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PERFORMANCE OF 2-D HYBRID FCC-MDW CODE ON OCDMA SYSTEM WITH THE PRESENCE OF PHASE INDUCED INTENSITY NOISE

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ABSTRACT

Phase induced intensity noise (PIIN) is one of the noises involved in incoherent OCDMA systems. In this paper, we analyze the influence of PIIN on the system performance of new proposed 2-D Hybrid FCC- MDW code. The numerical result indicates PIIN is a major factor of the performance depreciation as compared to the shot noise and thermal noise. The comparison results with thermal noise and shot noise reveals that the system performance is seriously affected by PIIN and other two noises can be neglected. Moreover, the numerical analysis demonstrates the PIIN value of the proposed code is lower than the 2-D Perfect Difference (PD) code and 2-D Modified Double Weight (MDW) code. Consequently, the performance of the 2-D Hybrid FCC- MDW OCDMA system is better than other two codes. The results presented here may facilitate improvements in the understanding to develop a new incoherent OCDMA code.

Keywords: optical code division multiple access, phase induced intensity noise, modified double weight, flexible cross correlation.

INTRODUCTION

The knowledge of the PIIN and multiple access interference (MAI) in OCDMA system is important for an understanding of code development. This is due to the PIIN and MAI are related to each other (E.D.J Smith *et. al,* 1998). PIIN occurs when the incoherent lights are mixed and incident on the photo detector. The mixing of two uncorrelated light fields with same spectrum and intensity, identical polarization and insignificant self-intensity noise (Z. Wei and H. Ghafouri-Shiraz 2002), (M.S Anuar *et al,* 2009), (T.H. Abd. *et. al,* 2011). Nonetheless, MAI is generated from the overlapping light spectra from interfering users which replicate the signature sequence of the user (N. Din Keraf *et. al,* 2014). Although MAI can be eliminated, especially in spectral-amplitude-encoding OCDMA and the 2-D OCDMA system, the performance of the system still affected by the PIIN (H. Ghafouri-Shiraz and M. M. Kabassian, 2012).

It appears from the aforementioned that numerous investigation have been conducted to examine the effects of PIIN in OCDMA system. The limiting factor in most digital incoherent optical systems are a large optical self-SNR is needed in order to have a minimal PIIN (Mohammad M. Rad and Jawad A. Salehi, 2006). Furthermore the investigations of PIIN in the fiber Bragg-grating-pair delay line structures have been conducted (E.H.W. Chan, 2009). It was found that the transmissive and reflective filters can have the same transfer characteristic but different phase noise behaviors. In addition, it has been proven that PIIN can be maximally suppressed by minimizing the cross correlation property (A.R Arief *et. al,* 2012). Nevertheless, few studies are to be found providing detailed the impact of PIIN on the performance of 2-D Wavelength/Time (W/T) scheme OCDMA codes.

The aim of the present work is to investigate the effects of shot noise, thermal noise and PIIN on the performance of newly developed 2-D Hybrid FCC-MDW code employed W/T code scheme. This paper also explores the capability of this proposed code to enhance the performance of the system in comparison with the existing 2-D codes. The comparison is done with related codes include a 2-D PD and 2-D MDW codes in order to evaluate the performance of the system. On top of that, this study also tested the hypothesis that in the incoherent OCDMA system, PIIN is the main contribution of the performance deterioration.

This paper is organized as follows. The development and correlation property description of newly 2-D Hybrid FCC-MDW code is detailed out in the next section and followed by the performance analysis of 2-D Hybrid FCC-MDW code, numerical results and discussion and finally, the conclusion of this paper.

2-D HYBRID FCC-MDW CODE DEVELOPMENT

The 2-D Hybrid FCC-MDW code is developed by using the combination of two different codes i.e 1-D FCC (C.B.M Rashidi *et. al.*, 2014) and 1-D MDW (S.A Aljunid *et. al.*, 2004) codes. The proposed code denoted by $(M \times N, w, \lambda_a, \lambda_c)$; M is the number of wavelengths, N is the temporal code length, w is code weight, λ_a and λ_c is auto-correlation and cross correlation respectively. Let code sequences for 1-D MDW represented by $X = \{x_0, x_1, \ldots\ldots x_{M-1}\}$ and $Y = \{y_0, y_1, \ldots\ldots y_{N-1}\}$ represents 1-D FCC code sequences. The code weights of these two codes i.e 1-D MDW and the 1-D FCC are represented by k_1 and k_2 respectively.

As previously mentioned, M is related to the number of available wavelengths and N is the number of time chips. Integer M represents the code length for the 1-D MDW code and N is the code length for 1-D FCC code. Hence, the code lengths of X and Y are represented by $M = 3\sum_{j=1}^{\frac{k1}{2}} j$ and $N = K\ k_2 - (K\ \text{-}1)$ where k_1 and k_2 are the

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code weights for these two codes sequence respectively. Although the 1-D FCC code offers the choice of flexible in cross correlation, but the maximum number of cross correlation, $\lambda_{max} = 1$ is used in this proposed code. The uniqueness of this 1-D FCC code is that the number of users, K can be decided, thus we choose the number of K to be as minimum as possible in our numerical analysis. Then, the 2-D Hybrid FCC-MDW can be generated by $A_{g,h} = Y_h^T X_g$ where $g \in$ (1, 2, 3,....., $M-1$) and $h \in$ (1,2,3,....., $N-1$). Y_h is the time spreading patterns while X_g is the wavelength encoding patterns. Table-1 shows some examples of 2-D Hybrid FCC-MDW code sequences for $k_1 = 4$ and $k_2 = 2$, where k_1 and k_2 are the code weights for X_g and Y_h respectively.

Table-1. 2-D Hybrid FCC-MDW code for k_1=4 and k_2=2 sequences.

$A_{g,h}$	000011011]	011000110]	[110110000] X_g
1 1 0	000011011 000011011 000000000	011000110 011000110 000000000	110110000 110110000 000000000
0 1 1	000000000 000011011 000011011	000000000 011000110 011000110	000000000 110110000 110110000
Y_h			

As highlighted in previous work by (A.R Arief *et al.*, 2011), four characteristic matrices $A^{(d)}$, $d \in$ (0, 1, 2, 3) has been used to obtain the cross-correlation property. Following the same assumption, $A^{(d)}$ for 2-D Hybrid FCC-MDW codes can be defined as:

$$A^{(0)} = Y^T X, \tag{1}$$

$$A^{(1)} = Y^T \bar{X}, \tag{2}$$

$$A^{(2)} = \bar{Y}^T X, \tag{3}$$

$$A^{(3)} = \bar{Y}^T \bar{X} \tag{4}$$

Parameters $\bar{X}$ and $\bar{Y}$ are the complementary of X and Y respectively. Thus, the cross-correlation of 2-D Hybrid FCC-MDW code $A^{(d)}$ and $A_{g,h}$ is expressed as

$$R^{(d)}(g,h) = \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{ij}^{(d)} a_{(i+g)(j+h)} \tag{5}$$

where $a_{ij}^{(d)}$ is the (i, j) th of $A^{(d)}$ and $a_{(i+g)(j+h)}$ is the (i, j) th of $A_{g,h}$. Table-2 illustrates the cross-correlation between any two codes $A^{(d)}$ and $A_{g,h}$ of 2-D Hybrid FCC-MDW code generated from equation (5). This property is very important in order to cancel the MAI and suppress the PIIN.

Table-2. Cross correlation of 2-D hybrid FCC-MDW code.

