Design of Synchronization Signal Embedded Optical Wireless Differential OOK

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***Abstract*—In this paper, as binary modulation schemes, the differentially on-off keying (DOOK) system, which can achieve anti-background noise capability and high data transmission efficiency, is considered. One of the serious problems encountered in the optical-wireless framed-DOOK system is to overcome the synchronization slip problem. In order to improve the performance of synchronization signal detection, is designed $\{-1, 1\}$-synchronization pattern embedded framed-DOOK so far. In this paper, the theoretical formula of synchronization retention time is derived. Also, the bit error rate characteristic under the perfect synchronization is shown. The synchronization retention time taking into account false alarm rate is evaluated when the false alarm rate achieves 10^{-2} under the optical-wireless channel with scintillation and background noise. Consequently, in the evaluation of synchronization retention time taking into account false alarm rate, the proposed framed-DOOK system outperforms the conventional framed-DOOK system. Moreover, the evaluation of synchronization retention time taking into account false alarm rate achieves 10^8 blocks when transmission power per bit is more than -40[dBm], the number of the information bits per frame is larger than 4 and background noise is less than -38[dBm].**

I. Introduction

The optical wireless communications, which include visible light communications using Light Emitting Diode (LED) and infrared communications, have been increasing interest due to simplicity of equipment and easiness of globalization with license-free. Especially, the optical wireless communications using Intensity Modulation / Direct Detection (IM/DD) schemes are considered [1][2]. In the IM/DD schemes, the binary modulation schemes can avoid nonlinear characteristics of optical transmission / photodetector. A pulse position modulation (PPM) and an on-off keying (OOK) are well known as the binary modulation scheme [3]∼[6].

PPM selects one slot from M slots in frame by the source data. Since PPM is one of the M-ary orthogonal modulation schemes, the error rate performance can be improved by increasing M. Moreover, PPM has an anti-background noise capability because the PPM signal is demodulated by a maximum value decision. Also, the information transmission efficiency per slot decreases with increasing M because the information transmission efficiency per slot becomes $(\log 2M)/M$ [bit/slot]. In addition, PPM needs accurate frame synchronization.

OOK is a modulation scheme that expresses a source bit-data by having pulse signal or not. Thus, OOK can achieve 1[bit/slot] in information transmission efficiency. However, OOK is affected by background noise because the transmitted signal is estimated by threshold decision. Moreover, in OOK, a synchronization slip occurs with the period of time during which same-valued signal continues.

In this paper, we focus on OOK, which is better than PPM in information transmission efficiency. Especially, we consider a differential OOK (DOOK) scheme which is a modified version of OOK. Although DOOK has the anti-background noise capability, DOOK also has synchronization slip problem like the OOK scheme. In order to solve the synchronization slip problem, the synchronization signal-embedded framed-DOOK system has been proposed [7]. In [7], the conventional framed-DOOK system, which adds 1-bit synchronization signal to the frame signal, can reduce the synchronization slip. To improve the synchronization performance of the conventional framed-DOOK system, we suggested a new framed-DOOK system that has the synchronization signal in a frame [8].

In this paper, we describe the proposed framed-DOOK system which solves the synchronization issue by embedding the synchronization signal consisting of 2 bits patterns. We explain the new DOOK frame structure in detail. We derive the theoretical formula of synchronization signal detection probability taking into account false alarm rate. We derive the theoretical formula of synchronization retention time. Moreover, we show the bit error rate characteristics of the proposed framed-DOOK system under the complete synchronization and influence of background noise on the synchronization performance.

The outlines of this paper are as follows. In Sect. II, we explain the structure of the proposed framed-DOOK system. In Sect. III, we derive the theoretical formula of synchronization retention time of the proposed framed-DOOK system. In Sect. IV, we evaluate the synchronization retention time of the proposed framed-DOOK system. Finally, we summarize the main results in Sect. V.

II. System Structure

Figure 1 shows the transmitter of the proposed framed-DOOK system and Fig.2 illustrates the transmitted signal structure.

