

Attenuation Characteristics of High Rate Home-Networking PLC Signals

Charles J. Kim, *Member, IEEE*, and Mohamed F. Chouikha, *Member, IEEE*

Abstract—This paper reports an experimental investigation of the influence of the high-frequency (HF) signal attenuation on the load in residences and offices. A laboratory test and actual measurements were performed in a residence and an office. The experiments show that the attenuation characteristics are more dependent on the number of loads than the type of loads connected. In addition, the concentration of loads was found to determine where the maximum attenuation of the HF signals would occur. The types and the size of the loads, however, did not affect the attenuation characteristics of the HF signals. Therefore, for a successful high-rate power line carrier (PLC) home networking, the analysis on the placement of the loads may have to be considered for better understanding of signal attenuation for PLC modems and other PLC-to-media adapters.

Index Terms—Home networking, PLC modem, power line carrier, signal attenuation.

I. INTRODUCTION

THE POWER line carrier (PLC) is a communication technique that uses the existing power line to carry information. Traditionally, the PLC communication sends information in the carrier signals by conduction over the power wire. The carrier signals are contained within the frequency band of 30 to 500 kHz. The most popular PLC transceiver is available in either X-10 or Consumer Electronics Bus (CEBus) specification. The X-10 is more economical and popular than the CEBus; however, CEBus was accepted as a standard for connecting intelligent appliances to PCs [1].

Lately, there has been an interest in high-speed communication on residential power lines. In most of the recent applications, PLC is used for transferring data rather than its traditional use as a control medium of home automation or utility protection systems. Furthermore, as promising new PLC modem technologies emerge, which allow data to be transferred over power lines in the home and office at the speed of more than one mega-bit per second (Mbps), the PLC becomes a possible competitor of Internet communication medium against phone-line modem, digital subscriber line (DSL), and wireless Internet.

In the PLC modem market, Inari (formerly *Intelogis*) introduced a high rate “home networking solution” using high data rate PLC communication for Internet, PC, and printer sharing for home and small office/home office (SOHO) [2]. Inari’s home networking and residential access solutions include

the 350 Kb/s power line modems. This year, the company announced that their next power modem would be over 1 Mb/s speed. Other companies are introducing similar high rate PLC modems; the Itran Communication, an Israeli company, is one with a 10 Mb/s PLC modem that is to be introduced to the market soon [3].

Since the data transfer demand and requirement for Internet communication is getting higher, the PLC modem should follow the higher carrier frequency requirement. For over 1-Mb/s communication, the low-frequency band cannot accommodate this data rate.

A communication channel uses a specific frequency to transmit the signal energy that represents the data. However, transmitting information takes more than a single frequency; a band of the spectrum around the nominal frequency is required. This is called the bandwidth of the signal, and sending information at a higher rate requires a wider bandwidth. The channel capacity, or simply bit per second (b/s) rate, is the relationship between the bandwidth needed and the data rate that can be achieved with that bandwidth [4]. To meet the channel capacity for an over 1-Mb/s rate, PLC data applications use higher than a 2–3 MHz, high-frequency (HF) band.

The intensity of the signal is distance-sensitive because attenuation occurs as it travels through the line. The propagation and the attenuation of an HF carrier signal are very dependent on the power line structure, current variation, and loads, among other things [5]–[7]. Moreover, the characteristics are not well defined since the electrical and impedance characteristics of electric power circuits are very complicated to analyze. Therefore, the influence of the load at home and office on the quality of the PLC communication channels can only be realistically understood by actual measurements of the HF signal attenuation characteristics.

II. SIGNAL ATTENUATION AND LOAD INFLUENCE

A recent study to measure the attenuation of HF signal over power line was the one directed on power transmission and distribution lines [8]. In this study, on a de-energized 15-kV power distribution line, the attenuation and characteristics impedance were found to be relatively constant at frequencies between 15 and 30 MHz, with minimal influence from line geometry and power equipment placement. This may be valuable information for the PLC technology in the broadband internet service providers; however, it provides no help for the home-networking community.

From the data communication point of view, home power lines are an extremely hostile communication medium. Power

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The authors are with the Department of Electrical Engineering, Howard University, Washington, DC 20059 USA (e-mail: ckim@howard.edu; cm@scs.howard.edu).