$X_{g,h}$	$R^{(0)}(g,h)$	$R^{(1)}(g,h)$	$R^{(2)}(g,h)$	$R^{(3)}(g,h)$
$g = 0, h = 0$	$k1k2$	0	0	0
$g = 0, h \neq 0$	$k1$	0	$k1$	0
$g \neq 0, h = 0$	$k2$	$k2(k1-1)$	0	0
$g \neq 0, h \neq 0$	1	$k1-1$	1	$k1-1$

Hence, the derivation of new correlation functions can be expressed as

$$R^{(0)}(g,h) - \frac{R^{(1)}(g,h)}{(k1-1)} + \frac{R^{(3)}(g,h)}{(k1-1)} - R^{(2)}(g,h) = \begin{cases} k1k2, & for\ g = 0, h = 0 \\ 0, & otherwise \end{cases} \tag{6}$$

PERFORMANCE ANALYSIS

There are certain parameters that highly considered such as correlation function values, BER and cardinality in order to analyze the performance of 2D Hybrid FCC-MDW code. The Gaussian approximation is used to calculate the BER. Subsequently, three types of noises are taken into account for calculating the BER including PIIN, shot noise and thermal noise in the photodiodes. The general form of the photocurrent noise emitted from the photodiodes can be expressed as follows:

$$\langle i^2 \rangle = I^2 B\tau c + 2eIB + \frac{4K_b T_n B}{R_L} \tag{7}$$

where I is the average photocurrent output from the photodiode, B is the electrical bandwidth, τ_c is the coherence time of the light source, e is electron's charge, K_b is Boltzmann's constant, T_n is the absolute receiver noise temperature and R_L is the load resistance. In addition, the following assumptions are made to simplify the analysis. Firstly, the output of broadband light source is ideal unpolarized and has a flat spectrum over $\left[f_0 - \frac{\Delta f}{2}, f_0 + \frac{\Delta f}{2}\right]$ where f_0 and Δf are the central frequency and the bandwidth of the source. Secondly the spectral width of each spectral component is identical. Thirdly, every single user has equal received power and lastly, the bit stream from different transmitter is synchronous. Based on the abovementioned assumption (Cheing-Hong Lin *et al.*, 2005), the power spectral densities of the received optical signals can be written as:

$$r(f) = \frac{P_{sr}}{k_2 \Delta f} \sum_{w=1}^{W} d(w). \sum_{i=0}^{M-1} \sum_{j=0}^{N-1} a_{ij}(w) \times$$

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$$\left\{u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i)\right]-u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i+2)\right]\right\} \quad (8)$$

where P_{sr} the effective source power at the receiver, Δf is the source bandwidth, k_2 is the code weight of the time spreading code sequence, W is the number of simultaneous active users, $d(w)$ is the data bit of the w th user, which can be "1" or "0", M is the code length of the wavelength encoding code sequence and N is the code length of the time spreading code sequence, $a_{ij}(w)$ represents an element of the w th user's code word while $u(f)$ is the unit step function.

Hence, the power spectral density during one bit period of optical signals at PD0, PD1, PD2 and PD3 of the receiver by using cross-correlation between codeword $A_{g,h}$ and $A_{0,0}^{(d)}$ can be written as:

$$G_0(f)=\frac{P_{sr}}{k_2\Delta f}\sum_{w=1}^{W}d(w).\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}a_{ij}^{(0)}a_{ij}(w)\times\left\{\begin{matrix}u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i)\right]\\-u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i+2)\right]\end{matrix}\right\} \quad (9)$$

$$G_1(f)=\frac{P_{sr}}{(k_1-1)k_2\Delta f}\sum_{w=1}^{W}d(w).\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}a_{ij}^{(1)}a_{ij}(w)\times\left\{\begin{matrix}u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i)\right]\\-u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i+2)\right]\end{matrix}\right\} \quad (10)$$

$$G_2(f)=\frac{P_{sr}}{k_2\Delta f}\sum_{w=1}^{W}d(w).\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}a_{ij}^{(2)}a_{ij}(w)\times\left\{\begin{matrix}u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i)\right]\\-u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i+2)\right]\end{matrix}\right\} \quad (11)$$

$$G_3(f)=\frac{P_{sr}}{(k_1-1)k_2\Delta f}\sum_{w=1}^{W}d(w).\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}a_{ij}^{(3)}a_{ij}(w)\times\left\{\begin{matrix}u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i)\right]\\-u\left[f-f_o-\frac{\Delta f}{2M}(-M+2i+2)\right]\end{matrix}\right\} \quad (12)$$

