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LETTER

Modulation level adaptive stochastic resonance receiver with low-resolution ADCs for multilevel amplitude modulated signals

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Abstract Utilizing an analog to digital converter (ADC) with low-resolution is preferred in terms of high sampling rate, low energy consumption and low implementation cost. Against these advantages, utilizing low-resolution ADCs would lead to degrade the signal detection performance. This paper focuses on addressing this issue by introducing a novel receiver that incorporates a new stochastic resonance (SR) processing method, which adaptively adjusts the intentional noise base on the modulation level of the signal, for the detection of multilevel amplitude modulated signals. Through computer simulation, we confirmed the further improvement by applying the proposed adaptive SR. Moreover, we observed that the proposed receiver is more resistant to channel noise.

Keywords: low-resolution analog-to-digital converter, stochastic resonance, multilevel amplitude modulated signal
Classification: Wireless communication technologies

1. Introduction

An analog-to-digital converter (ADC), which is a device that detects signals by quantizing an analog signal into a multilevel digital signal, is often discussed in the context of its resolution; ADCs are known to have a trade-off between resolution and sampling rate [1, 2]. Recently, the demand for low-resolution ADCs is increasing to achieve a high sampling rate corresponding to the high frequency band in the future wireless communications [3]. Moreover, the architecture scale and energy consumption of an ADC increase exponentially with the number of bits of resolution [1, 2]. Therefore, we could reduce the energy consumption and implementation cost of the receiver simply by reducing the resolution of ADCs. In particular, systems employing multiple ADCs, e.g., successive interference cancellation (SIC) [4, 5] and massive multiple-input multiple-output (MIMO) [2], benefit greatly from the use of low-resolution ADCs.

In contrast to the above advantages of utilizing low-resolution ADCs, reducing the resolution of ADCs will degrade the signal detection performance of the receiver due to its nonlinearity. In the detection of multilevel amplitude modulated signals, ADCs with insufficient-resolution for the signal modulation levels are unable to accurately detect the signals. This deficiency also leads to an increase in errors in symbol determination. To address this issue, we focus on a nonlinear phenomenon called stochastic resonance (SR) [6, 7] that enhances the response of nonlinear systems to a input signal by intentionally adding a noise signal that randomly fluctuates the amplitude of the signal. To achieve better performance than the conventional SR-based receiver, we propose a novel SR-based receiver incorporating a new SR method that adaptively adjusts the intensity of the intentional noise based on the modulation level of the signal.

1.1 Related works

The application of SR has gained attention as a method to enhance the performance of nonlinear systems. The effects and principles of SR have been studied and confirmed in various fields, from biology to physics and engineering. Moreover, its application to ADCs has been discussed [4, 5, 8], and its effectiveness in detecting multilevel amplitude modulated signals has been confirmed [5, 8].

However, the performance in detecting multilevel amplitude modulated signals [5, 8] has not achieved linear performance, especially in low-noise conditions, and further improvements are required. To solve this problem, we focus on the method of adding the intentional noise. In the conventional SR receiver, uniform-intensity noise is added during all signal detections, regardless of the modulation level of the symbols. Therefore, depending on the modulation level, the application of SR may degrade the detection performance of some symbols.

1.2 Contributions

In this paper, we introduce a novel SR processing method for the detection of multilevel amplitude modulated signals with low-resolution ADCs. The main contributions of this paper are summarized as follows:

- We present a novel SR method that solves the problem of degradation of some symbols due to the intentional noise added in the conventional SR. This method adaptively adjusts the intentional noise for each modulation level of multilevel amplitude modulated signals.
- Additionally, we specify the intensity of the intentional noise to be added for each modulation level of the signals. We also provide a design framework for the proposed adaptive SR receiver.
- Through computer simulations, we demonstrate and evaluate the performance of the proposed adaptive SR receiver with 1-bit deficient ADCs.

