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Closed BER expression of multi-user DS UWB systems in indoor fading channel

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Abstract: The bit error rate (BER) performance of multi-user direct spreading bi-phase shift keying (DS-BPSK) direct impulse ultra wideband (UWB) systems is analyzed and simulated based on a statistical indoor multi-path fading channel model. The BER of the system is theoretically derived and given in closed form, which is expressed in terms of channel parameters and system parameters such as pulse width parameter, pulse repeat period, user number and pulse waveform. With this BER expression, the effect of these parameters on the system performance can be evaluated in a uniform way. Simulation results well match the theory numerical results, and prove that the multi-access interference (MAI) of DS-BPSK UWB is a normal distribution.

Key words: ultra wideband (UWB); direct spreading (DS); bi-phase shift keying (BPSK); multi-user; fading channel; performance analysis

Ultra wideband (UWB) technique has been attracting great interest in recent years and has become one of the hotspots in the wireless communication field. As compared to the performance of original simple AWGN channel, single user, single antenna, and perfect receiving systems[1 – 4], many new developments and research topics have appeared about the system performances which now have spread to practical multi-path, multi-user, multi-antenna, and with non-ideal factors[5 – 12]. In Ref. [5], UWB system performance with multi-user interference (MUI) was studied. Ref. [6] mainly discussed the performance of antenna array or MIMO UWB systems, while Ref. [7] dealed with the system capacities. The choice of multi-access codes and time hopping sequences, the RAKE receiver and its new detecting and receiving techniques were presented in Refs. [8 – 12].

Two classes of UWB wireless transmission techniques can be divided according to the basic characteristics of UWB signals, i. e., impulse based and carrier based systems. Information data are modulated and transmitted on discrete pulse signals for impulse radio UWB, while the latter on continuous carriers for carrier based UWB systems. The impulse UWB technique is widely adopted as the main method for classical UWB systems and IEEE 802. 15. 4a Low Data Rate WPAN Task Group. The performance of direct spreading direct impulse multi-user UWB system in indoor multi-path channel is discussed in this paper based on the IEEE indoor statistical channel model[13]. The system bit error rate (BER) is derived in closed form, which is expressed in terms of the channel parameters, pulse parameters and user numbers. This BER expression will help to evaluate the effect of multi-path channels and system parameters and user numbers on performance, and help to design UWB systems.

1 Channel Model and Signal Model of the DS-BPSK UWB System

Use of the notes similar to those in Ref. [3] and the direct spreading bi-phase shift keying (DS-BPSK) system is considered. Supposing that the channels for different users are independent and without loss of generality, the single cluster is considered for the dual-exponential channel model. Thus, the multi-path channel of the u-th user is

$$h_u(t) = \Omega_u \sum_p c_{u,p}\delta(t - \tau_{u,p}) \tag{1}$$

where the ray delays $\{\tau_{u,p}, p = 1, 2, \dots\}$ are modeled as the arrive time of a Poisson process with the parameter λ, but for the first ray $\tau_{u,1} = 0$. The ray coefficients can be expressed as $c_{u,p} = \varepsilon_{u,p}\zeta_{u,p}$, and $\{\varepsilon_{u,p}\}$, $\{\zeta_{u,p}\}$ and $\{\Omega_u\}$ are independent. Where Ω_u is the path loss, $\varepsilon_{u,p}$ is the sign of $c_{u,p}$ and takes value 1 and -1 with equal probability, and $\zeta_{u,p}$ is the amplitude of $c_{u,p}$ which is a log normal random variable, i. e., $20\log_{10}\zeta_{u,p}$ has a normal distribution $N(\mu_{u,p}, \sigma^2)$, where

$$\mu_{u,p} = -\frac{10\tau_{u,p}/\gamma}{\ln 10} - \frac{\sigma^2 \ln 10}{20} \tag{2}$$

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The channel energy $Y_u = \sum_p c_{u,p}^2$ is a log normal random variable, i. e., $s = \ln Y_u$ is a normal random variable with a normal distribution $N(\mu_s, \sigma_s^2)$.

