16QAM-OFDM Receiver Using 1-bit ADC that Utilizes Noise and Performs Frequency Conversion in the Digital Domain

Characterization in a Frequency Flat Rician Fading Channel

Arata ISOZAKI[†], ***Student Member***, **Takaya YAMAZATO**[†], ***and*** **Masato SAITO**[††], ***Senior Members***

SUMMARY In this study, we propose the 1-bit ADC receiver that performs frequency conversion in the digital domain to simplify the circuitry in the receiver and reduce power consumption. Then, we evaluate the SNR vs. BER of the 1-bit ADC receiver we propose. In the proposed receiver, the average of the 1-bit ADC outputs in parallel is taken, the received signal is restored, and the baseband signal is demodulated by multiplying the restored received signal by the carrier wave. The SNR vs. BER in the 1-bit ADC receiver we propose is improved by about 2.5 dB compared to it in the conventional receiver [1] that performs frequency conversion before input received singal to the 1-bit ADC. In addition, for the receiver proposed in the reference [2], which demodulates the baseband signal by multiplying the 1-bit ADC output with the carrier wave and then averaging it, the SNR vs. BER is improved by approximately 2.5 dB when the SNR is around 5.0 dB, and by approximately 7.5 dB when the SNR exceeds 20 dB.
key words: *1-bit ADC, Stochastic resonance, Noise, Rician fading, OFDM*

1. Introduction

A large power consumption of multi-antenna receivers in next-generation communication systems is an issue. ADCs (Analog to Digital Converter) account for most of the power consumption of receivers [3]. Since a power consumption of 1-bit ADC increases exponentially with increasing resolution, a power consumption of 1-bit ADC is several thousand times lower than that of 10-14-bit ADC typically used in base stations [4]. Furthermore, a 1-bit ADC has a wide dynamic range and do not require complicated comparative operation circuits. Therefore, it has the advantage of high-speed operation and small circuit area. However, a 1-bit ADC distorts a input waveform and output it, so it is generally difficult to estimate the amplitude of the input waveform when we use a 1-bit ADC in receivers.

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

In previous studies [7, 8], authors propose a 1-bit ADC receiver that utilizes noise. 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 the 1-bit ADC.

In the literatures [1,9], 4PAM transmission experiments have been conducted, and it is experimentally confirmed that the 1-bit ADC receiver improves its BER due to the noise. Reference [10] shows that signals with large amplitude variations, specifically OFDM signals using 16QAM as the primary modulation, can be demodulated with good BER (Bit Error Rate) when signals are received by a 1-bit ADC receiver that takes advantage of wideband noise.

In the references [1, 10], frequency conversion is performed by multiplying the received signal by the carrier wave before inputting it to the 1-bit ADC, so an oscillator and mixer are required at the receiver. In all of these references, the AWGN channel is adopted as the channel model. In the literature [2], it is shown that demodulation with a good BER can be achieved for 16QAM-OFDM signals received with a 1-bit ADC receiver that utilizes noise 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 by sampling with a 1-bit ADC and then multiplying it by the carrier wave in the digital domain.

In the receiver described in the literature [2], the baseband signal is demodulated by multiplying the 1-bit ADC output by the carrier wave and then taking the average. In this method, the baseband signal is demodulated from the value obtained by multiplying the 1-bit ADC output and the carrier wave, which deteriorates the BER. In this study, we propose a 1-bit ADC receiver that demodulates the baseband signal by multiplying the carrier wave after averaging the 1-bit ADC output. In proposed method, we accurately demodulates the baseband signal by restoring the received signal from the average of the 1-bit ADC output and then multiplying it by the carrier wave. In this paper, we use the proposed receiver to receive 16QAM-OFDM signals in a rician fading channel, and evaluate its SNR (Signal to Noise Ratio) vs. BER.

In section 2, we describe the system model. In this paper, we transmit and receive 16QAM-OFDM signals. We adopt a frequency flat rician fading as the channel model. The proposed 1-bit ADC receiver configuration is also explained in this section. In section 3, we describe the demodulation method for baseband signals. In this section, we first explain the output analysis method of the 1-bit ADC proposed in the previous study [7]. Next, we propose a method

[†]†The author is with Nagoya University, Furou Cho, Chikusa Ku, Nagoya, Aichi 464-8601, Japan.
[††]††The author is with University of the Ryukyus, 1, Sembaru, Nakagami Gun Nishihara Cho, Okinawa, 903-0213, Japan.

