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RESEARCH ARTICLE

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Analysis of electromagnetic field emitted from home plug power line used for indoor high-speed broadband communication

Abstract High-speed broadband power line communication (BPL) is a novel and practicable technique for Net-atHome or home area local area networking (LAN). Because of the characteristics of BPL, the electromagnetic wave emitted from the BPL transmission media will influence the indoor electromagnetic environment, which would also affect the performance of other wireless communications. Based on the analysis of the communication channel characteristic, network impedance and attenuation characteristic of the BPL, this paper proposes a novel model for calculating the BPL radiation and the computer simulation model, which are proved by the coherence of the simulation and the test data. The interferences from the high-speed BPL to indoor wireless communications are analyzed to stipulate the standards of high-speed BPL in the future.

Keywords broadband power line communication (BPL), electromagnetic radiation, electromagnetic interference, wireless communication, Net-atHome

1 Introduction

Broadband power line communication (BPL) is a novel technology for broadband network access. It originated from the narrowband power-line multiple-carrier communication in high-voltage transmission networks, and medium-voltage and low-voltage distribution networks, making use of the home electrical outlets to implement broadband data communication.

The evolution of the power line communication can be traced back to the 1920s. At that time the application was mainly focused on high-voltage long-distance transmission power lines with working frequency below 150 KHz. In the 1950s, low-frequency high-voltage power line communication was being used widely for various fields including monitoring, remote control, equipment guard, voice transmission, and so on. From the late 1950s to the early 1990s, power line communication began to be applied in medium-voltage and low-voltage distribution networks for automatic meter reading, load control and supply management, etc. However, the use was limited owing to the serious electromagnetic radiation interference from the narrow band power line communication to short-wave communication caused by immature signal modulation. Recently, with the development of digital modulation and demodulation chips, power line communication has achieved a great leap forward to high-speed broadband communication. The latest special BPL chips have a transmission speed of up to 224 Mbit/s.

BPL can make full use of the most popularly existing power line network, needs no new line distribution, and requires only low investment. Users may utilize the power outlets all over the rooms to access the Internet, which will allow people to realize the so called ‘mobile line communication’ and be superior to any other communication access technology [1].

At present, the European Union (EU) considers BPL as a crucial technology for the e-Europe project. Meanwhile, the Federal Communications Commission (FCC) promotes the current BPL platform to enhance the American broadband service. China has also launched research into the technology, and owns the biggest practical network with more than 80000 consumers [1].

However, the electromagnetic radiation safety problem brought by BPL has now become a hot issue. This paper discusses the evaluation and testing methods of the radiation field produced by BPL, and analyzes the disturbance from the BPL to other wireless communication services.

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2 Characteristics of BPL Technology

2.1 Transmission characteristics of BPL

The frequencies used by BPL are restricted within the range from 1 MHz to 30 MHz. Though there is louder noise in the BPL channel and has an impact on high-frequency transmission signals, the attenuation of signals is less than that of noise within a certain distance. Hence, it is feasible to use an appropriate modulation technology to couple the broadband signals on the power lines.

The disadvantages of transmitting high-frequency signals over power lines are the serious signal attenuation caused by the physical properties of the components constructing the power line network, the relatively serious reflections while transmitting in the complicated topological structure and numerous branches in the home plug power line, and the network impedance fluctuation with the changes of the electric and electronic equipment plugged in. Thus, the power lines show some overall characteristics such as frequency selective fading, multiple-path reflection, amplitude attenuation [2], etc. In a word, because power lines are not an ideal communication medium, most parts of the attenuation energy of the signals becomes the leakage electromagnetic energy and causes the radiation interference to other devices.

2.2 Electromagnetic interference characteristics of BPL

Electromagnetic interference means that the working electric and electronic devices will produce some unintentional electromagnetic radiation energy and disturb other devices. The use of the narrowband power line system is limited because of the serious interference to the surrounding environment.

The BPL devices are operated in a frequency range of approximately 1–30 MHz and the emission energy of signals while transmitting through the power line is just the right frequency band. The BPL interference to the outside can be divided to two categories — the carrier frequency interference and the out band interference. However, a lot of the frequency subdivisions are appointed to other radio communication systems, such as broadcast, amateur radio, etc. Therefore, the available frequency bands left for BPL are discontinuous chimney like frequency intervals. The available frequency bands are defined by the specification of the Home Plug AV [3] in American.