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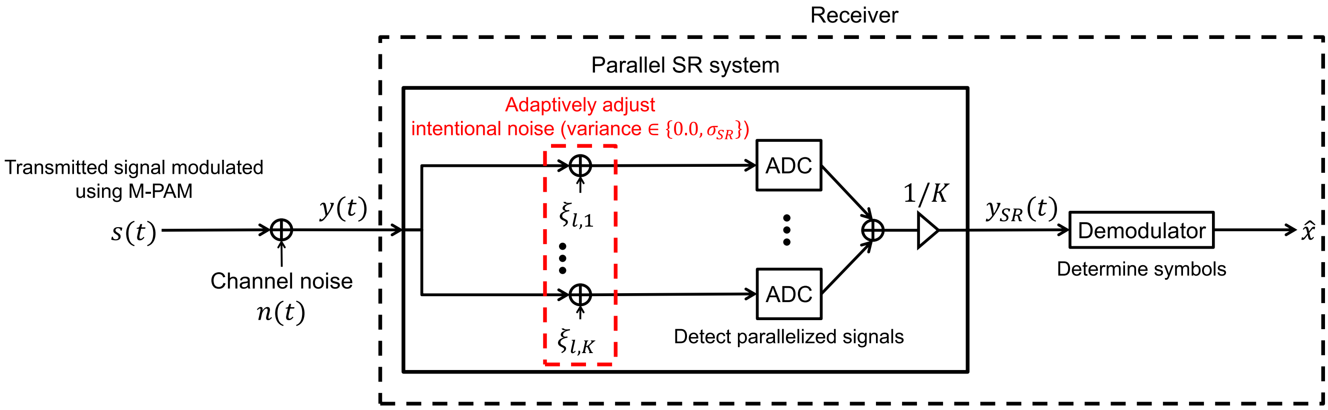


Fig. 1 Block diagram of system model. Before the detection process at ADCs, we add the intentional noise $\xi_{l,k}$, which is adaptively adjusted based on the modulation level l (see Section 2.2), to each parallelized unit k.

2. Proposed adaptive stochastic resonance receiver

We focus on a system shown in Fig. 1, in which the modulated signal is detected in a receiver with the ADCs. Additive white Gaussian noise with two-sided power spectral density of $N_0/2$ is assumed to be added as channel noise. At the receiver, the data symbol x is demodulated from the received signal $y(t) = hs(t) + n(t)$, where h is the channel coefficient, $s(t)$ is the modulated signal and $n(t)$ is the channel noise with zero mean and variance $\sigma^2 = N_0/2$. In the system, $s(t)$ is mathematically given as

$$s(t) = \sum_{n=-\infty}^{+\infty} x g_{T_s}(t - nT_s)\,, \tag{1}$$

with the symbol duration T_s and the rectangular pulse g_{T_s}, which can be given as

$$g_{T_s}(t) = \begin{cases} 1 & (0 < t \le T_s)\,, \\ 0 & (\text{otherwise})\,. \end{cases} \tag{2}$$

In this paper, h is set as 1 to understand the fundamental performance of the receiver in ideal channels, e.g., a non-fading environment, and perfect time synchronization.

The data symbol $x = A_l$ is modulated using M-ary pulse amplitude modulation (M-PAM), where

$$A_l = \left(l - \frac{M+1}{2}\right) d \tag{3}$$

is the modulated signal amplitude with the index of the modulation level $l = 1, 2, \ldots, M$ and d is the distance between adjacent modulated signal points. Note that M must be a power of 2 as $M = 2^1, 2^2, \ldots, 2^i$. The signal-to-noise ratio (SNR) of the received signal can be defined as

$$\text{SNR} = \frac{A_{avg}}{2\sigma^2}\,, \tag{4}$$

where

$$A_{avg} = \frac{1}{M} \sum_{l=1}^{M} A_l^2 \tag{5}$$

is the average power of the modulated signals. In this paper, we focus on the communication with M-PAM, considering M-ary quadrature amplitude modulation (M-QAM), which is widely used in the wireless communications [9], as a modulation scheme that extends M-PAM in the phase direction.

The received signal is detected by the parallel SR system shown in Fig. 1 and the system output $y_{SR}(t)$ is demodulated to estimate $\hat{x}$. In the receiver, $\hat{x}$ is estimated by the demodulator as

$$\hat{x} = A_l, \quad \text{if} \quad \eta_{l-1} \le y_{SR}(t) < \eta_l\,, \tag{6}$$

where

$$\eta_l = \left(l - \frac{M}{2}\right) d \tag{7}$$

is the demodulation threshold.