The transmitted signal of the u-th user is

$$x_{\mathrm{tr}}^{(u)}(t) = \sum_i a_i^{(u)} d_{\lfloor i/K \rfloor}^{(u)} w_{\mathrm{tr}}(t - iT_{\mathrm{c}} - T^{(u)}) \quad (3)$$

where T_{c} is the frame repeat period, $\{a_i^{(u)}\}$ is the spreading code of the u-th user. K is the spread factor; i. e., each bit contains K pulses. $d_{\lfloor i/K \rfloor}^{(u)}$ is $1/-1$ sequence representing bit 1 or 0 of the u-th user, which keeps the same value over K pulses. $T^{(u)}$ is the asynchronism of user u relative to user 1, which is a random variable uniformly distributed over $[0, T_{\mathrm{c}})$, but $T^{(1)} = 0$. $w_{\mathrm{tr}}(t)$ is the basic transmitted pulse.

As well known, after the distortion of the transmit antenna and receive antenna, $w_{\mathrm{tr}}(t)$ is received as

$$w_{\mathrm{rec}}(t) = \left[1 - 4\pi\left(\frac{t}{t_n}\right)^2\right]\exp\left[-2\pi\left(\frac{t}{t_n}\right)^2\right] \quad (4)$$

In the multi-path channel, the received signal for each transmitted pulse is the multi-path spread version of $w_{\mathrm{rec}}(t)$:

$$w^{(u)}(t) = \Omega_u \sum_p c_{u,p} w_{\mathrm{rec}}(t - \tau_{u,p}) \quad (5)$$

The $x_{\mathrm{tr}}^{(u)}(t)$ is received as

$$x^{(u)}(t) = \sum_i a_i^{(u)} d_{\lfloor i/K \rfloor}^{(u)} w^{(u)}(t - iT_{\mathrm{c}} - T^{(u)}) \quad (6)$$

Denote the total user number as M, the total received signal is

$$y(t) = \sum_{u=1}^{M} x^{(u)}(t) + N(t) \quad (7)$$

where $N(t)$ is the AWGN noise.

Without generalization, the perfect Rake receiver is used; i. e., the receiver uses the perfect estimated waveform. Suppose that user 1 is the target user, then

$$w^{(1)}(t) = \Omega_1 \sum_p c_{1,p} w_{\mathrm{rec}}(t - \tau_{1,p}) \quad (8)$$

is the local match waveform to receive each pulse from the 1st user. The output of the correlator is denoted as

$$D_i = \langle y(t), w^{(1)}(t - iT_{\mathrm{c}}) \rangle \quad (9)$$

K correlation outputs of each bit are de-spread and summed up as the decision variable,

$$D = \sum_{i=(q-1)K+1}^{qK} a_i^{(1)} D_i \quad (10)$$

For BPSK modulation, the current bit $d_q^{(1)}$ will be estimated as

$$\hat{d}_q^{(1)} = \begin{cases} +1 & \text{if } D > 0 \\ -1 & \text{if } D < 0 \end{cases} \quad (11)$$

2 Performance Analysis

In D_i, the contribution from all the pulses of user u is

$$D_i^{(u)} = \langle x^{(u)}(t), w^{(1)}(t - iT_{\mathrm{c}}) \rangle \quad (12)$$

The contribution from one pulse of user u is

$$z_u(T) = \langle w^{(u)}(t - T), w^{(1)}(t) \rangle \quad (13)$$

The contribution from noise is

$$D_{i,n} = \langle n(t), w^{(1)}(t - iT_{\mathrm{c}}) \rangle \quad (14)$$

Then

$$D_i = \langle y(t), w^{(1)}(t) \rangle = \sum_u \sum_m a_m^{(u)} d_{\lfloor m/K \rfloor}^{(u)} z_u(mT_{\mathrm{c}} + T^{(u)}) + D_{i,n} = \sum_u D_i^{(u)} + D_{i,n} \quad (15)$$

If the pulse is short enough and the overlap of consecutive paths can be neglected, the received energy from one chip is

$$Y = z_1(0) = \sum_p \sum_q c_{1,p} c_{1,q} R(\tau_{1,p} - \tau_{1,q}) \approx \sum_p c_{1,p}^2 R(0) \quad (16)$$

In the decision variable D, the useful signal component is

$$\sum_{i=(q-1)K+1}^{qK} D_i^{(1)} \approx d_q^{(1)} KY \quad (17)$$

The remain part is the sum of interference and noise component,

$$X = \sum_{u>1} \sum_{i=(q-1)K+1}^{qK} D_i^{(u)} + \sum_{i=(q-1)K+1}^{qK} D_{i,n} \quad (18)$$

Now, the statistical distribution characteristics of the above useful information part, the multi-user interference MUI part, and the noise part are derived as follows. First, the moments of $D_i^{(u)}$, $D_{i,n}$, X and Y in Eqs. (17) and (18) should be obtained.

