TSINGHUA SCIENCE AND TECHNOLOGY
ISSN 1007-0214 07/18 pp784-789
Volume 13, Number 6, December 2008

Two-Way Digital Video Transmission over Medium-Voltage Power-Lines Using Time-Domain Synchronous Orthogonal Frequency Division Multiplexing Technology

SONG Jian (宋 健)**, WU Qing (吴 青), PAN Changyong (潘长勇), YANG Zhixing (杨知行), LIU Haitao (刘海涛)†, ZHAO Bingzhen (赵丙镇)†, LI Xiao (李 晓)†

Tsinghua National Laboratory of Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China;
† Beijing ECOM Communications Technology Co., Ltd., Beijing 100037, China

Abstract: This paper describes field trials of two-way digital video transmissions over a 700-m long medium-voltage power cable using a frequency division duplex scheme. The purpose is to check the feasibility of using time-domain synchronous orthogonal frequency division multiplexing (TDS-OFDM) technology in powerline communication (PLC). TDS-OFDM is the core technology in digital multimedia broadcasting-terrestrial (DMB-T), developed by Tsinghua University for digital television terrestrial multimedia broadcast applications and successfully adopted in the Chinese Digital Terrestrial Television Broadcasting Standard. PLC systems are widely believed to be bandwidth or data throughput limited. However, the use of known pseudo random sequences as guard intervals for synchronization and channel estimation in TDS-OFDM greatly reduces the system overhead and increases the spectrum efficiency. These experiments show that TDS-OFDM is appropriate not only for broadcasting but also for PLC applications with appropriate modifications.

Key words: time-domain synchronous orthogonal frequency division multiplexing (TDS-OFDM); powerline communications (PLC); digital multimedia broadcasting-terrestrial (DMB-T)

Introduction

Powerline communications (PLC) utilize the existing electrical power supply network to provide various services to customers. Since the communication signal (with working frequencies much higher than 50/60 Hz) can be carried by the power cables, there is no need to build new networks which reduces not only costs but also the time to provide services to customers not covered by existing communication networks but who receive service from the electrical utility company. Another advantage is the widespread coverage since there is no existing network that links more customers in very different areas than the electrical grids. Therefore, powerline communications have drawn great interest recently due to new technical developments in information technology[1-5].

The idea of using the power grid to provide communication services is actually quite old with the first PLC system built in the 1920s, providing several voice channels only for communications within the power utility. PLC systems can generally be divided into two categories in terms of the bandwidth and data throughput as narrow band systems with working frequencies below 150 kHz and the maximum physical layer transmission rate of less than 1 Mbps, and broadband systems with working frequencies normally

Received: 2007-03-19; revised: 2008-05-22
** To whom correspondence should be addressed.
E-mail: jsong@tsinghua.edu.cn; Tel: 86-10-62780681

from 2 to 30 MHz (with some systems higher than 40 MHz) and the maximum physical layer transmission rate above 200 Mbps. Spread spectrum and orthogonal frequency division multiplexing (OFDM) modulation techniques are widely utilized in PLC systems for different applications, with recently developed broadband PLC standards, such as HomePlug AV and Opera, all using the OFDM technology[6,7]. For consumer communications, PLC systems can be used as the last mile solution providing communication services over medium voltage (MV, ~10 kV) cables to provide high speed broadband access to supplement existing DSL, WiFi, and cable systems. PLC systems also offer the capability of home networking of various multimedia services, as well as a viable solution for the smart home concept, such as automatic control of appliances and video surveillance systems. In the electrical industry, PLC systems offer important value-added services, such as automatic meter reading, remote connections and/or disconnections, energy/load management, equipment/device monitoring, and power outage notification for utility companies to enhance power grid security and improve service quality as well as business efficiency.