The transmitter divides the source data, denoted (A), into n frames every m bits. The transmitter inserts the framed data, denoted (B), into the shift register. A sub-block consists of

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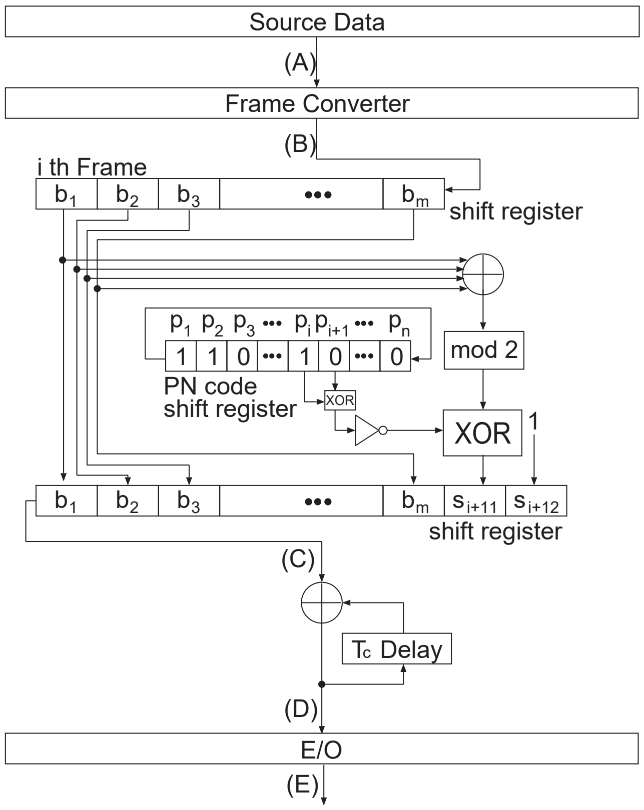

Fig. 1. Transmitter of the proposed framed-DOOK system

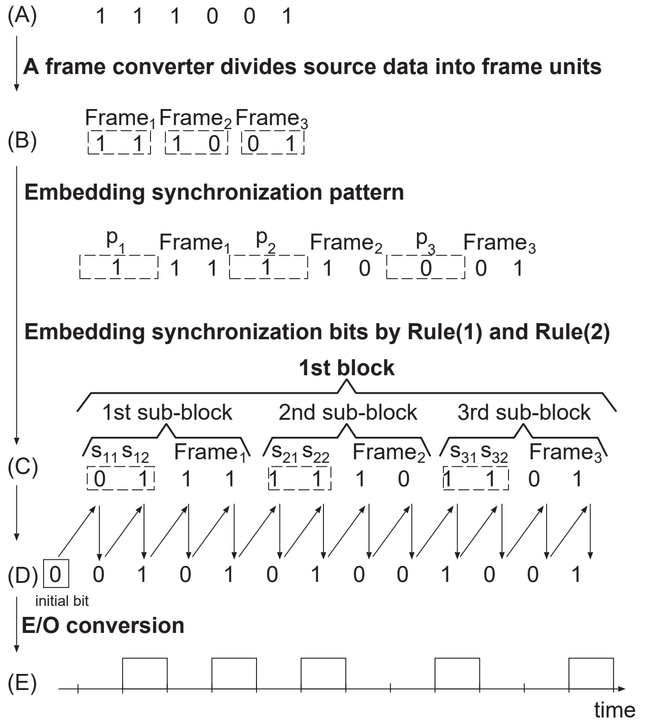

Fig. 2. Transmitted signal structure

the framed source data with m bits and the synchronization signal produced by a synchronization pattern generation rule. The synchronization signal is added to the framed source data. A synchronization signal is created on the basis of the pattern data stored in the shift register and the pseudo-noise (PN) code with length n chip. When the PN code is $\{p_1, p_2, \cdots, p_n\}$, the ith sub-block has p_i in the synchronization pattern. When the $i-1$th sub-block has p_{i-1}, the transmitter embeds two synchronization bits $\{s_{i1}, s_{i2}\}$ in the head of the ith sub-block, denoted (C), by the following rules.

Rule(1): the case of $p_i = p_{i-1}$

$$(s_{i1}, s_{i2}) = \begin{cases} (0,1) & \text{when the number of '1's} \\ & \text{in } (i-1)\text{th frame is odd} \\ (1,1) & \text{when the number of '1's} \\ & \text{in } (i-1)\text{th frame is even} \end{cases}$$

Rule(2): the case of $p_i \neq p_{i-1}$

$$(s_{i1}, s_{i2}) = \begin{cases} (1,1) & \text{when the number of '1's} \\ & \text{in } (i-1)\text{th frame is odd} \\ (0,1) & \text{when the number of '1's} \\ & \text{in } (i-1)\text{th frame is even} \end{cases}$$

The transmitter encodes the two synchronization bits embedded sub-block data by differential encoder, denoted (D), and transmits the encoded data by an electrical/optical (E/O) conversion, denoted (E).