The moments of Y (see appendix) are given by

$$E[Y] = \lambda\gamma + 1 \quad (19)$$

$$E[Y^2] = \lambda\gamma \frac{A}{2} + A + (\lambda^2\gamma + 2\lambda)\gamma + 2(\lambda^2\gamma + 2\lambda)\int_0^{\infty} \exp\left(-\frac{x}{\gamma}\right) R(x)^2 \mathrm{d}x \quad (20)$$

And the conditional moments of $D_i^{(u)}$ and $D_{i,n}$ for the given Y are

$$E[D_i^{(u)} \mid Y = Y_0] = 0 \quad (21)$$

$$E[D_{i,n} \mid Y = Y_0] = 0 \quad (22)$$

$$E[(D_i^{(u)})^2 \mid Y = Y_0] = Y_0(1 + \lambda\gamma)\frac{1}{T_{\mathrm{c}}} \cdot \int R(T)^2 \mathrm{d}T = Y_0(1 + \lambda\gamma)\frac{1}{T_{\mathrm{c}}} B \quad (23)$$

$$E[(D_{i,n})^2 \mid Y = Y_0] = \sigma_n^2 Y_0 \quad (24)$$

With these results and Eqs. (17) and (18), we have

$$E[X \mid Y = Y_0] = 0 \quad (25)$$

$$E[X^2 \mid Y = Y_0] = \sigma_{X|Y}^2 = K\{ME[(D_i^{(u)})^2 \mid Y] + E[(D_{i,n})^2 \mid Y]\} = K\left(MY\lambda\gamma \frac{1}{T_{\mathrm{c}}} B + Y\sigma_n^2\right) \quad (26)$$

Here the inter chip interference of the 1st user himself is also included in MUI.

Based on the above statistical results, the probability density functions (pdf) of X and Y are derived. According to the above channel model, Y is a lognormal random variable, i. e., $s = \ln Y \sim N(\mu_s, \sigma_s^2)$. With the property of log normal distribution

$$E[Y^m] = \exp\left(m\mu_s + \frac{1}{2}m^2\sigma_s^2\right) \tag{27}$$

And with the results of the above $E[Y]$ and $E[Y^2]$, we can obtain

$$\sigma_s^2 = \ln\frac{E[Y^2]}{\{E[Y]\}^2} \tag{28}$$

$$\mu_s = \ln\frac{\{E[Y]\}^2}{\sqrt{E[Y^2]}} \tag{29}$$

The pdf of $s = \ln Y$ is

$$f_s(s) = \frac{1}{\sigma_s\sqrt{2\pi}}\exp\left[-\frac{(s-\mu_s)^2}{2\sigma_s^2}\right] \tag{30}$$

For any given Y, when the total user number M is large, $(X \mid Y)$ will approach a normal variable, i. e., $(X \mid Y) \sim N(0, \sigma_{X\mid Y}^2)$. With Eq. (25), the conditional variation is

$$\sigma_{X\mid Y}^2 = \left(M\lambda\gamma\frac{1}{T_c}B + \sigma_n^2\right)K\exp(s) \tag{31}$$

Now the conditional pdf of X is

$$f_{X\mid Y}(x) = \frac{1}{\sqrt{2\pi\sigma_{X\mid Y}^2}}\exp\left(-\frac{x^2}{2\sigma_{X\mid Y}^2}\right) \tag{32}$$

For the given $Y = \exp(s)$, the conditional bit error rate condition on Y is

$$\begin{aligned} P_{e\mid Y} &= \Pr\{KY + X < 0 \mid Y\} = \\ &\int_{-\infty}^{-KY}\frac{1}{\sqrt{2\pi\sigma_{X\mid Y}^2}}\exp\left(-\frac{x^2}{2\sigma_{X\mid Y}^2}\right)\mathrm{d}x = \\ &\frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{-KY}{\sqrt{2\sigma_{X\mid Y}^2}}\right)\right] = \\ &\frac{1}{2}\left[1 + \operatorname{erf}\left(-\sqrt{\frac{K\exp(s)}{2(M\lambda\gamma B/T_c + \sigma_n^2)}}\right)\right] \end{aligned} \tag{33}$$

Then the total BER is

$$\begin{aligned} P_e &= \int P_{e\mid Y}\, f_s(s)\,\mathrm{d}s = \\ &\int\frac{1}{2}\left[1 + \operatorname{erf}\left(-\sqrt{\frac{K\exp(s)}{2(M\lambda\gamma B/T_c + \sigma_n^2)}}\right)\right]\cdot \\ &\frac{\exp\left[-\frac{(s-\mu_s)^2}{2\sigma_s^2}\right]}{\sqrt{2\pi\sigma_s^2}}\mathrm{d}s \end{aligned} \tag{34}$$

From this closed form formula which is directly expressed as the resolution function of channel parameters, pulse parameters and system user number, we can evaluate the effect of channel parameters and system parameters on the BER efficiently.

3 Numerical and Simulation Results

We will compare the simulation results and corresponding numerical results for the following parameters combinations: $\lambda = 0.5, 1, \ldots, 2.5\ \mathrm{ns}^{-1}$, $\gamma = 6, 8, \ldots, 12$ ns, pulse repeat period $T_f = 10$ ns, user number $M = 20$, spread factor $K = 1$, the energy of each received pulse $w_{rec}(t)$ is normalized to 1. For each user, 700 channel realizations are used, and in each channel realization 200 bits are transmitted.

The results calculated by analysis and given by simulation are then compared, the variances are compared in Fig. 1 with $T_c = 10$ ns, user number $M = 20$, $K = 1$, $\lambda = 2\ \mathrm{ns}^{-1}$. And the pdfs are compared in Fig. 2 with $T_c = 10$ ns, user number $M = 20$, $K = 1$, $\lambda = 2\ \mathrm{ns}^{-1}$, $\gamma = 12$ ns. It is clear that the curves are normally distributed. Thus, the assumption that the MUI is normal distribution is validated.

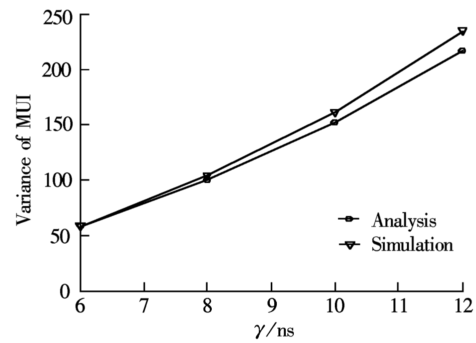

Fig. 1 Variance of MUI X given by simulation and analysis

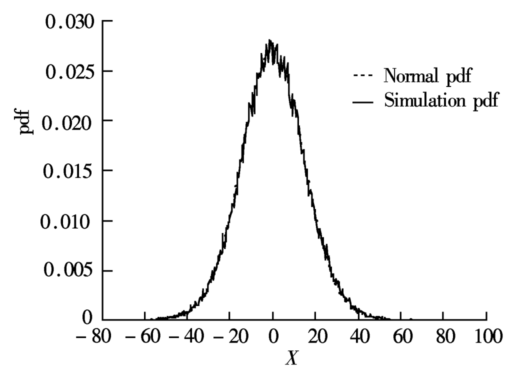

Fig. 2 Probability distribution function of X given by simulation and analysis

The BERs given by Eq. (34) and by simulation are compared in Fig. 3 with $T_c = 10$ ns, user number M

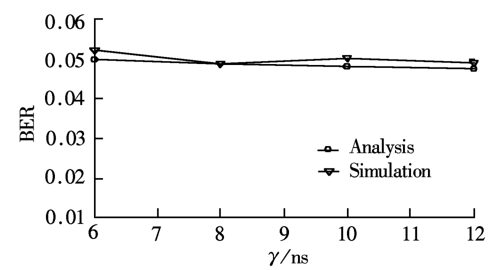

Fig. 3 Bit error rates given by simulation and analysis

$=20$, $K=1$, $\lambda=2\ \mathrm{ns}^{-1}$. It also clearly indicates that the numerical results fit the simulation results quite well.

