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LETTER

16 QAM-OFDM receiver using 1-bit ADC for noise utilization: Characterization in fading channels with large amplitude fluctuations

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Abstract The performance of 1-bit Analogue-to-Digital Converter (ADC) receivers is vulnerable to degradation in environments with significant signal amplitude fluctuations, due to quantization errors inherent in binary outputs. Thus, it becomes crucial to verify the effectiveness of 1-bit ADC receivers under such conditions. In this study, we conduct an evaluation of previously proposed 1-bit ADC receivers in Rician and Rayleigh fading channels, where both signal amplitude and phase exhibit dynamic fluctuations. We confirm the effectiveness of 1-bit ADC receivers in such fading environments. However, we observe that the degree of degradation of Signal-to-Noise Ratio (SNR) versus Bit Error Rate (BER) due to signal amplitude and phase variations depends on the employed demodulation method.

Keywords: 1-bit ADC, stochastic resonance, noise, OFDM
Classification: Wireless communication technologies

1. Introduction

The substantial power consumption of multi-antenna receivers in next-generation communication systems poses a significant challenge. Analog-to-Digital Converters (ADCs) contribute substantially to the power consumption of these receivers [1]. Consequently, we explore the potential utilization of 1-bit ADCs in receivers to reduce power consumption.

1-bit ADCs exhibit the lowest power consumption among ADCs, due to the fact that the power consumption of ADCs tend to exponentially increase with resolution [2, 3]. Additionally, 1-bit ADCs have the narrowest dynamic range and do not necessitate intricate comparative operation circuits, offering advantages such as high-speed operation and a compact circuit footprint. However, the use of 1-bit ADCs introduces distortion to the input waveform, making it generally challenging to accurately estimate the amplitude of the input signal in receivers.

To compensate for the shortcomings of 1-bit ADCs, the authors apply the phenomenon of stochastic resonance and investigate a demodulation method that can obtain good BER (Bit Error Rate) even when 1-bit ADCs are used in a receiver. Stochastic resonance is a phenomenon in which the characteristic of a nonlinear system approaches that of a linear system when we apply a moderate amount of noise to a nonlinear system.

In previous studies, a 1-bit ADC receiver is proposed that utilizes noise [2, 4]. This receiver applies Gaussian noise to the modulated signal, samples it with a 1-bit ADC, and estimates the transmitted signal from the sample mean. By utilizing noise in this way, we can estimate the input signal to a 1-bit ADC.

In the literature [5, 6], they conduct 4PAM transmission experiments and confirm that the 1-bit ADC receiver improves its BER due to the noise. The reference [7] shows that we can demodulate 16 QAM-OFDM signals with good BER.

In the references [5, 7], Ohtaguro et al. use a 1-bit ADC receiver that performs frequency conversion before inputting it to the 1-bit ADC. Therefore, a receiver needs an oscillator and mixer. Moreover, all of these references adopt AWGN channel as channel models. Then, the literature [8] shows that we can achieve demodulation with a good BER for 16 QAM-OFDM signals with a 1-bit ADC receiver in a 2-pass fading channel. Furthermore, to simplify the receiver, a method is proposed to convert the received signal in the IF (Intermediate Frequency) band into a baseband signal in the digital domain.

In the paper [9], authors propose a 1-bit ADC receiver that demodulates the baseband signal by multiplying the carrier wave after averaging the 1-bit ADC output. However, in the paper [9], authors evaluate BER in only one Rician fading channel.

Since the output of a 1-bit ADC is binary, we can expect the effect of quantization errors in a 1-bit ADC receiver to be larger in environments with large signal amplitude variations. There are no studies to confirm the effectiveness of 1-bit ADC receivers on Rayleigh and Rician fading channels, where the amplitude and phase of the signal fluctuate dynamically. Then, in this paper, we evaluate 1-bit ADC receiver proposed in [5, 8, 9] in terms of SNR (Signal-to-Noise Ratio) vs. BER in Rician and Rayleigh fading channels. Our results demonstrate that the 1-bit ADC receivers exhibit their effectiveness even in channels with substantial signal amplitude and phase variations.

