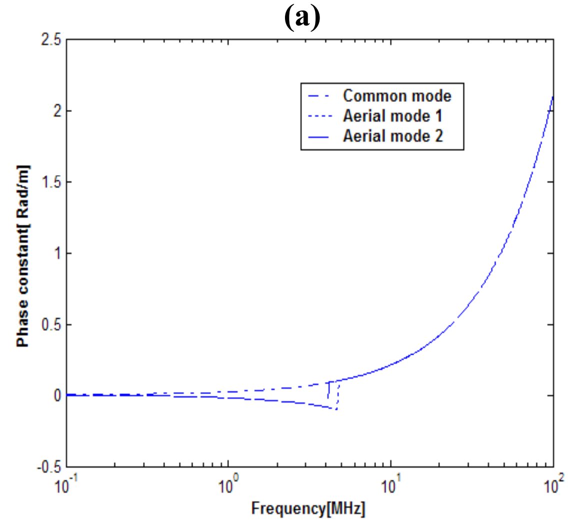
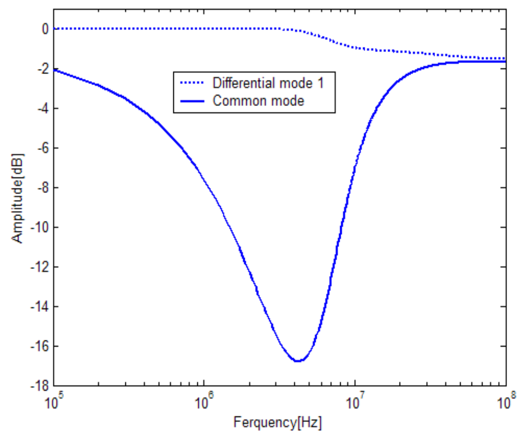


(b)

Fig.-2 Frequency response of (a) Attenuation constants, and (b) Phase constants of an MTL system

The fact that MV overhead power lines resemble a low loss transmission system shows promise for data delivery at high rates. Also, this is a cause for concern, regarding potential interference into existing services, as elaborated on extensively in NTIA report volumes [8]. Fig.-3b illustrates the water filling [9] channel capacity of BPL as it has been discussed in [10] for matched transmission system with a 1 Km repeater span at different transmitted power levels. According to Fig.-3 (a), with an ideal matched MTL system, over 50 MHz of channel band, we can deliver almost 600 Mbps by launching 10dBm transmit power. In reality, this low loss nature of MTL systems changes extensively by several factors.



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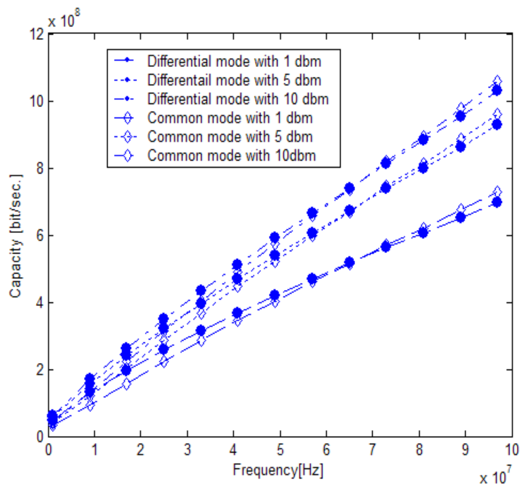
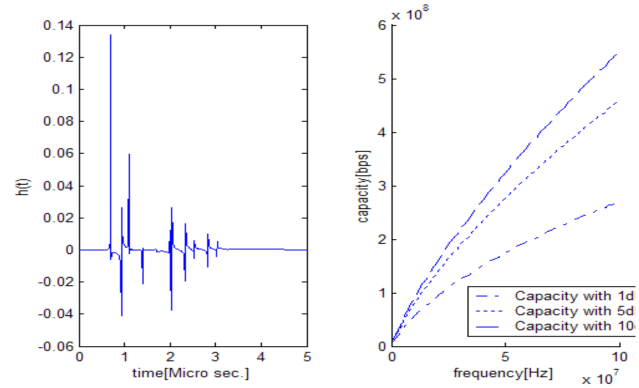


(b)

Fig.-3 (a) Frequency response of matched MTL transmission over 1 Km for differential and common modes coupling (b) Corresponding capacity values for different coupling methods and transmit power levels as a function of frequency band

Over an actual power line network, there always exist several branches and junctions between a transmitter and a receiver. These branches cause nulls in the transmission channel frequency response due to multipath. To investigate this, we simulate the complex network shown in [10]. In this network, we have three branches between a transmitter and a receiver, which are by 1Km apart. Each end of these branches is an open-circuit, so reflection factor at each end is unity. Also, we have assumed that the transmitter and receiver impedance are matched to that of the line. Channel impulse response of this system is shown in Fig.-4 (a). Our simulation results show 12 paths are dominant and from Fig.-4 (a), 12 pulses with different arrival times are distinguished. Fig.-4. (b) is an illustration of the channel capacity values for this complex network. The average capacity in this network with a 10 dBm launched transmit power level for a 50 MHz band is about 300 Mbps. Obviously, the junctions and branches between transmitter and receiver reduce the value of system capacity, extensively, compared to the ideal point-to-point case.



