Design and implementation of channel estimation for low-voltage power line communication systems based on OFDM*

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Abstract: An optimized channel estimation algorithm based on a time-spread structure in OFDM low-voltage power line communication (PLC) systems is proposed to achieve a lower bit error rate (BER). This paper optimizes the best maximum multi-path delay of the linear minimum mean square error (LMMSE) algorithm in time-domain spread OFDM systems. Simulation results indicate that the BER of the improved method is lower than that of conventional LMMSE algorithm, especially when the signal-to-noise ratio (SNR) is lower than 0 dB. Both the LMMSE algorithm and the proposed algorithm are implemented and fabricated in CSMC 0.18 μm technology. This paper analyzes and compares the hardware complexity and performance of the two algorithms. Measurements indicate that the proposed channel estimator has better performance than the conventional estimator.

Key words: OFDM; PLC; channel estimation; time-domain spread; VLSI

DOI: 10.1088/1674-4926/33/10/105012 **EEACC:** 6150; 2570

1. Introduction

The low-voltage power line communication (PLC) refers to the data transmission communication utilizing low-voltage power lines[1]. Owing to adopting multi-carrier modulation, orthogonal frequency division multiplexing (OFDM) technology[2] can fight against frequency selective fading and inter-carrier interference effectively. Therefore, low-voltage PLC systems based on OFDM technology have been a research focus in the power line carrier communication field. The physical environment of a low-voltage power line channel is very poor; it is full of noise, interference, and rapid load impedance change. The most severe challenge in power line channel is that the signal-to-noise ratio (SNR) is very low. Due to the effects of these non-ideal factors, it is inevitable that the OFDM signals are distorted through the low-voltage power line channel, so this problem needs to be solved by an effective channel estimation algorithm.

Recently, there have been many channel estimation algorithms for PLC[3, 4]. In the low-voltage PLC systems, the channel estimation algorithm based on the criteria of least square (LS) is superior to adaptive algorithms, such as the least mean square (LMS) and the recursive least square (RLS), but the simulation channel is only fit for power line channels with a fixed change cycle; besides, the performance of LS is poor under low SNR conditions[3]. The non-linear decision feedback channel estimation algorithm based on the self-organizing network (SOM) is proposed[4]. It can achieve a good effect under an indoor PLC channel, but the rate of convergence is slow and causes the error propagation easily.

In this paper, OFDM low-voltage PLC systems adopt the time-domain spread structure, which can improve the reliability of data. Based on this OFDM time-domain spread structure, this paper gains the relationship between the performance of the LMMSE algorithm and the number of time-domain spread, optimizes multi-path delay in linear minimum mean square error (LMMSE) algorithm, and proposes an optimal channel estimation to reduce the BER. The simulation results show that the improved method is better than the LMMSE algorithm in the case of low SNR. The proposed architecture of channel estimation is implemented in CSMC 0.18 μm CMOS technology. The comparison of performance and measurement indicates the advantage of the proposed algorithm.

2. System model

An OFDM PLC system with sufficient length of cyclic prefix (CP) is considered. The proposed low-voltage OFDM PLC system model is shown in Fig. 1, in which the channel is a 220 V low-voltage power line.

In the transmitter chain, after serial data is transformed to parallel data, comb-type pilots are inserted according to the protocol. The symbols are OFDM-modulated by inverse fast Fourier transforms (IFFT). Every OFDM symbol is expanded M times in the time domain to format a group, which is called time-domain spread, and then a cyclic prefix is added before every OFDM symbol. In the receiver, after synchronization, CP removal and OFDM-demodulated with FFT are accomplished. The pilots are extracted and the average of pilots in one group of time-domain spread symbols is gained, and sent to the channel estimation module.

This paper adopts the time-domain spread structure of OFDM symbols as shown in Fig. 2. One OFDM symbol expands M times in time domain, each OFDM symbol includes 97 subcarriers of conjugate symmetry in positive and negative axis, respectively, in which there are 72 valid data subcarriers, and the number of pilot subcarriers N_p is 25. The pilot subcarriers are at a fixed location, while the valid data subcarriers are

* Project supported by the Major National Science & Technology Program of China (No. 2009ZX01034) and the National Natural Science Foundation of China (No. 61102072).