4 Conclusion

In this paper, the performance of DS-BPSK multi-user ultra wideband wireless system with RAKE receiver is analyzed and simulated based on the modified final indoor statistical multi-path model which is proposed by Intel and adopted by IEEE 802. 15. 3a Task Group for high speed wireless personal area network (WPAN) applications. Through theoretical analysis, the bit error rate of the system is derived in closed form, which is directly expressed in terms of channel parameters and system parameters such as the pulse width, pulse repeat period and user number. By comparing the variances of MUI and the probability distribution function of the numerical results and simulation results, the assumption that the MUI is normal distributed is effectively validated. The BER performance of the numerical results also fits that of the simulation results quite well. With the BER expression derived in this paper, the effect of the channel and system parameters on the performance of the DS-BPSK UWB system can be evaluated in a convenient and uniform way.

Appendix Moments of X and Y

For convenience we give the moments of path coefficient

$$C_2(\tau)=E[c^2\mid\tau]=\exp\left[\frac{\sigma^2}{2}\left(\frac{\ln 10}{10}\right)^2+\mu(\tau)\frac{\ln 10}{10}\right]=\exp\left(-\frac{\tau}{\gamma}\right) \quad (\mathrm{A1})$$

$$C_4(\tau)=E[c^4\mid\tau]=\exp\left[\frac{\sigma^2}{2}\left(\frac{\ln 10}{5}\right)^2+\mu(\tau)\frac{\ln 10}{5}\right]=\exp\left[\frac{\sigma^2}{4}\left(\frac{\ln 10}{5}\right)^2-\frac{2\tau}{\gamma}\right]=A\exp\left(-\frac{2\tau}{\gamma}\right) \quad (\mathrm{A2})$$

and

$$\int_0^\infty C_2(x)\,\mathrm{d}x=\gamma \quad (\mathrm{A3})$$

$$\int_0^\infty C_4(x)\,\mathrm{d}x=A\frac{\gamma}{2}=\frac{\gamma}{2}\exp\left[\frac{\sigma^2}{4}\left(\frac{\ln 10}{5}\right)^2\right] \quad (\mathrm{A4})$$

According to the channel model, the mean of any path coefficients is 0, and coefficients of different paths are independent, then it is obvious that

$$E[Y]=E[z_1(0)]=E\left[\sum_p\sum_q c_{1,p}c_{1,q}R(0+\tau_{1,p}-\tau_{1,q})\right]=E\left[\sum_q c_{1,q}^2R(0)\right]=\int C_2(x)R(0)\lambda\,\mathrm{d}x+C_2(0)=\lambda\gamma R(0)+1=\lambda\gamma+1 \quad (\mathrm{A5})$$

$$\begin{aligned}E[Y^2]&=E[z_1(0)^2]=E\left[\sum_{p_1,p_2,p_3,p_4}c_{1,p_1}c_{1,p_2}c_{1,p_3}c_{1,p_4}\cdot R(\tau_{1,p_1}-\tau_{1,p_2})R(\tau_{1,p_3}-\tau_{1,p_4})\right]=\\
&E\Big[\sum_{p_1=p_2=p_3=p_4}c_{1,p_1}^4R(0)^2\Big]+E\Big[\sum_{p_1=p_2\neq p_3=p_4}c_{1,p_1}^2c_{1,p_3}^2R(0)^2\Big]+\\
&E\Big[\sum_{p_1=p_3\neq p_2=p_4}c_{1,p_1}^2c_{1,p_2}^2R(\tau_{1,p_1}-\tau_{1,p_2})^2\Big]+\\
&E\Big[\sum_{p_1=p_4\neq p_2=p_3}c_{1,p_1}^2c_{1,p_2}^2R(\tau_{1,p_1}-\tau_{1,p_2})R(\tau_{1,p_2}-\tau_{1,p_1})\Big]=\\
&\lambda\gamma\frac{A}{2}+C_4(0)+\int_0^\infty\mathrm{d}x\int_0^\infty\exp\left(-\frac{x+y}{\gamma}\right)\cdot[1+2R(x-y)^2]\lambda^2\mathrm{d}y+2C_2(0)\int_0^\infty C_2(y)\cdot\\
&[1+R(-y)^2+R(y)R(-y)]\lambda\mathrm{d}y=\lambda\gamma\frac{A}{2}+\\
&C_4(0)+\lambda^2\frac{\gamma}{2}\int_{-\infty}^\infty\exp\left(-\frac{|x|}{\gamma}\right)[1+2R(x)^2]\mathrm{d}x+\\
&2C_2(0)\int_0^\infty C_2(y)[1+R(-y)^2+R(y)R(-y)]\lambda\mathrm{d}y=\\
&\lambda\gamma\frac{A}{2}+A+(\lambda^2\gamma+2\lambda)\gamma+2(\lambda^2\gamma+2\lambda)\cdot\\
&\int_0^\infty\exp\left(-\frac{x}{\gamma}\right)R(x)^2\mathrm{d}x\end{aligned} \quad (\mathrm{A6})$$

