論 文

가우스 잡음과 CO-CHANNEL 간섭이 존재하는 채널에서의 최대추정 프레임 동기

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ML Frame Synchronization for Gaussian Channel with Co-channel Interference

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ABSTRACT

The problem of locating a periodically inserted frame synchronization pattern in random data for a binary pulse amplitude modulated (PAM) digital communication system over an additive white Gaussian noise (AWGN) channel with co-channel interference is considered. The performance degradation of frame synchronization for the correlation rule due to the presence of co-channel interference is shown. The maximum likelihood (ML) decision rule for the frame synchronization over an AWGN channel with co-channel interference is derived. For the entire range of SNR considered, the ML frame synchronization rule obtains about 1dB signal energy gain over the correlation rule. Specially, the ML rule obtains as much as 2dB gain over the correlation rule when the SNR is greater than 0dB.

要 約

본 논문에서는 백색 가우스 잡음과 Co-channel 간섭이 존재하는 채널에서의 2진 펄스 진폭변조 통신 시스템에서 주기적으로 삽입되는 프레임 동기 문제를 다루었다. Co-channel 간섭이 존재함으로서 발생되는 Correlation Rule 의 성능 저하를 보이고 백색 가우스 잡음과 Co-channel 간섭이 존재하는 채널에서의 최대 추정 프레임 동기 공식을 유도하였다. 최대 추정 동기 공식은 신호 에너지에 있어 Correlation Rule 보다 약 1dB 정도의 성능 향상을 보였다. 특히, 신호대잡음비가 0dB 이상일 경우 최대 추정 동기 공식은 최대 2dB 정도의 성능향상을 보였다.

I. Introduction

The ML decision rule for locating a frame synchronization pattern periodically inserted in

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random binary data over an AWGN channel was derived by Massey[1]. It was verified by simulation that the optimum rule provided about 3dB advantage over the correlation rule in the interesting case of signal-to-noise ratio (SNR) near unity. Nielsen[2] showed similiar simulation results of the ML rule in the limiting cases of high SNR's Geoghiades and Synder derived the ML rule for frame synchronization pattern in a direct detection optical communication system employing Q-ary pulse position modulation (PPM). Analytical frame synchronization probability performance evaluation and simulation results illustrated that the ML rule obtained substantially more than 3dB performance improvement over the correlation rule.[3] The results shown[1],[3] considered only channels impaired by noise with either Gaussian or Poisson statistics. It is also implicitly assumed that a single modulated carrier is transmitted in the system. However, the co-channel interference might be caused by another digital or analog modulated carriers on the same nominal carrier frequency.

In this paper, the ML decision rule for the frame synchronization over the AWGN channel with co-channel interference is derived. The performance of the ML decision rule is compared with the correlation rule in order to show power advantage gained by the ML decision rule. Since it seems intractable to obtain the exact evaluation of the frame synchroniation of the ML decision rule, we resortecd to computer simulation for performance evaluation.

Ⅱ. ML Frame Synchronization rule

Let N denote the frame length, i. e., each L digit synchronization word is followed by $(N-L)$ random data. It is assumed that the receiver is to process an N bit span of the received sequence in order to locate the L bit long synchronization word. It is also assumed that all the interference power is concentrated in a single interferer and the interferer behaves to be an independent source for each digit for the sake of simplicity. Then, the demodulator output r_i over one of the assumed known bit intervals can be written as

$$r_i = \sqrt{E}\, c_i + n_i + \sqrt{2I}\cos\theta_i. \tag{1}$$

The symbol c_i denotes either a synchronization bit or a data bit depending on the subscript i. E and I represent signal and interference energy, respectively. The component, n_i, is statistically independent Gaussian random variable with mean of zero and variance of $N_0/2$ where N_0 is the one sided noise spectral density. The rendom phase, θ_i, is assumed statistically independent and uniformly distributed over $(0, 2\pi)$.

Let $\vec{r} = (r_0, r_1, \ldots, r_{N-1})$ denote the received sequence to be processed where each r_i is defined in Eq. (1). Let $\vec{s} = (s_0, s_1, \ldots, s_{L-1})$, where each s_i is either $+1$ or -1, be synchronization word and let $\vec{d} = (d_L, d_{L+1}, \ldots, d_{N-1})$ denote $(N-L)$ random data bits wher d_i is statistically independent random variable with $\Pr[d_i = +1] = \Pr[d_i = -1] = 1/2$. Consider the concatenation $\vec{s}\ \vec{d} = (s_0, \ldots, s_{L-1}, d_L, \ldots, d_{N-1})$. Let T_c be the cyclie shift operator defined as $T_c(\vec{s}\,\vec{d}) = (d_{N-1}, s_0, \ldots, s_{L-1}, d_L, \ldots, d_{N-2})$.

The synchronization word is assumed equally likely to begin in any of the N positiions of $\vec{r}$. If the synchronization word actually begins in digit r_m of $\vec{r}$ where $0 \le m \le N-1$, then the received sequence can be written as

$$\vec{r} = \sqrt{E}\, T_c^{m}(\vec{s}\,\vec{d}) + \vec{n} + \sqrt{2I}\,\overrightarrow{\cos}\,\theta \tag{2}$$

where $\vec{n} = (n_0, n_1, \ldots, n_{N-1})$ is the contribution of the AWGN to the received output and $\sqrt{2I}\,\overrightarrow{\cos}\,\theta = \sqrt{2I}\,(\cos\theta_0, \cos\theta_1, \ldots, \cos\theta_{N-1})$ is the contribtution of the co-channel interference to the received output

Let $\vec{\rho} = (\rho_0, \rho_1, \ldots, \rho_{N-1})$ denote the actual value assumed by the random vector $\vec{r}$.

Then, the ML decision rule is to choose the estimate of m as the value μ, $0 \le \mu \le N-1$, which maximizes

$$\Lambda_1=p_{\vec r}(m=\mu|\vec r=\vec\rho)=\frac{p_{\vec r}(\vec\rho|m=\mu)Pr(m=\mu)}{p_{\vec r}(\vec\rho)} \quad (3)$$

Since $Pr(m=\mu)=1/N$ for all μ, it is equivalent to maximize

$$\Lambda_2=p_{\vec r}(\vec\rho|m=\mu). \quad (4)$$

Let $\vec\delta=(\delta_L,\delta_{L+1},\ldots,\delta_{N-l})$, where each δ_i is either +1 or −1, denote a random possible binary data vector $\vec d$. Then, Eq. (4) is equivalent to maximizing

$$\Lambda_3=\int_0^{2\pi}\cdots\int_0^{2\pi}\sum_{all\,\vec\delta}p_{\vec r}(\vec\rho|m=\mu,\vec d=\vec\delta,\vec\theta)d\,\theta_0\ldots d\theta_{N-1}. \quad (5)$$

Upon use of Eq.(1), Eq.(5)becomes

$$\Lambda_3=\int_0^{2\pi}\cdots\int_0^{2\pi}\sum_{all\,\vec\delta}$$

$$p_{\vec n}(\vec\rho-\sqrt{E}\,T_c^{\mu}-(\vec s\,\vec d\,)-\sqrt{2I}\cos\vec\theta)\,d\theta_0\ldots d\theta_{N-1}. \quad (6)$$

By the Gaussian assumption on $\vec n$, Eq.(6) is equivalent to

$$\Lambda_4=\int_0^{2\pi}\cdots\int_0^{2\pi}\sum_{all\,\vec\delta}\left[\frac{1}{2\pi}\right]^{N/2}$$

$$\prod_{i=1}^{L-1}\exp\left[\frac{-1}{N_0}\ (\rho_{i+\mu}-\sqrt{Es_i}-\sqrt{2I}\cos\theta_i)^2\right]$$

$$\prod_{i=L}^{N-1}\exp$$

$$\left[\frac{-1}{N_0}(\rho_{i+\mu}-\sqrt{Es_i}-\sqrt{2I}\cos\theta_i)^2\right]d\theta_0\ldots d\theta_{N-1}. \quad (7)$$

By removing terms that are independent of μ, Eq.(7) can be reduced to

$$\Lambda_5=\prod_{i=0}^{L-1}\exp\left[\ \frac{2\sqrt{E}}{N_0}\ \ s_i\rho_{i+\mu}\right]\cdot\Gamma_1(\rho_i+\mu).$$

$$\sum_{all\,\vec\delta}\ \prod_{i=0}^{L-1}\exp\left[\frac{2\sqrt{E}}{N_0}\ \ \delta_i\rho_i+\mu\right]\cdot\Gamma_2(\rho_{i+\mu},\delta_i). \quad (8)$$

where

$$\Gamma_1(\rho_{i+\mu})=\int_0^{2\pi}\exp\left[\frac{-2I}{N_0}\ \ (\cos^2\theta_i-a(i)\cos\theta_i)\right]d\theta_i, \quad (9)$$

$$\Gamma_2(\rho_{i+\mu},\delta_i).=\int_0^{2\pi}\exp\left[\frac{-2I}{N_0}\ \ (\cos^2\theta_i-b(i)\cos\theta_i)\right]d\theta_i, \quad (10)$$

$$a(i)=2\rho_{i+\mu}\sqrt{2I}-2\sqrt{E}\,s_i\sqrt{2I}, \quad (11)$$

and $b(i)=2\rho_{i+\mu}\sqrt{2I}-2\sqrt{E}\,s_i\sqrt{2I}$, (12)

By carring out the summation with respect to $\vec\delta$, Λ_5 can be rewritten as

$$\Lambda_6=\prod_{i=0}^{L-1}\exp\left[\frac{2\sqrt{E}}{N_0}\ \ s_i\rho_{i+\mu}\right]\cdot\Gamma_1(\rho_{i+\mu}).\prod_{i=L}^{N-1}.\ \Gamma_3(\rho_{i+\mu}) \quad (13)$$

where

$$\Gamma_3(\rho_{i+\mu})=\frac{1}{2}\exp\left[\frac{-2\sqrt{E}}{N_0}\ \rho_{i+\mu}\right]\cdot\Gamma_2(\rho_{i+\mu},1)$$

$$+\frac{1}{2}\exp\left[\frac{-2\sqrt{E}}{N_0}\ \rho_{i+\mu}\right]\cdot\Gamma_2(\rho_{i+\mu},-1). \quad (14)$$

By taking the logarithm on Eq. (14), Γ_6 is equivalent to

$$\Lambda_7=\sum_{i=0}^{L-1}\left[\frac{-2\sqrt{E}}{N_0}\ s_i\rho_{i+\mu}+\ln\Gamma_1(\rho_{i+\mu})\right]+\sum_{i=L}^{N-1}\ln\Gamma_3(\rho_{i+\mu}). \quad (15)$$

Note that the sum

$$\sum_{i=L}^{N-1}\ln\Gamma_3(\rho_{i+\mu}) \quad (16)$$

is independent of μ because of the periodic frame boundaries. By subtracting this term from Λ_7, the ML decision rule for the frame synchronization that takes into accout both the AWGN channel and co-channel interference is obtained as follows.

$$\Lambda_{ML}=\sum_{i=0}^{L-1}\left[s_i\rho_{i+\mu}+\frac{N_0}{2\sqrt{E}}\ \ln\Gamma_1(\rho_{i+\mu})\right.$$

$$-\frac{N_0}{2\sqrt{E}} \ln \Gamma_3(\rho_{i+\mu}) \Big]. \qquad (17)$$

Note that the first term in the summation accounts for the ordinary correlation rule and the second and the third terms account for the random data surrounding the synchronization word and co-channel interference.

Ⅲ. Simulation results

The commonly used correlaition rule is obtained by deleting the second and the third terms in the ML rule and can be written as follws.

$$\Lambda_c = \sum_{i=0}^{L-1} s_i \rho_{i+\mu}. \qquad (18)$$

The correlation rule is computationally much simpler to implement than the ML rule. Because of the simplicity, the correlation rule was adopted in virtually all frame synchronization problems subsequent to Barker's pioneering work(4).

The performance of frame synchronization for the ML rule and the correlation rule over and AWGN channel with co-channel interference is considered. Since the exact theoretical performance is impossible to obtain, computer simulation is performed to evaluate the performance of the ML rule and the correlation rule. Two cases of different length of N and L are considered in simulations. For the first case, a 7-bit Barker(4) sequence of (1,-1,1,1,-1,-1,-1) is used for synchronization word for N=28. For the second case, a 13-bit Barker sequence of (1,1,1,1,1,-1,-1,1,1,-1,1,-1,1) is used for synchronization word for N=91. For a given SNR and a signal-to-interference ration (SIR), 100 frame synchronization simulations are performed to evaluate the probability of correct frame synchronization.

In simulations, it is assumed that the synchronization word is located at the beginning of the frame. The correlation rule simply correlates the known synchronization word and the received sequence and indiciates the location of the synchronization word where the maximum correlation value is obtained. Similary, the ML rule determines the location of frame sync according to Eq.(17) which involves more calculations than the correlation rule.

The summary of simulations for the ML rule and the correlation rule over an AWGN channel with co-channel interference is shown in Table 1 and Table 2. They illustrate the performance of the ML rule and the correlation rule by indicating the number of correct frame sync out of 100 simulation trials for N=28 and N-91, respectively. As shown in Fig. 1, the performance degradation for the correlation rule due to the co-channel interference is as much as 2dB signal energy loss when the SIR is equal to 5dB. As shown in Fig. 2, the ML rule obtains signal energy gain of 1dB over the correlation rule when the 7-bit Barker sequence is used for synchronization word. Similiar results are obtained in Fig.3 and Fig.4 when the 13-bit Barker sequence is used for synchronization word. Specially, as shown in Fig.4, the ML rule obtains signal energy gain of 2dB over the correlaiton rule when the SNR is greater than 0 dB.

Table 1. Number of correct frame synchronization for the correlation and the ML rule over the AWGN channel with co-channel interference fo N=28 out of 100 simulation trials. The synchronization word used is 7-bit Baker sequence of (1,-1,1,-1,1,-1,-1).

SNR(dB)	CIR(dB)					
	Correlation rule			ML rule		
	5	10	15	5	10	15
-3	72	76	76	75	79	82
-2	75	84	84	81	88	89
-1	79	87	89	85	94	94
0	86	93	94	88	95	96
1	88	94	96	92	96	99
2	90	96	97	94	99	100
3	93	97	97	95	100	100

Table 2. Number of correct frame synchronization for the correlation and the ML rule over the AWGN channel with co-channel interference for *N*-19 out of 100 simulation trials. The synchronization word used is 13-bit Baker sequence of (1,1,1,1,1,-1,1,1,-1,1,-1,1)

SNR(dB)	CIR(dB)					
	Correlation rule			ML rule		
	5	10	15	5	10	15
-3	61	62	66	59	70	72
-2	67	73	74	69	78	80
-1	75	78	79	71	85	88
0	76	84	85	74	91	92
1	79	88	89	79	96	99
2	83	91	97	83	99	100
3	84	95	100	86	100	100

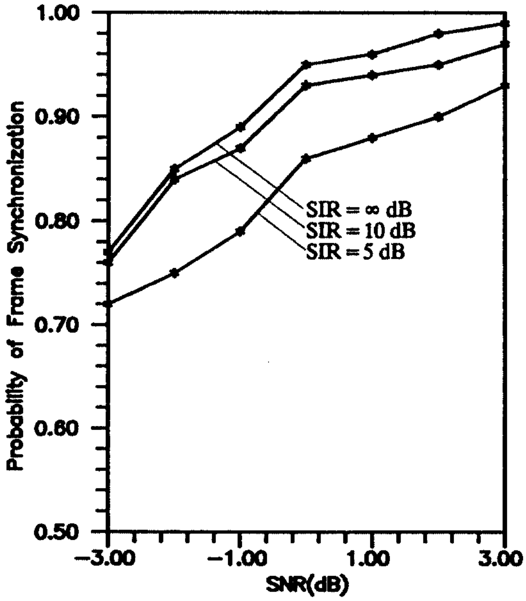

Fig. 1. Probability of frame synchronization for the correlation rule over the AWGN channel with co-channel interference. The synchronization word used is 7-bit Barker sequence of (1,-1,11, -1,-1,-1)

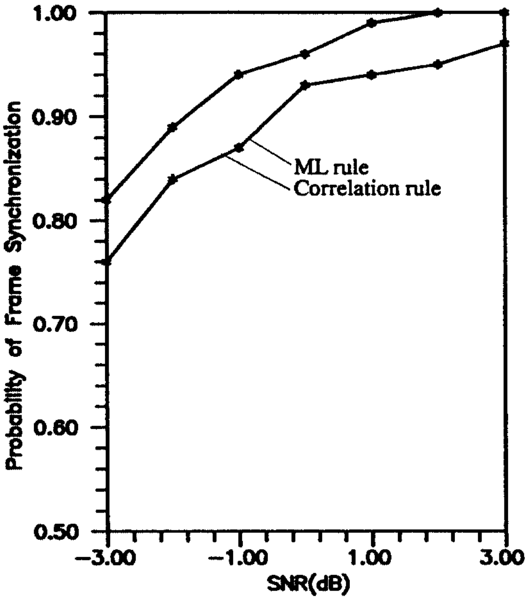

Fig. 2. Probability of frame synchronization for the ML rule and the correlation rule over the AWGN with co-channel interference at SIR=15 dB. The synchronization word used is 7-bit Barker sequence of (1,-1,1,1,-1,-1,-1).

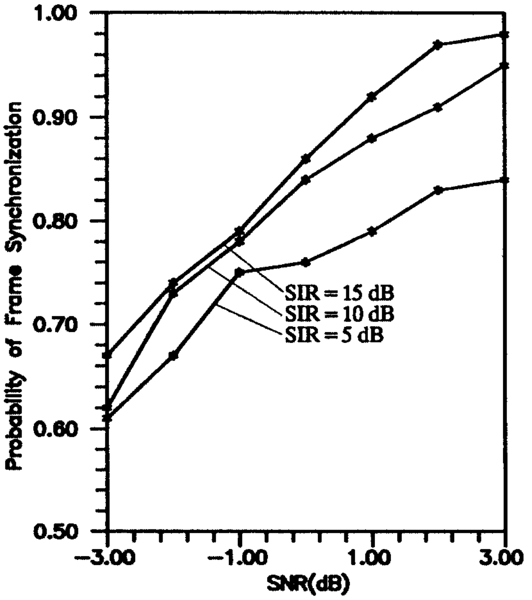

Fig. 3. Probability of frame synchronization for the correlation rule over the AWGN channel with

co-channel interference. The synchronization word used is 13-bit Barker sequence of (1,1,1,1,1,-1,-1,1,1,-1,1,-1,1) for N=91.

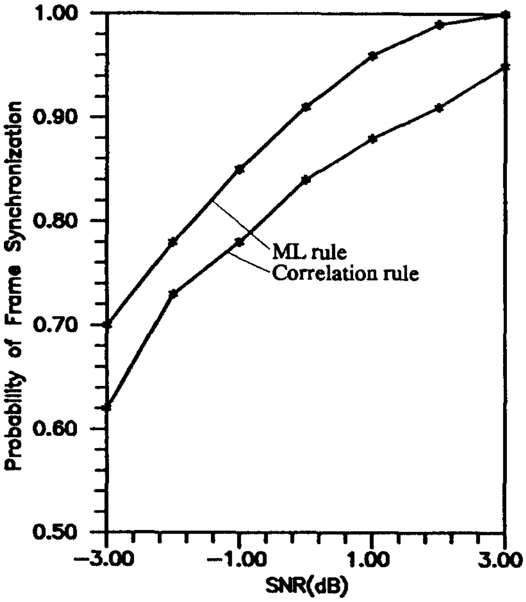

Fig. 4. Probability of frame synchronization for the ML and the correlation rule over the AWGN with co-channel interference at SIR=10 dB. The synchronization word used is 13-bit Barker sequence of (1,1,1,1,1,-1,-1,1,1,-1,1,-1,1) forn N=91.

The complexity of the ML rule is increased compare with the correlation rule. However, If the communication system has tight power limitation with sever co-channel interference, the ML rule for frame synchronization would be a good candidate for consideration in spite of increased complexity. For instance, when SIR is 10dB and SNR is 2dB, the probability of correct frame synchronization of 0.91 is obtained by the correlation rule. On the other hand, the ML rule obtains almost perfect frame synchronization at the same level of SNR and SIR.

Ⅳ. Conclusion

The ML frame synchronization rule over an AWGN channel with co-channel interference is derived under the assumption that the power of co-channel interference is concentrated in a single interferer. When SIR is 5dB, the performance degradation for the correlation rule due to the co-channel interference is equivalent to signal energy loss of 2dB. The ML frame synchronization rule obtains signal energy gain of 1dB compared to the correlation rule over the entire range of the SNR. When the SNR is greater than 0dB, the ML frame synchronization rule obtains as much as 2dB signal energy gain over the correlation rule.

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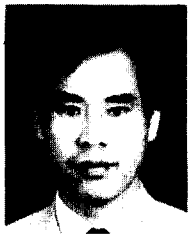

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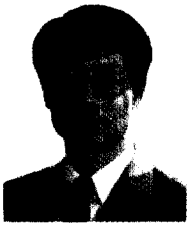

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