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Received 10 April 2012, revised manuscript received 2 May 2012

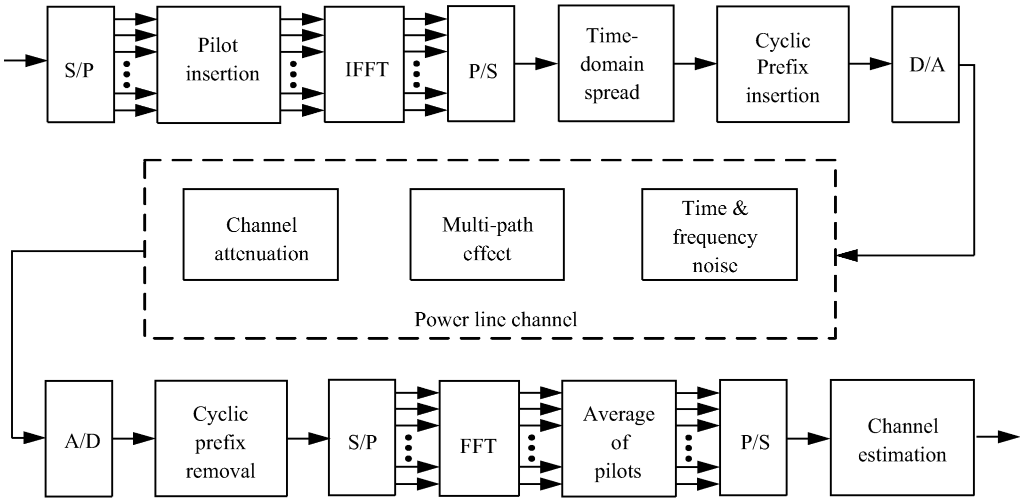

Fig. 1. OFDM PLC model.

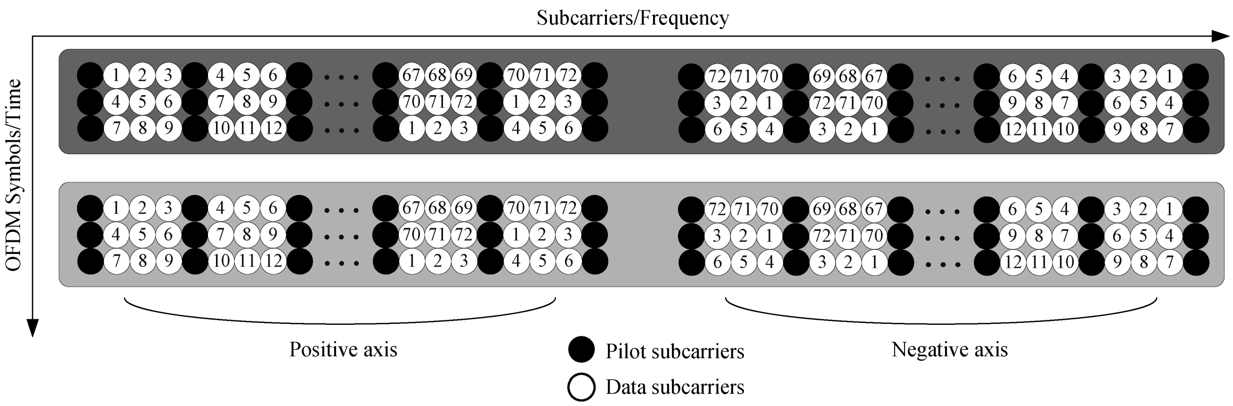

Fig. 2. Time-domain spread structure.

shifted to different positions in different time-domain spread symbols. For channel estimation in the receiver, the pilots in a group of time-domain spread symbols are extracted, and the channel response of a pilot is the average of pilots in the same position of different OFDM symbols:

$$\hat{H}_{\mathrm{p}}(k) = \sum_{k=0}^{M} H_{\mathrm{LS}}(k)/M, \tag{1}$$

where k is the serial number in one group of spread OFDM symbols, M is the number of time-domain spread, $H_{\mathrm{LS}}(k)$ is the channel response of the pilot in the kth symbol in one time-domain spread group. The receiver uses $\hat{H}_{\mathrm{p}}(k)$ as the input pilot information of channel estimation. As the time-domain spread is adopted in low voltage PLC systems, the impact of noise and interference can be reduced, and the reliability of pilots can be improved effectively.

