Performance Analysis of DS-BPAM UWB System over Fading Channels─ Uncoded and Coded Schemes

Zhiquan Bai, Shaoyi Xu, Weihua Zhang, and Kyungsup Kwak

UWB Wireless Communications Research Center (INHA UWB-ITRC),
Graduate School of Information Technology and Telecommunications,
Inha University, 402-751, Incheon, Korea
{sdzqbai, shaoyixu, zhweihua}@hotmail.com
kskwak@inha.ac.kr

Abstract. This paper investigates the performance of two direct sequence ultra wideband (DS-UWB) communication systems over multipath fading channels. The first system is the classic DS-UWB system and the second is obtained by adding a forward error control code (FEC), convolutional code. For the two systems, bipolar pulse amplitude modulation (BPAM) is applied. In the receiver end, the selective diversity combining receiver-SRake receiver is used as a feasible receiver. In the proposed coded scheme, we use soft output Viterbi algorithm (SOVA). The analysis shows that the coded DS-UWB system outperforms the conventional DS-UWB system significantly with the increase of the SRake fingers. The effective order of processing gains achieved by the coded scheme is the product of the number of SRake branches and the free distance of the code applied.

Keywords: Direct sequence (DS), Ultra wideband (UWB), Convolutional codes, Soft Output Viterbi algorithm (SOVA), Multipath fading channel, SRake receiver.

1 Introduction

Ultra Wideband radio presented in [1]-[2] is already used in military applications. Now it has attracted much interest for indoor high rate communications for its significant characteristics. In UWB system, data is transmitted directly using sub-nanosecond baseband pulses and the occupied frequency band is about several gigahertzes. Because of the large bandwidth, UWB technology can achieve high throughput and has the ability of robustness to co-channel interference and narrowband interference, and greater spectrum sharing. The characteristics of low cost and low power usage make it promising for mobile applications. UWB system can provide the fading robustness; wideband nature of the signal reduces time varying amplitude fluctuations (fading). Two popularly considered multiple access techniques for an impulse radio system are time hopping (TH), where users are distinguished by their pulse arrival time sequence, and direct sequence (DS) where users are distinguished by their pulse polarity sequence.

In [3]-[4], the coded and uncoded schemes of TH Pulse Position Modulation (TH-PPM) UWB communication systems were proposed over AWGN channel. The performance of the coded TH-PPM UWB system over multipath fading channels was presented in [5]. It is shown the coded scheme can achieve better performance. In our knowledge, there are no much literatures about the analysis of coded and uncoded scheme of DS-BPAM UWB system. In this paper, the bit error rate (BER) of the two systems is analyzed in detail over UWB multipath fading channels. For the coded system, we use convolutional encoder and the soft output Viterbi algorithm (SOVA) is considered here. The computer simulations show that the coded DS-BPAM UWB system can get better performance with the acceptable complexity compared with the uncoded scheme.

The organization of this paper is as follows. In Section II, an overview of the DS-BPAM UWB system model is provided and the performance analysis is given in detail over multipath fading channels and SRake receiver. Section III presents the proposed coded DS-UWB system and also gives the upper bound and lower bound of the coded scheme. Section IV describes the simulation results obtained and interpretations. Finally, conclusions are presented in Section V.

2 DS UWB System Description

The performance analysis of the direct sequence spread spectrum UWB system over multipath fading channels is presented in this section. The transmitter of DS-BPAM UWB system is shown in Fig.1. This DS-BPAM UWB system is similar with [6]. We assume that desired user has a unique pseudo-noise (PN) sequence with N_c chips per message symbol period T_f such that $T_f = N_c T_c$, where N_c is the spread spectrum processing gain. A typical transmitted signal can be expressed as

$$s_{tr}\left(t\right) = \sum_{j=-\infty}^{\infty} \sum_{n=0}^{N_c-1} d_j c_n w_{tr}\left(t - jT_f - nT_c\right), \tag{1}$$

where $w_{tr}(t)$ is the transmitted monocycle waveform, seen in [1], $\left\{D_j\right\}$ is the binary information bit and $\left\{d_j\right\}$ is the modulated data symbols with $d_j = 2D_{\lfloor j/N_s \rfloor} - 1$, N_s is the pulse repetition time, $\left\{c_n\right\}$ is the spread chips with duration T_c . We show the