In order to restrain co-frequency interference, the BPL system employs orthogonal frequency division multiplexing (OFDM) technology to modulate BPL signals part by part to use the discontinuous frequency intervals for data transmission. In detail, the signals are loaded to the discontinuous chimney like frequency intervals, and the transmitting power is increased to raise the data rate. However, the radiation interference from the BPL system is related to random network states, so an accurate prediction model is not easy to propose. In this paper, a novel model is put forward to analyze the stray interference and cross modulation from BPL to broadband wireless access system and co-frequency interference to short wave communication.

3 Channel analysis of BPL

The indoor high-speed broadband power line network is an unstable network with a complex impedance of $Z(f)$. This “data communication network” is not designed to transmit high-speed data specially, but to send the electric energy with minimum losses, guarantee the safety and reliability of the low frequency current network. So the network itself does not possess symmetry, homogeneity and other electric characteristics [4] as the telecommunication network. It is necessary to investigate how to transmit the signals in power lines.

3.1 Multiple-path propagation of power line channels

The transmission environment of the power line network is complicated, whose physical structure determines the signals to be transmitted in multiple paths. After the modulated signals are sent out from the transmitter node, it will not merely reach the receiver node along a single route, but transmit to each node of the network and reflect at the closing ends. The receiver node can obtain multiple signals from any node including the transmitter node. So the signal in the whole BPL network indicates the mixing characteristics of the traveling wave and standing wave.

Though the power line network contains multiple reflection signals, the majority of the reflection signals will attenuate greatly to be neglected. Therefore, we combine N signals into a pulse response, given by

$$H(f) = \sum_{i=1}^{N} a_i \mathrm{e}^{-\alpha(f)l_i} \mathrm{e}^{-\mathrm{j}2\pi f \tau_i}, \tag{1}$$

where, a_i represents signal’s amplitude. $\mathrm{e}^{-\alpha(f)l_i}$ represents attenuation factor, which is the function of the power line’s length and the signal’s frequency. τ_i is defined as the delay of the reflection wave. Thus, the BPL’s performance has a tight link with the network’s structure, the power line’s length and the signal’s characteristics.

3.2 Attenuation analysis of BPL

The signals in BPL can be expressed by transmission line mode. According to transmission line theory, the propagation coefficient r can be regarded as

$$r = \sqrt{(R + \mathrm{j}\omega L)(G + \mathrm{j}\omega C)} = \alpha + \mathrm{j}\beta, \tag{2}$$

where R, G, L and C represent the resistance, conductance, inductance, and capacitance per unit length, respectively. R is dominated by the skin-effect and thus is proportional to $\sqrt{f}$. G is mainly influenced by the dissipation factor of the dielectric material and therefore proportional to f. With typical geometry and material properties, we have $R \ll \omega L$, $G \ll \omega C$ in the frequency range of interest. Thus, Eq. (2) can be simplified as

$$r = \frac{1}{2}\frac{R}{Z_L} + \frac{1}{2}GZ_L + \mathrm{j}\omega\sqrt{LC}. \qquad (3)$$

Based on these derivations and extensive investigations of measured frequency response, an approximating formula for the attenuation factor is found in the form

$$\alpha(f) = \frac{1}{2}\frac{R}{Z_L} + \frac{1}{2}GZ_L = k_1\sqrt{f} + k_2 f \approx b_0 + b_1 f^k, \quad (4)$$

b_0 and b_1 are empirical data within [0.5, 0.7]. Combining multiple-path propagation and frequency- and length-dependent attenuation leads to

$$H(f) = \sum_{i=1}^{N} |a_i(f)| \mathrm{e}^{\varphi_i(f) - (b_0 + b_1 f^k) l_i - \mathrm{j}2\pi f \tau_i}. \qquad (5)$$

3.3 Analysis of signal's reflection

The indoor power line network generally has a dozen access points to produce the complicated reflection signal. However, the measurement shows that the received signal is only influenced by close nodes and the reflected signals at other nodes will decay approximately to zero. Thus, the phase of reflected signals near the receiver node stays intact. The final version of the frequency response is given by

$$H(f) = \sum_{i=1}^{N} g_i \mathrm{e}^{-(b_0 + b_1 f^k) l_i - \mathrm{j}2\pi f (l_i / v_p)}. \qquad (6)$$

It can be easily seen from Fig. 1 that the numerical simulation agrees well with the measurement [5].

4 Computation of BPL's electromagnetic radiation

The indoor power line is not a unified network structure, which brings great difficulty in the calculation of its space radiation field. Therefore, the whole network is divided into numerous small Hertzian dipole antennas. In any observation point, the radiating electric field is calculated by adding every radiating field from the corresponding antenna [6].