3. Channel estimation algorithms

3.1. LMMSE channel estimation algorithm

Channel estimation algorithm based on minimum mean square error (MMSE) criterion has a good reject effect to additive white Gaussian noise[5, 6], but the high complexity of the MMSE algorithm means that it is too difficult to implement, so the simplified LMMSE algorithm[7–9] is widely used in OFDM systems. The core idea of the LMMSE algorithm is using the singular value decomposition (SVD) to derive an optimal low-level estimator and achieving the approximation performance of MMSE with low complexity of the algorithm. The channel impulse response of the LMMSE estimation algorithm can be expressed as:

$$H_{\mathrm{LMMSE}} = R_{\mathrm{HH}}(R_{\mathrm{HH}} + \sigma_{\mathrm{n}}^2 (XX^H)^{-1})^{-1} H_{\mathrm{LS}}, \tag{2}$$

$$R_{\mathrm{HH}} = E\left\{HH^H\right\}, \tag{3}$$

where H_{LS} is the LS estimation of $\hat{H}_{\mathrm{p}}$, R_{HH} is the autocorrelation matrix of channel impulse response, σ_{n}^2 is the variance of the additive white Gaussian noise. To reduce the complexity of the LMMSE algorithm, $(XX^H)^{-1}$ is replaced with its expectation:

$$E\left\{(XX^H)^{-1}\right\} = E\left\{\left|\frac{1}{x_k}\right|^2\right\} I, \tag{4}$$

where I is the identity matrix. The definition of SNR is:

$$\mathrm{SNR} = E\left\{|x_k|^2\right\}\Big/\sigma_{\mathrm{n}}^2, \tag{5}$$

$$\beta = E\{|x_k|^2\} \Big/ E\{|1/x_k|^2\}. \tag{6}$$

Then Equation (2) can be simplified as

$$\hat{H} = R_{\text{HH}} \left(R_{\text{HH}} + \frac{\beta}{\text{SNR}} I \right)^{-1} H_{\text{LS}}. \tag{7}$$

3.2. Improved channel estimation algorithm

In Eq. (7), the expression of R_{HH} is comprised of the average SNR, the channel statistical properties of the maximum multipath delay τ_{rms}, and filter step tap. In order to reduce the complexity of implementation, the average SNR and tap are generally fixed to constant values. When τ_{rms} equals the theoretical maximum multipath delay, the performance of the algorithm is at its best. When τ_{rms} is bigger or smaller than the theoretical value, the performance drops significantly. In the case of high SNR, the trend of the BER following with τ_{rms} is very clear. But when the SNR is very low, the improvement of the BER performance is limited, even when τ_{rms} equals the theoretical maximum multipath delay. Under low SNR conditions, τ_{rms} makes few contributions to the reduction of the BER. Under extremely poor channel conditions, the performance of the LMMSE algorithm cannot meet the requirements of PLC. In this paper, the channel estimation algorithm is improved based on the characteristics of time-domain expansion structure and optimization of τ_{rms}.

In OFDM PLC systems, owing to the time-domain spread, the relationship between τ_{rms} and BER at the optimal performance is different from normal OFDM systems. In the M time's time-domain spread OFDM systems, the same valid data is transmitted $M + 1$ times in different sub-carriers with different OFDM symbols. Through research and analysis, this paper draws the conclusion that it is able to enhance the impact of channel estimation effectively after using more pilots in one OFDM symbol in channel estimation. The number of time-domain spread decides the value of τ_{rms} as achieving the best BER performance. With the increment of the number of time-domain spread, the value of τ_{rms} achieving the best performance is far from the theoretical value.

This paper proposes that, as the number of time-domain spread increases to a certain value, the BER achieves the lowest point when τ_{rms} equals zero, and the BER increases with τ_{rms} almost linearly. When τ_{rms} equals zero, Equation (7) is simplified to the average of all pilots' channel responses in one symbol. It means that in a time-domain spread structure, the average in time and frequency can reject noise in different subcarriers and improve the reliability of pilots. The channel estimation of the proposed algorithm is:

$$\hat{H}_{\text{pro}} = \frac{\sum\limits_{l=0}^{N_{\text{p}}-1} \hat{H}_{\text{p}}(l)}{N_{\text{p}}}. \tag{8}$$

4. Simulation results

The effect of the number of time-domain spread on τ_{rms} and BER is simulated by parameters in Table 1. Using the additive white Gaussian noise and multipath channel, the normalized maximum multipath delay is 11.

Table 1. Simulation conditions for evaluation of performance.