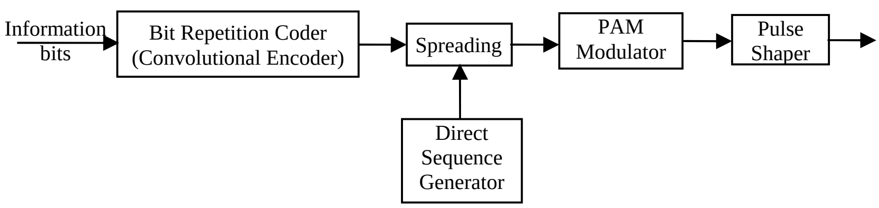

Fig. 1. Transmitter diagram of DS-BPAM-UWB (Uncoded/Coded) System

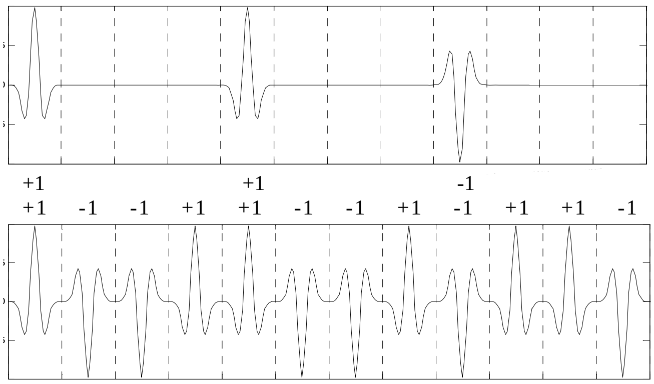

Fig. 2. DS-BPAM UWB modulation waveform (N_c=4, N_s=1)

modulated waveforms of the DS-BPAM UWB modulation waveforms in Fig.2, where the DS sequence is $\{+1,-1,-1,+1\}$ with $N_c = 4$ and $N_s = 1$.

In this paper, we consider a simple *L*-tap multipath channel model instead of the clustered multipath channels in order to simplify the analysis and high light the benefit of SRake receiver [7]. The channel mpulse response can be expressed by

$$h(t) = \sum_{l=0}^{L-1} a_l \delta(t - \tau_l), \tag{2}$$

where a_l and τ_l are the amplitude attenuation and time delay of the l^{th} path, respectively, and *L* is the number of the corresponding branches in the SRake receiver.

An ideal channel and antenna system is known to modify the shape of the transmitted monocycle $w_{tr}(t)$ to $w_{rec}(t)$ at the output of the receiver antenna. For the purpose of analysis, we have assumed that the true transformed pulse shape $w_{rec}(t)$ is known at the receiver.

Through the UWB multipath fading channels, the received signal $r(t)$ can be expressed as [8]

$$r(t) = s_{rec}(t) * h(t) + n(t), \tag{3}$$

where $s_{rec}(t) = \sum_{j=-\infty}^{\infty} \sum_{n=0}^{N_c-1} d_j c_n w_{rec}(t - jT_f - nT_c)$.

We can further write the expression of the received signal as

$$r(t) = \sum_{j=-\infty}^{\infty} \sum_{n=0}^{N_c-1} \sum_{l=0}^{L-1} a_l d_j c_n w_{tr}(t - jT_f - nT_c - \tau_l) + n(t), \tag{4}$$

where $n(t)$ is the AWGN noise modeled as $N\left(0, \frac{N_0}{2}\right)$.

SRake receiver with MRC (maximum ratio combination) is employed in the receiver. The diagram of SRake receiver is shown in Fig.3. We can make the decision of the received information bit according to the output of branch combining. Since we assume that the receiver has achieved perfect synchronization for the signal transmitted by the transmitter. According to the estimated channel impulse response, the template can be set as

$$v_{bit}(t)=\sum_{n=0}^{N_c-1} c_n w_{rec}\left(t-jT_f-nT_c\right)*h(t)=\sum_{l=0}^{L-1}\sum_{n=0}^{N_c-1} a_l c_n w_{rec}\left(t-jT_f-nT_c-\tau_l\right). \quad (5)$$

The SRake correlation output can be expressed as

$$\alpha=\sum_{j=0}^{N_s-1}\int_0^T r(t)v_{bit}(t)dt=\sum_{j=0}^{N_s-1}\int_0^T r(t)\sum_{l=0}^{L-1} a_l\sum_{n=0}^{N_c-1} c_n w_{rec}\left(t-jT_f-nT_c-\tau_l\right)dt. \quad (6)$$

For the quantity a_l, we assume the order $a_1>a_2>...>a_L$. $[0,T]$ is the time interval includes the selected L paths.

