Direct-Sequence / Spread-Spectrum Communication System with Sampling Rate Selection Diversity

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***Abstract*— In this paper, sampling rate selection diversity (SRSD) scheme for Direct-Sequence / Spread-Spectrum (DS/SS) is proposed. In DS/SS communication systems, oversampling may be employed to increase the signal-to-noise ratio (SNR). However, oversampling enlarges the power consumption because signal processing of the receiver has to be carried out with higher clock. Higher sampling rate does not always maximize the SNR. In the proposed SRSD scheme, the power consumption can be reduced by selecting the optimum sampling rate depending on the characteristics of the channel. The proposed SRSD scheme can also reduce the BER more than the conventional oversampling scheme under the certain channel conditions.**

I. INTRODUCTION

Recently, DS/SS is a mainstream technology for wireless communication systems, such as Wideband-Code Division Multiple Access (W-CDMA), or IEEE802.11b Wireless Local Area Network (WLAN). In the DS/SS system, a RAKE receiver is used to improve the BER performance. The RAKE receiver can gather more signal energy and achieve multipath diversity.

In [1] the effect of tap spacing on the RAKE receiver has been evaluated, particularly when the received signal is sampled at higher than the Nyquist rate. By using the optimum combining rule, the filtered noise is whitened [3], [4]. The BER can be then reduced when the sampling rate is high. However, the tap positions and the sampling rate are fixed regardless of the characteristics of the channel in the conventional scheme. The RAKE receiver with oversampling can not always gather the largest signal energy. Furthermore, the power consumption of the RAKE receiver becomes high in proportion to the sampling rate.

In order to reduce the power consumption, the sampling rate should be low. In this paper, the SRSD scheme is proposed to reduce the average oversampling rate without degradation of the BER. The proposed scheme selects the tap positions and the sampling rate depending on the characteristics of the channel. When the delay spread is large, signal energy can be gathered even if sampling rate is low. This is because the RAKE receiver is able to cover the dominant multipath. On the other hand, when the delay spread is small, the RAKE receiver with higher oversampling rate works effectively. Therefore, the sampling rate is selected to maximize the SNR [3], [4].

In this paper, the proposed SRSD scheme in IEEE802.11b is simulated. The BER of the proposed scheme is compared with the conventional scheme in which the tap positions and the oversampling rate, are fixed and the probability of the sampling rate reduction is evaluated. The total power consumption may be reduced in proportion to this probability.

This paper is organized as follows. Section 2 gives the system and channel models. In Section 3, the proposed schemes are explained. Section 4 shows the numerical results through computer simulation. Section 5 gives our conclusions.

II. SYSTEM AND CHANNEL MODEL

A. System Model

Fig.1 shows a system model used in this paper. The IEEE802.11b baseband model for the case of one user is assumed [3], [4]. The transmitted signal is expressed as

$$x(t) = \sqrt{E_b} \sum_{i=-\infty}^{+\infty} \frac{s(i)}{\sqrt{N}} \sum_{n=0}^{N-1} c(n) p(t - nT_c - iT) \tag{1}$$

where E_b is the average symbol energy, T is the symbol period, $s(i)$ is the ith BPSK symbol (± 1), T_c is the chip period, $\{c(n); n = 1, \ldots, 11\}$ is the 11 chip Barker code, $p(t)$ is the chip pulse shape, and N is the spreading factor $(= 11)$ [6], [7]. The chip pulse is filtered by a root raised cosine filter with the rolloff factor of 0.5.

The received signal at the receiver front end can be expressed as

$$r(t) = \sum_{l=1}^{L} g_l \otimes x(t - \tau) + n(t) \tag{2}$$

where $\otimes$ denotes the convolutional operation, g_l is the channel impulse response of the lth path, L is the number of paths, and $n(t)$ is the additive white Gaussian noise (AWGN).

The tap spacing of the RAKE receiver is not integer times of the chip duration when the received signal is oversampled. The noise components of the signal on all the taps are correlated to each other. To solve this problem, the optimum combining rule of the RAKE receiver has been proposed in [3].