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lines of residence and office are generally optimized to supply electrical power at 60 Hz. In addition, appliance and office loads further shunt the HF signal so that the overall residence and office electrical environments are very unpredictable for assessing overall PLC communication performance. Moreover, electrical appliances such as motors, light dimmers, and fluorescent light ballast inject noise and may mask low-level HF signals. Worse yet, these electrical characteristics vary from instant to instant, presenting continuously changing communication channel property.

This paper presents an experimental study result on the propagation characteristics of HF carrier signals over residential and office power lines. In this study, the signals in the range of 5-30 MHz were generated by a function generator and injected, through an isolation transformer (or “coupler”), into energized power distribution circuits for residence and office. The highest limit of 30 MHz was chosen because it was reported that signals above 30 MHz were normally attenuated below the noise at a modest distance [9]. We measured the output voltage of the injected signal in a receiver through another coupler. By positioning the reception coupler in different locations, the magnitude of the injected voltage could be measured along the power line, thus allowing the relationship between the attenuation level and the distance from the transmitter to be obtained. In the next section, we will discuss the measurements made in a test setup.

III. HF ATTENUATION MEASUREMENT IN A TEST SETUP

A. Modulation Coupler

A coupler is used to modulate a carrier signal to a power line. The one shown in Fig. 1 allows the transmission and receiving of the HF carrier signal and blocks the nominal 60-Hz power signal. The coupler is composed of an isolation transformer and capacitor(s). The combination acts as a highpass filter circuit. In our coupler design, the inductance of the isolation transformer was about 9 μ H, and the capacitance was selected as 10 nF so that the coupler could pass signals above 0.5 MHz to the power line and block the dominant 60-Hz power signal to the transmitter/receiver.

B. HF Signal Attenuation Test Set-Up

The test setup for the propagation characteristics on different load conditions is illustrated in Fig. 2. We connected the wire-end to the outlet via a two-prong plug so that line was live with a 110 V at 60 Hz. The wire used was a two-line standard Polyvinyl Chloride (PVC) insulated flexible cord with a rated current of 40 A.

Five loads were placed 5 m apart, starting from the left, in the order of a 1000-W window-type air-conditioner (A/C), a 20-W fluorescent lamp (F/L), a 30-W electric fan (Fan), a 200-W refrigerator (REF), and a 600-W personal computer (PC). A signal was injected at the left end using a signal generator, and a receiver was moved to each load branch for measurement.

C. Behavior of the HF Signals

We examined the attenuation characteristics of all of the HF signals individually when 1) no load was connected, and 2) all loads were connected. The signal attenuation characteristic was

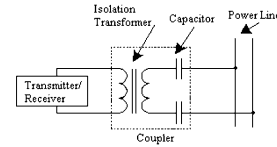


Fig. 1. HF signal coupler.

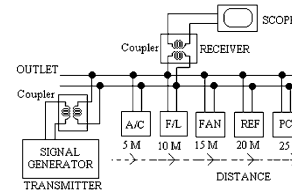


Fig. 2. Experimental setup for signal attenuation measurement.

represented as the ratio of the received peak-to-peak voltage (V_{rpp}) to the transmitted peak-to-peak voltage (V_{tpp}) in decibels as in

$$P(\text{dB}) = 20 \log \left(\frac{V_{rpp}}{V_{tpp}} \right).$$

No-Load Condition: Fig. 3 shows the result of the attenuation characteristics when no load was connected. The no-load characteristics of the HF signals show gradually decreasing curves as the receiver moves away from the transmitter. Also, the higher is the frequency, the greater the attenuation. It is obvious that the behavior of a HF signal roughly follows another HF signal.

All-Load Condition: When all five loads are connected at their respective locations, all of the HF signals gradually decrease as the receiver is moved away from the transmitter. Fig. 4 shows that, with a minor exception, the HF signals show the same attenuation characteristic: more attenuation in higher frequency.

From the results of the “no-load” and “all-load” conditions, we are able to conclude that the analysis of collective signals would show similar characteristics as those of the individual signals. Therefore, for the attenuation study in the paper, we applied the collective analysis approach.