Parameter	Value
System bandwidth	48 kHz
Initial carrier frequency	41.748046875 kHz
End carrier frequency	89.111328125 kHz
Sample signal duration	4 μs
Subcarrier space	0.488281250 kHz
Cyclic prefix	48
FFT length	512
Modulation mode	BPSK/QPSK/16QAM

Figure 3 illustrates the influence of the maximum multipath delay and number of time-domain spread on BER in the LMMSE algorithm. Figure 3(a) shows that in the condition of –4 dB SNR with no spread in the time domain, when τ_{rms} equals the theoretical maximum multi-path delay, the performance of LMMSE is at its best. As τ_{rms} is far from the theoretical value, the performance of LMMSE algorithm becomes worse. The BER curve complies with the law of τ_{rms} in LMMSE, but even τ_{rms} equals the theoretical value of optimization, BER (0.476) is too large to satisfy the PLC systems.

In Fig. 3(b), the SNR is also -4 dB, and the number of time-domain spread is 2. It can be seen from the curves, due to the spread of the time-domain, the BER curve moves down compared to Fig. 2(a). The lowest BER is 0.02, and τ_{rms} is smaller as achieving the best BER performance. In Fig. 3(c), this trend of BER is more obvious. As the number of time-domain spread increases to 5, the BER curve of the LMMSE algorithm clearly changes with the increment of τ_{rms}. When τ_{rms} equals zero, BER is the lowest and the performance of LMMSE is the best.

It can be seen from the above simulation that, with the increment in the number of time-domain spread, the reliability of pilots increases with more pilots in the same location from different OFDM symbols participating in channel estimation. In the time-domain spread structure, the relationship between τ_{rms} and BER does not follow the rule of the conventional LMMSE algorithm. As the number of time-domain spread is enough, the BER curves of the LMMSE algorithm increases with τ_{rms}.

Figure 4 is the BER comparison between the proposed algorithm which optimizes τ_{rms} and the conventional LMMSE algorithm in BPSK, QPSK, and 16QAM modulation, respectively. In the simulation, the number of time-domain spread is 5 in both of the algorithms, but τ_{rms} always equates to 0 in the proposed method and τ_{rms} equates to the theoretical multi-path delay time in LMMSE. In a variety of modulation modes, the proposed method is better than the LMMSE algorithm. Figure 4(a) is the BER comparison under the AWGN channel. The BER of proposed method is much smaller than the original algorithm when the SNR is smaller than 0 dB. Figure 4(b) is the performance comparison of two algorithms in a multipath channel. The BER performance of the proposed optimization method is better than the LMMSE algorithm.

Simulation results show that under very low SNR conditions, the proposed channel estimation algorithm can reduce the BER and improve the performance in OFDM low-voltage PLC systems with time-domain spread structure.