k_1 is the code weight of the wavelength encoding code sequence. Thus, the average output currents of photo detector can be determined as:

$$I_0=\Re\int_0^{\propto}G_0(f)df=\frac{\Re P_{sr}}{Mk_2}\left\{\begin{matrix}k_1k_2+k_1\frac{(W-1)(N-1)}{(MN-1)}+k_2\frac{(W-1)(M-1)}{(MN-1)}\\+\frac{(W-1)(M-1)(N-1)}{(MN-1)}\end{matrix}\right\} \quad (13)$$

$$I_1=\Re\int_0^{\propto}G_1(f)df=\frac{\Re P_{sr}}{Mk_2}\left\{k_2\frac{(W-1)(M-1)}{(MN-1)}+\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right\} \quad (14)$$

$$I_2=\Re\int_0^{\propto}G_2(f)df=\frac{\Re P_{sr}}{Mk_2}\left\{k_1\frac{(W-1)(N-1)}{(MN-1)}+\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right\} \quad (15)$$

$$I_3=\Re\int_0^{\propto}G_3(f)df=\frac{\Re P_{sr}}{Mk_2}\left\{\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right\} \quad (16)$$

Hence, the total output photocurrent from the receiver can be obtained as follows

$$I_r=\Re\int_0^{\propto}[G_0(f)-G_1(f)-G_2(f)+G_3(f)]\,df=\frac{\Re P_{sr}k_1}{M} \quad (17)$$

From the derivation of equation (17), we can see that $G_0(f)$ and $G_2(f)$ do not overlap the spectrum of $G_1(f)$ and $G_3(f)$. Accordingly, the power of PIIN that exists in photocurrent of the receiver (A.R Arief *et al,*. 2012) can be expressed as:

$$\langle i_{PIIN}^2\rangle = B_r\Re^2\int_0^{\propto}[G_0{}^2(f)+G_1{}^2(f)+G_2{}^2(f)+G_3{}^2(f)-2G_0(f)G_2(f)-2G_1(f)G_3(f)]\,df \quad (18)$$

Thus, under the circumstances that all of the users transmit bit "1" or worst case scenario, PIIN can be written as:

$$\langle i_{PIIN}^2\rangle = B_r\Re^2\int_0^{\propto}[G_0{}^2(f)+G_1{}^2(f)+G_2{}^2(f)+G_3{}^2(f)-2G_0(f)G_2(f)-2G_1(f)G_3(f)]\,df$$

$$=\frac{B_r\Re^2P_{sr}^2}{k_2^2M\Delta f(MN-1)^2}\{[k_1k_2(MN-1)+k_2(W-1)(M-1)]^2+[k_2(W-1)(M-1)]^2\} \quad (19)$$

Additionally, the power of shot noises from all photodiodes i.e. PD0 – PD3, can be written as:

$$\langle i_{shot}^2\rangle = 2eB_r(I_0+I_1+I_2+I_3) \quad (20)$$

Also applying the same assumption that all the users transmit bit "1", shot noise can be expressed as:

$$\langle i_{shot}^2\rangle = 2eB_r\frac{\Re P_{sr}}{Mk_2}\left[k_1k_2+2k_1\frac{(W-1)(N-1)}{(MN-1)}+2k_2\frac{(W-1)(M-1)}{(MN-1)}+4\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right] \quad (21)$$

By assuming that the probability of each user sending bit "1" is equal or 1/2, the equation of PIIN and

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shot noise can be revised as equation (22) and (23) respectively.