Figure 3 shows the receiver of the proposed framed-DOOK system and Fig.4 illustrates the signal waveforms of the respective parts in the receiver.

The receiver detects the received signal, denoted (F), by the avalanche photo-diode (APD) detector. The received signal passes a differential detector. Consequently, the output signal of the differential detector, denoted (G), takes three levels $\{-1, 0, 1\}$. The synchronization system correlates the output signal of the differential detector with the reference signal, $r(=\{r_1, r_2, \cdots, r_n\})$. This reference signal is obtained by replacing '0' of the PN code used in the transmitter with '-1'. The synchronization system can acquire the synchronization timing by comparing the correlation values with a prescribed threshold. The frame data, denoted (H), is extracted from a sub-block by using the acquired synchronization timing signal. The message bits of the extracted frame data are decoded by using the threshold decision, and the transmitted data are estimated.

III. Performance Analysis

A. Optical wireless channel and APD

In this paper, we consider background noise and scintillation as optical wireless channel. The received power under the background noise and scintillation is given by

$$P_r = \begin{cases} XP_t + P_b & \text{(data '1')} \\ XP_tM_e + P_b & \text{(data '0')} \end{cases} \tag{1}$$

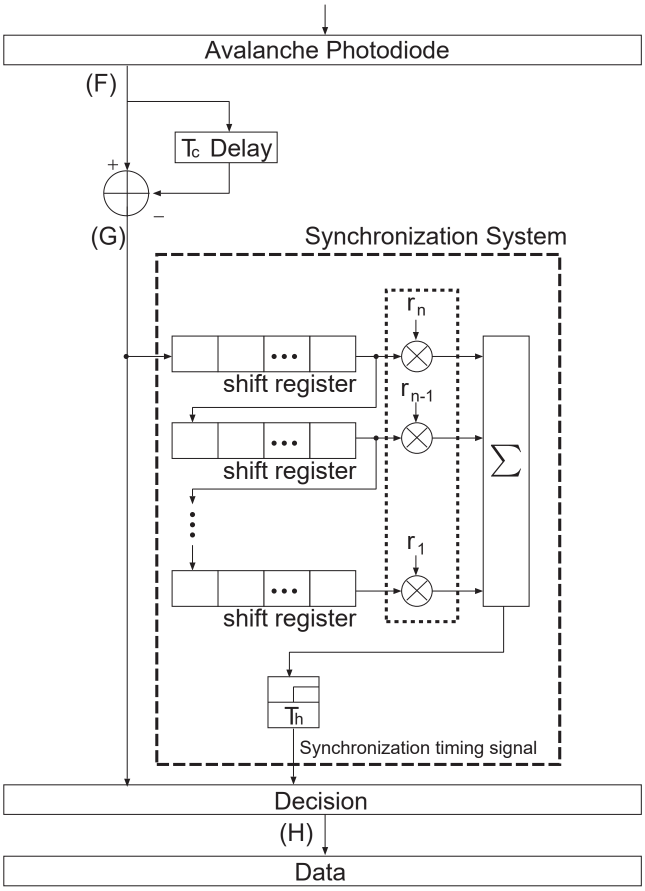

Fig. 3. Receiver of the proposed framed-DOOK system

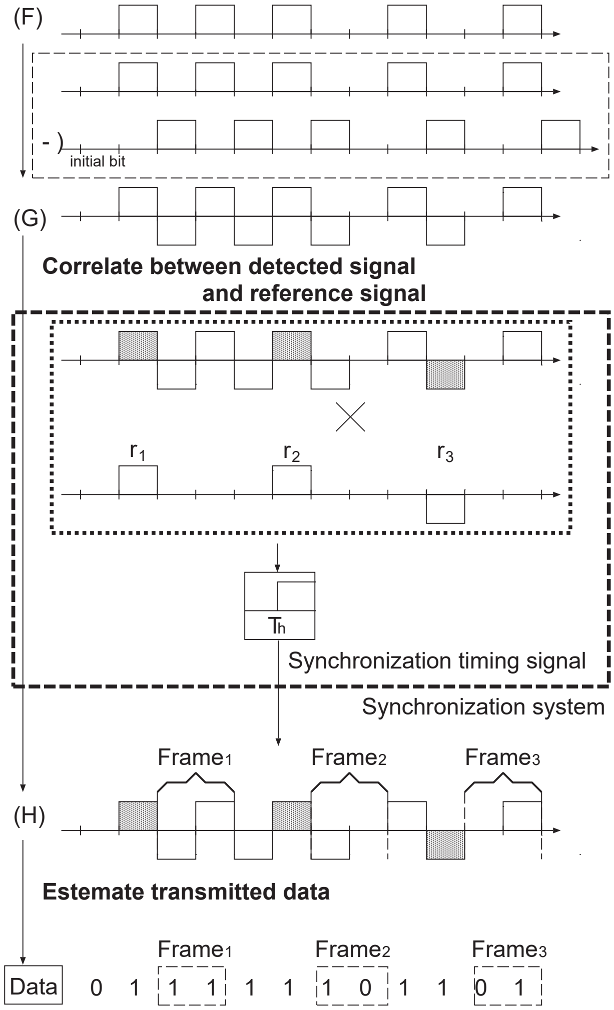

Fig. 4. Received signal structure

where P_t is the average transmission power per bit, P_b is background noise and X is the scintillation characterized by stationary random process. X follows the probability density function $p(X)$.

$$p(X) = \frac{1}{\sqrt{2\pi\sigma_s^2}X} \exp\left\{-\frac{(\log X + \frac{\sigma_s^2}{2})^2}{2\sigma_s^2}\right\} \tag{2}$$

Provided that the average value of scintillation is normalized to 1, and the logarithmic variance is decided by the state of the atmosphere and so on.

APD is used for the photodetector of the receiver side. The APD accumulates the energy of the slot interval T_s and outputs. The average $\mu(P_r)$ and variance $\sigma(P_r)^2$ of the output of the APD is given by