Observation: The collective attenuation of all six HF signals, of no-load and all-load conditions clearly shows the influence of the load as indicated in Fig. 5. The attenuation with the “all-load” condition is much larger than the “no-load” condition. Also, we see that the differences in the attenuation amount between the two conditions increase as the distance goes farther away from the transmitter.

However, another important observation is that for the “all-load” condition, the maximum attenuation occurs not at the farthest distance of 25 m, but at 20 m. Our study relates the maximum attenuation point to the “load concentration point” (L_c), which could be considered as “the average distance of all the loads connected” from the signal injection point. The load concentration point can roughly be defined as

$$L_c = \frac{\sum_{i=1}^N D_i}{N}$$

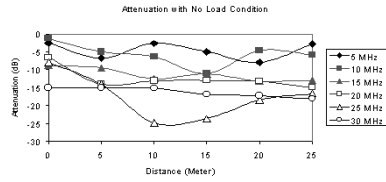


Fig. 3. Attenuation with no-load condition.

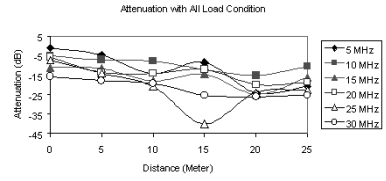


Fig. 4. Attenuation with all the loads connected.

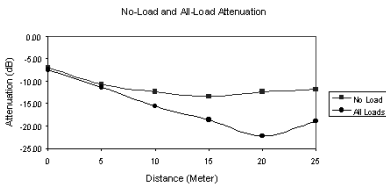


Fig. 5. Collective attenuation for no-load and all-load conditions.

where N is the total number of load connected, and D_i is the distance of the i^{th} load from the transmitter.

For example, if we have an F/L at 10 m and a Fan at 15 m, then the average load distance is $L_c = (10+15)/2 = 12.5$. The load concentration point indicates the approximate location of the most heavily loaded location. In the next section, we will discuss the relationship of the maximum attenuation point versus the load concentration point.

D. Collective Behavior of HF Signal Attenuation

In this section, we analyzed the collective signal attenuation on one-, two-, three-, and four-load conditions.

One-Load Condition: We tested the following five different one-load conditions.

- Only the A/C is connected at 5 m.
- Only the F/L load placed at 10 m.
- Only the Fan is connected at 15 m.
- Only the REF is connected at 20 m.
- Only the PC is connected at 25 m.

The behavior depicted in Fig. 6 indicates that the attenuation behaviors of all one-load conditions are almost identical, and there are no distinctive features that are attributable to the types of load. The attenuation is low: between the -7 and -12 dB level.

Two-Load Condition: We tested the following six different two-load conditions. We indicated the load concentration points of each condition inside the parentheses.

- F/L and Fan ($L_c = 12.5$);
- Fan and PC ($L_c = 20$);
- Fan and REF ($L_c = 17.5$);
- A/C and F/L ($L_c = 7.5$);
- REF and PC ($L_c = 22.5$);
- F/L and PC ($L_c = 17.5$).

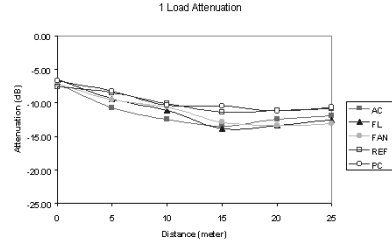


Fig. 6. Collective behavior of HF signal attenuation with one-load conditions.

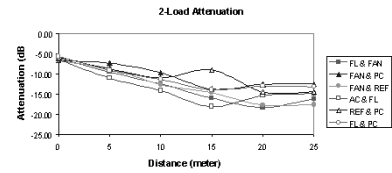


Fig. 7. Collective behavior of HF signal attenuation with two-load conditions.

In general, the attenuation gradually increases with distance; however, it is apparent that not all the load conditions have their maximum attenuation at the farthest location (i.e., at 25 m), as depicted in Fig. 7. The “A/C and F/L” condition with $L_c = 7.5$ shows the maximum attenuation is at 15 m and the “F/L and Fan” with $L_c = 12.5$ at 20 m. Others are not that apparent in their relationship of the load concentration point and the maximum attenuation point; however, the relation of two is much clearer when more loads are connected. We will discuss about this relationship through the analysis.

