Broadband Access over Medium and Low Voltage Power-lines and use of White Light Emitting Diodes for Indoor Communications

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ABSTRACT

Home users are in need for broadband communications access, globally. Broadband power-line communication has advanced through last decade and it is going to be a mature access technology in near future. Meanwhile, indoor optical wireless communications through lighting LEDs has been investigated, recently. Suitable channel models are proposed for each of these systems and the corresponding transmission capacity values are calculated. It is shown that marriage of these two technologies creates an efficient delivery mechanism for fulfilling the premise of broadband access for home networking, while providing efficient and low-cost lighting.

Keywords – Broadband communications, channel model, impulse response, power-line communications, medium voltage, capacity, indoor wireless communications, white LED.

I. INTRODUCTION

The increasing interest in modern multimedia applications, such as broadband Internet, HDTV, etc. requires new access techniques for connecting private premises to the public communication backbone. One promising technology, Broadband over Power-lines (BPL), uses electric power-lines as a high-speed digital data channel to connect a group of private users to a very high data rate backbone, such as fiber optic network. The lines in power delivery network can be categorized based on several criteria. Depending on line voltage, HV (high voltage), MV (medium voltage), and LV (low voltage) grids are typically defined. Most HV/MV transformers locations are equipped with a high-speed fiber connection. Therefore, MV lines can act as the first pipeline of high-speed connection from backbone to home users.

Channel characteristics of medium voltage overhead power-line grid, a common type of grid in the USA, were investigated in details by the authors in [1] and [2]. It is shown that although the overhead power-line grid is a very low loss medium, it may suffer with deep fading nulls caused by a multipath reflection scenario. Mismatch at the branches of power-line network reflects signals back and creates several signal paths from a transmitter to a receiver. In the same paper, the Shannon capacity limits of such channel have been investigated. It is shown that overhead power-line network has a high capacity limit compared to other similar wireline structures such as cable and twisted pair.

Each home is equipped with electricity by means of LV power-line grid. LV lines are distributed to each power plug in every room in a house. More than 99% of the homes in the USA have access to electricity, whereas connectivity level is far less for cable and phone lines. Thus, a combination of MV and LV power-lines can be an appropriate candidate for providing broadband access to every home in the country. The characteristics of LV power-lines are very well known and there are a variety of research activities going on in this area to exploit different features of LV grid. One of the most recent and comprehensive efforts of this kind is done by Galli and Banwell [3,4]. This research uses Multi Transmission Line (MTL) theory, which is also used in [1], to characterize the indoor LV power-line networks.

Indoor wireless connectivity is always appealing to consumers because of its ease of use. One of the conventional wireless access systems is Wi-Fi. These systems and similar other wireless schemes suffer from so many shortages, such as interference, not providing quality-of- service (QoS), adequate coverage, etc.

A better candidate for wireless home networking is optical wireless. Use of conventional lasers for optical indoor communications has not been feasible as yet, because of the high cost of laser sources. Instead of lasers, LEDs can be used as communications transmitters connected to electric grid, receiving high data rate signals via BPL.

Recently, white LEDs emerged in the market and are considered as future "lamps". Apparently, in near future, the incandescent and fluorescent lamps will be replaced by the low cost, efficient and miniature white LEDs. Researchers pledge that by 2012, these devices will reach 7W and 1000lm. This is brighter than a 60-w bulb and yet draws a current provided by 4 D-size batteries [5]. A Japanese research team suggested the use of the same white LEDs not only for lighting the homes, but also as light sources for wireless in-house communications [6]. Using this new and developing technology along with MV/LV power-line communications can create a revolution in the area of consumer networking due to its efficiency and affordability. In this paper, we investigate the potential of each of these technologies for providing broadband communications. In section II, a brief review of channel characteristics of MV power-line systems is cited. Section III provides transfer function of a typical LV system and its associated capacity. White LED communications systems and its characteristics are described in section IV. Concluding remarks and references end the discussion.

