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ANALYSIS AND SIMULATION OF A LOW-VOLTAGE POWERLINE CHANNEL USING ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

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ABSTRACT

Based on the experimental results, a simplified model for low-voltage powerline used as a high frequency communication channel is presented. With this model, the Orthogonal Frequency Division Multiplexing (OFDM) based high rate digital communication over low-voltage powerline is analyzed and simulated. The capability of the signal transmission system in overcoming multi-path interference and selection of the system parameters are discussed. And time-domain simulation is carried out to investigate the transmission capability of the OFDM communication system for different mapping schemes and transmission power levels. Simulation results show that it is possible to realize high rate digital communication over low-voltage powerline using OFDM when the transmitted power is large enough.

Keywords: *low-voltage powerline communication, modeling of channel, OFDM, time-domain simulation.*

I. INTRODUCTION

With the development of information science, it has become a hot topic to realize high rate digital communication over low-voltage powerline. Up to now, most important applications of powerline communications are load management, remote meter reading, home automation, intelligent buildings, local area networks, and so on [1]. With the deregulation of the telecom market, the power distribution network can also be used as an access network besides already existing ones like the telephone access network or the CATV access network. Digital customer services like electronic banking, e-mail, internet access and digital audio and video broadcast should become feasible in the near future, using the low-voltage power network as a communication medium.

However, the powerline is not at all an ideal communication channel. Large numbers of experimental results show that the low-voltage distribution network abounds with all kinds of noises including background noise, narrow noise and impulse noise, and attenuation of the transmitted signal is also the key impairment [2-4]. Furthermore, due to the fact that the structure of the power distribution network is far from

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matching requirements, reflection exists at some nodes in the network. This results in multipath effects. Therefore it is a real challenge to realize high rate data transmission over the low-voltage distribution network. One of the most important problems to solve is to find out the appropriate modulation technique.

The orthogonal frequency division multiplexing (OFDM) modulation technique can achieve much higher bandwidth efficiency than spread spectrum systems and it allows an extremely flexible allocation of a given channel bandwidth [5]. Because of its information allocation property to different carrier sub bands, OFDM is very robust against narrow band interferences and frequency selective fading. Furthermore, combined with a well designed interleaving and forward error correction coding schemes, OFDM can be robust against impulsive noise. So it is taken for granted that the OFDM can be an idea choice to achieve high rate digital transmission over low-voltage powerline.

Based on experimental results, a model for the low-voltage power distribution network used as a communication channel over the frequency range of 500kHz ~ 3MHz is considered. With this model, analysis and simulation of the high rate digital transmission using OFDM are performed and some instructive results are obtained.

2. MODELING OF LOW-VOLTAGE POWERLINE

When modeling the low-voltage powerline as a high frequency communication, the input impedance, signal attenuation and noise, must be considered. The input impedance will directly affect the transmission efficiency between the signal coupling devices and the communication medium. The coupling loss characteristics can then be determined. For the matter of simplification, the coupling loss can be neglected by assuming the transmitter's output impedance to be low enough.

According to reference [6], the model of a low-voltage powerline communication channel can be represented as a multipath one. Based on experimental results performed on site in Wuhan, China, this multipath model can be simplified as follows [7]:

$$H(f) = \sum_{j=1}^{2} c_j \cdot e^{-j2\pi f \tau_j} \qquad (1)$$

The signal attenuation and the phase shifting characteristics of the channel related to experimental measurements are given in Fig. 1 and Fig.2. In these figures, 'a1' denotes the practical measurements and 'a2' denotes the theoretic results from (1).

The transmission function in frequency-domain expressed by (1) can be easily changed to an impulse response function in time-domain as follows:

$$h(t) = \sum_{j=1}^{2} c_j \cdot \delta(t - \tau_j) \qquad (2)$$

In general, noise in the low-voltage power network can be divided into two classes, background noise and transient noise. Since the background noise usually remains steady over the periods of minutes or even hours, for high-speed communication this kind of noise can be considered as a stationary random process. The transient noise includes periodic impulsive noises that are commonly synchronous with the frequency of the electric power system and aperiodic impulsive noise resulting from single event. The simulation model in this paper contains only the background noise, which is the most important noise source.