2.1 Design of ADCs

Typically, an ADC with m-bit resolution can accurately detect the amplitude of each modulation level of M-PAM signals without affecting symbol determination, provided that $2^m = M$. A m-bit ADC has 2^m output levels and the input-output characteristic for input $y(t)$, which can be given as

$$Q\left(y(t)\right) = \left(L - 1 - 2^{m-1}\right)\delta \equiv Q_L^m, \quad \text{if} \quad \eta_{L-1}^m \le y(t) < \eta_L^m\,, \tag{8}$$

where $L = 1, 2, \ldots, 2^m$ is the index of the output level, $\delta = d$ is the step size of the output amplitude and

$$\eta_L^m = \left(L - 2^{m-1}\right)\delta \tag{9}$$

is the threshold.

The example of the input-output characteristics of ADCs for 8-PAM signals is shown in Fig. 2. With the 3-bit ADCs shown in Fig. 2(a), we will have sufficient number of the output levels to detect each modulation level of 8-PAM signals. In this paper, we focus on a case with low-resolution q-bit ADCs, where the number of output levels is limited to $q < m$. In a case of $q = 2$ is shown in Fig. 2(b), the ADC has only four output levels. Therefore, The input signals with more than four amplitude levels ($2^q < M$) is difficult to detect. The input-output characteristics of q- bit ADCs in a case of 1-bit deficient ($q = m - 1$), can be given as

$$Q_L^q = \begin{cases} \left(L - \frac{1+2^q}{2}\right)\delta - \lambda & (l = 1)\,, \\ \left(L - \frac{1+2^q}{2}\right)\delta & (l > 1)\,, \end{cases} \tag{10}$$

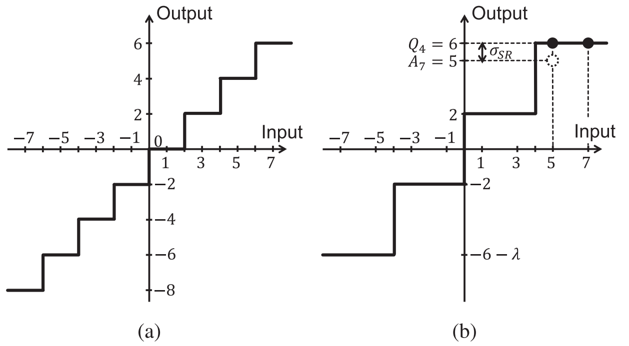


Fig. 2 Design of input-output characteristics of the ADC for the detection of 8-PAM signals with $d = 2$. (a) 3-bit ADC. (b) 2-bit ADC (including the example of the noise adjustment described in Section 2.2).

$$\text{if } \eta^q_{L-1} \le y(t) < \eta^q_L ,$$

where

$$\eta^q_L = \left(L - 2^{q-1}\right)\delta \tag{11}$$

is the threshold. Here, $\delta = 2d$ and subtracting λ at $l = 1$ is designed to detect A_1. We set $\lambda = 0.001$ empirically.

2.2 Adjustment of intentional noise

To enhance the detection of the ADCs, we utilize the parallel SR [6, 7] system as shown in Fig. 1. The received signal is first parallelized into K units. Before detection (quantization) at the ADCs, the intentional noise $\xi_{l,k}$ with zero mean and variance σ^2_{SR} is added to each parallelized received signal. Here, $\xi_{l,k}$ must be independent of the other parallelized units. Considering that all ADCs have a certain amount of noise, e.g., thermal noise [1], which have been actively removed in the conventional receivers, applying SR dose not require additional devices that need external energy supply for generating $\xi_{l,k}$. The system output $y_{SR}(t)$ is obtained by averaging the outputs of K parallelized units.