The decision consists of

$$if\ \ \alpha>0,\ D_j=1;\ if\ \ \alpha<0,\ D_j=0. \quad (7)$$

In the following, we assume that the received waveform satisfies the relation $\int_{-\infty}^{+\infty} w_{rec}(t)\,dt=0$.

Let $\alpha_{\pm1}$ and $\sigma_{\pm1}^2$ be the mean and variance of the correlation output conditioned on $D_j=1$ and $D_j=0$, respectively. We calculate these two values as follows:

$$\alpha_1=-\alpha_{-1}=N_s N_c\int_0^T v_{bit}^2(t)dt, \quad (8)$$

$$\sigma_1^2=\sigma_{-1}^2=\frac{N_s N_c N_0}{2}\int_0^T v_{bit}^2(t)dt, \quad (9)$$

with

$$\int_{T_1}^{T_2} v_{bit}^2(t)dt=\int_0^T\sum_{l=0}^{L-1} a_l w_{rec}(t-\tau_l)\sum_{k=0}^{L-1} a_l w_{rec}(t-\tau_k)dt=\sum_{l=0}^{L-1} a_l^2+\sum_{l=0}^{L-1}\sum_{k=0,l\neq k}^{L-1} a_l a_k R\left(\tau_l-\tau_k\right), \quad (10)$$

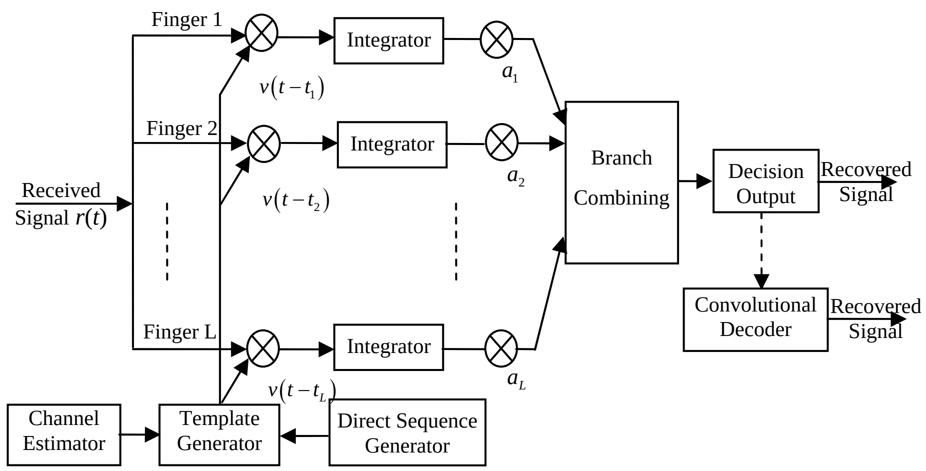

Fig. 3. Rake receiver diagram of DS-BPAM UWB (Uncoded and Coded) System

where $R(\tau)$ denotes the autocorrelation of pulse $w_{rec}(t)$, and that is, $R(\tau)=\frac{\int_{-\infty}^{\infty} w_{rec}(t)w_{rec}(t-\tau)dt}{E_w}$ with $E_w=\int_{-\infty}^{\infty} w_{rec}^2(t)dt$.

We first evaluate signal to interference ratio (*SIR*). For the BPAM scheme, the bit error probability is equal to $P_b=Q\left(\sqrt{SIR}\right)$, where the equation is taken on the fading parameters.

Through the above analysis, we can find

$$SIR=\frac{(\alpha_{\pm 1})^2}{\sigma_{\pm 1}^2}=\frac{2N_sN_c\int_0^T v_{bit}^2(t)dt}{N_0}. \tag{11}$$

The bit error probability of the system is given by

$$\begin{aligned}P_b&=Q\left(\sqrt{SIR}\right)=Q\left(\sqrt{\frac{2N_sN_c}{N_0}\int_0^T v_{bit}^2(t)dt}\right)\\&=Q\left(\sqrt{\frac{2N_sN_cE_w}{N_0}\left[\sum_{l=0}^{L-1}a_l^2+\sum_{l=0}^{L-1}\sum_{k=0,l\neq k}^{L-1}a_la_kR(\tau_l-\tau_k)\right]}\right),\end{aligned} \tag{12}$$

where $Q(\ )$ is the Gaussian probability integral.

