PAPER

# Power Reduction of Variable Wordlength OFDM Receiver in Time-Varying Fading Channels by Monitoring Subcarrier SNRs

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**SUMMARY** Determination of wordlength is essential for designing digital circuits because the wordlength affects system performance, hardware size, and power consumption. Variable wordlength methods that a system dynamically and effectively changes the wordlength depending on surrounding environments have been studied for power reduction in wireless systems. The conventional variable wordlength methods induce communication performance degradation when compared with a floating-point representation in time-varying fading channels. This paper discusses rapid wordlength control on packet basis and proposes a new method based on monitoring subcarrier SNRs in an OFDM receiver. The proposed method can estimate signal quality accurately and can decrease the wordlength decision errors. The simulation results have indicated that the proposed method shows better PER performance compared with the conventional methods.

***key words:*** *wireless communication, variable wordlength, OFDM, digital signal processing circuits*

## 1. Introduction

Wireless communication systems using orthogonal frequency division multiplexing (OFDM) and multiple-input multiple-output (MIMO) have been developed for high-throughput data transmission and they are widely used in cellular networks and wireless local area networks (LANs). These technologies require large numbers of operations and tend to increase power consumption in digital circuits. Reducing the power consumption of digital circuits is one of important factors for extending battery lifetimes in portable electronic devices.

Determination of wordlength (also called as bit width, length, and precision) is essential for designing digital circuits because the wordlength affects system performance, hardware size, and power consumption [1]. Typically, digital signal processing (DSP) systems and algorithms are evaluated on a floating-point representation by software simulation. In the hardware implementation, a fixed-point representation is used for reducing circuit area and power consumption with increasing clock frequency. This requires the conversion of fixed-point to floating-point representations.

In the fixed-point representation, excessively short wordlength leads to influence of bit rounding errors. On the other hand, excessively large wordlength causes redundant hardware components. Appropriate wordlength in the fixed-point representation is determined so that it keeps almost the same system performance as the floating-point representation. This wordlength determination is done by computer simulation and theoretical analysis. Since analysis in finite wordlength effects has difficulty finding optimum wordlengths for complicated systems, simulation-based wordlength optimizations have been adopted in digital circuit design of OFDM systems [2]. The wordlength of digital circuits is fixed in this time, which is named as *fixed* wordlength.

Actual wireless systems must be able to handle sharp fluctuations in amplitude caused by multipath fading. The fixed wordlength tends to be long in order to cope with the aforementioned worst-case condition. However, a system has good chances to use short wordlength in most cases that signals are not attenuated much. Thus, the *variable* wordlength that a receiver dynamically changes wordlength according to wireless conditions is effective in reducing power consumption [3]–[9]. As for similar concepts in analog circuits, an analog front-end is dynamically tuned in signal quality with optimization of a trade-off among noise, linearity, and power consumption [11], [12].

The variable wordlength technique has been applied to microprocessors [3], arithmetic units [4], and digital filters [5]. For instance, Brooks proposed a hardware mechanism for general-purpose microprocessors that dynamically changes the wordlength from a full 64-bit width to a narrower bit width depending on the application. Clock gating has been used for reducing power by disabling value changes in unneeded functional circuits [3]. In wireless applications, digital circuit components of an OFDM receiver have been dynamically tuned in wordlength [6]–[9]. Yoshizawa presented a tunable wordlength architecture that dynamically changes the wordlength in an OFDM receiver by estimating a channel condition from an error vector magnitude (EVM) [6]. Kim presented the adaptive wordlength control that switches short and long wordlengths by measuring a modulation error ratio (MER) [7]. The MER, corresponding to multiplicative inverse of the EVM, gives a similar metric to a signal noise-to-ratio (SNR) [8]. Nisar presented the supply voltage control where the power reduction is performed for short wordlength as well as clock gating [9]. The auto rate fallback (ARF) method that gradually decreases/increases the wordlength according to successful/failed packet receptions has been evaluated in [6], [10].

Our new challenge is to apply variable wordlength without sacrificing communication quality, which is ori-

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ented toward reliable communication used for industrial networks [13]. Those communication systems request very low bit error rate (BER) and packet error rate (PER) as much as possible. The conventional variable wordlength methods [6]–[10] target certain BERs and PERs (e.g., $2\times10^{-4}$ in BER [7] and $10^{-2}$ in PER [6]) and induce communication performance degradation when compared with a floating-point representation.

Their methods use *average* metrics of EVMs, MERs, and SNRs in estimating current signal quality. Measuring the average metrics cannot follow the instant changes of signal quality on packet caused from time-varying fading channels and induces the wordlength decision errors. The rapid wordlength control that finely switches the wordlength on packet basis is requested to keep the same communication quality as the fixed wordlength.

In this paper, we discuss rapid wordlength control on packet basis and propose a new variable wordlength method based on monitoring subcarrier SNRs in an OFDM receiver. The proposed method is more sensitive to estimating current signal quality and can avoid the wordlength decision errors. The simulation results have indicated that the proposed method has better PER performance compared with the conventional methods.

The rest of this paper is organized as follows. Section 2 outlines the mechanism of variable wordlength in digital circuits. Section 3 presents the proposed variable wordlength method comparing with the conventional methods. Section 4 explains the wordlength training that is commonly adopted in the proposed and conventional methods. The other conventional method based on packet received information is introduced in Sect. 5. Section 6 reports the evaluation of communication performance and power reduction in an OFDM receiver. Finally, the conclusions are drawn in Sect. 7.

## 2. Variable Wordlength Method for Reducing Power Consumption

Most of digital circuits in communication use a fixed-point representation where the bit sequence is expressed as $x = \{b_{n-1}, b_{n-2}, ..., b_1, b_0\}$ for a $n$-bit wordlength. A variable wordlength method dynamically changes the number of active bits depending on surrounding circumstances.

An example of a circuit structure switching between two wordlength modes by clock gating, i.e., $W_{\mathrm{Long}}$=12 and $W_{\mathrm{Short}}$=8, is illustrated in Fig. 1. The two wordlength modes are switched by the control signal of "Wsel". The short wordlength mode can be obtained by masking the last four bits. The reduction of power consumption is performed by halting switching activities in registers and arithmetic units, where power reduction of 33% is ideally achieved in this example.

When wordlength modes are switched by a clock unit, a timing skew by switching clock and control signal lines induces timing hazards in implementation of digital circuits. In OFDM systems, a receiver intermittently demodulates signals due to the existence of cyclic prefix and packet interval. Since changes in wordlength can be executed in those intervals, the timing hazards are not serious in switching wordlength modes.

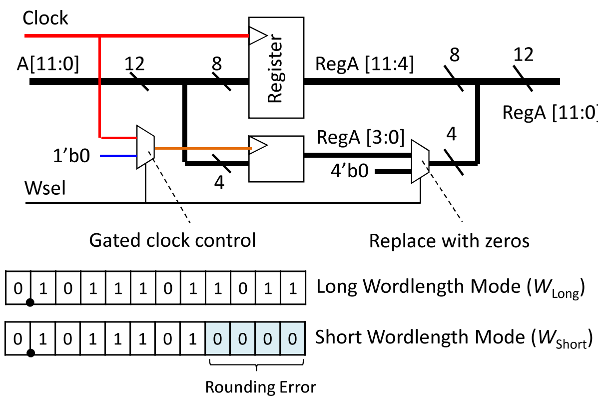


**Fig. 1** Circuit structure in variable wordlength method.

## 3. Rapid Wordlength Control

### 3.1 Wordlength Control in Time-Varying Fading Channels

Wireless channel conditions are affected by carrier-to-noise ratio (CNR), multipath interference, Doppler frequency shift, etc. The conventional variable wordlength methods [6]–[10] adjust the wordlength for a certain channel condition from statistical information based on the averaged metrics of EVMs, MERs and SNRs. This average procedure is effective in *slow* wordlength control of seconds and milliseconds. For *rapid* wordlength control in microseconds, a receiver must follow the time-varying fluctuations in signal amplitude.

Let us consider the changes of signal quality in slow (or fixed) and rapid wordlength controls, as drawn in Fig. 2. A packet error occurs when a signal quality value is less than a certain threshold. For slow wordlength control in Fig. 2(a), long wordlength tends to be excessive in most packets. Short wordlength induces packet errors because the signal quality becomes less than the threshold due to bit rounding errors. The rapid wordlength control in Fig. 2(b) can solve this issue. An OFDM receiver estimates the signal quality on packet basis. Short wordlength can be applied as long as the signal quality including bit rounding errors is more than the threshold. It indicates that the OFDM receiver can apply short wordlength as long as the packet error does not occur. Hence, we focus on rapid wordlength control that a receiver finely switches the wordlength modes (denoted by $W_{\mathrm{Variable}}$ in Fig. 2(b)).

A timing sequence of rapid wordlength control is illustrated in Fig. 3. As for OFDM wireless LAN systems such as IEEE 802.11a/g/n/ac, a physical layer (PHY) frame consists of preamble and data symbols. The signal quality is measured from the preamble. The wordlength mode is selected according to the measured signal quality. The selected wordlength mode is applied to the data symbols. This

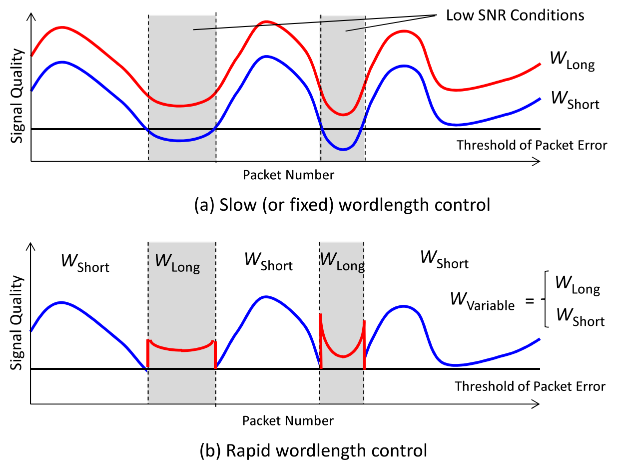


**Fig. 2** Slow (or fixed) and rapid wordlength controls in time-varying fading channels.

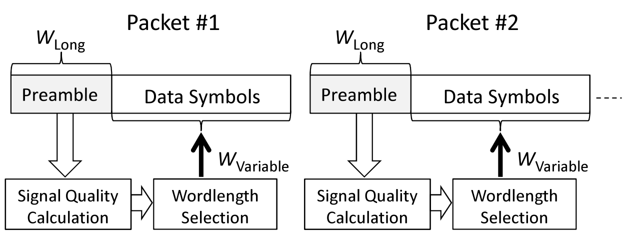


**Fig. 3** Timing sequence of rapid wordlength control.

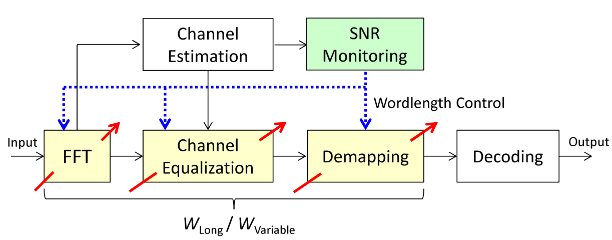


**Fig. 4** Block diagram of an OFDM receiver with variable wordlength control.

wordlength control is executed for every packet.

### 3.2 OFDM Receiver

A block diagram of an OFDM receiver with variable wordlength is shown in Fig. 4. The receiver consists of FFT, channel estimation, channel equalization, demapping, and Viterbi decoding blocks. The FFT block is based on radix-2 single delay feedback (R2SDF) pipeline architecture [14]. Switching two wordlength modes of $W_{\text{Long}}$ and $W_{\text{Short}}$ enables the power control of the FFT, demapping and Viterbi decoding blocks. A packet structure in PHY on IEEE 802.11a standard is illustrated in Fig. 5. The packet consists of short training field (STF), two long training fields (LTFs), signal field (SIG), and data symbols (DATAs). The long wordlength mode is applied to the STF, LTFs, and SIG for accurate time-synchronization and channel estimation as much as possible. Wordlength switching is adopted to the

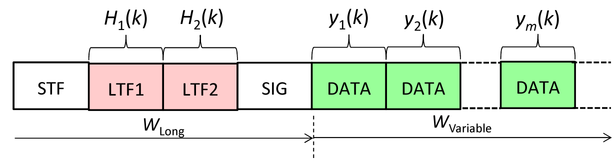


**Fig. 5** Frame format of IEEE 802.11a.

DATAs.

For a transmit data symbol $x_m(k)$ of an $m$-th data symbol and a $k$-th OFDM subcarrier number in frequency domain, a received symbol $y_m(k)$ in the DATAs is affected by the rounding error, as expressed by

$$y_m(k) = H_m(k)x_m(k) + n(k) + n_{\mathrm{R}}(k), \tag{1}$$

where $H_m(k)$ is a propagation channel coefficient that is affected by multipath fading. $n(k)$ and $n_{\mathrm{R}}(k)$ express components of channel noise and rounding error, respectively. The wordlength impacts on magnitude of rounding errors. When channel noise is large, the large wordlength mode should be selected in view of minimizing influence of rounding errors. When channel noise is small, an OFDM receiver has a chance to select the short wordlength mode.

The estimated channel coefficient $H_{\text{Ave}}(k)$ can be computed by an average of $H_1(k)$ and $H_2(k)$ from the LTFs. Using the estimated channel coefficients, an estimated transmit symbol $\hat{x}_m(k)$ can be obtained by minimum mean square error (MMSE) equalization as

$$\hat{x}_m(k) = \frac{H^*_{\text{Ave}}(k)}{|H_{\text{Ave}}(k)|^2 + E[\sigma^2(k)]} y_m(k), \tag{2}$$

where $E[\sigma^2(k)]$ denotes the average noise-power for all subcarriers and $(\cdot)^*$ expresses a complex conjugate.

### 3.3 Conventional Methods

The wordlength control is performed by measuring the signal quality in the estimated transmit symbol $\hat{x}_m(k)$. We explain EVM [6], [9] and MER [7] in the conventional methods. If the transmit data symbol $x_m(k)$ is known in advance, the EVM can be computed as

$$\mathrm{EVM}_m = \sqrt{\frac{\sum_{k=1}^{K} \left| x_m(k) - \hat{x}_m(k) \right|^2}{\sum_{k=1}^{K} \left| x_m(k) \right|^2}}, \tag{3}$$

where $K$ denotes the number of OFDM data subcarriers. The MER corresponds to the multiplicative inverse of the EVM, which is expressed as

$$\mathrm{MER}_m = \frac{\sum_{k=1}^{K} \left| x_m(k) \right|^2}{\sum_{k=1}^{K} \left| \hat{x}_m(k) - x_m(k) \right|^2}. \tag{4}$$

The wordlength of $W_{\text{Variable}}(p)$ for a $p$-th packet is determined by

$$W_{\text{Variable}}(p) = \begin{cases} W_{\text{Short}} \text{ if } E[\text{MER}_m(p)] > \text{MER}_{\text{Th}} \\ W_{\text{Long}} \text{ otherwise,} \end{cases} \quad (5)$$

where $E[\text{MER}_m]$ denotes the average of MERs for data symbols and $\text{MER}_{\text{Th}}$ indicates an MER threshold. The threshold value is obtained from the wordlength training, as explained in Sect. 4. The average SNR [8] is mentioned together with the proposed method in Sect. 3.4.

### 3.4 Proposed Method

The rapid wordlength using the MER would be realized by only measuring the first data symbol, i.e., limiting to $m$=1 in Eq. (5). However, the MER induces the wordlength decision errors, to be described later.

We estimate the received SNR computed from the LTFs by a ratio of received signal power of $P_{\text{Signal}}(k)$ and noise power of $P_{\text{Noise}}(k)$ as

$$P_{\text{Signal}}(k) = \left|\frac{H_1(k) + H_2(k)}{2}\right|^2 = |H_{\text{Ave}}(k)|^2 \quad (6)$$

$$P_{\text{Noise}}(k) = \left|\frac{H_1(k) - H_2(k)}{2}\right|^2 = \sigma^2(k) \quad (7)$$

$$\text{SNR} = 10\log_{10}\frac{\sum_{k=1}^{K} P_{\text{Signal}}(k)}{\sum_{k=1}^{K} P_{\text{Noise}}(k)} \text{ [dB]}. \quad (8)$$

The $k$-th subcarrier SNR is also estimated as

$$\text{SNR}_{\text{Sub}}(k) = 10\log_{10}\frac{P_{\text{Signal}}(k)}{\sum_{k=1}^{K} P_{\text{Noise}}(k)/K} \text{ [dB]}. \quad (9)$$

For instance, the subcarrier SNRs for two OFDM packets are plotted in Fig. 6 for 23-dB CNR with the simulation parameters described in Sect. 6. The difference of average SNRs between the two packets is 1 dB. However, the difference of minimum subcarrier SNRs becomes 5 dB.

Let us consider the signal quality of $\hat{x}_m(k)$ in Eq. (2). Assuming $H_m(k) \approx H_{\text{Ave}}(k)$ and $|H_{\text{Ave}}(k)|^2 \gg E[\sigma^2(k)]$, Eq. (2) can be rewritten by

$$\hat{x}_m(k) \approx x_m(k) + \frac{n(k) + n_{\text{R}}(k)}{H_{\text{Ave}}(k)}. \quad (10)$$

The dynamic range of $H_{\text{Ave}}(k)$ is much larger than those of $n(k)$ and $n_{\text{R}}(k)$ for typical cases of multipath fading environment. The noise and rounding error components of $n(k)$ and $n_{\text{R}}(k)$ are emphasized if $|H_{\text{Ave}}(k)|$ is small. Thus, the subcarrier SNR can be used for estimating whether the packet error occurs or not.

In the example of Fig. 6, the minimum subcarrier SNRs for the packets of $p$=1 and $p$=2 are 21 dB and 16 dB. If the threshold of packet error is set to 16 dB, the packet of $p$=1 has a chance to decrease wordlegnth by 5-dB bit rounding error. Hence, the proposed method is given by

$$W_{\text{Variable}}(p) = \begin{cases} W_{\text{Short}} \text{ if } \min(\text{SNR}_{\text{Sub}}(p,k)) > \text{SNR}_{\text{Th}} \\ W_{\text{Long}} \text{ otherwise,} \end{cases} \quad (11)$$

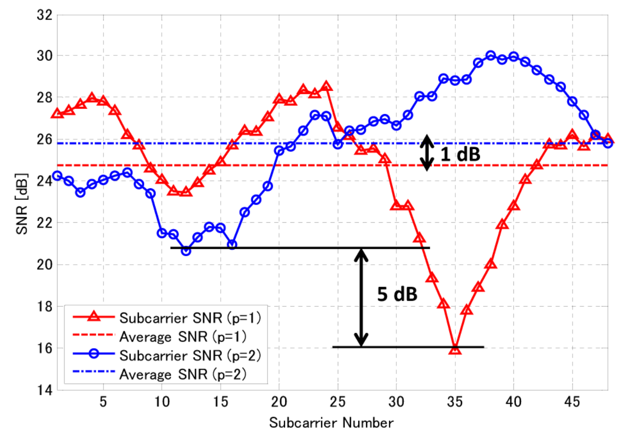


**Fig. 6** Subcarrier SNRs for two OFDM packets.

where $\text{SNR}_{\text{Th}}$ denotes an SNR threshold for the wordlength decision.

As for the wordlength decision based on the average SNR [8], we use

$$W_{\text{Variable}}(p) = \begin{cases} W_{\text{Short}} \text{ if } \text{SNR}(p) > \text{Ave-SNR}_{\text{Th}} \\ W_{\text{Long}} \text{ otherwise,} \end{cases} \quad (12)$$

where $\text{Ave-SNR}_{\text{Th}}$ denotes an SNR threshold used in the average SNR. The conventional methods of EVM, MER, and average SNR, given by averaging their metrics for subcarriers, have difficulty in detecting the differences of signal quality for the packets of $p$=1 and $p$=2 as shown in Fig. 6. Their methods are not suitable for the rapid wordlength control. This wordlength decision error causes degradation of communication quality as reported in Sect. 6.

The subcarrier SNR in Eq. (9) would be able to allocate the wordlength modes for every subcarrier. The receiver digital circuit in Fig. 4 executes pipeline processing whose block unit consists of data for all subcarriers. This processing requests that the wordlength modes are switched by a clock unit. It cannot avoid the issue of the timing hazards as mentioned in Sect. 2. The wordlength control by a subcarrier unit is not suitable for implementation of digital circuits in OFDM systems.

## 4. Wordlength Training

Both conventional and proposed methods have to know the SNR threshold beforehand. A theoretical BER is not suitable for determining an SNR threshold. Actual communication systems include analog front-end and error correcting blocks and are modeled by their complicated mechanism. The wordlength training for determination of an SNR threshold is shown in Table 1. For the iterations of receiving OFDM packets, succeeded (marked by “s” in the figure) and failed packet receptions (“f”) are tested with applying the two wordlength modes. When a packet reception succeeded in long wordlength and failed in short wordlength, a receiver is supposed to meet the worse channel conditions. The SNR

**Table 1** Wordlength training for determination of an SNR threshold.

| Packet Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Reception ($W_{\mathrm{Long}}$) | s | s | s | s | s | s | s | s | s |
| Reception ($W_{\mathrm{Short}}$) | s | s | f | f | s | s | f | s | s |
| SNR [dB] | | | 14 | 13 | | | 9 | | |

value in this packet (average for the conventional methods and minimum for the proposed method) is recorded as an SNR threshold candidate. Finally, the largest SNR value among failed packets is used as the SNR threshold.

The types of wordlength training are classified into on-line and off-line processing tasks. In the on-line processing, an OFDM receiver performs wordlength calibration that the wordlength mode is changed on a trial basis during receiving actual packets, as explained in [6] and [10]. Since the wordlength training requests a large number of iterations, the cost of energy dissipation in wordlength training becomes a drawback.

In future wireless communication, this drawback might be solved by cognitive radio networks (CRNs) [15] where a receiver can know optimal wireless parameters via cloud computing networks. Since the SNR threshold can be regarded as one of wireless parameters that are stored in database and provided by CRNs, a wireless user terminal will not need to execute the wordlength training. The wordlength training itself has been executed by other terminals having the same model (e.g., wireless hardware and LSI) as the user terminal, which is treated as the off-line processing. This similar concept has been presented in [8].

The off-line processing can solve the drawback of increasing energy dissipation in wordlength training. However, the wordlength mismatch would be considered when a channel condition itself is largely changing during acquiring the wireless parameters, which will be a future issue to be solved in those and our researches.

## 5. Other Conventional Method

In another conventional method, wordlength auto rate fallback (ARF) has been presented in [6], [10]. Originally, ARF is used for a rate control in medium access layer (MAC) where a transmit mode is changed according to information of packet receptions [16]. An example of the wordlength ARF is shown in Table 2. A receiver decreases or increases wordlength according to the number of consecutive successes (whose number is defined by $S$) in packet receptions. In this example, the receiver increases one bit after ten consecutive successful packet reception and decreases one bit after a single failed packet reception.

A guaranteed PER for the ARF can be set by the number of consecutive successes of $S$, and it can be expressed as

$$\begin{aligned}\mathrm{PER}_{\mathrm{ARF}} &= 0 \times P_{\mathrm{F}} + \frac{1}{S+1} \times P_{\mathrm{S}} \\ &= \frac{1}{2(S+1)},\end{aligned} \tag{13}$$

**Table 2** Wordlength auto rate fallback (ARF).

| Packet Number | 1 | 2 | 3 | ... | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Packet Reception | s | s | s | s | s | s | s | f | s | s | s |
| Wordlength | 12 | 12 | 12 | 12 | 12 | 11 | 11 | 11 | 12 | 12 | 12 |

ten consecutive successes — Decrease 1 bit — Increase 1 bit

where $P_{\mathrm{S}}$=1/2 is the probability of packets being successfully received and $P_{\mathrm{F}}$=1/2 is that of failure for the next packet after $S$ packets have been received. It is fair to assume that both the success and failure probabilities will be 1/2 when the next packet is sent, assuming the communication channel is unknown.

The ARF can keep high communication quality when $S$ becomes large. However, its change in wordlength becomes very slow. For instance, the guaranteed PER is $5 \times 10^{-4}$ for $S$=1,000. The receiver must wait for a 1,000 consecutive successful packet reception in decreasing one bit. On the other hand, the guaranteed PER becomes worse when $S$ is small. Hence, the ARF is not suitable for the rapid wordlength control.

## 6. Evaluation

### 6.1 Communication Performance

We evaluate PER performance in the proposed method and the conventional methods of average SNR, MER†, and ARF. The PER is measured from the number of failures in packet receptions. The packet reception failure is counted for BER > 0 in a whole packet.

The simulation parameters are described in Table 3. The baseband simulation is based on the IEEE 802.11a standard. The resolution of AD converter is 12 bits. The data types of floating-point representation, fixed-point representations (fixed wordlength and variable wordlength) are applied to the processing blocks of FFT, channel equalization, and demapping in Fig. 4.

The proposed method and the conventional methods except the ARF method switch two wordlength modes of 12 and 4 bits. In these methods, we perform the wordlength training mentioned in Sect. 4 on the same channel conditions as those in the evaluation. The channel coefficients in multipath fading are different between training and evaluation events. The ARF gradually changes the wordlength by one bit, which ranges 12 to 4 bits.

The results of PER performance for QPSK and 16-QAM transmit modes are plotted in Fig. 7. The target of rapid wordlength control is to keep the same PER as that of the floating-point representation. The average SNR and MER cannot reach this target. The proposed method shows almost the same PER for every $E_{\mathrm{b}}/N_{\mathrm{o}}$ condition and transmit mode. As for the ARF methods of $S$=100 and $S$=1000, the

†Since the EVM is reciprocal of the MER, the PER results of EVM are almost the same as those of MER.

**Table 3** Simulation parameters.

| | |
|---|---|
| Transmit Mode | QPSK / 16QAM |
| Coding Rate | 1/2 |
| Number of OFDM Symbols | 10 |
| FFT Size | 64 |
| Number of Pilot Carriers | 4 |
| Number of Data Carriers | 48 |
| OFDM Symbol Duration | 4.0 µs |
| GI Duration | 0.8 µs |
| Channel Bandwidth | 20 MHz |
| Subcarrier Frequency Spacing | 312.5 kHz |
| Resolution of A/D Converter | 12 bits |
| Floating-Point Representation | Double Precision (64 bits) |
| Fixed Wordlength | Fixed Point 4, 12 bits |
| Variable Wordlength (Proposed, Average SNR, MER) | $W_{\mathrm{Long}} = 12$ bits<br>$W_{\mathrm{Short}} = 4$ bits |
| Wordlength (ARF)<br>Consecutive Success Factor: $S$ | $4 \leq W_{\mathrm{ARF}} \leq 12$ bits<br>$S = 100$ / 1,000 |
| Propagation Model | 18-Path Rayleigh Fading |
| Multipath Model | HIPERLAN/2 Model A |
| RMS Delay Spread | 50 ns |
| Doppler Frequency | 25 Hz |
| Number of Packets (Training) | 100,000 |
| Number of Packets (Evaluation) | 100,000 |

PER floors of around $10^{-2}$ and $10^{-3}$ are observed. This limitation is associated with the guaranteed PER of Eq. (13)†.

Figure 8 shows the snapshot of how wordlength changes for QPSK and $E_b/N_o = 18$ dB in the simulation. The MER selects short wordlength for most packets. However, the wordlength selection error increases its PER. The ARF gradually changes the wordlength and its wordlength tends to be excessive. The proposed method provides good balance of keeping PER performance and taking short wordlength.

### 6.2 Power Consumption

We evaluate power reduction ratio on the presupposition of keeping the same PER as that of the floating point representation. The proposed method, the ARF of $S$=1,000 (excluding higher $E_b/N_o$ conditions), and the 12-bit fixed wordlength fulfill this presupposition. The results of average bit in selected wordlength are summarized in Table 4. The ARF hardly decreases its wordlength even for keeping the same PER.

Table 5 shows power consumption for each wordlength, which is based on circuit implementation in a 90-nm CMOS process standard cell library. We have measured average

†The ARF of $S$=100 shows that the PERs are less than $10^{-2}$ for QPSK and more than 14 dB in $E_b/N_o$ conditions. As shown in the PER plots of 4-bit fixed-point wordlength, the PERs would be less than $10^{-2}$ even if the 4-bit wordlength mode is selected for all packets.

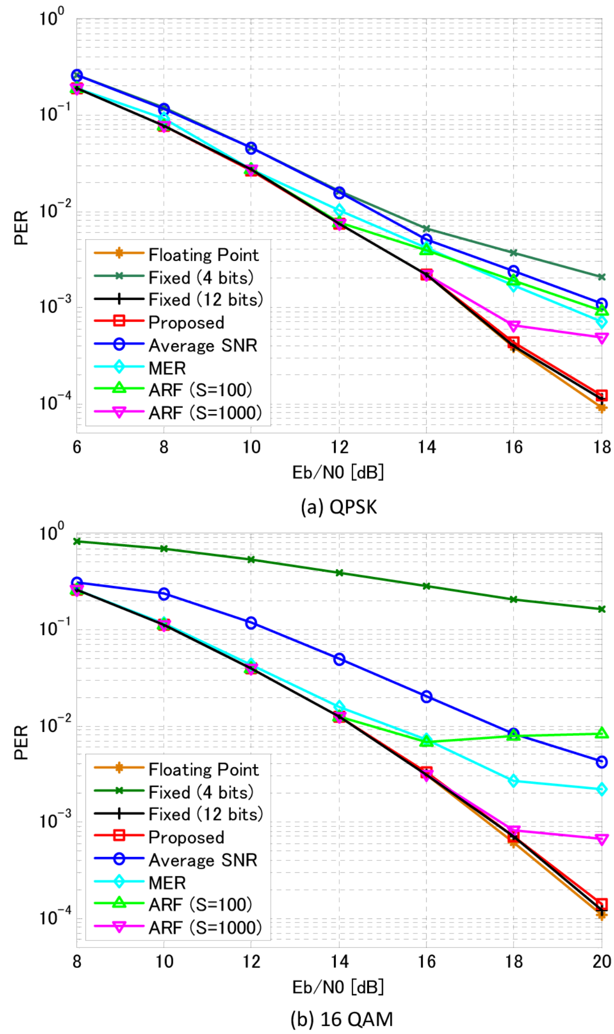


**Fig. 7** PER performance for QPSK and 16-QAM transmit modes.

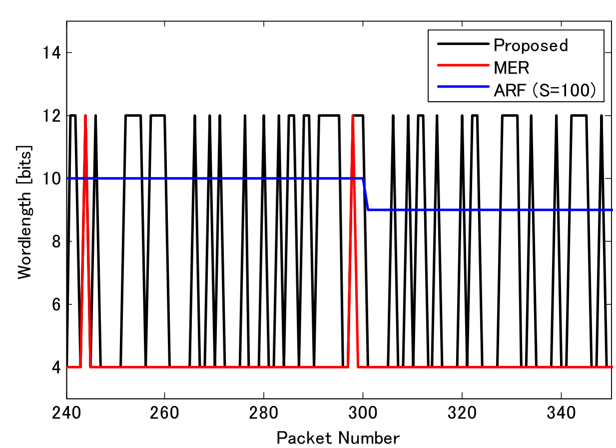


**Fig. 8** Wordlength changes for QPSK and $E_b/N_o = 18$ dB.

power consumption values in the processing blocks of FFT, channel equalization, demapping, and Viterbi decoding in receiving the data symbols (see Fig. 5). The supply voltage is 1.1 V and the operating clock frequency is set to 200 MHz.

**Table 4** Results of average bit in selected wordlength.

(a) QPSK

| $E_b/N_0$ [dB] | 6 | 8 | 10 | 12 | 14 | 16 | 18 |
|---|---|---|---|---|---|---|---|
| **Proposed** | **11.15** | **9.49** | **9.12** | **7.71** | **6.84** | **6.44** | **6.01** |
| Average SNR | 11.07 | 7.81 | 6.57 | 4.98 | 4.69 | 4.66 | 4.68 |
| MER | 11.10 | 8.23 | 7.09 | 5.30 | 5.08 | 5.12 | 5.08 |
| ARF (S=100) | 12 | 12 | 11.91 | 9.56 | 4.94 | 4.65 | 4.47 |
| **ARF (S=1000)** | **12** | **12** | **12** | **12** | **11.91** | **9.70** | **7.96** |

(b) 16 QAM

| $E_b/N_0$ [dB] | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|
| **Proposed** | **11.16** | **10.95** | **10.37** | **9.42** | **8.07** | **7.73** | **6.89** |
| Average SNR | 11.10 | 9.42 | 8.17 | 6.88 | 6.08 | 5.74 | 5.55 |
| MER | 11.12 | 10.09 | 8.87 | 7.67 | 6.68 | 6.42 | 6.15 |
| ARF (S=100) | 12 | 12 | 11.99 | 11.43 | 7.06 | 5.82 | 5.56 |
| **ARF (S=1000)** | **12** | **12** | **12** | **12** | **11.99** | **11.57** | **8.48** |

**Table 5** Power consumption of processing blocks in OFDM receiver for each wordlength.

(a) QPSK

| $W_{\text{Variable}}$ (bits) | FFT (mW) | Equalizer (mW) | Demapper (mW) | Viterbi (mW) | SNR Calc. (mW) | Total – Conv. (mW) | Total – Proposed (mW) |
|---|---|---|---|---|---|---|---|
| 12 | 17.1 | 1.83 | 0.090 | | | **32.9** | 33.1 |
| 11 | 16.4 | 1.73 | 0.082 | | | 32.1 | 32.3 |
| 10 | 15.6 | 1.57 | 0.076 | | | 31.2 | 31.4 |
| 9 | 14.9 | 1.48 | 0.069 | | | 30.3 | 30.5 |
| 8 | 14.1 | 1.30 | 0.063 | 13.9 | 0.18 | 29.4 | 29.6 |
| 7 | 13.3 | 1.20 | 0.056 | | | 28.5 | 28.7 |
| 6 | 12.6 | 0.99 | 0.050 | | | 27.5 | 27.7 |
| 5 | 11.6 | 0.89 | 0.043 | | | 26.4 | 26.6 |
| 4 | 10.8 | 0.66 | 0.037 | | | 25.4 | 25.6 |

(b) 16QAM

| $W_{\text{Variable}}$ (bits) | FFT (mW) | Equalizer (mW) | Demapper (mW) | Viterbi (mW) | SNR Calc. (mW) | Total – Conv. (mW) | Total – Proposed (mW) |
|---|---|---|---|---|---|---|---|
| 12 | 17.1 | 1.83 | 0.22 | | | **43.1** | 43.3 |
| 11 | 16.4 | 1.73 | 0.21 | | | 42.3 | 42.5 |
| 10 | 15.6 | 1.57 | 0.19 | | | 41.3 | 41.5 |
| 9 | 14.9 | 1.48 | 0.18 | | | 40.6 | 40.8 |
| 8 | 14.1 | 1.30 | 0.17 | 24.0 | 0.18 | 39.6 | 39.8 |
| 7 | 13.3 | 1.20 | 0.16 | | | 38.7 | 38.9 |
| 6 | 12.6 | 0.99 | 0.14 | | | 37.7 | 37.8 |
| 5 | 11.6 | 0.89 | 0.13 | | | 36.6 | 36.8 |
| 4 | 10.8 | 0.66 | 0.11 | | | 35.6 | 35.8 |

The other blocks of channel estimation and SNR monitoring have small impact on power consumption because their blocks are active only in receiving the two training symbols. The subcarrier SNR in Eq. (9) is rewritten as

$$\mathrm{SNR}_{\mathrm{Sub}}(k) = 10\log_{10}\frac{|H_{\mathrm{Ave}}(k)|^2}{E[\sigma^2(k)]}\ [\mathrm{dB}] = \frac{|H_{\mathrm{Ave}}(k)|^2}{E[\sigma^2(k)]}. \tag{14}$$

The proposed method does not need additional circuit components of computing $|H_{\mathrm{Ave}}(k)|^2$ and $E[\sigma^2(k)]$ because they are obtained from the computation of MMSE channel equalization in Eq. (2). Furthermore, the logarithm operation is unnecessary for the comparison of threshold values. The cost of real division is considered for the SNR calculation in the proposed method, which indicates 0.18 mW in Table 5. It gives the difference of power consumption between the conventional and proposed methods†.

According to the results of selected wordlengths for all packets, the average power consumption value can be calculated by

$$\xi_{\mathrm{Ave}} = \sum_{p=1}^{P} \xi_{\mathrm{Total}}(W(p))/P, \tag{15}$$

where $P$ denotes the number of total packets. The power consumption value for each wordlength $\xi_{\mathrm{Total}}(W(p))$ is exploited from Table 5 depending on the selected wordlength of $W(p)$. The power consumption of the 12-bit fixed wordlength is calculated by $W(p)$=12 for all packets.

The results of power ratio are summarized in Table 6. The values of power ratio are normalized by the reference values of the 12-bit fixed wordlength in Table 5, i.e., 32.9 mW and 43.1 mW for QPSK and 16QAM. The methods of average SNR, MER, and ARF of $S$=100 reduce more power than that of the proposed method. However, they cannot satisfy the presupposition of keeping the same PER as that of the floating point representation. The ARF of $S$=1,000 is not suitable in terms of power reduction. The proposed method shows the power reduction of up to 17% and 11% for QPSK and 16QAM compared with the 12-bit fixed wordlength.

**Table 6** Results of power ratio.

(a) QPSK

| $E_b/N_0$ [dB] | 6 | 8 | 10 | 12 | 14 | 16 | 18 |
|---|---|---|---|---|---|---|---|
| **Proposed** | **0.98** | **0.93** | **0.92** | **0.88** | **0.86** | **0.85** | **0.83** |
| Average SNR | 0.97 | 0.87 | 0.84 | 0.80 | 0.79 | 0.79 | 0.79 |
| MER | 0.97 | 0.88 | 0.85 | 0.81 | 0.80 | 0.81 | 0.80 |
| ARF (S=100) | 1 | 1 | 1 | 0.93 | 0.80 | 0.79 | 0.79 |
| **ARF (S=1000)** | **1** | **1** | **1** | **1** | **0.99** | **0.94** | **0.89** |

(b) 16 QAM

| $E_b/N_0$ [dB] | 8 | 10 | 12 | 14 | 16 | 18 | 20 |
|---|---|---|---|---|---|---|---|
| **Proposed** | **0.99** | **0.98** | **0.97** | **0.95** | **0.92** | **0.91** | **0.89** |
| