4×25-Gb/s Duo-Binary System over 20-km SSMF Transmission with LMS Algorithm

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Abstract. We propose a 4×25-Gb/s intensity-modulated direct detection (IM/DD) duo-binary system with 50-GHz channel spacing. Both of the modulator and photodetector (PD) have 10-GHz 3-dB electrical bandwidth. At receiver, least mean square (LMS) algorithm is used to compensate the signal distortion after transmission. After 20-km standard single mode fiber (SSMF) transmission, LMS algorithm improves about 2-dB receive sensitivity at forward error correction (FEC) limit (BER = 10^{-3}) in duo-binary system. With LMS algorithm, duo-binary system has about 5-dB receive sensitivity improvement at FEC limit compared to on-off keying (OOK) system over 20-km SSMF transmission. This paper proposes a feasible scheme for future high-speed passive optical network (PON).

Keywords: Duo-binary system · Intensity-modulated direct detection (IM/DD) · Least mean square (LMS) algorithm · Passive optical network (PON)

1 Introduction

100G passive optical network (PON) has been investigated to meet the demand of high-speed and low cost access network [1,2]. With the increase of data rate, the electrical bandwidth of devices and chromatic dispersion become limitation factors of transmission system. Duo-binary modulation technique was proposed as a high-speed transmission scheme in band-limiting system [3]. It attracts lots of attention due to its resistance to intersymbol interference caused by chromatic dispersion [4]. Orthogonal frequency-division multiplexing (OFDM) also has been applied in high-speed access network, its superiority in high spectral efficiency can reduce the required bandwidth, and it also has robustness against chromatic dispersion [5]. However, as a multi-carrier modulation technique, OFDM has high computational complexity and high peak-to-average power ratio (PAPR) [6], which make duo-binary system more likely to be chosen. Intensity-modulated direct detection (IM/DD) optical transmission system has been used in short-haul optical transmission system due to its simple structure

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and low cost [7]. So the high-speed and low cost duo-binary IM/DD system can be a feasible scheme for PON.

Varies duo-binary signal generating methods such as delay-and-add filter or low pass filter have been put forward and varies improved duo-binary schemes to increase system performance or decrease complexity and cost have been developed [8–10]. Differential precoding and electrical filter are used to generate three-level duo-binary signal in general. Precoding at transmitter makes it easier to decode at receiver because without precoding a more complex decoding process is required, which is likely to cause error propagation [8]. The precoded binary signal can convert to three-level duo-binary signal by delay-and-add method [8], this delay-and-add method can be approximated by using a low pass filter with about a quarter of data rate 3-dB bandwidth in electrical domain [9]. The methods to modulate the three-level electrical duo-binary to optical carrier are commonly classified into two categories. The three-level electrical signal can be directly modulated to three-level optical signal [8,10]. Another method is using Mach-Zehnder modulator (MZM) to modulate both amplitude and phase, so three-level electrical signal is modulated to two-level optical signal [9].

As we known, it is impossible to ignore the signal distortion after transmission, especially when the data capacity is increased to meet the transmission demand. Adding linear equalization algorithm is a feasible method to compensate the distortion and it does not require much cost. Least mean square (LMS) algorithm is a widely used simple linear equalization algorithm, its implementation only requires two multiplications and two additions per filter coefficient [11]. LMS algorithm can be used in different types of optical communication systems such as high speed OFDM system [12] and Nyquist single carrier visible light communication (VLC) system [13]. With LMS algorithm the distortion can be significantly compensated by updating tap-weight vector, so the bit error rate (BER) performance is improved.

In this paper, we propose a 4×25-Gb/s IM/DD duo-binary system with 50-GHz channel spacing. LMS algorithm can be employed to compensate the signal distortion after 20-km standard single mode fiber (SSMF) transmission. Both of the modulator and photodetector (PD) have 10-GHz 3-dB electrical bandwidth. The effect of LMS algorithm is analyzed and system performance of duo-binary system is compared with on-off keying (OOK) system.

2 Principle

2.1 Duo-Binary System

Figure 1 shows the duo-binary IM/DD system scheme for single wavelength transmission. At first, the 25-Gb/s digital OOK data sequence should conduct precoding, which is demonstrated in Fig. 2. The precoding process is needed at transmitter because without precoding a more complex decoding process is required at receiver, which is likely to cause error propagation due to the previous signal is useful to decode signal at the present time. We get inverse of the original signal, then add a zero at the front to perform differential encoding. After achieving the precoded signal, as shown in Fig. 3, the signal period is 0.04-ns, the first fourteen signals are the same as the corresponding signals in Fig. 2. Then the precoded signals pass through a low pass band-limiting filter with 6-GHz 3-dB bandwidth. The bandwidth of precoded signal is 25-GHz so that high-frequency components are attenuated by this filter. As shown in Fig. 3, if the precoded signal changes between “1” and “0” quickly, the low pass band-limiting filter causes the signal unable to achieve its original value, it only can achieve the value of about 0.5. Therefore, the three-level signal can be generated by this low pass band-limiting filter. Figure 4 reveals the electrical spectrum and eye diagram of the generated duo-binary signal. We can find the high-frequency components of 25-GHz bandwidth transmitted signal are attenuated by the 6-GHz 3-dB bandwidth filter seriously, and the eye diagram demonstrates the duo-binary signal with three levels. Then, we can adjust amplitude and bias to make all the signal positive. The three-level electrical signal is directly modulated to three-level optical signal by MZM. Therefore, the amplitude range of duo-binary signal and OOK signal are the same.

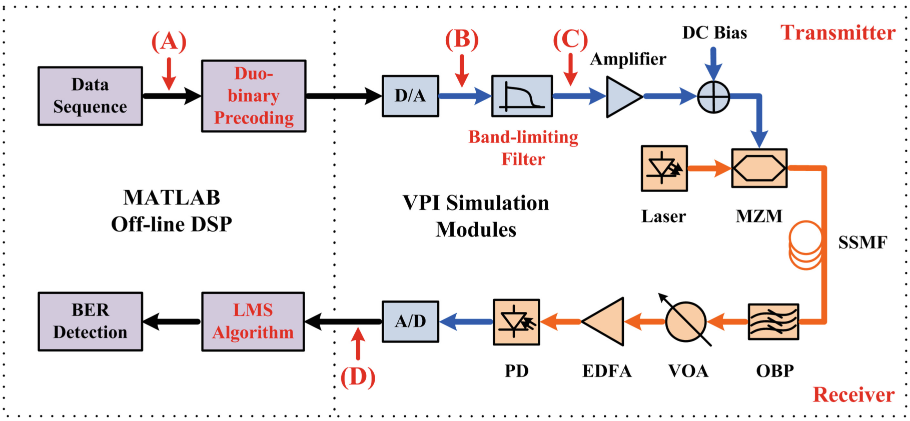

Fig. 1. Duo-binary IM/DD system scheme for single wavelength transmission.

At receiver side, we get the positive three-level duo-binary signal, decrease the amplitude of the signals by the mean value of them, and then adjust the amplitude of the signals by multiplying a proper number so that all the signal values are nearby “1”, “0” or “−1”, two thresholds are needed to make decision. LMS algorithm has significant effect to compensate the signal distortion. After getting the absolute value of the received signal, we can perform BER detection to obtain the system performance.

2.2 LMS Algorithm

LMS algorithm is one of the most widely used linear equalization algorithms, it can be considered as a stochastic implementation of steepest descent method [11].

Original signal (A):	**1 1 1 1 0 1 1 1 0 0 1 1 0 1**
Inverse of original signal:	**0 0 0 0 1 0 0 0 1 1 0 0 1 0**
Differential encoding:	**0 0 0 0 0 1 1 1 1 0 1 1 1 0 0**
Precoded signal (B):	**0 0 0 0 1 1 1 1 0 1 1 1 0 0**
Duo-binary signal (C):	**0 0 0 0 $\frac{1}{2}$ 1 1 1 $\frac{1}{2}$ $\frac{1}{2}$ 1 1 $\frac{1}{2}$ 0**
Received signal (D):	**-1 -1 -1 -1 0 1 1 1 0 0 1 1 0 -1**
Absolute value for BER detection:	**1 1 1 1 0 1 1 1 0 0 1 1 0 1**

Fig. 2. Transformation of data in duo-binary system.

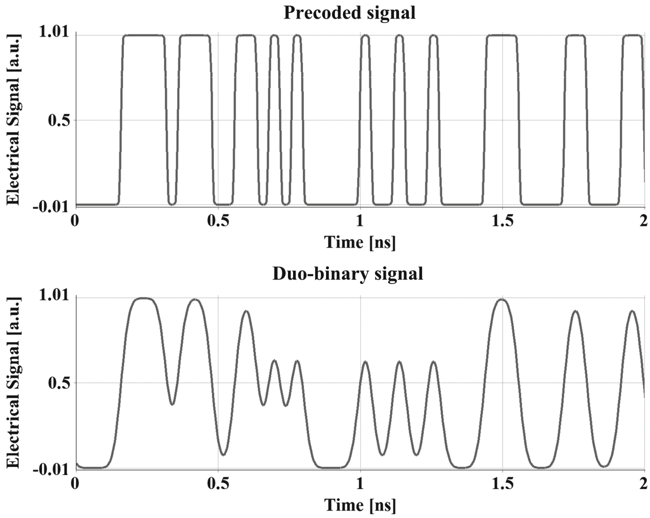

Fig. 3. The inputs and outputs of band-limiting filter corresponding to (B) and (C) in duo-binary system scheme.

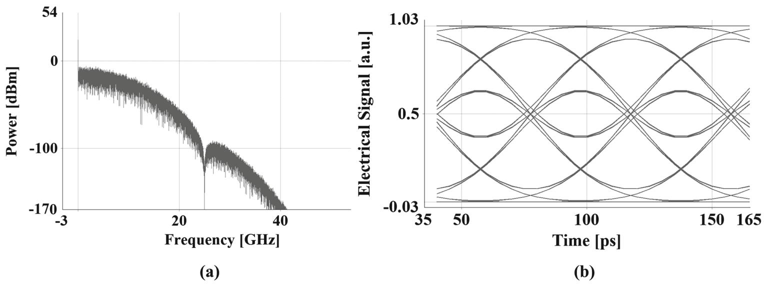

Fig. 4. (a) Electrical spectrum of duo-binary signal in (C); (b) eye diagram of duo-binary signal in (C).

Figure 5 reveals the structure of LMS algorithm with $N+1$ taps, the objective is achieving proper tap-weight vector $\mathbf{w}[n]$ so as to compensate the signal influence at other times to the signal at the present time. Three steps for each iteration are presented as follows.

The output signal $y[n]$ can be calculated by

$$y[n] = \mathbf{w}^H[n]\mathbf{x}[n] \tag{1}$$

where the tap-weight vector $\mathbf{w}[n] = [w_0[n], w_1[n], \ldots, w_N[n]]^T$ and the input signal $\mathbf{x}[n] = [x[n], x[n-1], \ldots, x[n-N]]^T$, $\mathbf{w}^H[n]$ means the complex conjugate of tap-weight vector $\mathbf{w}[n]$.

Then the error signal $e[n]$ is the difference between desired output signal $d[n]$ and actual output signal $y[n]$,

$$e[n] = d[n] - y[n] \tag{2}$$

Finally, we can utilize the error signal $e[n]$ and input signal $\mathbf{x}[n]$ to update the tap-weight vector, such as

$$\mathbf{w}[n+1] = \mathbf{w}[n] + 2\mu e^*[n]\mathbf{x}[n] \tag{3}$$

where μ is the step size, which is chosen sufficiently small, $e^*[n]$ means the complex conjugate of the error signal $e[n]$.

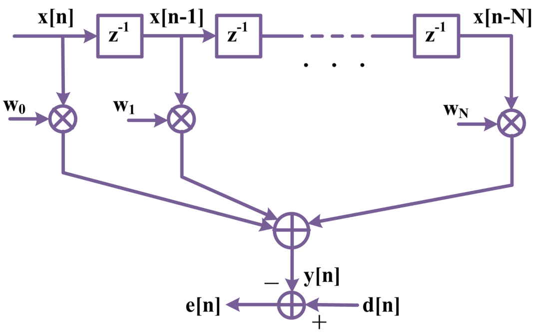

Fig. 5. The structure of LMS algorithm.

By LMS algorithm, the received signal can converge to desired signal so as to compensate the signal distortion. However, we should have the desired signal to converge to. From Fig. 2 we can find the received signal is nearby "1", "0" or "−1", these signals are generated by band-limiting filter at the transmitter. We only have the precoded signal saved in MATLAB off-line processing, so that we should encode the precoded signal at receiver to imitate the function of band-limiting filter to get desired three-level received signal. The encoding process is demonstrated in Fig. 6.

n:	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Precoded signal:		0	0	0	0	1	1	1	1	0	1	1	1	0	0
Bit to amplitude mapping m(n):	-1	-1	-1	-1	-1	1	1	1	1	-1	1	1	1	-1	-1
Desired signal d(n):		-1	-1	-1	-1	0	1	1	1	0	0	1	1	0	-1

Fig. 6. Encoding process to get the desired signal.

The precoded signal is consisted of “0” and “1”, if the original precoded signal is “0”, the corresponding bit to amplitude mapping signal $m(n)$ is set to “-1”, if the original precoded signal is “1”, the corresponding bit to amplitude mapping signal $m(n)$ is still set to “1”. Then add a “-1” at the front of $m(n)$. Equation (4) shows how to get the desired signal $d(n)$,

$$d(n) = \frac{m(n-1) + m(n)}{2}, \qquad n = 1, 2, \ldots \tag{4}$$

After obtaining the desired signal $d(n)$, LMS algorithm can be applied to compensate the signal distortion.

3 Simulation System and Results Discussion

3.1 Simulation System

Figure 1 reveals the duo-binary IM/DD simulation system for single wavelength transmission. We use MATLAB to perform off-line digital signal processing, the electrical and optical devices are VPItransmissionMaker (VPI) simulation modules. Data rate for each channel is 25-Gb/s, four channels are used to carry signal and seeds for data sequence of each channel are different. The center frequencies of four channels are set to 193.5-THz, 193.45-THz, 193.4-THz and 193.35-THz with 50-GHz channel spacing.

The simulation system is set up according to the actual experimental system. The OOK data sequence performs precoding, digital to analog conversion, and passes through a low pass band-limiting filter. After adjusting amplitude and bias, the duo-binary signal is modulated to the optical carrier by MZM with 10-GHz 3-dB electrical bandwidth, and four channels are multiplexed by optical multiplexer. The launching optical power is set to 0-dBm.

After 20-km SSMF transmission, the center frequency of optical band pass filter is set according to the center frequency of each channel, the bandwidth is set to 2.5 times of bit rate, that is 62.5-GHz, so all the signal of this channel can pass through the band pass filter. Then, a variable optical attenuator (VOA) is used to change the received optical power, and an Erbium doped fiber amplifier (EDFA) with power-controlled status can keep a constant input power of PD. The optical signal is converted to electrical signal by PD with 10-GHz 3-dB electrical bandwidth. After analog to digital conversion, the digital signal is handled by MATLAB off-line processing. We use LMS algorithm to compensate the signal distortion, and conduct BER detection at last.

To highlight the advantage of duo-binary system with LMS algorithm, we also compare it with the 4×25-Gb/s OOK system. Both the two systems have the same data rate and transmission distance. OOK system also use 10-GHz 3-dB electrical bandwidth devices and LMS algorithm is also applied.

3.2 Results Discussion

Figure 7 demonstrates the optical spectrum and BER performance of four channels for duo-binary system with LMS algorithm, the center frequency of four-channel signal is 193.425-THz and channel spacing is 50-GHz. After 20-km SSMF transmission, the BER performances of four channels are almost the same, because channel spacing is enough for the band-limiting duo-binary signal. The first channel with 193.5-THz center frequency is tested for performance evaluation.

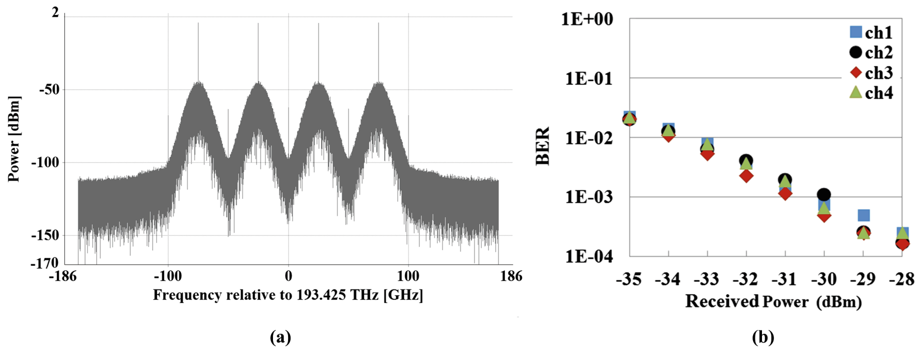

Fig. 7. (a) Optical spectrum of four channels; (b) BER performance of four channels after 20-km SSMF transmission.