We assume that the spreading code is an independent sequence, then for the given $Y=Y_0$, the conditional moments of interference component and noise component are

$$E[D_i^{(u)}\mid Y=Y_0]=E\Big[\sum_m z_u(T-mT_\mathrm{c})\mid Y=Y_0\Big]=0 \quad (\mathrm{A7})$$

$$E[D_{i,n}\mid Y=Y_0]=0 \quad (\mathrm{A8})$$

$$\begin{aligned}&E[(D_i^{(u)})^2\mid Y=Y_0]=E\Big[\sum_m z_u(T-mT_\mathrm{c})^2\mid Y=Y_0\Big]=\\
&E\left[\sum_{m,p_1,p_2,q_1,q_2}c_{u,p_1}c_{u,p_2}c_{1,q_1}c_{1,q_2}R(T-mT_\mathrm{c}+\tau_{u,p_1}-\tau_{1,q_1})\cdot R(T-mT_\mathrm{c}+\tau_{u,p_2}-\tau_{1,q_2})\mid Y=Y_0\right]=\\
&E\left[\sum_m\sum_p\sum_q c_{u,p}^2c_{1,q}^2R(T-mT_\mathrm{c}+\tau_{u,p}-\tau_{1,q})^2\mid Y=Y_0\right]=\\
&E\left[\sum_p\sum_q c_{u,p}^2c_{1,q}^2\int_{-\infty}^\infty\frac{1}{T_\mathrm{c}}R(T+\tau_{u,p}-\tau_{1,q})^2\mathrm{d}T\mid Y=Y_0\right]=\\
&E\left[\sum_p\sum_q c_{u,p}^2c_{1,q}^2\mid Y=Y_0\right]\cdot\int\frac{1}{T_\mathrm{c}}R(T+\tau_{u,p}-\tau_{1,q})^2\mathrm{d}T=\\
&E\Big[\sum_p c_{u,p}^2\sum_q c_{1,q}^2\mid Y=Y_0\Big]\cdot\int\frac{1}{T_\mathrm{c}}R(T+\tau_{u,p}-\tau_{1,q})^2\mathrm{d}T=\\
&Y_0\left[C_2(0)+\int C_2(x)\lambda\mathrm{d}x\right]\cdot\int\frac{1}{T_\mathrm{c}}R(T)^2\mathrm{d}T=\\
&Y_0(1+\lambda\gamma)\cdot\frac{1}{T_\mathrm{c}}\int R(T)^2\mathrm{d}T\end{aligned} \quad (\mathrm{A9})$$

for noise component

$$\begin{aligned}&E[(D_{i,n})^2\mid Y=Y_0]=E\left[\left(\int n(t)w^{(1)}(t)\mathrm{d}t\right)^2\mid Y=Y_0\right]=\\
&E\left[\iint n(t_1)n(t_2)w^{(1)}(t_1)w^{(1)}(t_2)\mathrm{d}t_1\mathrm{d}t_2\mid Y=Y_0\right]=\\
&E\left[\iint\delta(t_1-t_2)w^{(1)}(t_1)w^{(1)}(t_2)\mathrm{d}t_1\mathrm{d}t_2\mid Y=Y_0\right]=\\
&E\left[\sigma_n^2\int(w^{(1)}(t))^2\mathrm{d}t\mid Y=Y_0\right]=\sigma_n^2Y_0\end{aligned} \quad (\mathrm{A10})$$

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直扩多用户超宽带系统在室内衰落信道下的 BER 表达式

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摘要：基于室内多径衰落信道统计模型，分析并仿真了直扩二相相移键控多用户超宽带无线通信系统的比特误码率性能. 通过理论分析，推导出了系统比特误码率性能的解析表达式，该表达式表示为脉冲宽度、脉冲重复周期、用户数以及脉冲波形等信道参数和系统参数的函数，从而可以方便、统一地分析这些参数对系统性能的影响. 仿真结果与基于理论分析的数值计算结果相当吻合，表明直扩二相相移键控超宽带系统的多址干扰为正态分布.

关键词：超宽带；直扩；二相相移键控；多用户；衰落信道；性能分析

中图分类号：TN92