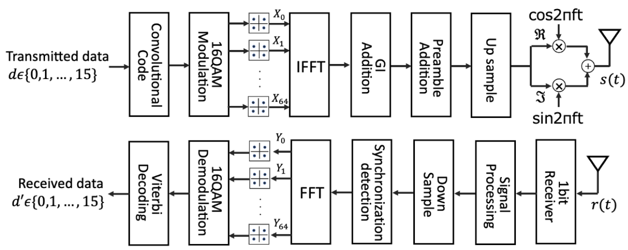

Fig. 1: System model

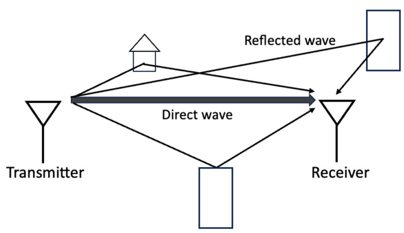

Fig. 2: Channel model : frequency flat rician fading

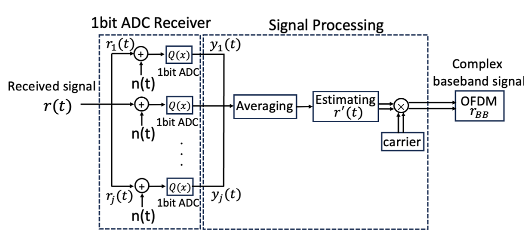

Fig. 3: 1bit ADC receiver

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. In section 4 we show numerical examples and evaluate the proposed 1-bit ADC receiver based on the obtained SNR vs. BER.

2. System Model

Figure. 1 shows the overview of this system.

2.1 Transmitter

The transmitter transmits 16QAM-OFDM signals according to the 24 Mbps mode of the IEEE802.11a wireless LAN standard. In 24 Mbps mode, convolutional codes are used as error correcting codes, and the coding rate is $1/2$. A preamble is inserted at the beginning of the OFDM frame. The preamble detects the arrival of the signal and is used for synchronization detection [11]. The number of data bits per OFDM symbol is 96. 16QAM 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 IEEE802.11a 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.

The transmitted data d_i takes 16 values and is $\{0, 1, \ldots, 15\}$. We multiply the generated 16QAM-OFDM complex baseband signal $s_{BB}(t)$ by an carrier wave of frequency f [Hz] to generate the transmit signal $s(t)$ expressed as follows.

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

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 the reference [1, 9], it is shown that we can demodulate multi-level modulated signals (4PAM) with good BER by the 1-bit ADC (Analog to Digital Converter) receiver. In the reference [10], it is shown that a 1-bit ADC receiver can demodulate a multiplexed signal (16QAM-OFDM) with a good BER. In all of these references, the AWGN channel is used as the channel model. In the literature [2], multiplexed signals (16QAM-OFDM) were transmitted and received in a 2-path fading channel, and it is shown that a 1-bit ADC receiver is effective for signals with large amplitude fluctuations. However, a 2-path fading channel is not suitable as a model for a actual environment. In this paper, we assume a frequency flat rician fading channel as a more practical channel model between a base station and mobile terminals, in which a direct wave and a reflected wave arrive at the receiver side. The probability distribution of the received signal amplitude $f_r(t)$ is called the Rician distribution and is expressed by the following equation [12].

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

Here, I_0 is the 0th order modified Bessel function of the first kind. a is the amplitude of the direct wave, σ is a parameter representing the strength of the scattered wave. The ratio of the direct wave power to the average power of the scattered wave K is

$$K = \frac{a^2}{2\sigma^2} \tag{3}$$

2.3 1-bit ADC receiver

We show the configuration of the 1-bit ADC receiver and the outline of signal processing in Fig. 3.

We arrange 1-bit ADCs in parallel, as in the reference [2, 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 input 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

$$r_k(t) = r(t) + n_k(t) \tag{4}$$

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

The following describes the signal processing flow in the receiver. The double arrows in Fig. 3 indicate that the real and imaginary parts are processed in parallel. The output of the kth 1-bit ADC at time t is

$$y_k(t) = Q\left(r_k(t)\right) = \begin{cases} +1 & r_k(t) \geq 0 \\ -1 & r_k(t) < 0 \end{cases} \tag{5}$$

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 [7]. We describe the demodulation method in detail in section 3.

After downsampling the demodulated 16QAM-OFDM complex baseband signal to 20 MHz, frame synchronization points are detected to start the reception processing. The cross-correlation value between the received signal and the preamble data, which is known beforehand at the receiver, is calculated and 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. Fourier transform is performed starting from the frame sync point. Finally, decoding is performed, and BER is calculated 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 [7]. Next, we describe how to demodulate the baseband signal at the receiver by using that analysis method.

3.1 Analysis method

In the paper [7], an analysis method is proposed 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.