The spectral analysis of a typical set of background noise in a practical power network is given in Fig.3. The power spectral density (PSD) is estimated by Welch method [8]. From this figure, it can be seen that in the frequency range of 500kHz ~ 3MHz the background noise can be approximated by band-limited white noise with a constant PSD (about –112dBW/Hz) plus some narrow-band interferences (such as those at the frequency of 0.6 MHz and 1.25 MHz).

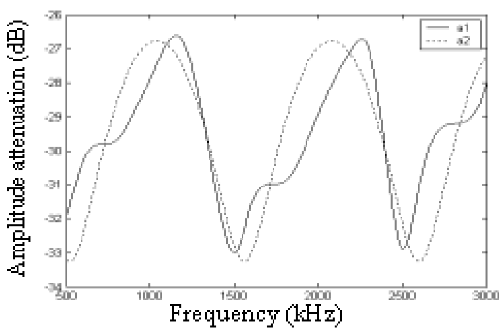

Fig.1 Amplitude attenuation characteristics of measurement and model

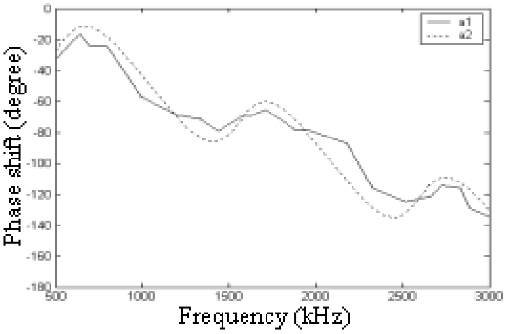

Fig.2 Phase shifting characteristics of measurement and model

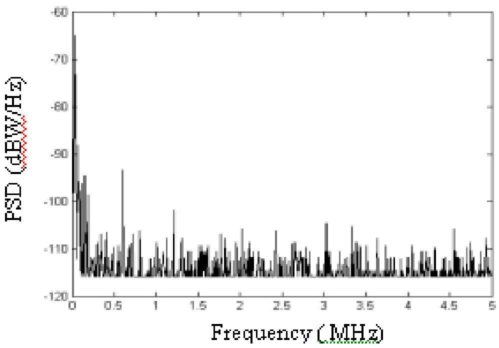

Fig.3 The power spectral density of the background noise

3. IMPLEMENTATION AND PERFORMANCE ANALYSIS OF A FUNDAMENTAL OFDM SYSTEM

The fundamental principle of OFDM has been well explained in many references [9-11]. Since the OFDM system can perform modulation and demodulation respectively with inverse fast Fourier transformation (IFFT) and fast Fourier transformation (FFT), the complexity of implementation of this system can be greatly reduced using DSP technique.

Fig.4 gives the block diagram of the OFDM based communication system. As OFDM signal is directly sent into the powerline in base band, the output of IFFT S(n) must be a real sequence. Assuming the periods of symbols of N subchannels behind serial to parallel converting equal to T, the frequency interval between adjacent subchannels is 1/T. If the truncation effect of the rectangular filter in time-domain is not considered, the highest frequency of S(n) is (N-1)/T. According to the Nyquist' sampling theorem, the required sampling frequency is $f_s \geq 2 \cdot (N-1)/T$. However there are only N samples in one symbol period, this also means, the practical sampling frequency equals to N/T. So frequency aliasing will happen in about N/2 subchannels. Without any further process, the N point IFFT can practically perform the parallel transmission of N/2 subchannels as well.

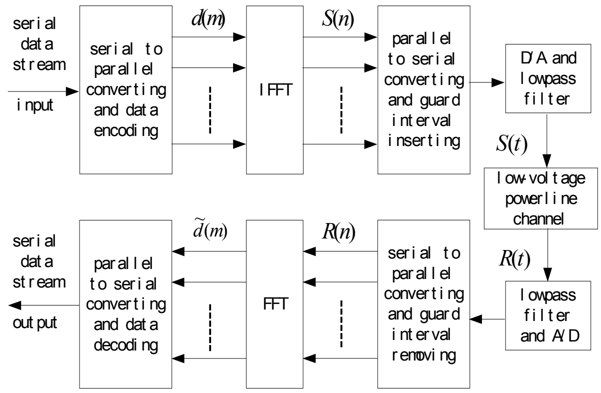

Fig.4 Block diagram of the OFDM based communication system

If useful data is modulated only on N/2 subcarriers and data modulated on the other N/2 subcarriers is obtained from the conjugate complex of the former, S(n) can be a real sequence with a highest frequency of (N/2-1)/T, which meets the Nyquist-criterion [12].