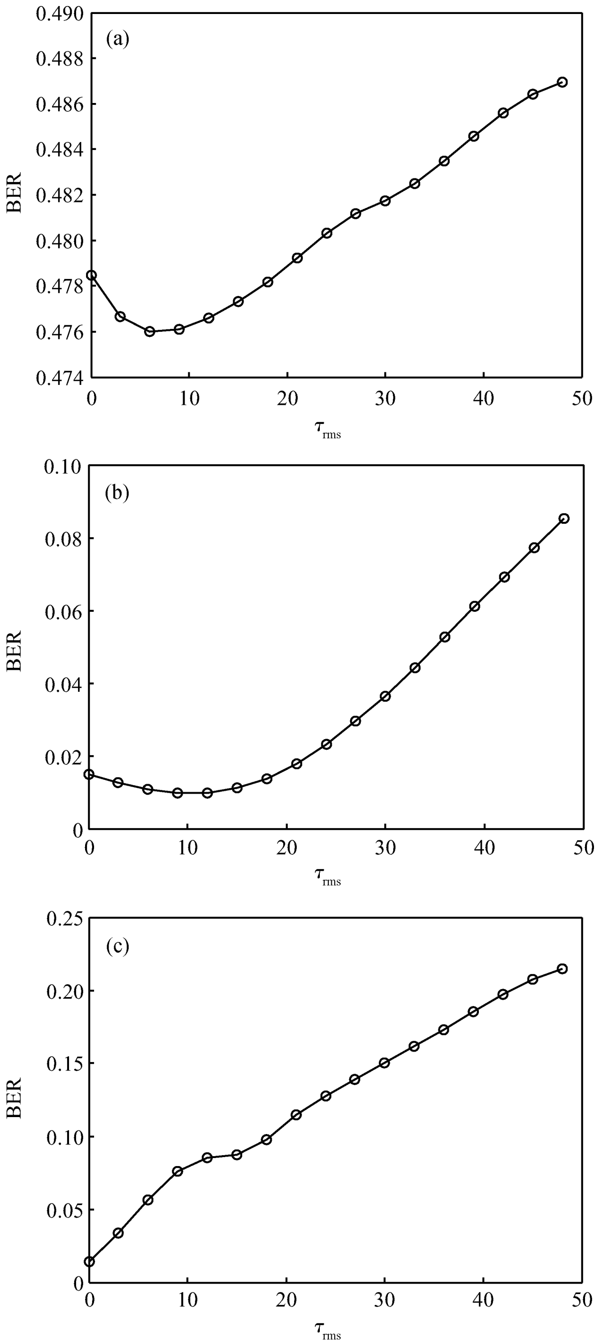

Fig. 3. BER versus SNR for τ_{rms} and the number of time-domain spread in the LMMSE algorithm. (a) SNR = −4 dB, without time-domain spread. (b) SNR = −4 dB, the number of time-domain spread is 2. (c) SNR = −4 dB, the number of time-domain spread is 5.

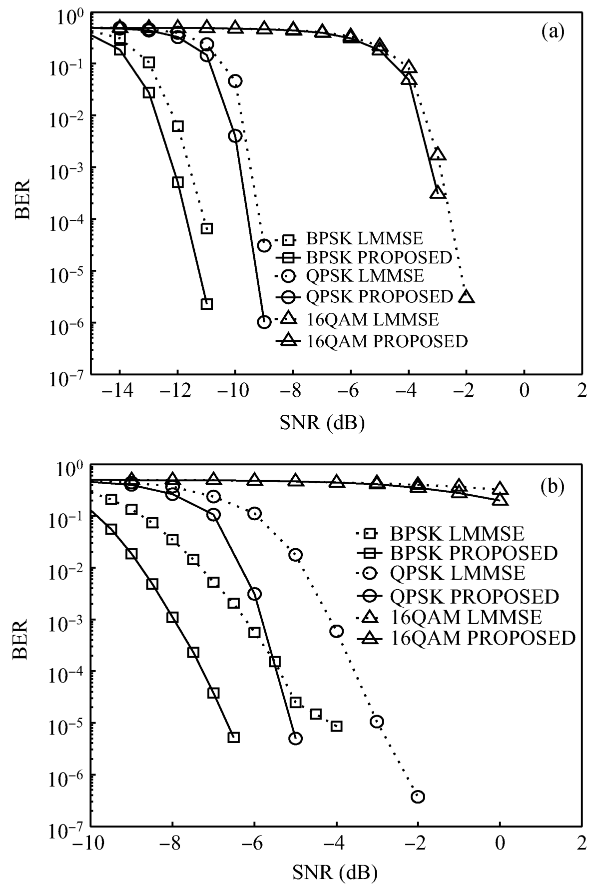

Fig. 4. BER versus SNR of the optimized method and LMMSE channel estimation. (a) AWGN channel. (b) AWGN and multi-path channel.

Table 2. Performance comparisons of the two channel estimation architectures.

Parameter	LMMSE algorithm	Proposed algorithm
Algorithm complexity	$O(n^2)$	$O(1)$
Power consumption (mW)	0.275	0.178
ROM	8192 × 26	None
Clock speed (MHz)	10	10
Technology	0.18 μm CSMC	0.18 μm CSMC

5. Implementation results

For the silicon implementation of the LMMSE channel estimation algorithm, the area requirement is dominated by multiplications and the storage of pre-computed coefficients of the auto-correlation matrix. 7 × 7 complex multiplications are required in one computation of channel estimation. In the PLC system used in this paper, the pilot interval mode is three and τ_{rms} is compartmentalized into 8 ranges, so the implementation of LMMSE requires storage of 6219 × 26 bits.

The proposed algorithm can be realized without matrix multiplications and without the need for any pre-computed coefficients. In the implementation of the proposed algorithm, the computation of Eq. (8) only requires an addition of N_p and a data shift instead of division.