In Section 2, we describe the system model. In this paper, we transmit and receive 16 QAM/OFDM signals. We adopt Rician and Rayleigh fading channels as channel models. We also explain the 1-bit ADC receiver configuration in this section. In Section 3, we describe the demodulation method for baseband signals. In this section, we first explain the

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output analysis method of the 1-bit ADC proposed in the previous study [4]. Next, we describe a method to demodulate the baseband signal by recovering the received signal from the average of the outputs of parallel 1-bit ADCs and multiplying it by the carrier wave in the digital domain, that is proposed in the paper [4]. In Section 4, we present numerical results and evaluate the proposed 1-bit ADC receiver by investigating SNR vs. BER. Section 5 concludes the paper.

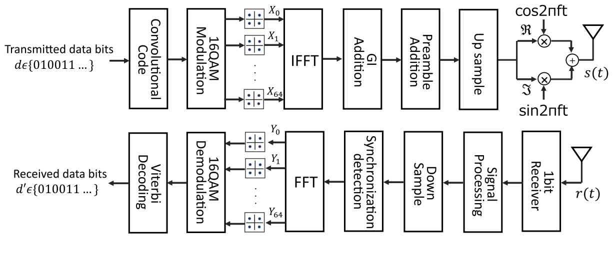
2. System model

Figure 1 shows the overview of this system. First, we describe the transmitter configuration. Next, we explain the channel model and 1-bit ADC receiver used in this study.

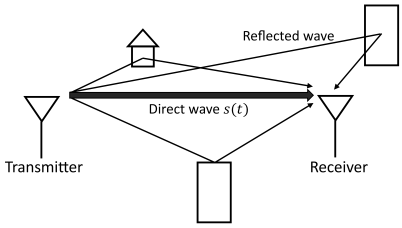
2.1 Transmitter

The transmitter transmits 16 QAM-OFDM signals according to the 24 Mbps mode of the IEEE 802.11a wireless LAN standard. In 24 Mbps mode, convolutional codes are used as error correcting codes, and the coding rate is 1/2. Preamble symbols are inserted at the beginning of the OFDM frame. The preamble detects the arrival of the signal and is used for synchronization detection [10]. The number of data bits per OFDM symbol is 96. 16 QAM symbols are inverse Fourier transformed with 64 points. We add a guard interval (GI) that has 16 samples to the inverse Fourier transform output to generate a total of 80 OFDM symbol samples.

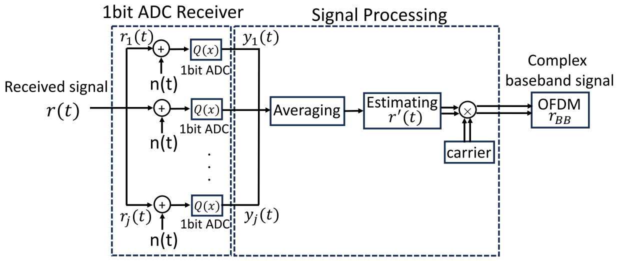
In the IEEE 802.11a standard, the sampling frequency of the OFDM baseband signal is 20 MHz, but we perform x times oversampling to obtain a waveform with a sampling frequency of $20 \times x$ MHz. In this case, the OFDM symbol including the guard interval has $80 \times x$ samples.



(a) System model



(b) Channel model:Rician and Rayleigh fading channel



(c) 1bit ADC receiver

Fig. 1 System overview and 1-bit ADC receiver configuration

We multiply the generated 16 QAM-OFDM complex baseband signal $s_{BB}(t)$ by a carrier wave of frequency f [Hz] to generate the transmit signal $s(t)$ expressed as follows.

$$s(t) = \Re\{s_{BB}(t)\}\cos(2\pi f t) - \Im\{s_{BB}(t)\}\sin(2\pi f t) \quad (1)$$

where $\Re\{s_{BB}(t)\}$ and $\Im\{s_{BB}(t)\}$ respectively represent the real and imaginary part of the baseband signal.

2.2 Channel model

In this paper, we assume Rayleigh and Rician fading channels as practical channel models between a base station and a mobile terminal. As we described in Section 1, there are no studies regarding a 1-bit ADC receiver on channels with dynamically varying signal amplitude and phase, such as Rayleigh fading channel. For example, in the reference [5, 6], it is shown that we can demodulate multi-level modulated signals (4PAM) with good BER by the 1-bit ADC receiver in AWGN channel. In the paper [9], authors transmit multiplexed signals (16 QAM-OFDM) and receive in only one Rician fading channel.

In a Rayleigh fading channel, the probability distribution of the received signal amplitude $f_r(t)$ is called Rayleigh distribution and is expressed by the following equation [11].

$$f_r(r) = \frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) \quad (2)$$

Here, σ is a parameter representing the strength of the scattered wave. In a Rician fading channel, the probability distribution of the received signal amplitude $f_r(r)$ is called Rician distribution and is expressed by the following equation [11].

$$f_r(r) = \frac{r}{\sigma^2}\exp\left(-\frac{a^2 + r^2}{2\sigma^2}\right) I_0\left(\frac{ar}{\sigma^2}\right) \quad (3)$$

I_0 where a is the amplitude of the direct wave, is the zeroth order modified Bessel function of the first kind. The ratio of the direct wave power to the average power of the scattered wave K, that is K-factor, is

$$K = \frac{a^2}{2\sigma^2} \quad (4)$$

2.3 1-bit ADC receiver

We show the configuration of the 1-bit ADC receiver and the outline of signal processing in Fig. 1(c).

We arrange 1-bit ADCs in parallel, as in the reference [8]. This is to demodulate the baseband signal from the average of the 1-bit ADCs, as described in Section 3. The receiver adds independent Gaussian noise with mean 0 and variance σ^2 to the received signal and inputs it to j 1-bit ADCs in parallel. That is, the input $r_k(t)$ to the kth 1-bit ADC at time t is

$$r_k(t) = r(t) + n_k(t) \quad (5)$$

In this method, we can demodulate the baseband signal close to the original baseband signal because we can accurately restore the received signal and then multiplied by the carrier wave.

The following describes the signal processing flow in the receiver. The double arrows in Fig. 1(c) indicate that the real and imaginary parts are processed in parallel. The output of the kth 1-bit ADC at time t is

$$y_k(t) = Q\left(r_k(t)\right) = \begin{cases} +1 & r_k(t) \geq 0 \\ -1 & r_k(t) < 0 \end{cases} \tag{6}$$

We calculate the average value of $y_1(t) \sim y_j(t)$, multiply that average value by the carrier wave in the digital domain, and then demodulate the baseband signal by using conventional analysis methods [4]. We describe the demodulation method in detail in Section 3.

After downsampling the demodulated 16 QAM-OFDM complex baseband signal to 20 MHz, the receiver detects frame synchronization points to start the reception processing. The receiver calculates the cross-correlation value between the received signal and the preamble data, which is known beforehand at the receiver, and observes a peak corresponding to the number of symbols in the preamble appears every 16 samples. The point at which the peaks no longer exceed the threshold is the frame synchronization point. The receiver starts Fourier transform from this frame sync point. Finally, the receiver performs decoding, and calculates the BER by comparing the transmitted and received data.

3. Baseband signal demodulation method

In this section, we first describe the 1-bit ADC output analysis method proposed in our previous study [4]. Next, we describe how to demodulate the baseband signal at the receiver by using that analysis method.

3.1 Analysis method

In the paper [4], Nakashima et al. propose an analysis method to decompose the 1-bit ADC output into a deterministic signal for the input and an output noise. In this study, we also use this method as a 1-bit ADC output analysis method.

Here, let the deterministic signal $\mu(x)$ be the expected value of the random variable $z_k(t)$ corresponding to the input amplitude x. The output $z_k(t)$ of the k-th 1-bit ADC at time t is expressed by the following equation using the deterministic signal $\mu(x_k(t))$ for the $x_k(t)$ which is input to the k-th 1-bit ADC at time t and the output noise $q_k(t)$ uncorrelated with the input [4]. Therefore, the output $z_k(t)$ of the k-th 1-bit ADC is

$$z_k(t) = \mu(x_k(t)) + q_k(t) \tag{7}$$

Next, we derive the deterministic signal $\mu(x_k(t))$ representing the expected value of the k-th 1-bit ADC output. The probability density function $p(n)$ of Gaussian noise $n(t)$ with mean zero and variance σ^2 is

$$p(n) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{n^2}{2\sigma^2}\right) \tag{8}$$

That is, as described in the paper [12], the probability that the output of the 1-bit ADC is +1 for the input $x_k(t)$ is

$$P(+1|x_k(t)) = \int_0^\infty \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(n - x_k(t))^2}{2\sigma^2}\right\} dn \tag{9}$$

$$= \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{x_k(t)}{\sqrt{2\sigma^2}}\right) \tag{10}$$

The expected value of the output of the 1-bit ADC is

$$\mu(x_k(t)) = P(+1|x_k(t)) + (-1)\left(1 - P(+1|x_k(t))\right) \tag{11}$$

$$= \mathrm{erf}\left(\frac{x_k(t)}{\sqrt{2\sigma^2}}\right) \tag{12}$$

Thus, if the noise follows a Gaussian distribution, the function representing the expected value of the output of the kth 1-bit ADC at time t is $\mu(x_k(t)) = \mathrm{erf}\left(x_k(t)/\sqrt{2\sigma^2}\right)$ [13]. That is, Eq. (7) can be rewritten as

$$z_k(t) = \mathrm{erf}\left(\frac{x_k(t)}{\sqrt{2\sigma^2}}\right) + q_k(t) \tag{13}$$

3.2 Demodulation of baseband signal

Turning our attention to Fig. 1(a), we explain how to demodulate the complex baseband signal $r_{BB}(t)$. Equation (6) shows the k-th 1-bit ADC output at time t. Let $E[y(t)]$ be the average value of $y_1(t) \sim y_j(t)$. From Eq. (13), the average value $E[y(t)]$ is equal to the average value of $z_1(t) \sim z_j(t)$. Now the input signal to the 1-bit ADC is the received signal, that is

$$E[y(t)] = \mathrm{erf}\left(\frac{r(t)}{\sqrt{2\sigma^2}}\right) \tag{14}$$

From the above, the value of the received signal at time t, $r(t)$, can be estimated by the inverse function of the error function as follows

$$r'(t) = \sqrt{2\sigma^2}\mathrm{erf}^{-1}\left(E[y(t)]\right) \tag{15}$$

Therefore, the real and imaginary parts of the complex baseband signal demodulated at the receiver side are respectively

$$\Re\{r_{BB}(t)\} = \sqrt{2\sigma^2}\mathrm{erf}^{-1}\left(E[y(t)]\right)\cos(2\pi f t) \tag{16}$$

$$\Im\{r_{BB}(t)\} = \sqrt{2\sigma^2}\mathrm{erf}^{-1}\left(\{E[y(t)]\}\right)\sin(2\pi f t) \tag{17}$$

4. Numerical example

In Fig. 1(a), the number of 1-bit ADCs in parallel is 120. The frequency of the orthogonal carrier wave is set to 30 MHz. The number of transmitted symbols is 200,000 bits. The 16 QAM-OFDM baseband signal of IEEE 802.11a standard is oversampled 10 times, upsampled to a sampling frequency of 200 MHz. We use Rayleigh and Rician fading channels as channel models. In Rician fading channels, we set the K-factor in Eq. (4) to 3.

Figures 2 and 3 [3] show that SNR vs. BER in Rician and Rayleigh fading channels when we use 1-bit ADC receiver proposed in the paper [5, 8, 9] to receive 16 QAM-OFDM. The receiver in the reference [5] converts signal in the IF band to baseband by multiplying the carrier wave before inputting it to the 1-bit ADC. The receiver in the literature [8] inputs the received IF band signal to 1-bit ADCs and calculate the average value of 1-bit ADC outputs multiplied by the carrier wave, and perform demodulation from that average value. The receiver proposed in [9] inputs the received IF band signal to 1-bit ADCs and takes average of 1-bit ADC