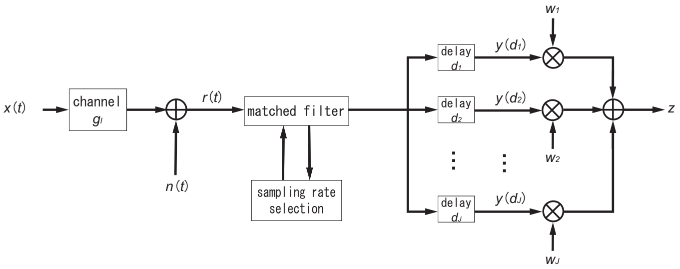

Fig. 1. System Model

The received signal is despread by the matched filter. The spreading waveform $a(t)$ can be expressed as

$$a(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} c(n) p(t - nT_c). \tag{3}$$

From Eqs.(2) and (3), the output of the matched filter can be written as

$$y(d_j) = \sum_{m=0}^{MN-1} r_s(m + d_j) a_s(m) \tag{4}$$

where $r_s(m) = r(m\frac{T_c}{M})$, $a_s(m) = a(m\frac{T_c}{M})$, and $\{d_j; j = 1, \ldots, J\}$ is the delay of the jth branch of the RAKE receiver, M is the oversampling ratio. J is the number of taps. d_j is varied depending on the oversampling rate. The despread signals are combined using the optimum combining weights $\mathbf{w} = [w_1, w_2, \ldots, w_J]$. The output value of RAKE receiver can be expressed as

$$z = \mathbf{w}^H \mathbf{y} \tag{5}$$

where $\mathbf{y} = [y(d_1), y(d_2), \ldots, y(d_J)]^T$. $\mathbf{y}$ can be expressed as

$$\mathbf{y} = \mathbf{h} s(0) + \mathbf{u} \tag{6}$$

where $\mathbf{h}$ is the vector of values corresponding to the symbol of interest and $\mathbf{u}$ models the overall noise (noise and interference). $\mathbf{h}$ can be approximated as

$$\mathbf{h} \approx \mathbf{B}\mathbf{g} \tag{7}$$

where $\mathbf{B}$ is $J \times L$ matrix whose element in the ith row and jth column is $r_p(d_i - d_j)$ [3]. $r_p(m)$ is the deterministic autocorrelation function for the sampled chip pulse shape $p_s(m)$. $J \times J$ matrix $\mathbf{R}$ which is the covariance matrix of $\mathbf{u}$ is similar to $\mathbf{B}$. The elements of $\mathbf{R}$ can be approximated by $r_p(d_i - d_j)$.

Based on an maximum likelihood (ML) approach $\mathbf{w}$ can be expressed as

$$\mathbf{w} = \mathbf{R}^{-1}\mathbf{h}. \tag{8}$$

In this combining rule of the RAKE receiver, the filtered noise can be whitened.

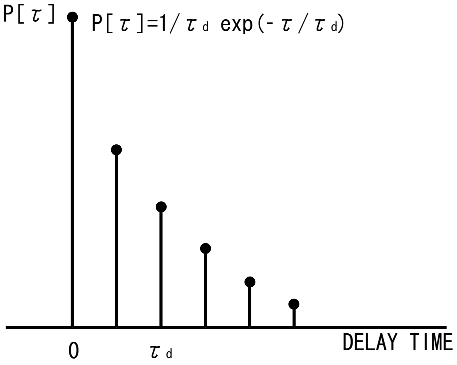

Fig. 2. Path Delay Profile For an Exponential Channel Model

B. Channel Model

In this paper, an uniform channel model and an exponential channel model are employed. The exponential channel model is recommended in IEEE802.11. This model represents a real world scenario in which the positions of the reflectors generate paths that have longer delay [8], [9]. As shown in Fig.2, the path delay profile for this model has the form: $P[\tau] = 1/\tau_d \exp(-\tau/\tau_d)$ where the parameter τ_d completely characterizes the path delay profile. For the exponential model, the maximum excess delay:

$$\tau_m = \frac{A \times \tau_d}{10 \times \log_{10}(e)},$$

where A is the amplitude of the smallest noticeable amplitude given in dB relative to the amplitude of the 0th delay (line of site) path.

In this paper, τ_d and A are set based on the JTC model which is presented in 1994 by the Joint Standards Committee (JTC) [9]. Table I and II shows τ_d and A for the 2 different channels that compose the indoor residential and the indoor office JTC model respectively.