According to the characteristics of powerline channel expressed by (2), the received signal can be represented as:

$$R(t) = c_1 S(t - \tau_1) + c_2 S(t - \tau_2) \quad (3)$$

Let the reference time $t = \tau_1$, then we have:

$$R(t) = c_1 S(t) + c_2 S(t - \tau) \quad (4)$$

where $\tau = \tau_2 - \tau_1 \geq 0$ is the relative delay of two paths. By sampling R(t) over one symbol period T, N samples with a T/N interval can be obtained as follows:

$$R(n) = c_1 S(n) + c_2 S(n - \tau') \quad (5)$$

where $n = 0,1,2,\cdots,N-1$, and $\tau' = \tau/(T/N)$ is a normalized delay represented by the number of samples.

If the length of the cyclic extension (or guard interval) of the time-domain OFDM symbol is greater than the normalized relative delay τ', using the circular shift characteristics of DFT (discrete Fourier transformation), the FFT of (5) can lead to:

$$\tilde{d}(m) = FFT[R(n)] = c_1 FFT[S(n)] + c_2 FFT[S(n)] \cdot e^{-j\frac{2\pi}{N}m\tau'}$$
$$= d(m) \cdot \left(c_1 + c_2 \cdot e^{-j\frac{2\pi}{N}m\tau'} \right) \qquad (6)$$

where $m = 0,1,\cdots,N/2-1$. From (6), it can be seen that when the length of the guard interval inserted between the OFDM symbols is greater than the delay spread of multipath channel, the multipath interference on every subcarriers becomes simple multiplicative signal fading process, which represents the transfer function of the corresponding subchannel. In general, the transmission characteristics of the low-voltage powerline channel change slowly compared with the OFDM symbol period. So these transfer functions of the subchannels can be gained using differential encoding method and otherwise. And then the transmitted signal can be correctly restored after appropriate equalization.

4. TIME-DOMAIN SIMULATION

The multipath delay spread of the powerline network on which we perform measurements is about $1\mu s$. According to reference [4] the delay is ranging between $1.6\mu s$ and $2.5\mu s$. So it is suitable for the guard interval (Δ) to take $5\mu s$. Considering that inserting the guard interval will reduce the effective transmission power, bandwidth efficiency and traffic capacity, it is reasonable to let $\Delta \le T/4$ where T is the useful symbol period. Then we have $T \ge 20\mu s$.

For the same guard interval, Table I provides performance parameters of the OFDM signal corresponding to different values of the number of the point of IFFT (N). From Table I, it can be seen that, in the same frequency band, the useful symbol period and its ratio to the total symbol period rise with N increasing, and then the transmission efficiency of the system is promoted. Therefore, in order to ensure higher data rate and bandwidth efficiency, N should be selected to be large enough. However large N will result in computational complexity of the system. In addition, if N is too large, the interval between adjacent subcarriers will become so small that the system is subject to InterChannel Interference (ICI). Moreover, the OFDM symbol period will become too large. This leads to some intolerable communication delay. So the selection of the number of IFFT point must be done with special care. In this paper, we assume $N = 512$.

Table I
PERFORMANCE PARAMETERS
of the OFDM signal

Frequency band	500kHz~3MHz				
Number of point of IFFT	1024	512	256	128	64
Useful symbol period (us)	170.67	85.33	42.67	21.33	10.67
Interval between subcarriers (kHz)	5.86	11.72	23.44	46.88	93.75
Total symbol period (us)	175.67	90.33	47.67	26.33	15.67
Number of useful subchannels	426	212	106	52	26
Total baud rate (Mbaud/s)	2.43	2.35	2.22	1.97	1.66