In the proposed adaptive SR receiver, we adaptively adjust the intensity of the noise $\xi_{l,k}$ based on the modulation level of the M-PAM signal. To detect the M-PAM signal with 1-bit deficient q-bit ADCs, we consider two cases: (A) the modulation level that requires the enhancement by SR, and (B) the modulation level that dose not require the enhancement. In case (A), the modulation level can be given as $l = \{2, 3, 5, ..., 2n + 1\} = \{2, 2n + 1\}$ $(n = 1, 2, ..., (M/2) - 1)$ according to Eq. (3), (6), and (10). In this case, the standard deviation σ_{SR} of the intentional noise required for the detection of l-level signals can be specified as

$$\sigma_{SR} = \begin{cases} |Q^q_1 - A_l| & (l = 2)\,, \\ |Q^q_{n+1} - A_l| & (l = 2n+1)\,, \end{cases} \tag{12}$$

that is, the distance between the desired modulated signal amplitude and the nearest ADC output amplitude. In case (B), the modulation level can be given as $l = \{1, 4, 6, ..., 2n\} = \{1, 2n\}$ $(n = 2, 3, ..., (M/2))$. The example of the noise adjustment is shown in Fig. 2(b). To detect $A_7 = 5$ of the 8-PAM signal with 1-bit deficient q-bit ADCs, we add $\xi_{7,k}$ with $\sigma_{SR} = |Q^q_4 - A_7| = 1$, while the detection of $A_8 = 7$ dose not require the intentional noise.

3. Simulation results and discussion

We demonstrate that the proposed receiver can correctly demodulate transmitted data symbols even with low-resolution ADCs. With the parameter shown in Section 3.1, we evaluate the performance of the proposed receiver through computer simulations. The performance is evaluated in terms of symbol-error-rate (SER) versus SNR[dB] $\in [-10, 50]$, for M-PAM modulation signals.

3.1 Parameter setup

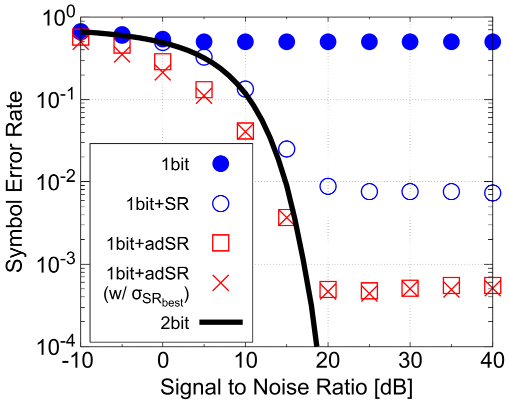
SER is evaluated using the system shown in Fig. 1. The symbol with 16-PAM signal is detected with 4-bit and 3-bit ADCs, the symbol with 8-PAM signal is detected with 3-bit and 2-bit ADCs and the symbol with 4-PAM signal is detected with 2-bit and 1-bit ADCs. In this paper, the distance between adjacent modulated signal amplitude is $d = 2$, that is, $A_l \in \{\pm1, \pm3, \pm5, \pm7, \pm9, \pm11, \pm13, \pm15\}$ for 16-PAM signals, $A_l \in \{\pm1, \pm3, \pm5, \pm7\}$ for 8-PAM signals and $A_l \in \{\pm1, \pm3\}$ for 4-PAM signals. In this case, $A_l \in \{+1, -3, +5, -7, +9, -11, \pm13\}$ for 16-PAM signals, $A_l \in \{+1, -3, \pm5\}$ for 8-PAM signals and $A_l \in \{\pm1\}$ for 4-PAM signals are undetectable with 1-bit deficient ADCs given as Eq. (10). The standard deviation σ_{SR} is set to 1.001 for $l = 2$, 1.0 for $l = 2n + 1$, according to Eq. (12). The number of the transmitted data symbols per each SNR is set to 1×10^6, the number of the parallel units K is determined by simulation and set to 1×10^3.