Three-Load Condition: We tested the following five different three-load combinations. The load concentration is indicated for each of the three-load conditions.

- A/C and F/L and PC ($L_c = 13.3$);
- F/L and Fan and REF ($L_c = 15$);
- F/L and Fan and PC ($L_c = 16.7$);
- F/L and REF and PC ($L_c = 18.3$);
- Fan and REF and PC ($L_c = 20$).

As in the two-load conditions, the attenuation gradually increases with distance; however, we see a clear indication of the relationship between the load concentration and the maximum attenuation points (see Fig. 8). For “A/C and F/L and PC” with $L_c = 13.3$, the maximum attenuation occurs at 15 m, and for “F/L and Fan and REF” with $L_c = 15$, the maximum attenuation is at 20 m. Also, we can see that the load condition of “Fan and REF and PC” with $L_c = 20$ shows its maximum attenuation at 25 m. In other words, the larger the load concentration, the farther the maximum attenuation point. The only exception is the load condition of “F/L and Fan and PC” of $L_c = 13.3$ with a maximum attenuation at 15 m.

Four-Load Condition: The 4-load conditions tested are listed below. As above, the load concentration point is indicated for each load condition.

- A/C and F/L and Fan and PC ($L_c = 13.75$);
- F/L and Fan and REF and PC ($L_c = 17.5$);
- A/C and F/L and REF and PC ($L_c = 15$).

In Fig. 9, we definitely see the positive relationship between the load concentration and the maximum attenuation points. The load condition of “A/C, F/L, Fan, and PC” of $L_c = 13.75$ has its maximum attenuation at 15 m, whereas “F/L, Fan, REF, and

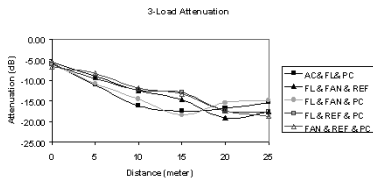


Fig. 8. Collective behavior of HF signal attenuation with three-load conditions.

PC” of $L_c = 17.5$ has its maximum point at 25 m. The in-between load condition, “A/C, F/L, REF, and PC” with $L_c = 15$ has its maximum attenuation between the other two load conditions at 20 m. The positive relationship of average load distance versus maximum attenuation distance becomes more obvious when more loads are connected to the power line.

Observations: Next, we attempted to find the empirical relationship between the load concentration and the maximum attenuation points. The result is illustrated in Fig. 10. By the scatter plot, we indicated all the load combinations (in terms of the load concentration) in the y -axis and their maximum attenuation points in the x -axis. The solid line indicates a linear equation $y = a + b \cdot x$ with $a = 13.93$ and $b = 0.314$. In order to include the error margin of the fitted line, we also indicated, by the dashed lines, a prediction band of upper and lower 80% limits. It is obvious that there is a general trend of linearity inside the band of 80% prediction limit.

From the analysis, we can draw the following conclusions.

- 1) The number of loads is an important factor in HF signal attenuation.
- 2) The load level (load current or load size in power) is not a factor in attenuation.
- 3) The types of load are not important.
- 4) The difference of the attenuation amount increases as the distance or/and the number of load increases.
- 5) There is linear relationship between the maximum attenuation and the load concentration points. This observation becomes more obvious with more loads.

IV. ACTUAL ATTENUATION TESTS

A. Test in a Residence

To validate the signal attenuation characteristics observed in the laboratory set-up, a similar test was performed in a residence as illustrated in Fig. 11. A transmitter was installed in an outlet of the Room 1 (living area), closest to the power distribution panel, and the HF signals were modulated to the power line through the outlet.

The loads were distributed around the rooms and plugged to the outlet(s) in each room. The loads were almost evenly distributed except in Room 5, where it was more lightly loaded with only lamps. During the measurement, all loads were in the operating (“ON”) state. The load distribution is tabulated in Table I.