BER performance for duo-binary system and OOK system before and after using LMS algorithm of the first channel is compared. Figure 8 reveals for duo-binary system, LMS algorithm has effect of converging the received signal to its original signal to compensate the distortion, especially when the received optical power is not too small. Figure 8(a) reveals the required received power for duo-binary system with LMS algorithm is about 2-dB less than duo-binary system without LMS algorithm for both back-to-back (BTB) and 20-km SSMF transmission at forward error correction (FEC) limit (BER=10^{-3}). Figure 8(b) and 8(c) depict the constellations before and after using LMS algorithm for 20-km SSMF transmission, respectively. The color bar represents numbers of received data as different colors. The constellation points with LMS algorithm are closer to "1", "0" or "−1" than the constellation points without LMS algorithm. The constellation points around "1" is not as close as the constellation points

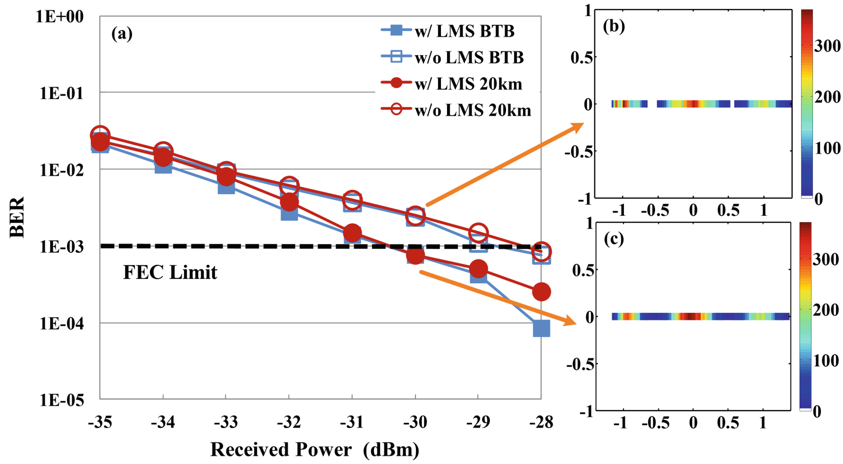

Fig. 8. (a) BER performance of the first channel for duo-binary system with or without LMS algorithm; (b) duo-binary constellation before using LMS algorithm for 20-km SSMF transmission; (c) duo-binary constellation after using LMS algorithm for 20-km SSMF transmission. (Color figure online)

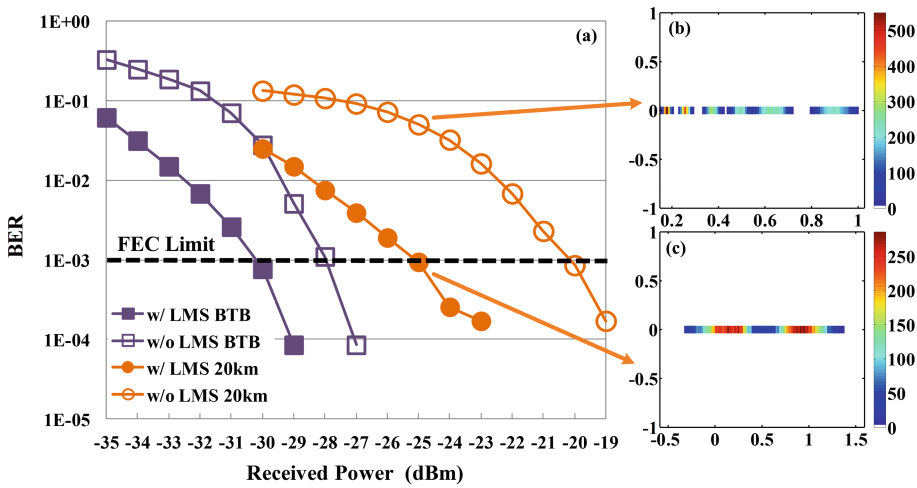

Fig. 9. (a) BER performance of the first channel for OOK system with or without LMS algorithm; (b) OOK constellation before using LMS algorithm for 20-km SSMF transmission; (c) OOK constellation after using LMS algorithm for 20-km SSMF transmission.