$$\langle i_{PIIN}^2\rangle = \frac{B_r \Re^2 P_{sr}^2}{2k_2^2 M\Delta f (MN-1)^2}\left[k_1 k_2 (MN-1) + k_2 (W-1)(M-1)\right]^2 + \left[k_2 (W-1)(M-1)\right]^2 \quad (22)$$

$$\langle i_{shot}^2\rangle = \frac{eB_r \Re P_{sr}}{Mk_2}\left[k_1 k_2 + 2k_1 \frac{(W-1)(N-1)}{(MN-1)} + 2k_2 \frac{(W-1)(M-1)}{(MN-1)} + 4\frac{(W-1)(M-1)(N-1)}{(MN-1)}\right] \quad (23)$$

Moreover, the thermal noise can be written as:

$$\langle i_{thermal}^2\rangle = \frac{4K_b T_n B_r}{R_L} \quad (24)$$

Accordingly, by using the equation (17), (22), (23) and (24) the SNR at the receiver can be obtained.

$$SNR = \frac{I_r^2}{\langle i_{PIIN}^2\rangle + \langle i_{shot}^2\rangle + \langle i_{thermal}^2\rangle} \quad (25)$$

Therefore, the BER can then be estimated as:

$$BER = \frac{1}{2}\, erfc\left(\sqrt{\frac{SNR}{8}}\right) \quad (26)$$

RESULTS AND DISCUSSIONS

The results of numerical analysis can be obtained by using the parameters listed in Table-3. Three types of noises i.e. PIIN, shot noise and thermal noise has been used to investigate the influence of these noises to the proposed 2-D Hybrid FCC-MDW code. Gaussian approximation is used for the calculation of BER. The performance evaluation for three noises in terms of BER is shown in Figure-1, Figure-2 and Figure-3.

Table-3. Parameters used in the numerical calculation.

Parameter description	Value
PD quantum efficiency Spectral width of broadband light source	η = 0.75 Δλ= 30nm (Δf = 3.75 THz)
Operating wavelength	λ_o= 1550 μm
Receiver noise temperature	T_n = 300K
Receiver load resistor	R_L = 1030 Ω
Boltzmann's constant	$K_b = 1.38 \times 10^{-23}$ W/K/Hz
Electron charge Light velocity	$e = 1.60217646 \times 10^{-19}$ $C = 3 \times 10^8$ m/s

Figure-1 depicts the effect of PIIN, shot noise and thermal noise on the performance of 2-D Hybrid FCC-MDW code when the effective source power, P_{sr} is fixed at -10dBm and data rates at 622Mbps. There is a clear trend that PIIN of our proposed 2-D Hybrid FCC-MDW code significantly a dominance noise factor as compared to shot noise and thermal noise. All three curves are identical when the analysis of BER in the presence of PIIN noise on each combination. This result indicates that with or without a combination of shot noise and thermal noise, the value of BER influences of the PIIN noise. In addition, the lower BER value is obtained when the number of simultaneous users is increased.

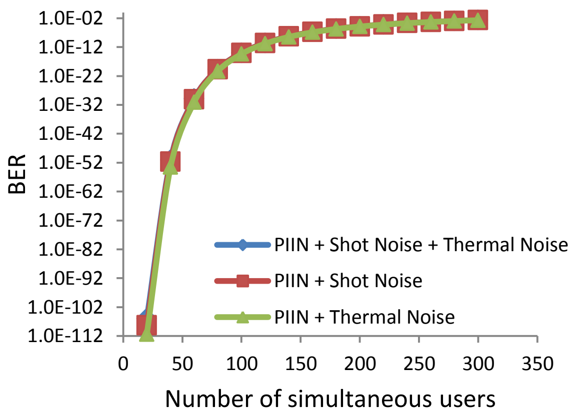

Figure-1. The effect of PIIN, shot and thermal noises for 2-D Hybrid FCC-MDW code.

The thorough understanding of PIIN noise is presented in Figure-2. As shown in the figure, when only one noise either shot noise or PIIN noise are taking into account in numerical analysis, there is severely difference of BER value between the two noises. For instance, when the number of simultaneous users is 140, the BER value of the system is at a permissible BER of 10^{-9} for data rate 622Mbps and the effective source power, P_{sr} is -10dBm. On the contrary, BER value for the system is at $10e^{-310}$

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when only shot noise is considered in the calculation. Hence, the most striking result to emerge from the Figure-2 is that shot noise and thermal noise can be negligible since the system performance of these two noises are very low as compared to the PIIN noise. In actuality, shot noise is associated with the particle nature of light.in optical devices, while thermal noise is the thermal agitation of the charge carriers inside the electric conductor.