TABLE I
INDOOR RESIDENTIAL JTC CHANNEL MODEL

	Channel A	Channel B
τ_d [ns]	18	70
A [dB]	18.9	20.3

TABLE II
INDOOR OFFICE JTC CHANNEL MODEL

	Channel A	Channel B
τ_d [ns]	35	100
A [dB]	7.2	21.7

C. Synchronization

The synchronization with the received signal is achieved by detecting the peak of the matched filter output [5]. The output

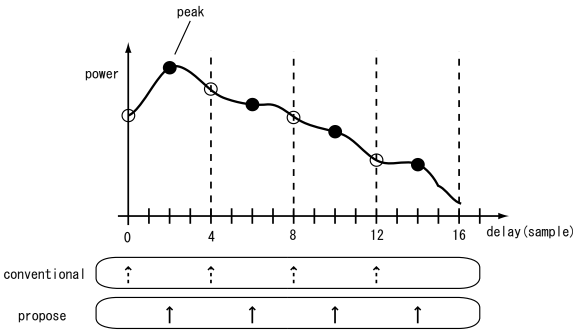

Fig. 3. Tap Position

TABLE III

SIMULATION CONDITIONS

Number of Trials	10000 times
Modulation Scheme	BPSK
Data Length	1000 bits
Preamble Length	128 bits
Number of Taps	4
Number of Users	1
Spreading Sequence	Barker code
Sequence Length	11

of the matched filter is averaged in terms of the corresponding phase of the spreading code during the preamble period. As shown in Fig.3, the first tap of the RAKE receiver is placed at the maximum peak of the averaged matched filter output.

III. SAMPLING RATE SELECTION DIVERSITY

A. Conventional Scheme

In [1] the effect of tap spacing on the RAKE receiver has been evaluated, particularly when the tap spacing is not integer times of the chip duration. The noise components of the signal on all the taps are correlated to each other. Optimum combining rule has been used in order to whitening filtered noise. By enlarging the number of taps in the RAKE receiver with a narrower tap spacing over the full range of the delay spread, the RAKE receiver can gather more signal energy and achieve multipath diversity. For this reason, the BER can be reduced when the sampling rate is high.

However, as the number of taps increases, the complexity and the power consumption of the receiver also grow.

B. Proposed Scheme

The SRSD scheme is proposed to reduce the power consumption. The oversampling rate is selected to maximize the SNR depending on the characteristics of the channel. The SNR of the fading channel is given by [3]:

$$\mathrm{SNR}(\mathbf{h}) = E_b/N_0 \mathbf{h}^H \mathbf{R}^{-1} \mathbf{h} \tag{9}$$

where $\mathbf{h}$ and $\mathbf{R}$ are the net channel response and the normalized noise covariance as defined in section 2. $\mathrm{SNR}(\mathbf{h})$ is estimated at each oversampling rate in the preamble period of the packet. The oversampling rate for the data signals is selected to maximize the SNR.

With the SRSD scheme, the BER can be reduced without increasing the number of taps. It can also reduce the average oversampling rate which is relative to the power consumption.

IV. NUMERICAL RESULTS

A. Simulation Conditions

The simulation conditions are shown in Table III. BPSK is employed as the modulation scheme. Barker code with the length of 11 is used for spreading. One packet consists of the preamble part of 128 bits and data part of 1000 bits. 10000 packets are simulated with different channel conditions. The number of RAKE taps is set to 4.

B. Effect of the Tap Position

Independent multipath Rayleigh fading is assumed here. The number of multipath is set to 4 and uniform delay profile is employed.

Figs.4, 5, 6 and 7 depict the BER versus E_b/N_0 of the conventional scheme which employs oversampling at the rate of 1, 2, and 4 and the proposed scheme. ”Theory” means the theoretical BER of BPSK modulation on a Rayleigh fading channel with diversity order 1, 2 and 4. The tap delay d_j is set to $\{1, 2, 3, 4\}$ for any oversampling rate. The delay spread and the path interval are set as T_c and $0.25T_c$ for Figs.4 and 5, $4T_c$ and T_c for Figs.6 and 7. The tap positions are fixed in Figs 4 and 6 and the first tap is placed at the maximum peak of the output of the matched filter in Figs.5 and 7. Comparing Fig.4 with Fig.5, and Fig.6 with Fig.7, the effect of the tap position is clearly shown. From these results the BER of the peak tap approach is better than the fixed tap approach. This is because the RAKE receiver can gather more signal energy from the reliable path. Table IV shows the probability of the sampling rate selection. From Table IV, the peak tap approach has higher probability of selecting the sampling rate of 1 as compared to that of the fixed tap approach.