around "−1" because the signal with high amplitude is easier to be affected by amplified spontaneous emission (ASE) noise in the process of transmission.

The effect of LMS algorithm is more apparent in Fig. 9, especially for 20-km SSMF transmission due to LMS algorithm has the function of compensating

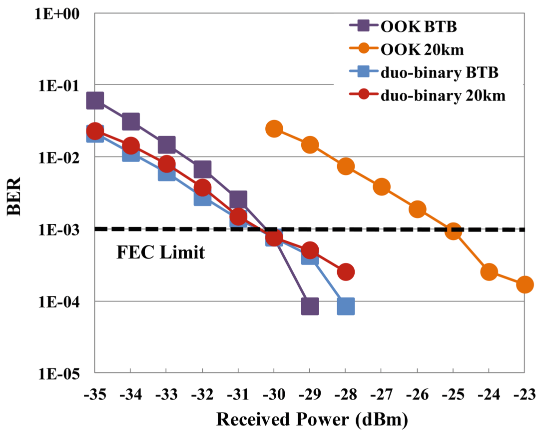

Fig. 10. Comparison of BER performance of the first channel between OOK system and duo-binary system for BTB and 20-km SSMF transmission.

chromatic dispersion. Figure 9(a) reveals the required received power for OOK system with LMS algorithm is about 2-dB and 5-dB less than OOK system without LMS algorithm for BTB and 20-km SSMF transmission at FEC limit, respectively. Figure 9(b) and (c) depict the constellations before and after using LMS algorithm for 20-km SSMF transmission, respectively. The constellation points with LMS algorithm are closer to "1" or "0", while the distribution of constellation points without LMS algorithm is relatively confused, because the OOK signal is more sensitive to chromatic dispersion and 10-GHz 3-dB electrical bandwidth devices cause the high-frequency signal distortion. Therefore, LMS algorithm has significant effect to compensate the signal distortion.

Figure 10 depicts the BER performance of the first channel for OOK system and duo-binary system with BTB and 20-km SSMF transmission. LMS algorithm is used for all of them. For duo-binary system, the BER performances for BTB and 20-km SSMF transmission are almost the same, due to the 3-dB electrical bandwidth of 20-km SSMF transmission caused by chromatic dispersion is 9.6-GHz [14], which is more than 6-GHz of duo-binary signal. However, for OOK system, the BTB transmission has about 5-dB improvement in power penalty compared with 20-km SSMF transmission at FEC limit, because this 25-GHz electrical bandwidth signal suffers from more influence by chromatic dispersion. The BER performance of duo-binary system with 20-km SSMF transmission has about 5-dB improvement in power penalty compared with OOK system with 20-km SSMF transmission at FEC limit. Consequently, duo-binary system has advantage over OOK system in its resistance to chromatic dispersion due to the low spectral bandwidth, and LMS algorithm has effect to compensate the signal distortion.

4 Conclusion

In this paper, a 4×25-Gb/s IM/DD duo-binary system with 50-GHz channel spacing is demonstrated. Both of the modulator and PD have 10-GHz 3-dB electrical bandwidth, and the system performance is improved by LMS algorithm. LMS algorithm can converge received signal to its original value, so the signal distortion is compensated after transmission. For duo-binary system, LMS algorithm improves about 2-dB receive sensitivity at FEC limit for both BTB and 20-km SSMF transmission. For OOK system, LMS algorithm improves about 2-dB and 5-dB receive sensitivity at FEC limit for BTB and 20-km SSMF transmission, respectively. After using LMS algorithm, duo-binary system has about 5-dB improvement of receive sensitivity at FEC limit compared to OOK system for 20-km SSMF transmission. This paper proposes a feasible scheme for future high-speed passive optical network.

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