II. OVERHEAD MV POWER-LINE CHANNEL MODEL AND ITS CAPACITY

Channel transfer function of a matched transmission power-line follows (1-2).

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

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

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. To find an exact solution for γ at high frequencies with lossy ground return, several research efforts have been conducted since early last century. One of the most recent investigations in this area is done by D'Amore and Sarto in [7]. By applying this method, the propagation constant of overhead power-lines can be obtained for frequencies up to 100 MHz [1].

Channel transfer function of a matched transmission power-line follows (2). In the case of unmatched junctions, part of a propagating signal gets reflected back to the transmitter at branch junctions due to impedance mismatch and the remainder travels through [8]. 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. Coefficient g_i is very well defined in [8].

Using the mentioned method, we simulate the complex network shown in [1]. Our simulation results show 12 paths are dominant. The maximum delay spread of this channel is approximately 3 microseconds. Fig.-1illustrates channel capacity limits of this channel. For evaluating channel capacity, we chose a uniform –105 dBm/Hz as a representative average background noise spectral density level. Referring to [9], this value is a conservative average estimate of practical background noise level for MV power lines. According to Fig.-1, the average capacity in this network with a 10 dBm launched transmit power level at 50 MHz band is about 400 Mbps.

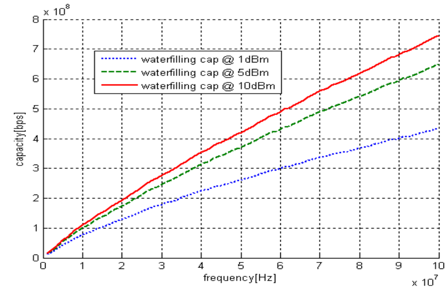


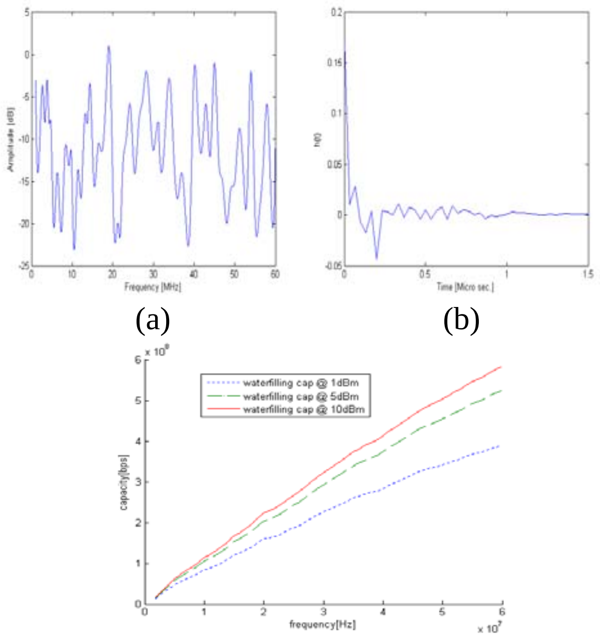
Fig.-1 Channel transmission capacity of a MV overhead power-line network

III. LV POWER-LINE TRANSFER FUNCTION AND ITS CAPACITY

As in [1], characteristic of LV power-line grids have to be utilized by means of MTL theory. As it is mentioned in [3], the conventional two-conductor transmission line (TL) is not able to explain the physical reasons of propagation behavior on LV power-line networks, completely. For an MTL with (n+1) conductors placed parallel to the *x*-axis, there are *n* forward- and *n* reverse-traveling waves with respective velocities. These waves can be described by a coupled set of 2*n*, first-order, matrix partial differential equations which relate the line voltage V_i (*x*, *t*), i=1, 2, … , *n*, and line current I_i(*z* , *t*), i=1, 2,…*n*. Each pair of forward- and reverse-traveling waves is referred to as a mode. This approach for modeling LV power-line networks is described in details and comprehensively in [3]-[4]. Using methods and algorithms mentioned in this research, we simulate the channel configuration shown in Fig. 7 of [3]. The result of frequency response and impulse response of such channel is illustrated in Fig.-2 (a) and (b). The average loss of this system is more than MV line but it has less resonance than MV line network. Our result and results in [3] are in agreement. It is seen from impulse response of Fig.-2 (b) that the maximum delay spread is less than 1 microsecond and there are 4 significant paths from the transmitter to the receiver. The capacity limits of this channel are depicted in Fig.-2(c). For evaluation of these limits we assumed an additive uniform background noise, with –120 dBm/Hz as spectral density level. According to [9], the background noise in LV networks has a smaller PSD level than in MV and has the average value around –120 dBm/Hz. It is seen from Fig.-2(c) that the average capacity in this network with 10 dBm launched transmit power can reach 600 Mbps at 60 MHz.