C. Relation Between the Probability of the Sampling Rate Selection and the Characteristics of the Channel

The paths with the small delay spread and the large delay spread are considered in order to show the relation between

TABLE IV

PROBABILITY OF THE SAMPLING RATE SELECTION: CHANNEL MODEL IS RAYLEIGH

Delay Spread	Path Interval	Tap Placement	Sampling Rate Per Chip	
			1	4
T_c	$0.25T_c$	Fixed	8.82 %	91.18 %
		Peak	24.44 %	75.56 %
$4T_c$	T_c	Fixed	68.83 %	31.17 %
		Peak	90.95 %	9.05 %

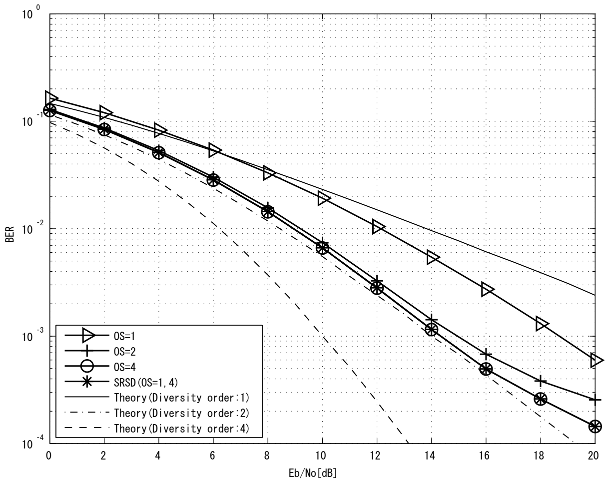

Fig. 4. BER vs. E_b/N_0; delay spread is T_c; path interval is $0.25T_c$; fixed tap placement

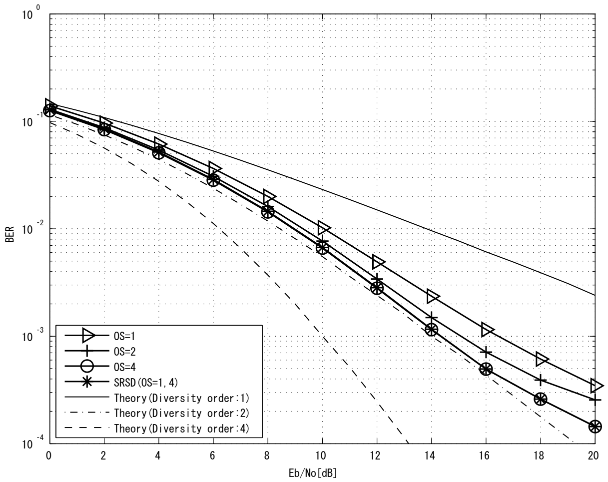

Fig. 5. BER vs. E_b/N_0; delay spread is T_c; path interval is $0.25T_c$; peak tap placement

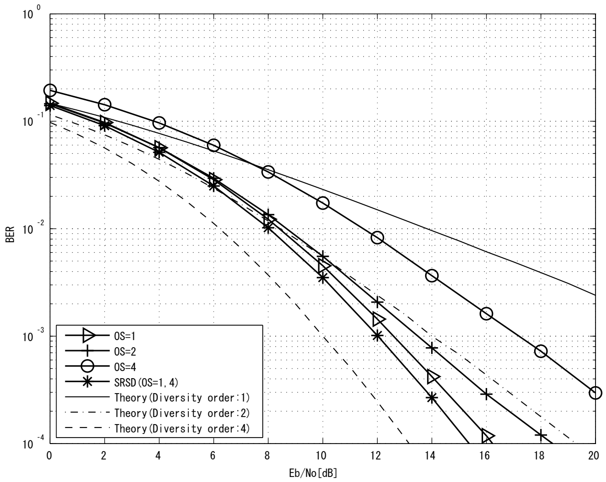

Fig. 6. BER vs. E_b/N_0; delay spread is $4T_c$; path interval is T_c; fixed tap placement