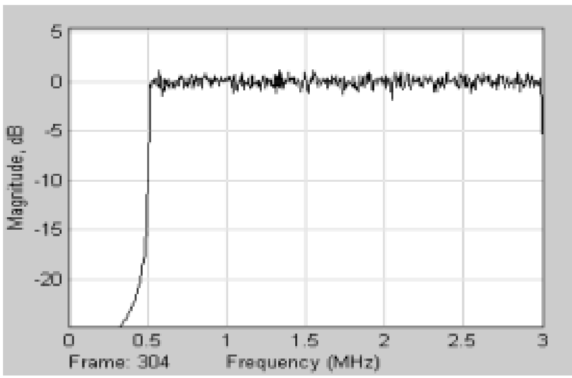

Fig.5 Power spectrum of the transmitted signal

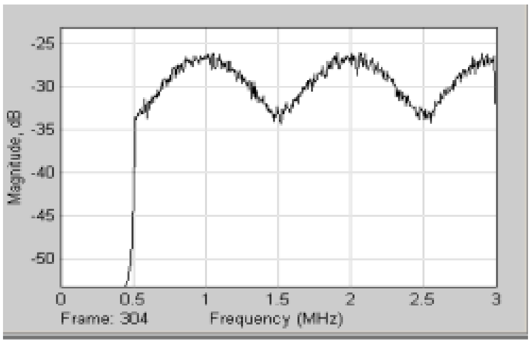

Fig.6 Power spectrum of the received signal

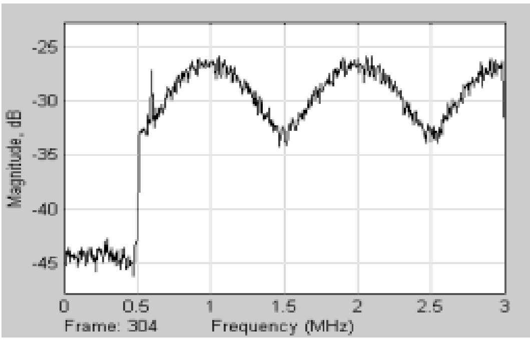

Fig.7 Power spectrum of received signal plus noise

According to experimental results and analysis in section II, the model of the low-voltage powerline communication channel has been implemented using MATLAB SIMULINK environment. Based on this model, time-domain simulation is performed to investigate the transmission performance of the OFDM based communication system. Fig.5, Fig.6 and Fig.7 give power spectrums of the transmitted signal at sending location, the received signal attenuated by the powerline channel and the received signal plus noise at receiving end, respectively.

Fig.5 shows that the power spectrum of the OFDM signal is nearly constant over the whole simulation frequency range (the simulation sampling frequency is 6MHz), except for 0~500KHz, corresponding to closed subchannels. The OFDM signal in time-domain generally behaves like white noise with variance σ^2 (equal to the power spectrum). The power spectrum in Fig.5 is 1W. Considering that subchannels below 500kHz are closed, the average power of the transmitted OFDM signal is $2.5/3 = 0.833W$. Comparing Fig.5 and Fig.6 signal attenuation characteristics of the simulation model can be observed. This attenuation is quite similar to that observed in Fig.1. From Fig.7, it can be seen that the narrow band interference at the frequency 0.6MHz distinctly affects the normal communication on the subchannels about this frequency. In order to reduce BER (bit error ratio) of the transmission system, the relevant subchannels should be shut down.

In the sequel, we assume that in all subchannels the same modulation technique, the quadrature amplitude modulation with M points rectangular constellation (MQAM), is employed. For M=4, 16, 64, 256, the BER simulation results of the OFDM based communication system are given in Fig.8.

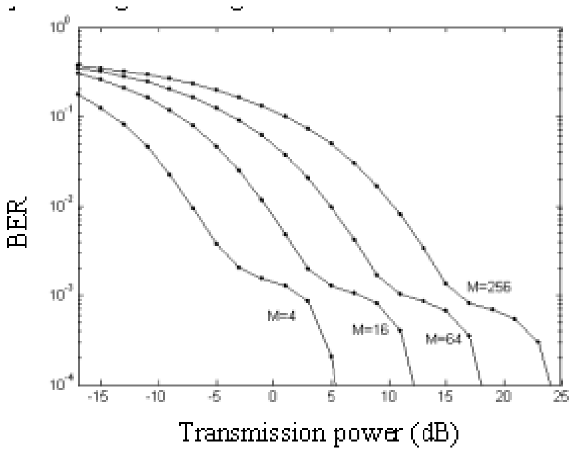

Fig.8 BER of the OFDM system

The estimation of BER is based on 10M bits data, which are produced by Bernoulli random binary generator. From Fig.8, it can be seen that with M increasing the system requires augmenting the transmission power in order to achieve a certain BER. For example, if M=4, to achieve BER of 10^{-4}, the transmission power need to be only about 3.5W. And if M=16, 64 and 256, to achieve the same BER, the transmission power need to be 16W, 64W and 256W respectively. So M should not take too large value when signal power is limited. However, the larger M is, the higher the maximum data transmission rate of the system is. According to the maximum Baud rate of the system shown in Table I (N=512), the maximum bit rate of the system can be obtained as shown in Table II.