$$\mu(P_r) = GT_s\left(\frac{\eta P_r}{hf} + \frac{I_b}{e}\right) + \frac{I_s T_s}{e} \tag{3}$$

$$\sigma^2(P_r) = G^2 F T_s\left(\frac{\eta P_r}{hf} + \frac{I_b}{e}\right) + \frac{I_s T_s}{e} + \frac{2K_B T_r T_s}{e^2 R_L} \tag{4}$$

where G is the APD gain, η is the quantum efficiency, hf is the energy of one photon, I_b is the bulk leakage current, e is the charge of the electron, I_s is the surface leakage current, K_B is the Boltzmann constant, T_r is thermal noise, R_L is the load resistor, F is the excess noise coefficient. F is expressed by the following equation.

$$F = k_{eff}G + (1 - k_{eff})\left(\frac{2G-1}{G}\right) \tag{5}$$

Note that k_{eff} is the effective ionization rate of APD.

B. Synchronization Retention Time

The average and variance of the output of the APD of data '0' μ_0, μ_1 and '1' σ_0^2, σ_1^2 are given by

$$\begin{cases} \mu_1 = \mu(XP_t + P_b) & \text{for the output signal} = \text{'1'} \\ \mu_0 = \mu(XP_tM_e + Pb) & \text{for the output signal} = \text{'0'} \end{cases} \tag{6}$$

$$\begin{cases} \sigma_1^2 = \sigma^2(XP_t + P_b) & \text{for the output signal} = \text{'1'} \\ \sigma_0^2 = \sigma^2(XP_tM_e + P_b) & \text{for the output signal} = \text{'0'} \end{cases} \tag{7}$$

Since DOOK does differential detection on the receiver side, four patterns outputs are considered for the binary transmission. The four patterns are ('1'-'0'), ('0'-'1'), ('1'-'1') and

('0'-'0'). The averages of each are defined as $\mu_{10}, \mu_{01}, \mu_{11}$ and μ_{00} and the variances of each are defined as $\sigma_{10}^2, \sigma_{01}^2, \sigma_{11}^2$ and σ_{00}^2. When the average and variance of the output of the APD of data '0' and '1' are μ_0, μ_1 and σ_0^2, σ_1^2, averages and variances of the outputs after differential detection are expressed by the following equation.

$$\begin{cases} \mu_{10} = \mu_1 - \mu_0 \\ \mu_{01} = \mu_0 - \mu_1 \\ \mu_{11} = \mu_1 - \mu_1 \\ \mu_{00} = \mu_0 - \mu_0 \end{cases}$$

$$\begin{cases} \sigma_{10}^2 = \sigma_1^2 + \sigma_0^2 \\ \sigma_{01}^2 = \sigma_0^2 + \sigma_1^2 \\ \sigma_{11}^2 = \sigma_1^2 + \sigma_1^2 \\ \sigma_{00}^2 = \sigma_0^2 + \sigma_0^2 \end{cases}$$

In the proposed framed-DOOK system, the receiver acquires the synchronization timing by threshold decision using correlation value between differential detected data and reference code. When one block consists of n sub-blocks, the maximum correlation value at the correct synchronization point is n. Therefore, the average and the variance of the correlation value are $n\mu_{10}$ and $n\sigma_{10}^2$. Also, the proposed framed-DOOK system uses N_v blocks for verification when the synchronization signal detection. From the above, taking scintillation X into account, the probability of detection of the proposed framed-DOOK system P_D and probability of false alarm rate of the proposed framed-DOOK system P_{FA} given by

$$\begin{aligned} P_D &= \left[\int_0^\infty p(X) \int_{T_h}^\infty \frac{1}{\sqrt{2\pi n \sigma_{10}^2}} \exp\left(-\frac{(x - n\mu_{10})^2}{2n\sigma_{10}^2} \right) dx dX \right]^{N_v} \\ &= \left[\int_0^\infty p(X) \left\{ \frac{1}{2} \text{erfc}\left(\frac{T_h - n\mu_{10}}{\sqrt{2n\sigma_{10}^2}} \right) \right\} dX \right]^{N_v} \end{aligned} \tag{8}$$

$$\begin{aligned} P_{FA} &= \left[\int_0^\infty p(x) \frac{1}{4^n} \sum_{l=1}^{4^n} \int_{T_h}^\infty \frac{1}{\sqrt{2\pi\sigma_l^2}} \exp\left(-\frac{(x - \mu_l)^2}{2\sigma_l^2} \right) dx dX \right]^{N_v} \\ &= \left[\int_0^\infty p(x) \left[\frac{1}{4^n} \sum_{l=1}^{4^n} \left\{ \frac{1}{2} \text{erfc}\left(\frac{T_h - \mu_l}{\sqrt{2\sigma_l^2}} \right) \right\} \right] \right]^{N_v} \end{aligned} \tag{9}$$

where T_h is threshold level.

After detecting synchronization signal, the time for keeping synchronization is called synchronization retention time. When N_v blocks are used for detect synchronization signal, the probability of breakout of synchronization in the next N_v block is $1 - P_D$. Also, the probability of breakout of synchronization in the $2N_v$ block is $P_D(1 - P_D)$. Thus, the probability of breakout of synchronization at the lth N_v block is given by

$$P_D^{l-1}(1 - P_D) \tag{10}$$

The fact that synchronization is breakout at the lth N_v block means that synchronization can be retention until lth N_v block. Therefore, the expected value of the synchronization retention time T_R is given by

$$\begin{aligned} T_R &= N_v \sum_{l=1}^\infty l P_D^{l-1}(1 - P_D) \\ &= \frac{N_v}{1 - P_D} \end{aligned} \tag{11}$$

IV. Performance Evalution

In this paper, we show the bit error rate characteristic and evaluate the performance of the synchronization retention time when the false alarm rate P_{FA} achieves 10^{-2} and the number of message bits per frame m are 4, 8 and 12. We compare the proposed framed-DOOK system with the conventional framed-DOOK system [7].

TABLE I
THE NUMERICAL CONDITIONS

Name	Value
Bit rate	156×10^6
Wave Length	450
Quantum Efficiency	0.5511
Excess noise factor	3.9502
Energy per a photon	$47.17333333 \times 10^{-20}$
Electric charge	$1.602176469 \times 10^{-19}$
APD gain	100
Bulk leakage current	1.09×10^{-10}
Surface leakage current	1.09×10^{-8}
Modulation extinction ratio	0.01
Boltzmann constant	$1.38065039 \times 10^{-23}$
Receiver noise temperature	1100.0
Receiver load resistor	1030.0

Figure 5 shows the bit error rate versus the average transmission power per bit under the complete synchronization when the number of message bits is 8 and background noise P_b are -45[dBm] and -40[dBm] where the numerical condition is shown in TABLE I[9]. Fig.5 shows that the bit error rate characteristics of the proposed framed-DOOK system is worse than that of the conventional framed-DOOK system because the number of synchronization signal becomes 2[bit]. Although the bit error rate performance of the pure DOOK system is best in three systems under the complete synchronization timing. It is difficult to acquire the precision synchronization timing in the conventional framed-DOOK system after all.

Figure 6 shows the retention time taking into account the false alarm rate versus background noise when the transmission power is -45[dBm] where the numerical conditions are shown in TABLE I. The retention time of the proposed framed-DOOK system is much better than that of the conventional framed-DOOK system. In this evaluation, since the bit rate is

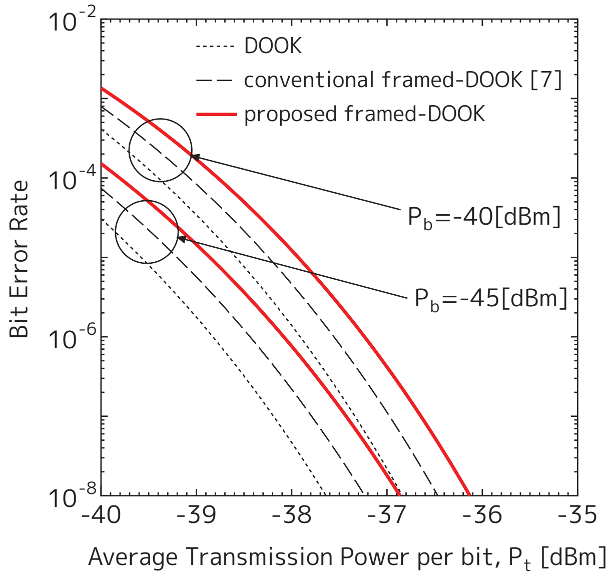

Fig. 5. Bit error rate versus background noise under the complete synchronization where $m = 8$.

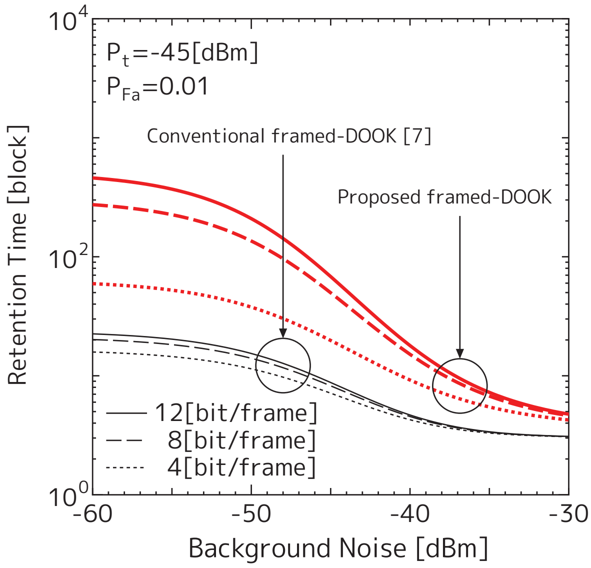

Fig. 6. Synchronization retention time versus background noise where the false alarm rate is 10^{-2}, $n = 3$ and $N_v = 3$.

156×10^6[bit/sec], the retention time of the proposed framed-DOOK system needs to be 10^8 blocks or more in order to retain synchronization.

Figure 7 shows the retention time taking into account the false alarm rate versus background noise when the transmission power is -40[dBm] where the numerical conditions are shown in TABLE I. When the transmission power is -45[dBm], the retention time of the proposed framed-DOOK system is much better performance than that of the conventional framed-DOOK system. Moreover, the retention time of the proposed framed-DOOK system can achieve 10^8 blocks

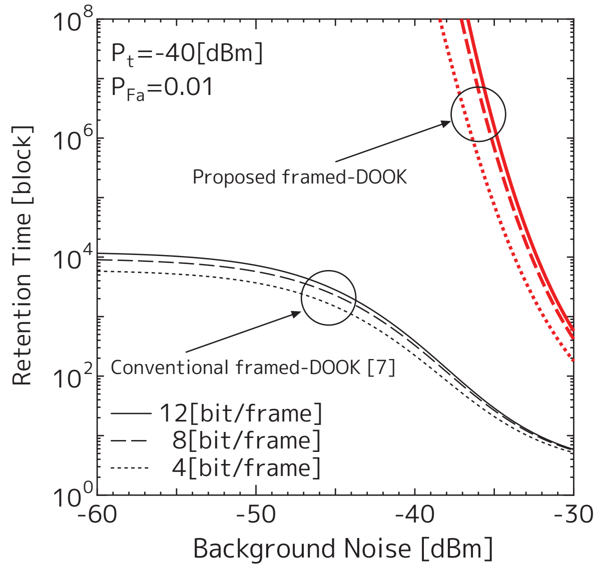

Fig. 7. Synchronization retention time versus background noise where the false alarm rate is 10^{-2}, $n = 3$ and $N_v = 3$.

when background noise is less than -38[dBm] and the number of message bits per frame are more than 4. However, the synchronization retention time of the conventional framed-DOOK system is 10^4 blocks at the longest.