(a) (b)

Fig.-4 (a) Channel impulse response of a complex network and (b) Associated capacity values

IV. Electromagnetic Interference

Another very important factor that should be considered for evaluating BPL system performance is interference to other wireless systems. As stated earlier, the NTIA reports [8] on potential for interference in using BPL are quite extensive. In displaying channel capacity values, we used the entire frequency range between 1 to 100 MHz. In reality, FCC has disallowed use of some frequency bands that are already occupied by other services, especially the critical ones as, homeland security, emergency, etc [8]. This should discourage BPL system designers in considering these frequency bands. Meaning, higher capacity values at 100 MHz on our figures are by the FCC rules, unattainable.

From the very beginning of BPL experiments, the Radio Amateur Associations have expressed concern that this new type of emission will interfere with radio communications [12]. Recently, NTIA, in their extensive reports [8], made recommendations to the FCC, so to devise regulatory methods for radiation measurements, deployment and simulation of BPL systems. According to this report, there are some frequency intervals that are dedicated to emergency services and all BPL systems have to avoid occupying these frequency intervals. It is also noted in this report that for evaluating radiation patterns from power-lines, both far- and near-end fields should be considered and neither can violate the FCC regulatory limits.

Some example techniques that if applied, could potentially mitigate the interference are differential-mode signal injection, power control, filters and signal terminations, and avoidance of locally used frequencies.

In general, emission from a single line is highly dependant on the impedance between the line and ground. In theory, emissions from differential aerial mode currents cancel one another at far field, given line symmetry (balanced loads). MV power-lines are not typically symmetrical; discontinuities might occur at different locations on different wires, causing asymmetry. Asymmetry causes broadening of near-field and far-field patterns.

For simulation purposes, we used GNEC [13] to evaluate the far field radiation patterns along the wire for the power-line system configuration shown in Fig.-5.

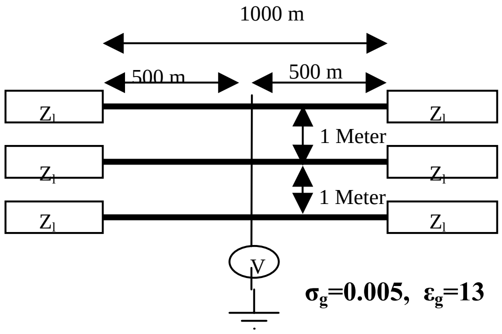


Fig.-5 Power-line configuration for radiation pattern simulations

In our simulations, we examined both common and differential mode injections. In common mode, signal can be injected either on the middle conductor or on a side conductor. The far field radiation patterns for differential and two common modes are depicted in Fig.-6. Horizontal axis unit is μv/m. The far field radiation pattern has higher values in both common mode injections than in differential mode. In differential mode injection, reverse and forward paths are two current flows with the same amplitude in opposite directions, as shown in Fig.-1. These currents travel in two parallel identical conductors with relatively small separation distance. Due to their opposite direction and small distance, their radiated electric fields tend to cancel out one another at the far field region. On the other hand, in common mode injection, forward path is a current flow in one phase conductor and the return path is the ground surface, which is a dielectric with losses. The distance between one phase and earth is at least ten times the separation of two phases. Also, in common mode injection, forward current is traveling in a near-perfectly conducting material, whereas return current has to go through a material with loss. Because of these facts, it is expected that the cancellation of electric fields, emitted from forward and return paths, at far field, in common mode injection, is much less than those in differential mode injection. We should keep in mind that the cancellation level is reduced in differential mode if the load impedances between each wire and earth are not equal. As it is seen from Fig.-6a and b, the radiation pattern from central common mode injection is symmetric but this is not true for the radiation pattern of the side injection. It is due to the fact that the environment around the injected wire in central injection is symmetrical. This is not the case for side injection. Fig.-7 shows the far field radiation patterns from power-line configuration shown in Fig.-5, for differential modes and three different load mismatches. From these figures and Fig.-6c, one can conclude that load mismatch between two lines degrades the far field cancellation in differential mode injection. Therefore, the radiation pattern from the differentially injected power-line with load mismatch has higher amplitude than the radiation pattern of differentially injected power-line with balanced loads. The more the mismatch increases, the more radiation is generated by the power-line system.