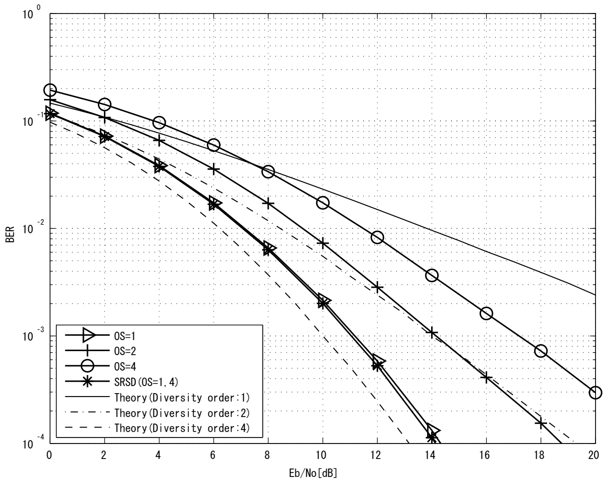

Fig. 7. BER vs. E_b/N_0; delay spread is $4T_c$; path interval is T_c; peak tap placement

the probability of the sampling rate selection and the characteristics of the channel.

Figs.4 and 5 shows that oversamping reduces the BER if the delay spread is small. The BER of the proposed SRSD scheme is similar to that of the conventional system with the oversampling rate of 4. The RAKE receiver can gather signal energy and achieve multipath diversity because the tap position is close to the path delays. In contrast, Figs.6 and 7 show that oversamping deteriorates the BER. The RAKE receiver with the oversampling rate of 4 can not gather the signal energy or achieve multipath diversity because the tap delay is smaller than the path delay. However, the BER of the proposed SRSD scheme shows similar BER performance to that of the conventional system with the oversampling rate of 1 when the delay spread is large.

From these results, higher sampling rate does not always reduce the BER. Therefore, the optimum sampling rate is depending on the characteristics of the channel and it should be selected in order to gather more signal energy and achieve multipath diversity.

D. BER of the Proposed SRSD Scheme Under the Practical Indoor Channel Model

In order to simulate the proposed SRSD scheme under the practical indoor channel model, the exponential channel model based on JTC indoor model are used [9]. Figs.8, 9, 10 and 11 show the BER versus E_b/N_0 of the conventional system which employs oversampling at the rate of 1, 2, and 4 and the proposed system. The tap delay d_j is set to $\{1, 2, 3, 4\}$ for any oversampling rate. The channel model of Figs.8, 9, 10 and 11 are indoor residential A, indoor residential B, indoor office A and indoor office B. Table V shows the probability of the sampling rate selection.

From these results, it is shown that, the BER of Figs.8 and 10 is similar to that of Figs.4 and 5. This means that the oversamping reduces the BER. This is because the delay