IV. WHITE LED COMMUNICATIONS AND ITS EFFICIENCY

White LEDs are considered as strong candidates for the future of lighting technology [10]. The reason is that LEDs offer very favorable characteristics such as high brightness, very low power consumption and high lifetime expectancy. Therefore, it is predicted that in near future, white LEDs will replace the conventional incandescent and fluorescent lamps.



(a) (b)

(c)

Fig.-2 (a) Frequency and (b) impulse response of a LV power-line network depicted in [3] and (c) its associated capacity limits

Moreover, LEDs can be used as a wireless communications transmitter. This is not possible for any other kinds of lamps in broadband transmissions. This functionality of LEDs as a transmitter is based on a fast response time and modulation of visible light for wireless communications. Fig.-3 shows a very general realization of visible light communication system using white LEDs. This system is a wireless optical indoor system that uses visible light as communications carrier. The concept of indoor optical communications has been an active area of research since early 1980's. Most of the research in this area is done based on Infrared (IR) as the communication carrier and results from these efforts are nearly all applicable to any parts of the light frequency spectrum.

There are several advantages using white LEDs for communications over Wi-Fi and IR for indoor communications:

- Installation is easier than most of wireless systems.
- White LED communications do not need any band licensing because it does not cause or suffer from any electromagnetic interference. Whereas, there are always concerns in using Wi-Fi or any other RF communications systems regarding interference from or to other wireless communication systems.
- Different users in different rooms and buildings do not interfere with one another because LED signal rays do not go through walls. On the other hand, in Wi-Fi, it is possible that different transmitted access point signals interfere and cause a degraded performance.
- Shadowing effect is so much less compared to IR case because LED light fixtures are distributed throughout the room.
- LEDs are less expensive than laser sources used in IR.
- Receiver obtains at least one strong Line-of-Sight (LoS) signal as the transmitters are on the ceiling. This is not the case in most IR transmission situations.

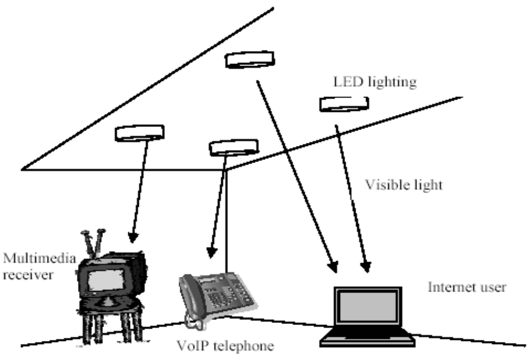


Fig.-3 Visible light communications using white LED

For any optical transmitter half-power (HP) angle and for any optical receiver, field-of-view (FOV) is defined. Half-power angle, is the highest angle that the transmitter can illuminate and FOV is the highest angle within which the receiver can receive signal rays. The mathematical definitions of these parameters are given by equations (4) and (5).

$$FOV = \tan^{-1}(\frac{r_1}{H}) \qquad (4)$$

$$HP = \tan^{-1}(\frac{r_2}{H}) \qquad (5)$$

where r_1, r_2 and H are shown in Fig.-4.