Even though PLC systems offer numerous benefits, there are several non-technical and technical hurdles that still need to be overcome to enable large-scale deployment. Non-technical issues include policies and standardization. Since PLC systems will inevitably introduce interference to existing services, such as short-wave radios operating within the same 2-30-MHz band, proper regulations are needed that lift stringent requirements on PLC systems so that these systems can co-exist within the same frequency band. There are several industrial PLC standards using modulation technologies such as OFDM, but the functional blocks are quite different. The lack of a universal standard makes customers hesitate to consider PLC products rather than other communication systems that do not have interoperability issues and makes manufacturers hesitate to enter an industry without standards, so PLC products tend to be expensive. The technical issues are also quite challenging. In the physical layer, as power cables were originally designed for power delivery, high frequency communication signals incur large attenuation rates that increase with increasing frequency, which limits transmission lengths, and high intensity noise whose power level decreases with increasing frequency. Also, unlike communication cables which are quite stable and are rarely affected by other systems, PLC systems are quite vulnerable to environmental interference and noises; therefore, the electromagnetic compatibility needs to be addressed. Thus, channel modeling is quite critical and many papers with very good results and insights have been published[8-10]. For higher layers, effective and flexible protocols for simultaneous handling of various services are very important for the successful implementation of the PLC technology since the data throughput for these systems is not very high given the limited bandwidth.

This paper describes two-way digital video transmissions over a medium voltage power cable. The modulation used is time-domain synchronous-OFDM (TDS-OFDM) shown in Fig. 1 rather than the conventional cyclic prefix-OFDM (CP-OFDM).

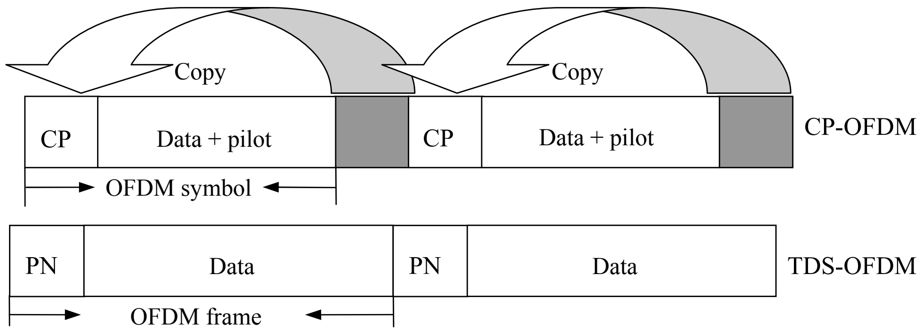


Fig. 1 Differences between the CP-OFDM and TDS-OFDM symbols in the time domain

The TDS-OFDM technology was developed for the digital multimedia broadcasting-terrestrial (DMB-T) system and was adopted into the Chinese Digital Terrestrial Television Standard in 2007. TDS-OFDM uses known pseudo random (PN) sequences as the guard intervals, providing multi-path protection similar to CP-OFDM. The pseudo random sequences can also be used as the training symbols in the signal to facilitate channel estimation as well as synchronization. The paper describes the DMB-T system and the TDS-OFDM coding/modulation schemes and field trial results of two-way digital video transmissions over a medium voltage power cable.

1 DMB-T System

Figure 2 gives a schematic diagram of the major functional blocks in the DMB-T transmitter.