With loads energized, we moved our receiver to the locations marked as R1 through R5 and recorded the attenuation of the HF signals. Since the wiring behind the wall of the house was not known, the influence of the distance of the loads was not intended nor possible to be related to signal attenuation characteristics. Instead, we tried to confirm our finding of the maximum

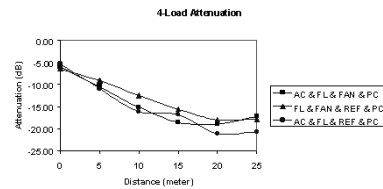


Fig. 9. Collective behavior of HF signal attenuation with four-load conditions.

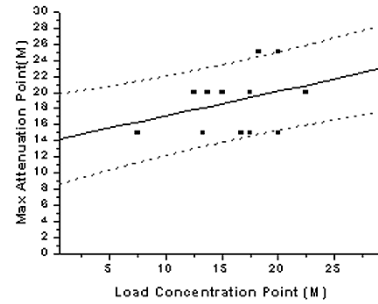


Fig. 10. Scatter plot and fitted curve for load concentration and maximum attenuation points.

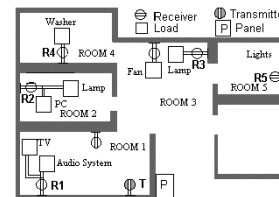


Fig. 11. Attenuation test scheme in a residence.

TABLE I
LOAD DISTRIBUTION AT THE ROOMS.

ROOM	LOADS	REMARKS
Room 1	a TV, an audio system	living area
Room 2	a PC, an incandescent lamp	
Room 3	a fan, an incandescent lamp	kitchen
Room 4	a washer	utility room
Room 5	four (4) incandescent lamps	

attenuation point versus load concentration point in a realistic situation.

Fig. 12 shows the measured signal levels at the five locations. All the locations show some level of attenuation, from 15 to 35 dB; however, there is no clear correlation between the amount of the attenuation and the frequency of the signal (see the dotted lines for individual HF signals).

The collective attenuation is indicated by the thick solid line in the figure, and the signal attenuation is almost same at every location. This behavior can be explained in the following: Since loads are evenly distributed around the measurement locations, there are no significant changes in the attenuation levels around the house. However, a closer look would find that the maximum attenuation point is around Room 3 or 4. This observation confirms the linear relationship between the maximum attenuation point and the load concentration point since evenly distributed loads will have the load concentration point at the middle, if we assume that outlets at the lower numbered rooms are electrically closer to the transmitter.

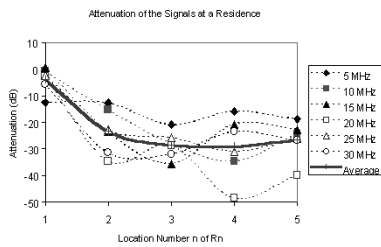


Fig. 12. Attenuation characteristics in a residence.

B. Test in an Office

The attenuation test condition at an office is illustrated in Fig. 13. Electricity supply to the office comes through the electric distribution panel installed at the outer wall of the office. Electric wires run inside the walls, and several outlets in each room are tapped from the main wires. Most of the loads in the office were computers. The only exception was a small dorm-size refrigerator in Room D. As we can see in the figure, the computer loads were not evenly distributed. Room A, a conference room, did not have any loads, and Room C had only one PC. However, Room B had 6 PCs and Room D had five PCs, in addition to the refrigerator. In addition to the office equipment loads, there were six 40-W fluorescent lamps in the ceiling, and they remained on during the measurement.

The transmitter was placed at an outlet closest to the distribution panel in Room D, and the HF signals were modulated through the outlet. There were six signal measurement locations marked as R1 through R6. The exact electrical distances from the transmitter to the measurement locations were not known; however, it was assumed that locations with higher number were farther away from the transmitter, based on the wiring diagram of the office building and our rough induction that the geometrical distance is proportional to the electrical distance. Therefore, it was thought that R6 was the farthest location of the measurement, and the next farthest one was R5, and so on.

The result of the measurement is illustrated in Fig. 14. In the figure, we can see that the HF signals show the same pattern of no clear correlation between the attenuation and the frequency of the signal (see the dotted lines for individual HF signals). The collective attenuation curve of the HF signals is indicated by a thick solid line. The collective signal attenuation shows that the signals are much more attenuated at R2 and R4, where it is heavily loaded, whereas the locations of R5 and R6, which are farther away from the transmitter, show a much smaller attenuation. Also, a closer look reveals that the maximum attenuation point is around R4 and since loads are unevenly distributed, this point seems to be the load concentration point. This observation further supports the linear relationship between the maximum attenuation and the load concentration points.