The comparisons of algorithm complexity and hardware performance are summarized in Table 2. The algorithm complexity of LMMSE is $O(n^2)$, which includes matrix multiplication, corresponding to $O(1)$ of the proposed architecture. LMMSE architecture needs an additional ROM to store the coefficients of the auto-correlation matrix. The power consumption of the proposed channel estimation is lower than LMMSE.

Both the LMMSE algorithm and the proposed algorithm have been verified in FPGA prototype design and the ASIC has been manufactured in CSMC 0.18 μm technology. The chip micrograph is provided in Fig. 5.

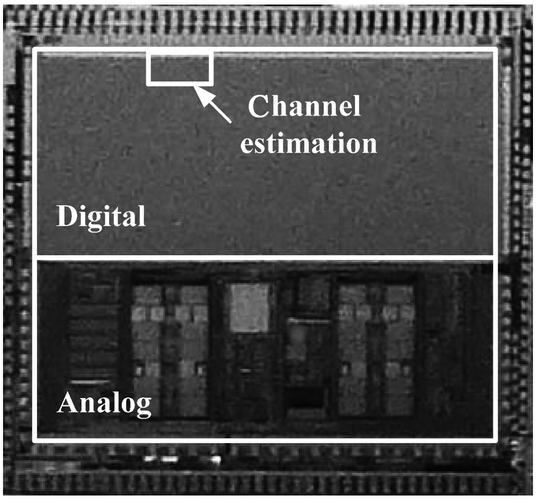

Fig. 5. Photo of the chip die.

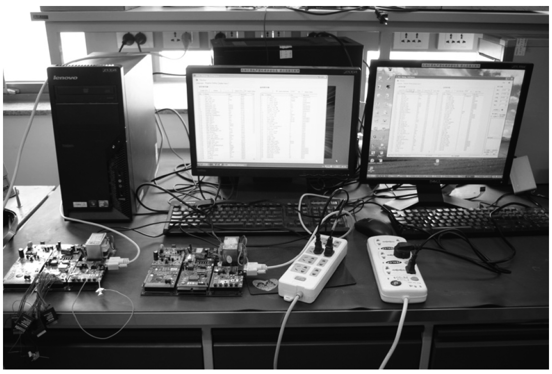

Fig. 6. Photo of PLC experimental systems.

The measurement setup is shown in Fig. 6. To verify the performance of the two channel estimation, three electrical outlets, called A, B, and C, are selected randomly in one office. One thousand OFDM packets are transmitted through a power line, and the packet error number statistic is memorized. As shown in Fig. 7, the packet error number of the proposed channel estimation is much less than that of the LMMSE in both BPSK and 16QAM modulation.

6. Conclusion

Under low SNR conditions, the channel estimation performance of the LMMSE algorithm cannot meet the requirements of the low-voltage PLC. An optimal channel estimation algorithm with the advantages of a time-domain spread structure is proposed. This paper achieves the relationship between the optimal value of the maximum multi-path delay and the BER, and enhances the channel estimation performance. Simulation results show that the improved method in multipath channels can reduce BER effectively and has practical significance in OFDM low-voltage PLC systems. Comparison of measurement results indicates that the proposed channel estimator performs better than the conventional architecture. The ASIC

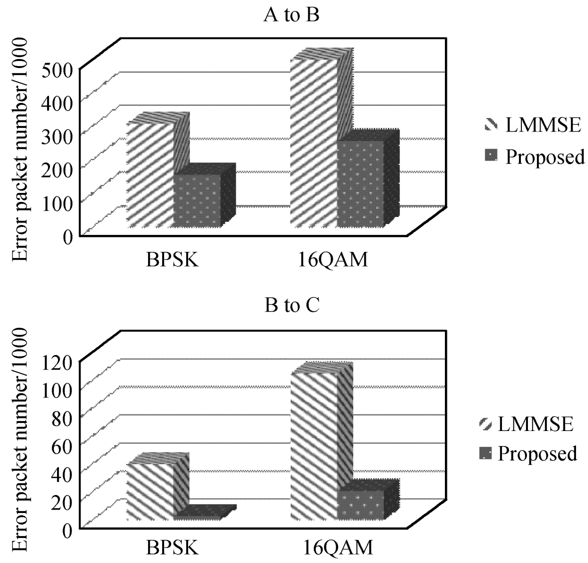

Fig. 7. Packet error number comparisons of the LMMSE algorithm and the proposed algorithm.

implementation demonstrates that the proposed channel estimator reduces the complexity of the algorithm and decreases power consumption.

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