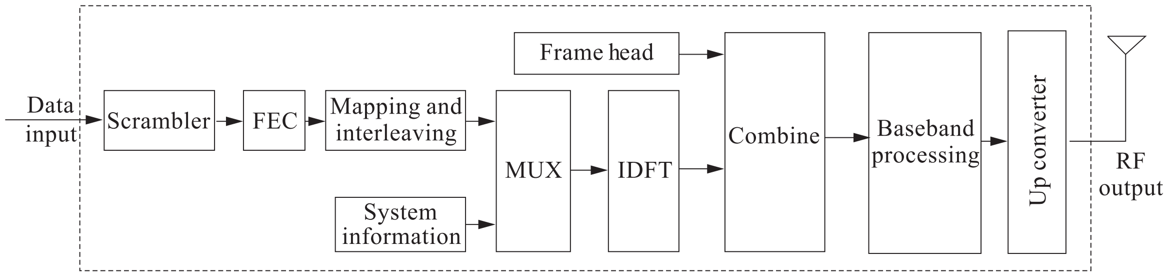


Fig. 2 DMB-T transmission system diagram

(1) Scrambler A binary pseudo random sequence $2^{15}-1$ bits long is used to randomize the input data (MPEG-2 for broadcasting) before the channel coding block to facilitate system synchronization.

(2) Forward error correction (FEC) code The forward error correction code is a concatenation of the outer Reed-Solomon RS (208, 188) and inner recursive systematic convolutional codes with rates of 4/9, 2/3, and 8/9 (all from puncturing the same mother code at a coding rate of 1/2).

(3) Signal constellation and mapping The output binary sequence of the FEC is converted to an *n*QAM (quadrature amplitude modulation with *n* constellation points) symbol stream with the first encoded input bit of each symbol as the least significant bit. DMB-T supports three constellations of 64QAM, 16QAM, and 4QAM with power normalization.

(4) Time interleaving Convolutional interleaver is used across many OFDM signal frames with interleaving branches of B=52 and interleaving depths of M=0, 48, 240, or 720 (corresponding to four modes from 0 to 3). The overall time interleaving/de-interleaving delay is $B\times(B-1)\times M$, which is 0, 34, 170, or 510 OFDM signal frames for the various modes for a maximum delay of ~0.3 s.

(5) Frequency interleaving within 3780 symbols for each OFDM frame body The frequency interleaving in each OFDM frame body uses 36 information symbols and 3744 data symbols.

(6) Hierarchical frame structure The DMB-T system uses the hierarchical frame structure given in Fig. 3 which from top to bottom includes the calendar day frame (starting from 00:00:00 each day Beijing Time), the minute frame lasting exactly one minute, the super frame with a fixed duration of 125 ms, and the signal frame. The fundamental block of this frame structure is the signal frame which will be described in the following:

Each signal frame consists of a frame head and a frame body. The baseband symbol rates for both are the same at 7.56 Mbps with each frame body of the signal frame lasting exactly 500 μs (3780×1/7.56 μs). The frame head uses a pseudo random sequence so this baseline technology is called the TDS-OFDM. The frame heads can be 420 or 945 symbols long (relative guard interval lengths of 1/9 or 1/4 with 225 or 200 signal frames per super frame) for different applications. The frame head always uses bi-phase shift keying (BPSK) modulation with an average power twice that of the frame body. For example, a frame head with 420 symbols includes a pre-amble of 82 symbols, a pseudo random sequence of 255 symbols (m-sequence), and a post-amble of 83 symbols. Both pre- and post-ambles are cyclic extensions of the 255 pseudo random symbols. The frame head can be rotated, i.e., each signal frame within the same super frame has a unique address and can be uniquely identified. The pseudo random sequences were carefully picked using computer simulations to minimize the cross-correlation between two adjacent sequences. As an option, the frame head can be fixed if frame addressing is not needed.