Figure 8 shows the bit error rate versus average transmission power per bit when the proposed framed-DOOK system achieves perfect synchronization when background noise are -40[dBm] and -45[dBm]. The bit error rate performance improves with increasing the information transmission efficiency[bit/frame] because the effective pulse-power becomes large.

Figure 9 shows the bit error rate versus background noise when the proposed framed-DOOK system achieves the complete synchronization. The bit error rate of the proposed framed-DOOK system can achieve 10^{-4} when background noise is less than -41[dBm] and the message bits per frame are less than 12 bits.

V. Conclusion

We described the frame signal structure of the proposed framed-DOOK system and derived theoretical formula of synchronization retention time of the proposed framed-DOOK system. We evaluated the synchronization retention time and the bit error rate characteristic under the complete synchronization. When the false alarm rate achieves 10^{-2}, the synchronization retention time of the proposed framed-DOOK system is much better than that of the conventional framed-DOOK system. Moreover, the retention time of the proposed framed-DOOK system achieves 10^8 blocks when the transmission power is more than -40[dBm], background noise is less than -38[dBm] and the number of message bits per frame are more than 4. Hence, the proposed framed-DOOK system is more attractive than the conventional framed-DOOK system from the viewpoint of the actual system construction.

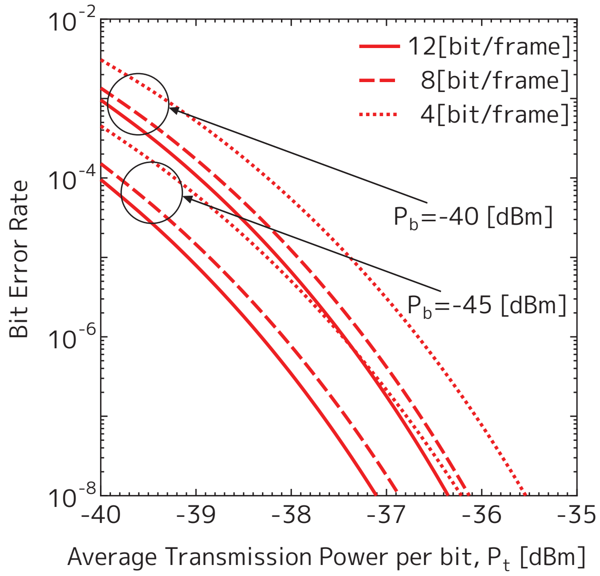

Fig. 8. Bit error rate versus average transmission power per bit where the false alarm rate is 10^{-2}, $n = 3$ and $N_v = 3$.

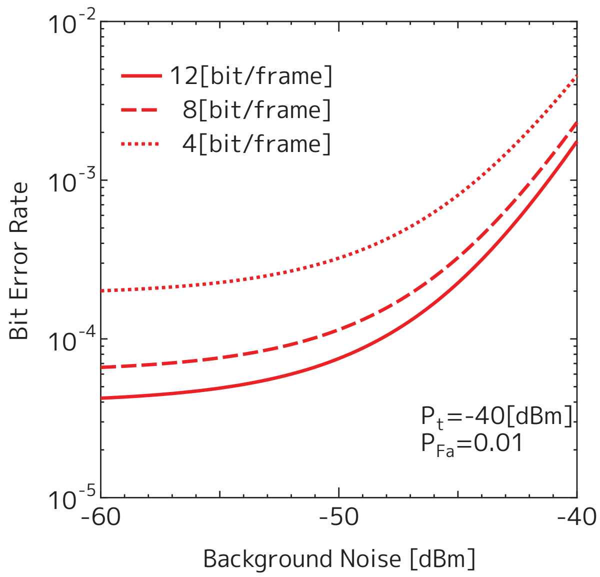

Fig. 9. Bit error rate versus background noise where the false alarm rate is 10^{-2}, $n = 3$ and $N_v = 3$.

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