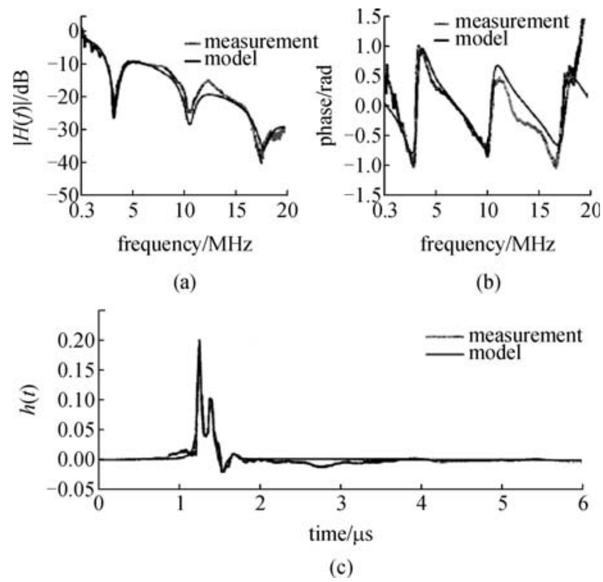

Fig. 1 Below 20 MHz, measurement and simulation. (a) Amplitude response; (b) phase details; (c) impulse response

4.1 Model of BPL network

Figure 2 shows a typical power line network structure. The whole network contains a main line and three branches, L_1, L_2, L_3, L_4 is 12 m, 4 m, 3 m and 3 m, respectively. Assume that the transmitter node A and the receiver node E are impedance matching, node F, node G, and node H all reflect the signal. r_{ij} is reflection factor, t_{ij} is transmission factor ($i = 1,2,\ldots$ represents the path number). The whole network is constructed with cables of the same type, which act together to give rise to the radiation result [7].

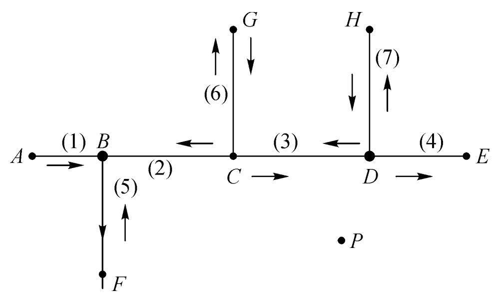

Fig. 2 Network configuration of multiple paths

4.2 Computation of electromagnetic radiation from BPL

BPL's transmission loop is decomposed as a differential mode loop and a common mode loop, whose current is defined as I_c, I_d, respectively. Figure 3 shows the current loop model. I_1 and I_2 represent the total current of the whole loop. The space radiation is mainly from the common mode loop. Therefore, the equivalent common current I_c is given as

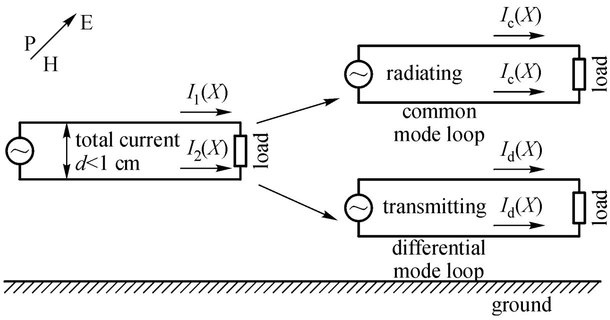

Fig. 3 Current loop model

$$I_c(X) = \frac{I_1(X) + I_2(X)}{2}. \quad (7)$$

The whole line is divided into numerous small Hertzian dipole antennas, each of which has the same length and basic character. In the observation point, the radiating electric field is calculated by adding every radiating field from the corresponding antenna. The space position and propagation phase of any Hertzian dipole antennas should be taken into account.

I_0 represents input signal's intensity, so the signal distributed along the line can be considered as

$$I = I_0 e^{-(b_0+b_1 f^k)l_i - j2\pi f(l_i/v_p)}. \quad (8)$$

The distance between the observation point and the Hertzian dipole antenna is defined as r. Δl represents the length of the antenna, λ is the signal's wavelength, η represents wave impedance in free space, $\eta = 120\pi, k$ represents phase constant in free space, θ represents the angle between the middle point of the antenna and the observation point. E_r and E_θ are the r component and θ component of E-field strength, respectively [8]:

$$\begin{cases} E_r = j\eta \dfrac{I\Delta l}{2\pi r}\left[\dfrac{1}{jkr} + \dfrac{1}{(jkr)^2}\right] e^{-jkr}\cos\theta, \\ E_\theta = j\eta \dfrac{kI\Delta l}{4\pi r}\left[1 + \dfrac{1}{jkr} + \dfrac{1}{(jkr)^2}\right] e^{-jkr}\sin\theta. \end{cases} \quad (9)$$

The vector adding procedure is given by [9]

$$E_0 = \sum_{i=1}^{N} \sqrt{E_{ir}^2 + E_{i\theta}^2}. \quad (10)$$

In addition, the reflection wave in the branches cause the standing wave phenomenon in the lines, the exciting signal's intensity can be expressed as

$$I = I_m \sin\beta(l - d), \quad (11)$$

where I_m represents the signal's wave loop, β represents phase constant.