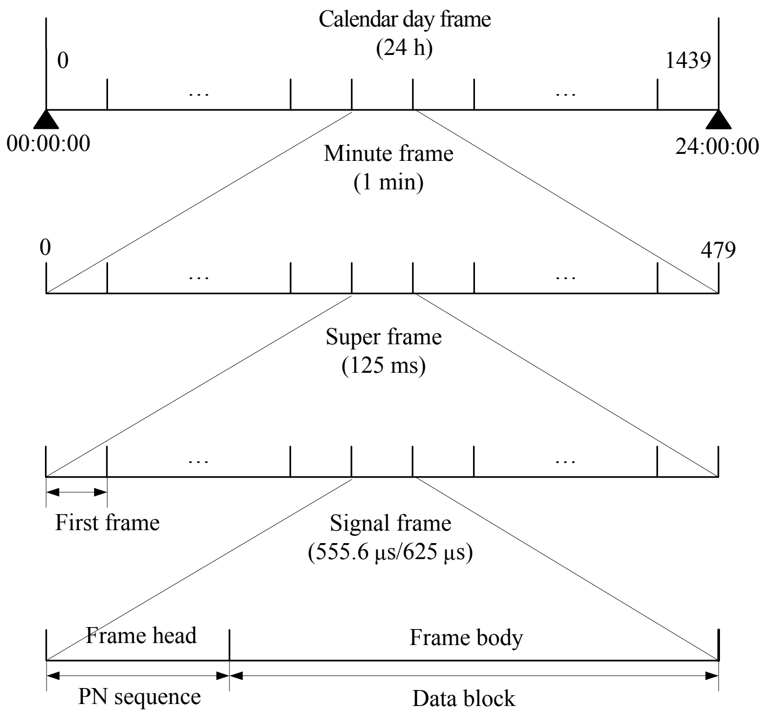


Fig. 3 DMB-T frame structure

The DMB-T payload within an 8-MHz bandwidth is summarized in Table 1, where QPSK is the quadrature phase shift keying.

Table 1 DMB-T payload in Mbps for the various working modes

Guard interval	Inner code rate	Constellation scheme		
		QPSK	16QAM	64QAM
125 μs (1/4)	4/9	4.813	9.626	14.438
	2/3	7.219	14.438	21.658
	8/9	9.626	21.658	28.877
55.6 μs (1/9)	4/9	5.414	10.829	16.243
	2/3	8.122	16.243	21.658
	8/9	10.829	21.658	32.486

The frame body has a 6-bit physical layer system information code (spectrum spread with BPSK mapping) to inform the receiver of the constellation mapping, code rate, interleaving mode, carrier mode information, and frame head information.

(7) Inverse discrete Fourier transform (IDFT) having 3780 points The frame body is sent as an inverse discrete Fourier transform with 3780 points with a sub-carrier spacing of 2 kHz, so the frame body is 500 μs long.

(8) Post-baseband processing A square root raised cosine filter with a roll-off factor of 0.05 is used to shape the baseband signal.

2 Two-Way Digital Video Transmission

Two DMB-T transceivers were built with transmitter central frequencies of 7.56 MHz and 23.56 MHz with an 8-MHz bandwidth. Each transceiver has an output port with a power amplifier with an average output of about +10 dBm, used in the field trial, and an output port without a power amplifier with an average output power of ~10 dBm. The transmit power intensity of the transceiver with the power amplifier is around −55 dBm/Hz for the 8-MHz bandwidth, well below the −50 dBm/Hz specification in the HomePlug 1.0 standard, so this system will not cause any noticeable interference with existing systems. The transmitter output could be even higher as long as the power amplifier is linear. Test results are given in Table 2 for the carrier to noise ratio (C/N) and the receiver sensitivities for the

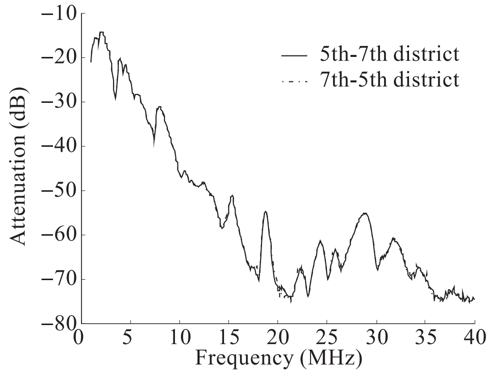
Table 2 Measured C/N and receiver sensitivities of transceivers on an AWGN channel

	C/N (dB)	Receiving sensitivity (dBm)
Transceiver 1	2.0	−96.0
Transceiver 2	2.1	−96.3