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 [7]. Note that $\mu(x_k(t))$ is a function that represents the expected value of the 1-bit ADC output given the input $x_k(t)$. Terefore, the output $z_k(t)$ of the k-th 1-bit ADC is

$$z_k(t) = \mu(x_k(t)) + q_k(t) \tag{6}$$

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 0 and variance σ^2 is

$$p(n) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{n^2}{2\sigma^2}\right) \tag{7}$$

That is, the probability that the output of the 1-bit ADC is +1 for the input $x_k(t)$ is

$$\begin{aligned} P(+1|x_k(t)) &= \int_0^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left\{-\frac{(n - x_k(t))^2}{2\sigma^2}\right\} dn & (8) \\ &= \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{x_k(t)}{\sqrt{2\sigma^2}}\right) & (9) \end{aligned}$$

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

$$\begin{aligned} \mu(x_k(t)) &= P(+1|x_k(t)) + (-1)\left(1 - P_{+1}(+1|x_k(t))\right) & (10) \\ &= \mathrm{erf}\left(\frac{x_k(t)}{\sqrt{2\sigma^2}}\right) & (11) \end{aligned}$$

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 $\mu(x_k(t)) = \mathrm{erf}\left(x_k(t)/\sqrt{2\sigma^2}\right)$. That is, equation (5) can be rewritten as

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

3.2 Demodulation of baseband signal

Turning our attention to Fig. 3, we explain how to demodulate the complex baseband signal $r_{BB}(t)$. Equation. (5) 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. (12), 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

$$E[y(t)] = \mathrm{erf}\left(\frac{r(t)}{\sqrt{2\sigma^2}}\right) \tag{13}$$

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

$$r'(t) = \sqrt{2\sigma^2}\,\mathrm{erf}^{-1}\left(E[y(t)]\right) \tag{14}$$

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

$$\begin{aligned} \Re\{r_{BB}(t)\} &= \sqrt{2\sigma^2}\,\mathrm{erf}^{-1}\left(E[y(t)]\right)\cos(2\pi f t) & (15) \\ \Im\{r_{BB}(t)\} &= \sqrt{2\sigma^2}\,\mathrm{erf}^{-1}\left(\{E[y(t)]\}\right)\sin(2\pi f t) & (16) \end{aligned}$$

4. Numerical example

In Fig. 1, the number of 1-bit ADCs in parallel is 120, and the number of transmitted symbols is 32,000 bytes. The frequency of the orthogonal carrier wave is set to 30 MHz. The 16QAM-OFDM baseband signal of IEEE802.11a standard is oversampled 10 times, upsampled to a sampling frequency of 200 MHz. The K-factor in Eq. (3) is set to 7.

We show that the method we propose, in which the received IF band signal is input to a 1-bit ADC and demodulated by multiplying the carrier wave in the digital domain after averaging the 1-bit ADC output, can also be used to demodulate with a good BER. We compare the SNR (Signal to Noise Ratio) vs. BER in the 1-bit ADC receiver we propose and in one used in the previous studies [1,2]. In the

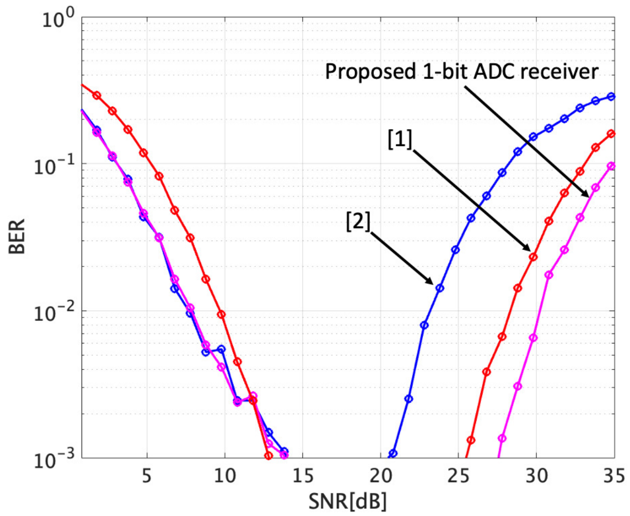

Fig. 4: SNR vs. BER in a frequency flat rician fading channel (24 Mbps, 16QAM-OFDM, 32000 bytes transmitted)

reference [1], the received signal in the IF band is converted to baseband by multiplying the carrier wave before inputting it to the 1-bit ADC. In the literature [2], the received IF band signal is input to a 1-bit ADC, the average value of the 1-bit ADC output multiplied by the carrier wave is calculated, and demodulation is performed from that average value. Figure. 4 shows the SNR vs. BER of the 1-bit ADC receiver we propose and proposed in previous studies.