3.2 SER performance of proposed receiver

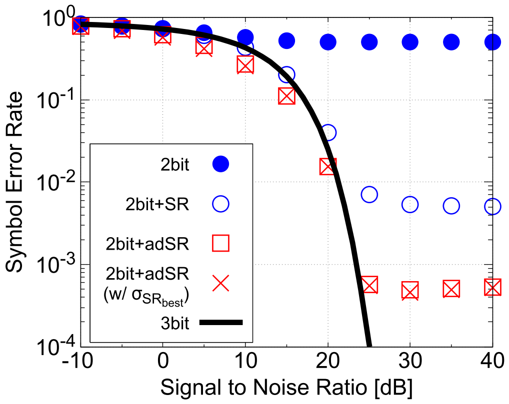
The SER performance of the proposed receiver is shown in Fig. 3. We present the performances with 1-bit deficient ADCs and sufficient-resolution ADCs. Here, we apply two methods, the conventional SR (SR) and the proposed modulation adaptive SR (adSR), to 1-bit deficient ADCs and compare their SER performance. Additionally, we also compare the SER performance of adSR with that of adSR using the optimal standard deviation $\sigma_{SR_{best}}$, which is obtained exhaustively under each SNR condition, and verify the validity of the noise adjustment method (Eq. (12)) in adSR.

In Fig. 3, we can observe huge performance differences between 1-bit deficient ADCs and sufficient-resolution ADCs. This is due to the inability of the ADCs, which is accurately detect each modulated signal, resulting in an increase in errors in symbol determination. We can also observe the improvement by applying SR and the further improvement by applying adSR. While 1-bit deficient ADCs with SR could achieve SER only around 1×10^{-2}, 1-bit deficient ADCs with adSR is achieved SER around 1×10^{-3}. Although under limited conditions of SNR, that is about -10 to 20 for 4-PAM signal, -10 to 25 for 8-PAM signal, -10 to 30 for 16-PAM signal, 1-bit deficient ADCs could perform almost same as sufficient-resolution ADCs. Moreover, we cannot observe much differences between adSR and adSR using $\sigma_{SR_{best}}$. Therefore, we could say that the noise adjustment method (Eq. (12)) in adSR is valid.

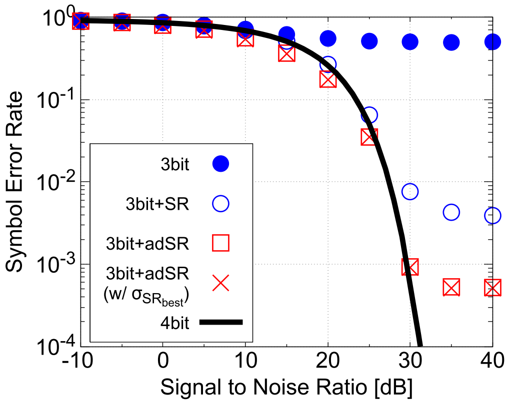
Furthermore, we can observe that 1-bit deficient ADCs could perform better than sufficient-resolution ADCs under



(a)



(b)



(c)

Fig. 3 SER performance of the proposed adaptive stochastic resonance receiver detecting each modulated signal. (a) 4-PAM signal. (b) 8-PAM signal. (c) 16-PAM signal.

conditions of SNR, that is about -10 to 15 for 4-PAM signal and 8-PAM signal, -10 to 20 for 16-PAM signal. This is due to the fact that the use of low-resolution ADCs makes symbol transitions between adjacent modulation levels less likely in the symbol detection in case (B). Therefore, the error in symbol determination, which caused by the channel noise, is reduced.

4. Conclusion

To solve the problem of degradation by applying the conventional SR, we proposed a novel SR method that adaptively adjusts the intentional noise for each modulation level of the signal. We also provided a design framework for the proposed adaptive SR receiver with low-resolution ADCs. In addition, we presented the noise adjustment method and specified the intensity of the intentional noise to be added for each modulation level.

Through computer simulations, we confirmed the further improvement by applying the proposed adaptive SR. we could observe large performance differences between low-resolution ADCs with the conventional SR and low-resolution ADCs with the proposed adaptive SR. We also confirmed the validity of the noise adjustment method in the proposed adaptive SR by comparing the performance with the optimal standard deviation.

Moreover, we confirmed another effect of applying the proposed adaptive SR, that is, low-resolution ADCs with the proposed adaptive SR could perform better than sufficient-resolution ADCs under high-noise channel conditions. This effect is due to the fact that the symbol transitions between adjacent modulation levels are less likely to occur in low-resolution ADCs. Since the errors in determining the symbol, which can be detected without applying SR, are reduce by applying the proposed adaptive SR, this fact affects more strongly, making the receiver more resistant to channel noise.

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