When the channel attenuation is assumed to be normalized to one, $\sum_{l=0}^{L-1}a_l^2=1$ with $\sum_{l=0}^{L-1}\sum_{k=0,l\neq k}^{L-1}a_la_kR(\tau_l-\tau_k)=0$, then the BER reduces to be

$$P_b=Q\left(\sqrt{\frac{2N_sN_cE_w}{N_0}}\right). \tag{13}$$

3 Coded DS-UWB System Model

In this section, we consider the proposed coded DS-BPAM UWB system. We show the proposed receiver diagram of the convolutional coded system in Fig.3. In order to give the comparison of these two systems, in the DS-UWB system, we will assume that each data bit is transmitted by N_s repetition pulses. We consider it as a simple repetition block code with rate $1/N_s$. In the coded DS-UWB system, we will use an orthogonal convolutional code with constraint length *K*. For each input bit, we can get 2^{k-2} coded bits, here we set $N_s=2^{k-2}$ in order to compare with the uncoded system. In the receiver end, we will apply soft output viterbi decoding algorithm.

For each encoded bit, the correlator output can be written as:

$$\alpha_j=\int_0^T r(t)\sum_{l=0}^{L-1}a_l\sum_{n=0}^{N_c-1}c_nw_{rec}\left(t-jT_f-nT_c-\tau_l\right)dt. \tag{14}$$

In the proposed SOVA scheme, we will normalize the correlator output α_j to the input of the decoder. The metric of SOVA is generated according to the correlator output α_j. According to the characteristics of the correlator output, the SOVA is the optimal decoding algorithm for this system. The decoding complexity grows linearly with *K*. Since in the practical system, the value of *K* is relatively low, the coded system is completely practical. In this paper, we use a simple convolutional encoder with code rate being 1/2.

According to the generating function of this kind of convolutional encoder given in [4], [9]

$$T_{SO}(\gamma,\beta)=\frac{\beta W^{K+2}(1-W)}{1-W\left[1+\beta\left(1+W^{K-3}-2W^{K-2}\right)\right]}, \tag{15}$$

where γ and β in each term of the polynomial indicate the number of paths and output-input path weights, respectively. We set $W=\gamma^{2^{K-3}}=Z^{2^{K-3}}$ and $Z=\int_{-\infty}^{+\infty}\sqrt{p_0(y)\,p_1(y)}dy$, where $p_0(y)$ and $p_1(y)$ are the probability density functions of pulse correlator output. The free distance of this code can be expressed as $d_f=2^{K-3}(K+2)=N_s(\log_2 N_s+4)/2$. The bit error probability can be obtained as [9],

$$P_b=Q\left(\sqrt{2\frac{E_s}{I_0}d_f}\right)\sum_{k=d_f}^{\infty}b_k e^{-k\left(\frac{E_s}{I_0}\right)}e^{d_f\left(\frac{E_s}{I_0}\right)}, \tag{16}$$

where $\frac{E_s}{I_0}=\frac{N_cE_w}{N_0}\left[\sum_{l=0}^{L-1}a_l^2+\sum_{l=0}^{L-1}\sum_{k=0,l\neq k}^{L-1}a_la_kR(\tau_l-\tau_k)\right]$.

For a uniform power delay profile (PDP), we obtain the following upper bound P_e on P_b according to (16), it can be expressed as below [4], [9]:

$$\begin{aligned}P_e&\le e^{d_f\left(\frac{E_s}{I_0}\right)}Q\left(\sqrt{2\left(\frac{E_s}{I_0}\right)d_f}\right)\frac{dT(Z,\beta)}{d\beta}\bigg|_{\beta=1,Z=e^{-\left(\frac{E_s}{I_0}\right)},Z=\gamma}\\&=\gamma^{-d_f}Q\left(\sqrt{2\left(\frac{E_s}{I_0}\right)d_f}\right)W^{K+2}\left(\frac{1-W}{(1-2W)\left(1-W^{K-2}\right)}\right)^2\\&=Q\left(\sqrt{2\left(\frac{E_s}{I_0}\right)d_f}\right)\left(\frac{1-W}{(1-2W)\left(1-W^{K-2}\right)}\right)^2,\end{aligned} \tag{17}$$