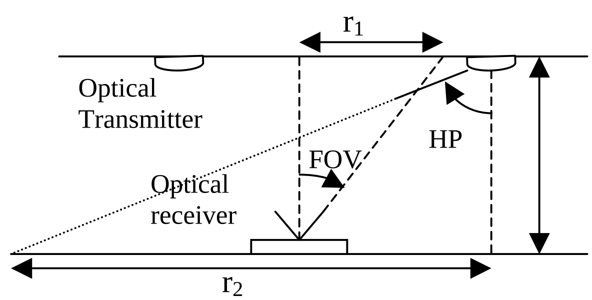


Fig.-4 An optical communications scenario

In order to illuminate a room with white LED, we need to use several LEDs. For modeling purposes, we used the scheme shown in Fig.-5. In this model room, nine LED lamps (which consist of several LEDs) are employed with 2 meters spacing between the lamp rows on the ceiling and 1 meter distance to the walls. It is shown in [10], to have a uniform illumination anywhere in the room, the HP angle has to be greater than 70 degrees.

The illumination coverage area of the center lamp is shown in Fig.-5 by a dashed circle. Receiver should be designed in a way that its FOV is high enough to at least receive a LoS signal ray from one transmitter. This way, there would be no blind spot in the room. The nearly blind spots in the room are near the corners. According to Fig.-5, if the receiver coverage area radius is greater than $\sqrt{2}$ meters, receivers at the corners will at least receive one LoS signal from the closest transmitter. If we assume the room height is 3 meters, this coverage area will correspond to an FOV equal to $\tan^{-1}(\frac{\sqrt{2}}{3}) \cong 25$ degrees. Therefore, the design for the receiver needs a FOV equal or greater than 25 degrees. Jivkova and Kavehrad in [11] have designed a receiver configuration for a 25-degree FOV. According to the results, a greater FOV needs more complexity and a greater receiver area. In the same paper, the authors have investigated different scenarios of wireless optical communications for covering an indoor space. They argue that an FOV approximately equal to 30 degrees can optimize the link budget both in cellular schemes, as with white LED, and multi-spot diffuse cases.

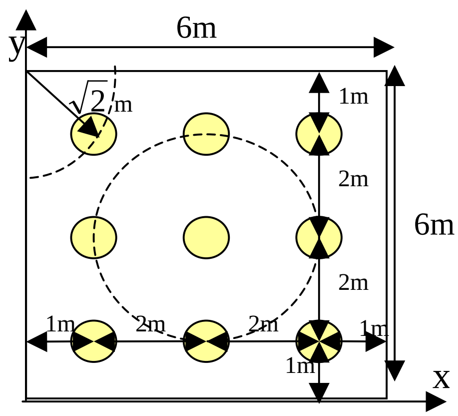


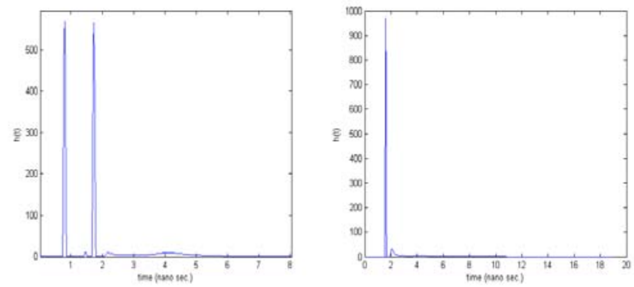
Fig.-5 A model room using white LED communication system configuration

Similar to other communications channels, modeling of wireless optical channels has been a challenge. The very first impulse response model for these channels was presented by Gfeller and Bapst [12]. Equation (6) is the result of this research.

$$h(t)=\begin{cases} \dfrac{2\tau_0^2}{t^3 \sin(FOV)} & \tau_0 < t < \dfrac{\tau_0}{\cos(FOV)} \\ 0 & \text{Else} \end{cases} \qquad (6)$$

where τ_0 is the delay of the shortest path from transmitter to the receiver. From (6), it is noticed that obtaining a narrower FOV results in a smaller delay spread in the channel. This delay spread is caused by reflections of the optical signals off the walls. For a room with dimensions of our model room and with a receiver with 25 degrees FOV, the delay spread cannot exceed 2 nanoseconds. Furthermore, equation (6) confirms that reflected signals have so much less power at the receiver compared to LoS path signals. This causes the impulse response to have a very significant LoS signal and some residual attenuated signals. Due to this fact some researchers, for example in [13], have assumed that for white LED communications, channel only consists of one straight LoS path.