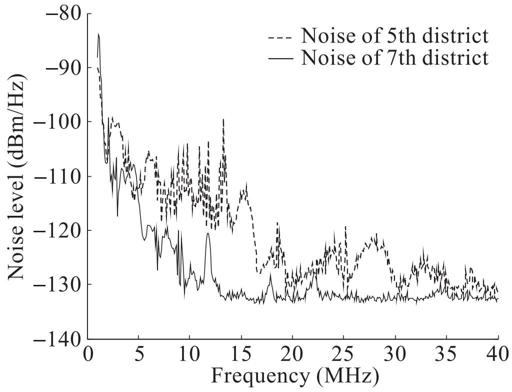
QPSK and 4/9 rate mode on an additive white Gaussion noise (AWGN) channel.

Previous measurements[11] on various lengths of medium voltage power cables showed that increasing the power cable length by 150% (from 400 m to 1 km) increased the channel attenuation by 30 dB, which significantly limits the transmission length. The current tests used a 700-m long medium voltage power cable for the two-way digital video transmissions. The channel attenuation and noise behavior in Fig. 4 show that the transmission attenuation is quite symmetric while the noise characteristics at each end are quite different. The experimental setup shown in Fig. 5 has one transceiver (TX1) using a DVD player as the video source which sends the signal at the central frequency of 7.56 MHz to RX2 while the other transceiver (TX2) sends a signal from a digital video source at the central frequency of 23.56 MHz to RX1. For illustration purposes, monitors were used instead of an MPEG-2 bit-error-rate tester to check the transmission performance.

The two transceivers successfully simultaneously transmitted two-way digital video without interference. With the 8 MHz bandpass filter at each receiver, the two-way transmission was successful with the 1/9 guard interval, 4/9 code rate, 48 symbol interleaving mode, and QAM modulation. The transmission was also successful with the 64QAM modulation and code rates from 4/9 to 2/3 with payload data rates higher than 21.6 Mbps. Tests with different interleaving modes also showed no significant difference. Therefore, the long-time interleaving, which is important for digital video broadcasting, may be omitted to reduce both the required memory and the processing delay. During the entire 2-hour test, the system worked very well with no stalled pictures.



(a)



(b)

Fig. 4 Transmission characteristics of (a) attenuation and (b) noise at each end of the transmission on a 700-m long medium voltage power cable

These results demonstrate the feasibility of using TDS-OFDM modulation in a PLC system. All the system parameters used in these tests were optimized for

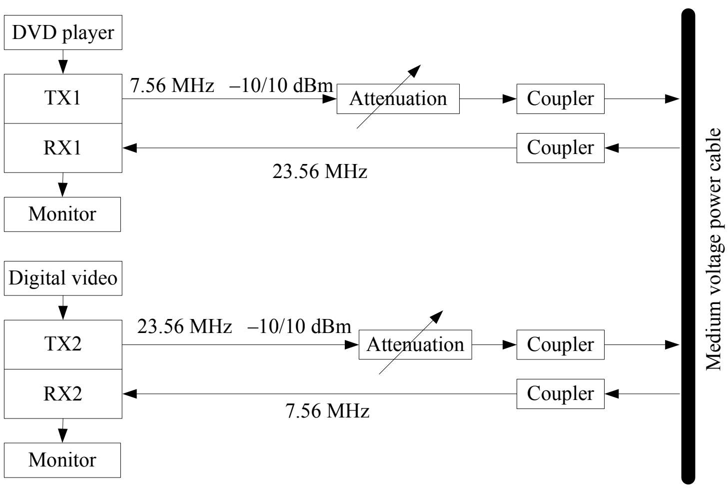


Fig. 5 Experimental setup for two-way digital video transmission over a medium voltage power cable