The BER is below 10^{-3} in the range of SNR from 13.5 dB to 27.5 dB when we use the proposed 1-bit ADC receiver. This is about 2.5 dB better than the charasteristics when we use conventional method [1]. This is because the conventional method in [1] performs frequency conversion before inputting the received signal to the 1-bit ADC, and high-frequency components remain at that time. In addition, compared to the conventional method in [2], the characteristics are improved by approximately 2.5 dB when the SNR is around 5.0 dB, and by approximately 7.5 dB when the SNR exceeds 20 dB. In the conventional method [2], the 1-bit ADC output is multiplied by the carrier wave and then averaged to demodulate the baseband signal. Therefore, it is necessary to estimate the baseband signal from the 1-bit ADC output multiplied by the carrier wave, resulting in a error. In contrast, in the method we propose, we estimates the received signal after averaging the 1-bit ADC output. As shown in Eq. (13), the inverse function of the error function is used for accurate estimation. The estimated received signal is then multiplied by the carrier wave to demodulate the baseband, which is more accurate than the conventional method in [2].

5. Conclusion

In this study, we proposed a 1-bit ADC receiver that performs frequency conversion in the digital domain. In this receiver, the average of the 1-bit ADC outputs in parallel is taken, the received signal is restored, and the baseband signal is demodulated by multiplying the restored received signal by the carrier wave.

The SNR vs. BER in the 1-bit ADC receiver we propose is improved by about 2.5 dB compared to it in the conventional receiver that performs frequency conversion before input to the 1-bit ADC [1]. In addition, for the receiver proposed in the reference [2], which demodulates the baseband signal by multiplying the 1-bit ADC output with the carrier wave and then averaging it, the SNR vs. BER is improved by approximately 2.5 dB when the SNR is around 5.0 dB, and by approximately 7.5 dB when the SNR exceeds 20 dB.

Acknowledgments

The authors would like to thank Profs. M. Katayama, H. Okada and C. BEN NAILA of Nagoya University for their valuable input.

References

[1] T. Ohtaguro, M. Saito, T. Yamazato, “An experimental study on the demodulation of 4-PAM signals using 1bit ADC with noise,” IEICE Technical Report, RCS2021-51, pp.133-138, June 2021

[2] A.Isozaki, T.Yamazato, M.Saito, “16QAM-OFDM receiver using a 1-bit ADC that multiplies the carrier wave in the digital domain,” IEICE Technical Report, CS2023, July 2023

[3] Z. Shao, Lukas Landau, Rodrigo C. de Lamare, “Dynamic Oversampling for 1-Bit ADCs in Large-Scale Multiple-Antenna Systems,” IEEE Transactions on Communications, May 2021

[4] B. Murmann, “The Race for the Extra Decibel: A Brief Review of Current ADC Performance Trajectories,” IEEE Solid-State Circuits Mag., 2015

[5] Y. Tadokoro, T. Yamazato, H. Tanaka, S. Arai, Y. Nakashima, S. Hiraoka, “For the Applications of Stochastic Resonance in the Telecommunications,” IEICE Transactions on Communications, vol.J102-B, no.6, pp.445-458, 2019.06.

[6] Y. Nakashima, T. Yamazato, S. Arai, H. Tanaka, K. Tadokoro, “An analysis of a noise-aided linearization range on a receiver with one-bit analog-to-digital converter,” IEICE Technical Report, RCS2019-149, pp.19-24, August 2019

[7] Y. Nakashima, T. Yamazato, S. Arai, H. Tanaka, Y. Tadokoro, ”Noise-Aided Demodulation With One-Bit Comparator for Multilevel Pulse-Amplitude-Modulated Signals,” IEEE Wireless communications letters, vol. 7, no. 5, October 2018

[8] Y. Nakashima(2020), “An analysis of a receiver with noise-aided 1bit analog-to-digital converters,”D. Thesis, Graduate School of Engineering, Nagoya University

[9] J. Zheng, T. Yamazato, M. Saito, “An Experimental Study on A Noise-aided 1-bit ADC Receiver for 4-PAM,” IEICE Communications Express, vol.11, no.12, pp.817-822, December 2022

[10] T. Ohtaguro, M. Saito, T. Yamazato, “Experimental study on reception of 16QAM-OFDM signals using wideband noise and 1bit ADC ,” IEICE Technical Report, vol. 122, no. 73, RCS2022-64, pp. 236-241, June 2022

[11] Y.Mukai, K.Naito, K.Mori, H.Kobayashi, “Study of preamble detection performance in OFDM in cooperative communication for IEEE802.11a,” IPSJ SIG Technical Report, Vol. 2013-MBL-68 No.9, November 2013

[12] J. G. Proakis, Masoud Salehi, Digital Communications, 5th ed., McGraw Hill Higher Education, 2001.

[13] A.Isozaki, T.Yamazato, M.Saito, H.Hatano, “Evaluation of the effect of nonlinear amplifiers on the input/output analysis of 1-bit-ADC,” IEICE General Conference, B-5-19, p.264, March 2023

[14] M. Saito, Y. Nakashima, T. Yamazato, S. Arai, H. Hatano, H. Tanaka, Y. Tadokoro, “Noise-assisted nonlinear estimation of a one-bit ADC output and its application to a multi-antenna receiver,” TechRxiv. Preprint, 2022.04