$$P_e\le Q\left(\sqrt{\frac{2d_fN_cE_w}{N_0}\left[\sum_{l=0}^{L-1}a_l^2+\sum_{l=0}^{L-1}\sum_{k=0,l\neq k}^{L-1}a_la_kR(\tau_l-\tau_k)\right]}\right)\left(\frac{1-W}{(1-2W)\left(1-W^{K-2}\right)}\right)^2. \tag{18}$$

The lower bound in this case can be obtained as

$$P_e>Q\left(\sqrt{\frac{2d_fN_cE_w}{N_0}\left[\sum_{l=0}^{L-1}a_l^2+\sum_{l=0}^{L-1}\sum_{k=0,l\neq k}^{L-1}a_la_kR(\tau_l-\tau_k)\right]}\right). \tag{19}$$

From the above equation, it can be realized that in the coded scheme, the effective order of the processing gains is the product of *L* (the number of branches in SRake receiver) and the free distance of the code. This product plays an important role in deciding the bit error performance and it makes the different performance of the coded and uncoded system. In order to get better BER performance, we can increase the SRake branches to gather more multipath components, but the system complexity will be increased correspondingly.

4 Simulations Results

In this section, we present some computer simulation results about these two systems. Like the same example in [1], the received pulse is modeled as $w_{rec}(t) = \left[1 - 4\pi\left(\frac{t}{\tau_m}\right)^2\right]\exp\left[-2\pi\left(\frac{t}{\tau_m}\right)^2\right]$, shown in Fig.4, where $\tau_m = 0.2$ ns, $T_w = 0.5$ ns. The gold code sequence used here has the characteristics with length $N_c = 7$ and chip duration $T_c = 20$ ns. For each information bit, we repeat it twice for the comparison of the two systems. The information bit rate is $R_b = 1/T_f = 1/(N_s N_c T_c)$ *bps.*

The channel impulse response of the IEEE model [10] can be expressed as follows:

$$h(t) = X\sum_{n=1}^{N}\sum_{k=1}^{K(n)}\alpha_{nk}\delta(t - T_n - \tau_{nk}), \tag{20}$$

where X is a log-normal random variable representing the amplitude gain of the channel, N is the number of observed clusters, K(n) is the number of multipath contributions received within the n-th cluster, α_{nk} is the coefficient of the k-th multipath contribution of the n-th cluster, T_n is the time arrival of the n-th cluster, and τ_{nk} is the delay of the k-th multipath contribution within the n-th cluster. The IEEE suggested an initial set of values for the parameters of UWB channel. The list of parameters for different environment scenarios is provided in Table 1.

Table 1. Parameters for IEEE UEB channel scenarios

Channel Model (CM1~4)	Λ	λ	Γ	γ	σ_ξ	σ_ζ	σ_g
Case 1 LOS (0-4m)	0.0233	2.5	7.1	4.3	3.3941	3.3941	3
Case 2 NLOS (0-4m)	0.4	0.5	5.5	6.7	3.3941	3.3941	3
Case 3 NLOS (4-10m)	0.0667	2.1	14	7.9	3.3941	3.3941	3
Case 4 NLOS Multipath Channel	0.0667	2.1	24	12	3.3941	3.3941	3

We have the parameters defined as:
- The cluster average arrival rate Λ,
- The pulse average arrival rate λ,

- The power decay factor Γ for clusters,
- The power decay factor γ for pulses within a cluster,
- The standard deviation σ_ξ of the fluctuations of the channel coefficients for clusters,
- The standard deviation σ_ζ of the fluctuations of the channel coefficients for pulses within each cluster,
- The standard deviation σ_g of the channel amplitude gain.

In the simulation, we consider the channel model is CM3 and CM4 suggested by IEEE and the number of SRake branches is 3 and 5. The BER performance of the coded and uncoded DS-UWB systems with different SRake branches (SRake=3 and 5) is shown in Fig.5 and Fig.6, respectively. When SRake=3 and BER is around 10^{-4}, the coded scheme can get about 1dB gains compared with the uncoded scheme under CM3 and CM4. When SRake=5, the coded scheme can get about 1dB or 3dB gains around the BER being 10^{-4} with CM=3 and CM=4, respectively. From these two figures, the performance of the coded DS-BPAM UWB scheme is better than the uncoded one with the increase of SRake branches.