broadcasting applications with a channel bandwidth of 8 MHz. Future work on the physical layer design must make this technology more implementation friendly and more efficient by (1) modifying the signal frame structure for the powerline transmission environment, (2) adding more constellation choices to boost the number of information bits carried by each subcarrier over good channels, (3) reducing the number of subcarriers to reduce the computational effort for the discrete Fourier transformation/inverse discrete Fourier transformation (DFT/IDFT), (4) adopting advanced coding schemes to further improve the bit error correction capability, (5) introducing a notch filter to remove the negative impact of narrow-band noise for relatively high power levels, (6) making each subcarrier programmable (i.e., subcarrier can be turned off) to meet electromagnetic compatibility (EMC) requirements, and (7) implementing a power allocation algorithm to either maximize the throughput for the same power level or reduce the power consumption (hence, the radiation) at a fixed data rate throughput. Since the technologies for these issues are quite mature, these modifications are definitely attainable.

Also, higher layer protocols are needed to make practical communication possible in PLC networks. This is beyond the scope of this paper which only sought to demonstrate the feasibility of using TDS-OFDM modulation in PLC systems.

3 Conclusions

The DMB-T system for broadcasting combined with TDS-OFDM modulation performed successfully in the two-way digital video transmissions over a 700-m long medium voltage power cable. Results show that the data throughput can exceed 21.6 Mbps for the given power margin. Higher constellation mapping can carry more information bits in each subcarrier provided the channel conditions are favorable. Time interleaving did not provide significant improvement in the transmission tests, contrary to what has been demonstrated in the broadcasting area. With the same guard interval, FEC coding rate, and constellation mapping, TDS-OFDM offers higher spectrum efficiency since no pilots or training symbols are needed for synchronization and channel estimation. Therefore, TDS-OFDM is an attractive modulation scheme for PLC systems with limited bandwidth. Moreover, with the pseudo random sequence used in each OFDM symbol, the system can perform fast channel acquisition to track any changes within a short period. The current work provides a proof-of-concept and more work is needed to fully implement this technology into PLC systems.

References

[1] Galli S, Scaglione A, Dostert K. Broadband is power: Internet access through the power line network. *IEEE Communications Magazine*, 2003, **41**(5): 82-83.

[2] Pavlidou N, Han Vinck A J, Yazdani J, Honary B. Power line communications: State of the art and future trends. *IEEE Communications Magazine*, 2003, **41**(4): 34-40.

[3] Gotz M, Rapp M, Dostert K. Power line channel characteristics and their effect on communication system design. *IEEE Communications Magazine*, 2004, **42**(4): 78-86.

[4] Hrasnica H, Haidine A, Lehnert R. Broadband Poweline Communications Networks — Network Design. Chichester: John Wiley & Sons Ltd, 2004.

[5] Ma Y H, So P L, Gunawan E. Performance analysis of OFDM systems for broadband power line communications under impulsive noise and multipath effects. *IEEE Transactions on Power Delivery*, 2005, **20**(2): 674-682.

[6] HomePlug AV Specification, Version 1.0.00, Dec. 16, 2005.

[7] Opera Specification — Part 1: Technology, Version 1.0, Jan. 31, 2006.

[8] Barmada S, Musolino A, Raugi M. Innovative model for time-varying power line communication channel response evaluation. *IEEE J. SAC*, 2006, **24**(7): 1317-1326.

[9] Sartenaer T, Delogne P. Deterministic modeling of the (shielded) outdoor power line channel based on the multiconductor transmission line equations. *IEEE J. SAC*, 2006, **24**(7): 1277-1291.

[10] Zimmerman M, Dostert K. A multipath model for the powerline channel. *IEEE Transactions on Communications*, 2002, **50**(4): 553-559.

[11] Liu Haitao, Song Jian, Zhao Bingzhen, Li Xiao. Channel study for medium-voltage power network. In: IEEE International Symposium on Power Line Communications and Its Application. Florida, USA, 2006: 245-250.