The more rigorous channel modeling process for indoor optical channels was suggested by Alqudah and Kavehrad in [14]. In this paper, authors consider up to three signal reflections from the transmitter to the receiver. Their models is used for infrared applications, which they have their signal source on a table aiming a beam at the ceiling. By some modifications, their method can be adapted for our system configuration. Following this modified method, we found the channel impulse response for two arbitrary points in our system, point A at (3,2.5,0.9) and point B at (0.5,0.5,0.9). The results are depicted in Fig.-6(a) and (b).



(a) (b)

Fig.-6 Impulse response of (a) point A at (3,2.5,0.9) and (b) point B at (0.5,0.5,0.9)

Other than reflections on the walls, optical path differences can cause delay spread. These path differences are due to LoS signal arrival from different sources to a receiver. If a receiver at a certain point in the room has enough FOV to have more than one straight path to two or more transmitters, this receiver will capture strong signals from different transmitters with time delays. This phenomenon is seen in Fig.-6(a), where there are two significant strong signals in the estimated impulse response. The delay between the signals is given by equation (7).

$$t_d = \frac{\sqrt{(w-x)^2 + h^2} - \sqrt{x^2 + h^2}}{c} \qquad (7)$$

where c is the speed of light and *w*,*x*,*h* are given in Fig.-7.

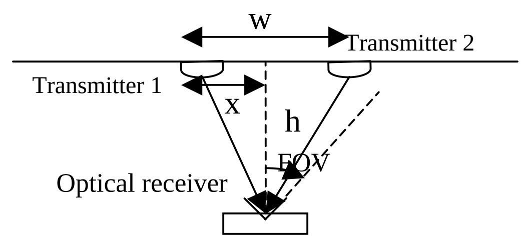


Fig.-7 Calculation of optical path difference.

With our room dimensions and the system configuration, a receiver at most can have LoS path to two transmitters and the worst delay between these two paths is 1 nanosecond. Therefore, in order to avoid a severe intersymbol interference (ISI) case, the transmission symbol rate needs to be less than one Giga symbols per second. This shows the superb transmission capacity of this kind of channels. If the conventional on-off keying modulation is used, a bit rate of 1 Gbit/sec is feasible.

CONCLUSIONS

This paper discusses the potential capacities of two emerging technologies, power-line communications and white LED indoor communications, for broadband access. Our investigations showed power-line networks, either medium or low voltage grid, could offer very high transmission capacity values, not achievable by any other wireline network, except fiber. Furthermore, it is shown that the reflections caused by mismatch throughout the network degrade the system performance. Therefore, to attain higher data rates; impedance matching in the network is necessary. If these networks are conditioned properly, a transmission rate as high as 1 Gbit/sec will be feasible.

Moreover, we discussed the fundamental analysis of visible-light communication systems using white LEDs. These systems should provide optical lighting as well as optical transmission. To meet these criteria, we designed a white LED system for lighting and high data rate indoor communications in a model room, such that there is no blind spot in the room for data communications, while the room is lit almost uniformly. Next, we developed a channel model for the proposed system based on modeling algorithms provided in [14]. It is shown that optical path difference can cause a signal distortion in high-speed data transmission. This distortion is highly dependant on the room dimensions and system configuration. If a system is designed appropriately, this distortion can be minimized. For example, our proposed system at worst, limits the data rates to 1 Gbit/sec.

Our investigations showed both systems could provide a very high data rate communications access for indoor networking. Consequently, the integrated system of these two technologies will have an important impact as a new signal transmission system.

ACKNOWLEDGEMENT

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