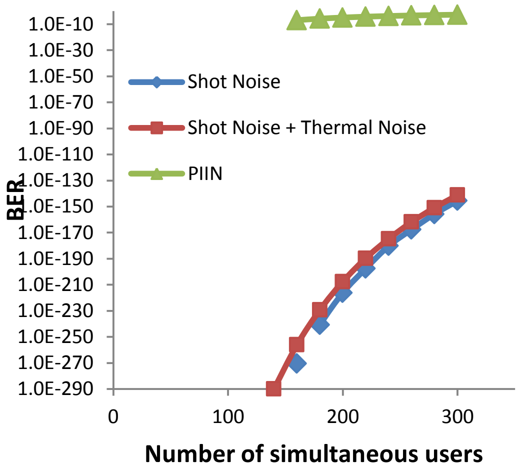

Figure-2. The comparison of PIIN, shot and thermal noise for 2-D Hybrid FCC-MDW code.

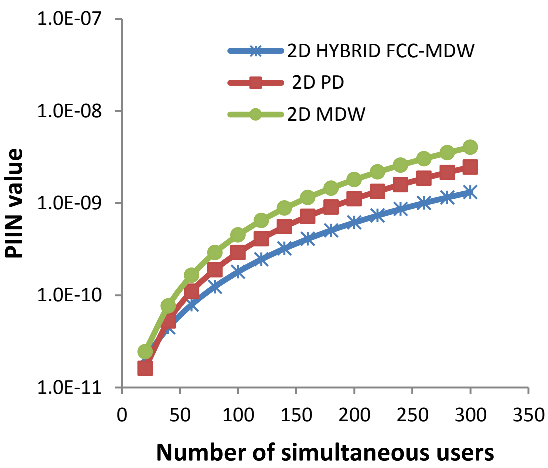

Figure-3. Variations of PIIN value for 2-D OCDMA codes with similar code length and fixed P_{sr} at 0dBm.

Figure-3 discussed the comparison of PIIN among 2-D W/T scheme OCDMA codes that has similar code length when the effective source power, P_{sr} is fixed at 0dBm and 622Mbps data rate. The codes involved are a newly proposed code 2-D Hybrid FCC-MDW code (M=18, N=9), 2-D PD code (M= 57, N=3) and 2-D MDW code (M= 18, N=9). It can be seen from Figure-3, 2-D Hybrid FCC-MDW code has the lowest PIIN value. In fact, for the number of simultaneous users is 300, the PIIN value for 2-D Hybrid FCC-MDW code is 1.3e^{-9} while for 2-D PD code and 2-D MDW code is 2.5e^{-9} and 4.0e^{-9} respectively. This finding provides evidence that the performance of the proposed system is better than other two codes. Interestingly, this relationship is not only related to the value of BER and PIIN but also the signal-to-noise ratio (SNR) of the system. A higher SNR can be expected and resulting the higher BER when the PIIN value is low.

CONCLUSIONS

The present study was designed to determine the effect of PIIN on the performances of a new code in OCDMA system, namely 2-D Hybrid FCC-MDW code. The proposed code is generated from two 1-D codes known as FCC code and MDW code which has the ideal cross correlation property. The numerical results demonstrate the PIIN noise as a major noise factor instead of shot noise and thermal noise. Furthermore, both shot noise and thermal noise can be neglected. In addition, the PIIN value of the proposed code apparently lower as compared to the other two codes that have the similar code length. These findings enhance our understanding of the PIIN optimally can be suppressed if the cross correlation property of the code in OCDMA system kept to the minimum as possible. The contribution of this study is obviously can be used as guidelines to new researcher to develop the new code with minimum PIIN value in order to enhance the system performance.

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