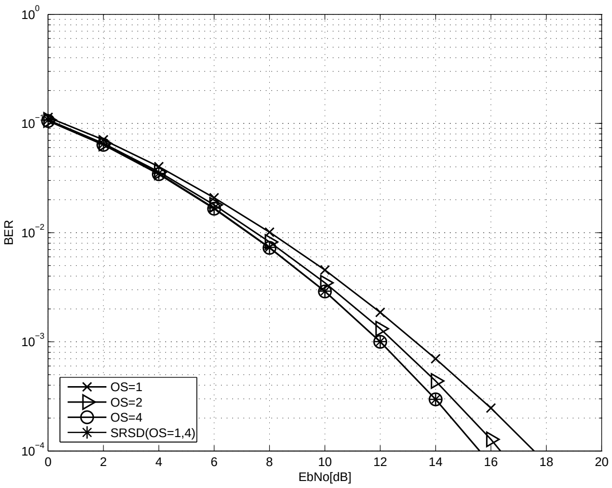

Fig. 8. BER vs. E_b/N_0: JTC indoor residential channel A

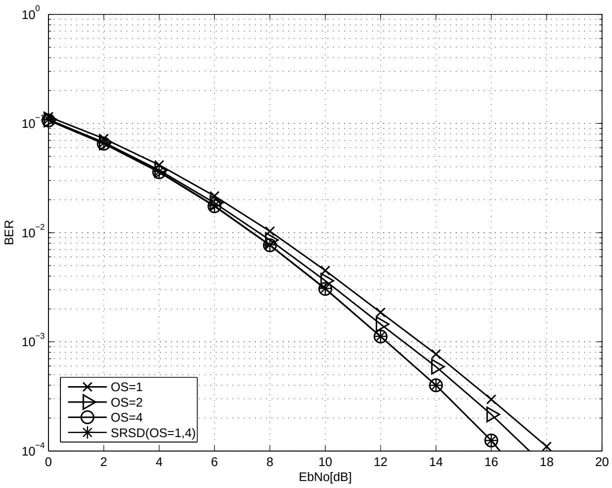

Fig. 10. BER vs. E_b/N_0: JTC indoor office channel A

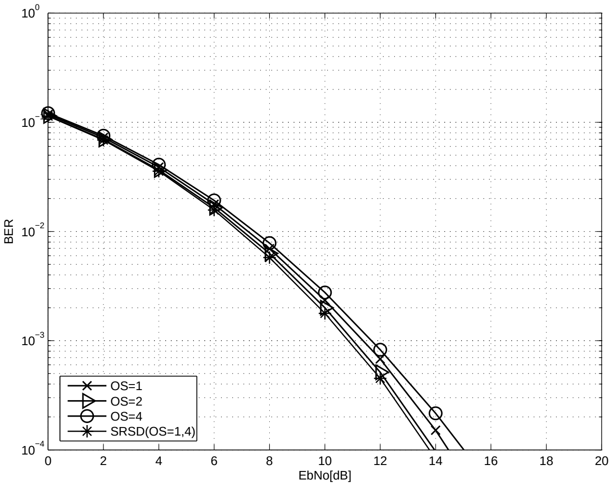

Fig. 9. BER vs. E_b/N_0: JTC indoor residential channel B

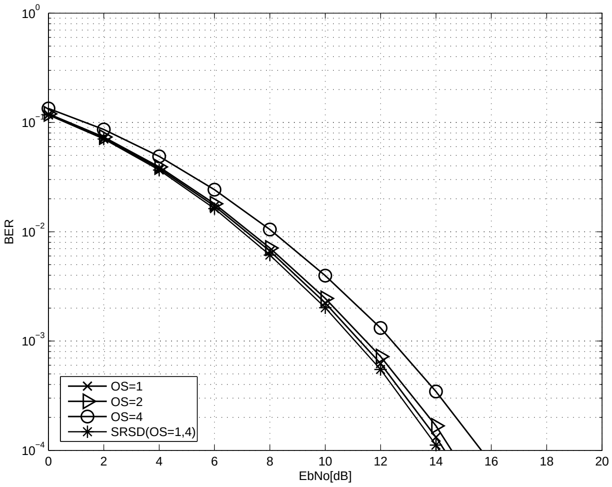

Fig. 11. BER vs. E_b/N_0: JTC indoor office channel B

spread of the indoor residential channel A and the indoor office channel A is small. From Table V, the probability of the oversampling rate switching from 4 to 1 is 38[%] and 33[%] for the indoor residential channel A and the indoor office channel A respectively. Suppose that the power consumption of the oversampling scheme is proportional to the oversampling rate. The power consumption in the proposed scheme is then almost the same as that of the oversampling rate of 3 when the probability of the oversampling rate of 1 is 33[%].

The BER of Figs.9 and 11 has the same tendency as that of Figs.6 and 7. It is shown that the oversamping deteriorates the BER. This is because the delay spread of the indoor residential channel B and the indoor office channel B is large. As for the SRSD scheme, the probability of the oversampling rate switching from 4 to 1 is 62[%] and 75[%] for the indoor residential channel B and the indoor office channel B respectively. The power consumption in the proposed scheme is close to that of the oversampling rate of 2 when the probability of the oversampling rate of 1 is 66[%]. Therefore the proposed SRSD scheme under the indoor residential channel B and the indoor office channel B can reduce the power consumption by half.

V. CONCLUSION

In this paper, the DS/SS with SRSD scheme has been proposed. It has been shown that, the proposed SRSD scheme can achieve the best BER under any channel conditions. It has also been shown, this SRSD scheme is able to reduce the power consumption in terms of the BER.

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TABLE V

PROBABILITY OF THE SAMPLING RATE SELECTION: CHANNEL MODEL IS THE EXPONENTIAL CHANNEL MODEL BASED ON JTC INDOOR CHANNEL MODEL

Indoor Scenario	Channel Model	Sampling Rate Per Chip	
		1	4
Indoor Residential	Channel A	37.84 %	62.16 %
	Channel B	61.92 %	38.08 %
Indoor Office	Channel A	32.92 %	67.08 %
	Channel B	74.66 %	25.34 %

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