Table II
The MAXIMUM Transmission Rate OF THE SYSTEM

M	4	16	64	256
R(Mbit/s)	4.7	9.4	14.1	18.8

From Fig.8 and Table II, it can be seen that, if let BER $\leq 10^{-4}$, the system can achieve about 5Mbit/s and 10Mbit/s data transmission rates when the transmission powers are about 3.5W and 16W respectively. Combined with the other techniques, such as data interleaving and adaptive allocation of subchannels, the fundamental OFDM system can greatly decrease the transmission power to achieve the same BER.

5. CONCLUSION

Based on experimental results, this paper presents a simple two-path time-domain model of the low-voltage powerline communication channel in the frequency range of 500kHz ~ 3MHz. The implement of the OFDM-based high-rate communication system and its performance of restraining multipath interference are analyzed, and the selection of system parameters appropriate for the practical powerline channel is discussed. Finally, by considering MQAM and transmission power applied in the aforementioned model, the time-domain simulation of the system performance is carried out using MATLAB SIMULINK. The results show that it is possible to achieve high rate (10Mbits/s) data transmission over the low-voltage powerline channel using OFDM when the transmitted power is large enough.

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REFERENCES

[1]. F. Petré, M. Engels, B. Gyselinckx and H. D. Man, "DMT-based power line communication for the CENELEC A-band", *in Proc. of 3rd International Symposium on Powerline Communications and its Applications*, Lancaster, U.K., Mar.-Apr., pp. 58-65,1999.

[2]. M. Tanaka, "High frequency noise power spectrum, impedance and transmission loss of power line in Japan on intrabuilding power line communications," *IEEE Transactions on Consumer Electronics*, vol. 34, no. 2, pp. 321-326, 1988

[3]. M. Zimmermann and K. Dostert, "The low voltage power distribution network as last mile access network-signal propagation and noise scenario in the HF-range," *AEŰ Int. J. on Electron. Commun.*, vol. 54, no. 1, pp. 13-22, 2000.

[4]. H. Philipps, "Development of a statistical model for powerline communication channels," *in Proc. of the 4th International Symposium on Power-Line Communications and its Applications*, Limerick, Ireland, 2000

[5]. S. Ramseirer, M. Arzberger, and A. Hauser, "MV and LV powerline communications: new proposed IEC standards," *in Proc. of Transmission and Distribution Conference*, pp. 235-239,1999.

[6]. M. Zimmermann and K. Dostert, "A multipath model for the powerline channel," *IEEE Trans. on Communications*, vol. 50, pp. 553□559, Apr. 2002

[7]. Y. B. Zhang, S. J. Cheng, H. B. He, L. Xiong, and J. NGUIMBIS, "Modeling of low voltage power network used as high frequency communication channel based on the experimental results in China," *in Proc. of* Power Conf. 2002, Kunming, China, Oct. pp.1280-1284,2002.

[8]. P. D. Welch, "The use of fast Fourier transform for the estimation of power spectral: a method based on time averaging over short modified periodgrams," *IEEE Trans. Audio and Electroacoust.*, vol. 15, pp.70-73, 1967

[9]. S. B. Weinstein, and P. M. Ebert, "Data transmission by frequency-division multiplexing using the discrete Fourier transform", *IEEE Trans. Commun. Technology*, vol. 19, no. 5, pp. 628-634, 1971

[10]. L. J. Cimini Jr., "Analysis and simulation of a digital mobile channel using orthogonal frequency division multiplexing," *IEEE Trans. on Commun*., vol. 33, no. 7, pp. 665-675, 1985

[11]. T Schmidl and D. Cox, "Robust frequency and timing synchronization for OFDM*," IEEE Transactions on Communications*, vol. 45, no. 2, pp. 1613-1621, 1997

[12]. W. T. Webb and L. Hanzo, *Modern quadrature amplitude modulation: principles and applications for fixed and wireless channels*. New York: IEEE, 1994.

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