V. CONCLUSIONS

This paper reports on the experimental investigation of the influence of HF signal attenuation on the load in the residence and the office. We performed two types of experiments: laboratory test and actual measurements. The first was to find the

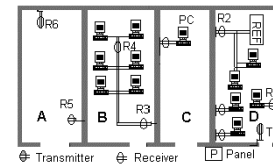


Fig. 13. Attenuation measurement in an office.

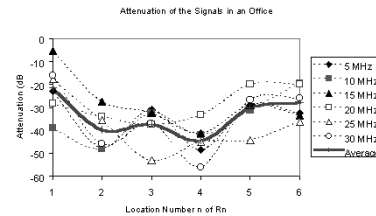


Fig. 14. Attenuation characteristics in an office.

direct load influence on the high-frequency propagation using a test setup. In this test, when more loads were connected, more attenuation was observed for all HF signals tested. The second test was performed in a residence and an office building to measure the signal attenuation in realistic conditions.

From the tests, we found that the attenuation amount increases as the number of load increases. Also, the linear relationship between the maximum attenuation point and the load concentration point were observed. The close connection between the two parameters was supported by the real-situation measurements.

The conclusion obtained from the experiments may not represent the signal attenuation characteristics for all the homes and offices, but the experiment setup in the measurements closely resembles actual homes and offices, at least in the load types and their distributed locations. Therefore, for a successful debut, and in order to earn customer confidence for high rate PLC home networking, the analysis on the different number and arrangement of the loads may have to be considered for better understanding of signal attenuation for PLC modems and other PLC-to-media adapters.

REFERENCES

- [1] *Communication Protocols*. Piscataway, NJ: IEEE Power Eng. Soc., 1995.
- [2] [Online]. Available: www.intelogis.com
- [3] [Online]. Available: www.itrancomm.com
- [4] W. L. Schweber, *Data Communication*. New York: Glencoe/McGraw-Hill, 1995.
- [5] R. M. Vines, H. J. Trussel, L. J. Gates, and J. B. O'Neal Jr., "Noise on residential power distribution currents," *IEEE Trans. Electromagn. Compat.*, vol. EMC-26, pp. 161-168, Nov. 1984.
- [6] A. A. Smith, "Power line noise survey," *IEEE Transaction on Electromagn. Compat.*, vol. EMC-14, pp. 31-32, Feb. 1972.
- [7] R. M. Vines, H. J. Trussel, L. J. Gates, and J. B. O'Neal Jr., "Impedance of the residential power-distribution circuit," *IEEE Trans. Electromagn. Compat.*, vol. EMC-27, pp. 6-12, Feb. 1985.
- [8] Z. A. Bukhala, M. T. Glinkowski, J. K. Nelson, and V. J. Forte, "Radio frequency signal transmission on medium voltage power distribution lines," *IEEE Trans. Power Delivery*, vol. 14, pp. 46-51, Jan. 1999.
- [9] D. Raphaeli and E. Bassin, "A comparison between OFDM, single carrier, and spread spectrum for high data rate PLC," in *Proc. Third Int. Symp. Power-Line Commun. Applicat.*, Lancaster, UK, Mar.-Apr. 30-1, 1999.



Charles J. Kim (M'90) received the Ph.D. degree in electrical engineering from Texas A&M University, College Station, in 1989.

From 1990 to 1994, he was a post-doctoral research associate and, later, a research faculty member at Texas A&M. From 1994 to 1998, he was an assistant professor at the University of Suwon, Suwon, Korea. Since 1999, he has been with Department of Electrical Engineering, Howard University, Washington, DC. His research interests include PLC home networking, embedded computing,

Internet-based decision-making, and intelligent systems application.



Mohamed F. Chouikha (M'88) received the Ph.D. degree in electrical engineering from the University of Colorado, Boulder, in 1988.

Since 1988, he has been with Department of Electrical Engineering, Howard University, Washington, DC. In July 2000, he became the Chair of the Electrical Engineering Department. His research interests include multimedia signal processing and communications, wireless communications, and home networking.