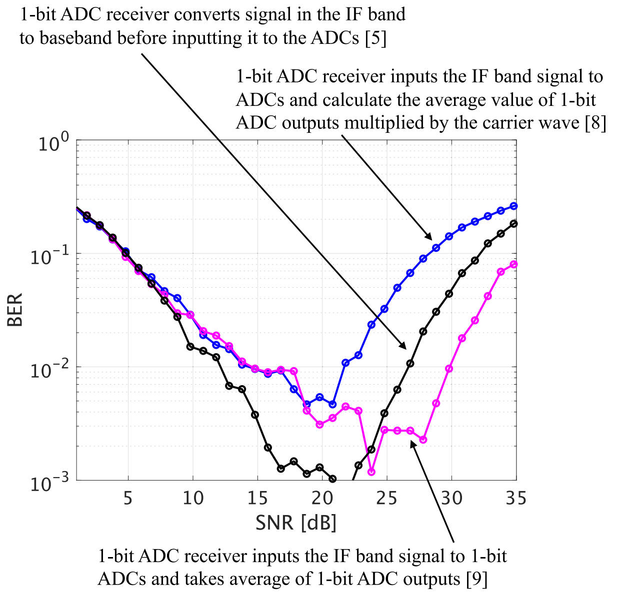


Fig. 2 BER performances of 16 QAM-OFDM in Rician fading channel. The number of 1-bit ADCs in receiver is 120. K-factor in Eq. (4) is 3.

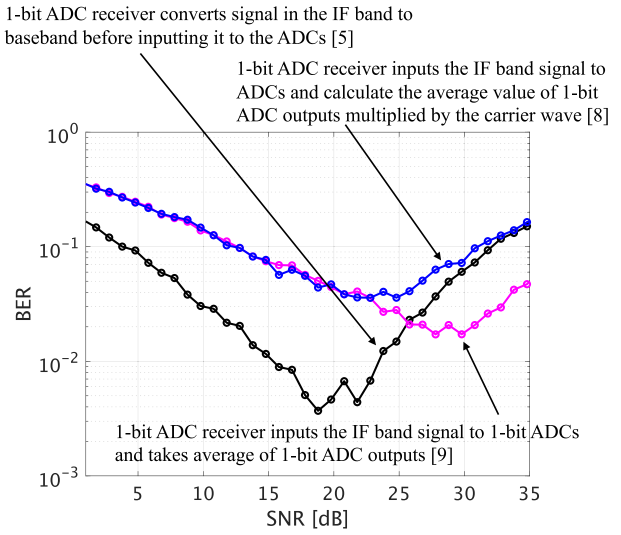


Fig. 3 BER performances of 16 QAM-OFDM in Rayleigh fading channel. The number of 1-bit ADCs in receiver is 120.

outputs. Next, the receiver demodulates the received signal by multiplying the carrier wave in the digital domain.

As we can see from Figs. 2 and 3, we can demodulate 16 QAM-OFDM signal in fading channel where the amplitude and phase of the signal fluctuate dynamically with good BER.

Comparing the receiver in [5] and the receiver in [8, 9], we can see that the receiver in [8, 9] degrades more severely as the direct wave power weakens. This is due to the different demodulation methods. The receiver in [5] multiplies the received wave by the carrier wave and converts it to baseband, then inputs it to 1-bit ADCs. On the other hand, the receiver in [8, 9] firstly inputs the received wave to 1-bit ADCs and next multiplies it by the carrier wave. Therefore, signal amplitude fluctuations makes demodulation difficult for the receivers, resulting in severe performance degradation.

The receiver proposed in [9] has improved BER characteristics by approximately 7.5 dB in the high SNR range above 20 dB compared to the receiver proposed in [8]. The receiver in [8] demodulates the baseband signal by multiplying the 1-bit ADC output by the carrier wave and then averaging the result. Therefore, it is necessary to estimate the baseband signal from the 1-bit ADC output multiplied by the carrier wave, resulting in a large error. In contrast, the receiver in [9] estimates the received signal after first averaging the 1-bit ADC output. As shown in Eq. (15), the inverse function of the error function is used for accurate estimation. The receiver in [9] demodulates the baseband signal by multiplying the estimated received signal by the carrier wave, so the receiver in [9] can demodulate more accurately.

5. Conclusion

In this study, we evaluate 1-bit ADC receivers proposed in previous studies in some fading channels where the amplitude and phase of the signal fluctuate dynamically and confirm that the 1-bit ADC receiver is effective. However, the degree of degradation of SNR vs. BER due to variations in signal amplitude and phase depends on the demodulation method.

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