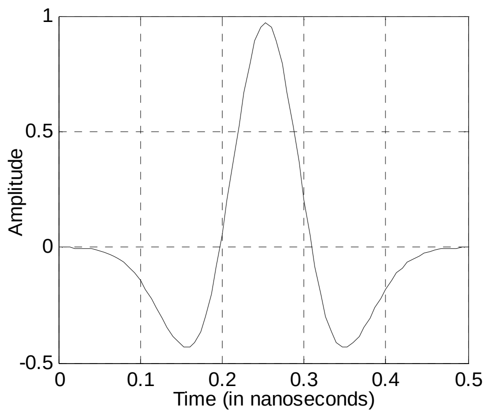

Fig. 4. Transmit Gaussian Waveform

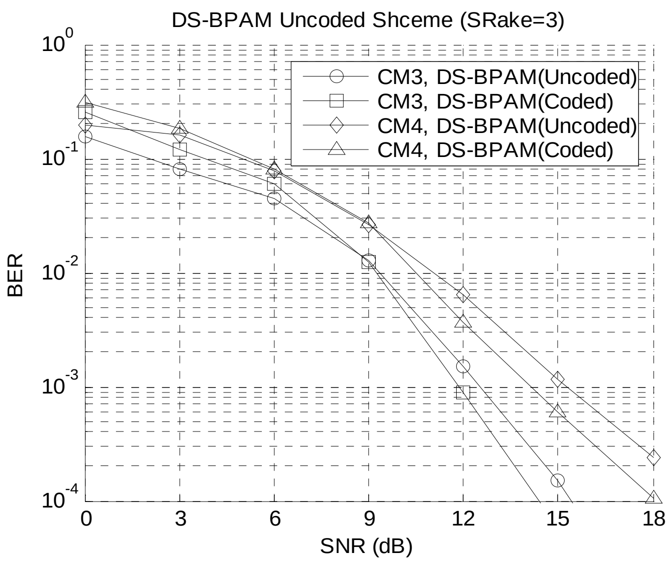

Fig. 5. BER performance of DS-UWB (SRake=3)

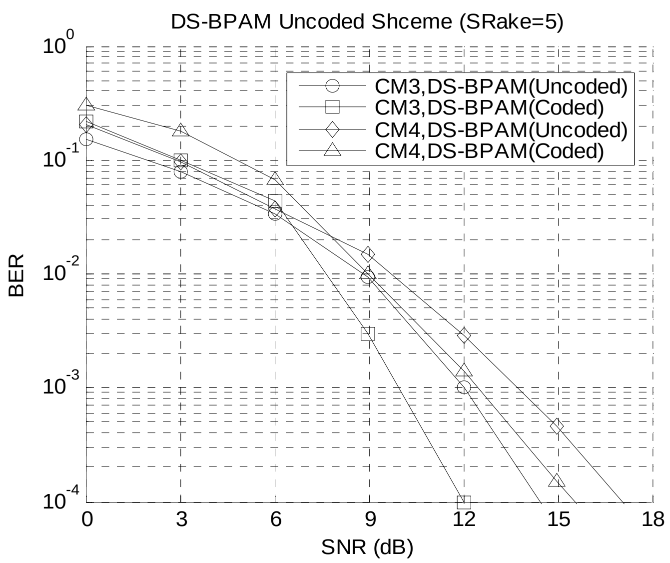

Fig. 6. BER performance of Coded DS-UWB (SRake=5)

5 Conclusions

In this paper, the performance of coded and uncoded DS-UWB system is analyzed over UWB multipath fading channel. In order to minimize the power consumption and get better performance, bipolar modulation is used here. A useful BER expression is deduced for uncoded DS-UWB scheme; for coded DS-UWB scheme, an upper bound and lower bound of BER are achieved. The analysis and simulation results show that the coded scheme is outperform the uncoded system significantly with acceptable complexity improvement. From the bit error probability expression of the coded scheme, we can see that the free distance d_f and the number of SRake fingers play an important role in deciding the system performance.

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