V. Conclusions

This research dealt with examining MV overhead power lines as a communications medium for broadband transmissions. Available models for overhead power lines were not suitable at high frequencies with a lossy ground return. D'Amore et al in [1] have proposed a model for multi-wires over ground, which is more suitable for application of BPL systems using overhead MV lines. Based on this model, we developed a new channel transfer characteristic function model. Our simulations show ideal overhead power-lines exhibit a low loss with a capacity value of about 1Gbps over a 1 Km repeater span, if 10 dBm transmit power and 100 MHz of channel bandwidth are available. Junctions and branches in a power-line network cause signals to reflect and produce a multipath channel. This causes a reduction in power line system capacity. Impairments of overhead MV lines are similar to those of mobile radio systems over metropolitan areas; can suffer with multi-path fading and are affected by unpredictable man-made or natural noise. Only measurements can demonstrate the reality of unguided modes at high frequencies and over non-flat grounds. Discontinuity (impedance mismatch) increases EM interference. Therefore, discontinuity must be eliminated by matching the load and the line impedance and by having symmetrical loads on these lines. Removing discontinuities by adaptive impedance matching [14] can enhance line data handling capacity. Use of differential aerial modes along with symmetric loads on these lines can potentially reduce interference.

On the economy side, the power grid is a valuable asset, as it has already been extended to isolated rural areas. The power poles are omnipresent, thus the poles themselves can be used to hang fiber over and then bring the fiber close residential areas. Via the power-lines or by using radio technology, broadband signals can be delivered to homes, including those in isolated rural areas that high-speed service providers do not see a significant return on investment to offer service to. In the age of gaping "broadband gap" in the US and other parts of the world, the power company "poles" can be viewed as a "National Treasure" in bridging the digital divide between the Have's and the Have not's of broadband services.

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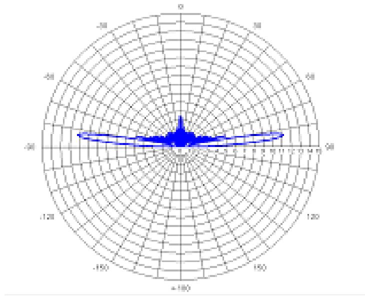
We would like to thank Dr. Raj Mittra of Electrical Engineering Dept. at The Pennsylvania State University for his suggestions regarding EMC issues and Dr. P.S. Henry of AT&T Research Labs for his insight on BPL transmissions. We are also grateful for the support of AT&T Labs in equipment and funding of this project.



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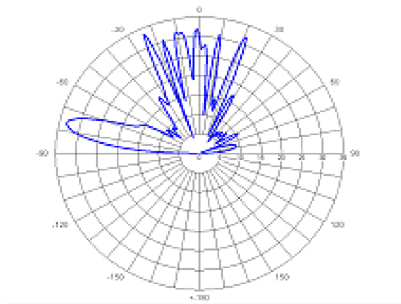

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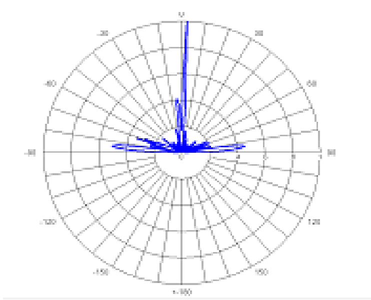

(c)

Fig.-6 Far field radiation from power-line configuration in Fig.-5, for (a) central common mode, (b) side common mode and (c) differential mode injections.

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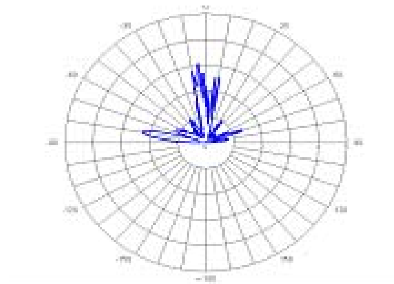

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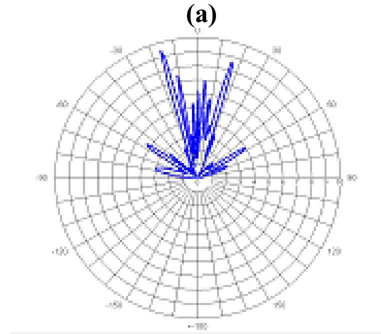

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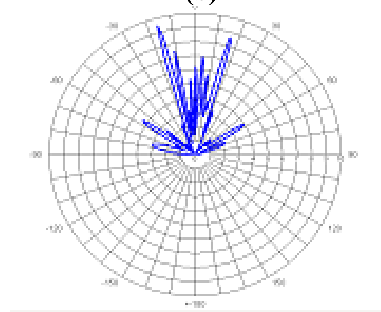

(c)

Fig.-7 Radiation pattern from an unbalanced power-line with (a) 10 mH in series difference, (b) 1 mF in parallel difference and (c) 1 μF in parallel difference.

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