We can get the radiating power at the observation point P on the basis of radiation field intensity. As depicted in Fig. 4, the simulation result is compared with the FCC standard, whose input power is 10 mW.

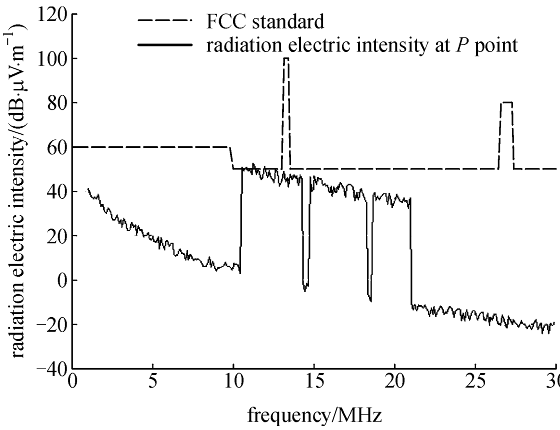

Fig. 4 Comparison of simulation and FCC standard

5 Test of radiation field from BPL

Because the electric network structure is large scale, it is difficult to carry out electromagnetic compatibility testing in a laboratory. Therefore, we implement the test under the indoor environment to verify the accuracy of the BPL radiation theory model through on-the-spot test.

5.1 Test scheme

We construct the experimental platform and join the network as follows: we utilize the reception system composed of the antenna array, HP spectrum analyzer and computers, to investigate the local noise and radiation field. According to the limit of BPL's data speed, the input power of the high-frequency signal is adjusted, a frequency sweep from 1 MHz to 10 MHz is adopted. We select different observation distances (such as 1 m, 3 m, 10 m, etc.), and get the corresponding data of the radiation field.

The BPL modem is provided by Intellon Company, whose Intellon 5500 CS chip supports data rates up to 85 Mbit/s. This modem meets the FCC standard, so the radiation it induces can be neglected, and the closing ends of the network have impedance matching.

5.2 Test results

We measure the two states: working and idle. First, we execute the peak value scanning, then use quasi-peak value to measure within the frequency band of 0.05–50 MHz. The power of the radiation field distributed in working state is plotted as Fig. 5. The input power is 10 mW in accordance with the simulation value.

It can be easily seen from Fig. 5 that the signal radiation field is concentrated within the range of 11–22 MHz, and the noise of both sides is higher than the local noise. The

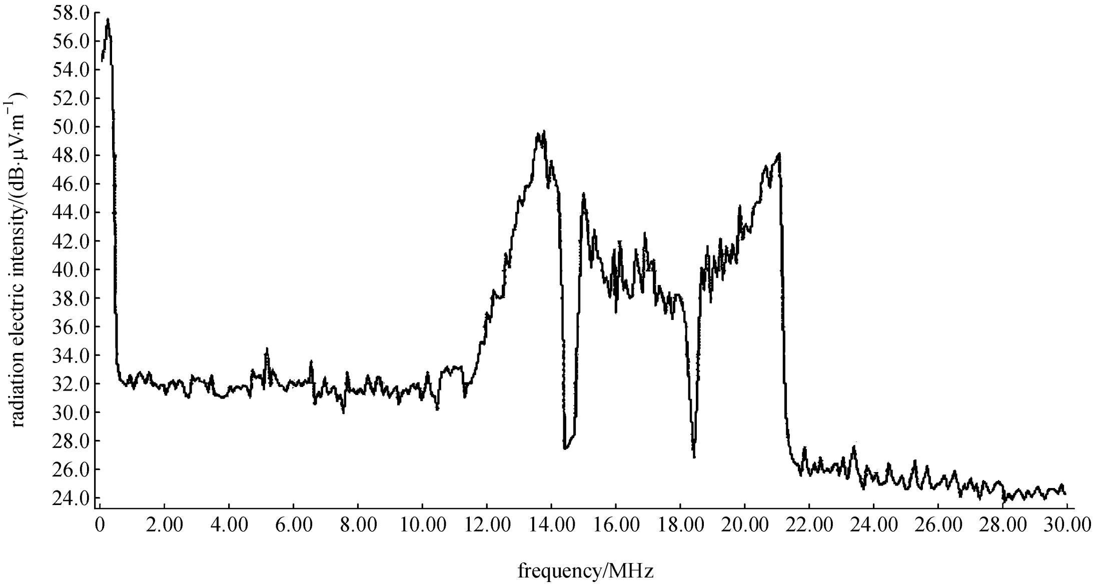

Fig. 5 Radiation electric intensity at 1 m distance

measurements agree well with the numerical results, whether peak value or frequency range.

As shown in Fig. 6, the radiation intensity is proportional to the input power of the signal, and inversely proportional to observation distance. Note that the radiation power may exceed the FCC standard when the input power is higher or the observation point is shorter than a certain value. Furthermore, when the distance is beyond 3 m, the radiation field no longer affects the other devices.

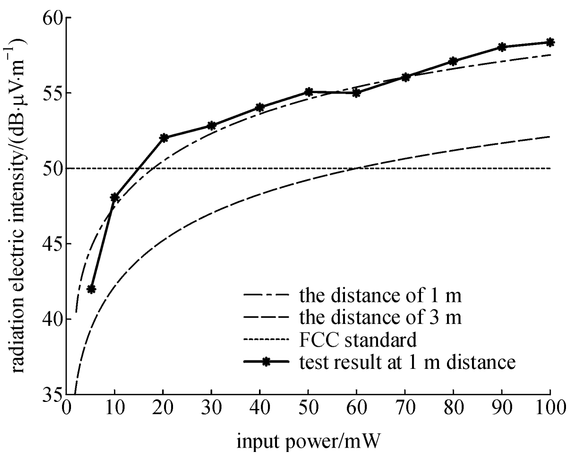

Fig. 6 Relation of radiation intensity and input power

6 Interference from BPL to other indoor wireless devices

Though signals transmitted in the power line are within 30 MHz, the radiation signals including other frequency bands interfere with other wireless devices in the same room.

The ultra wide band (UWB) is an indoor wireless communication technology using a higher frequency band within 3.1–10.6 GHz. Compared with the extensively used technology, such as 2 G and 3 G, etc., it operates in a higher frequency band and lower frequency spectrum, as a development direction of wireless communication in the future.

Quite a few researches demonstrate that BPL's radiation has interference to UWB. We can extract the interference signals having the same frequency band as that of UWB by highly sampling the radiation signals. Then, we use it as the channel noise to evaluate the systematic effect.

As indicated in Fig. 7, the bit error rate (BER) at the receiver node increases with the interference. When signal-to-noise ratio (SNR) is lower, the BER's increase is not obvious. But in a higher SNR, the BER increases up to

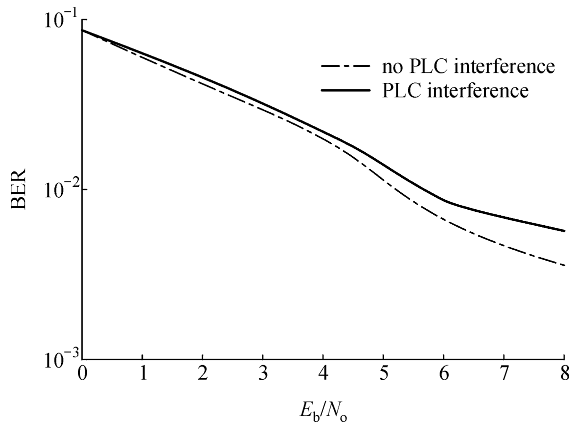

Fig. 7 BER of UWB signals interference by BPL

20%. Generally speaking, the BPL below a certain transmitted power has a radiation interference under the limitation of regulation.

7 Conclusions

As a kind of new access and network construction technology, high-speed broadband communication through power lines has an enormous application potential. The compatibility problem that exists in its practical application has attracted more and more attention. This paper, based on the channel characteristic of power lines, uses the Hertzian antenna model to realize the computation of the space radiation field of a typical power line network. The comparison of simulation results and the measurements validates the feasibility of the model. It can be used to investigate the coexistence of indoor wireless communication technology between BPL and others. The interference in high-speed power line communication can be reduced through measures including control of the input power, setting the protection distance and so on. A further study will focus on combining the existing standards to put forward a new high-speed broadband power line communication technical standard for shortwave communication and novel wireless businesses.

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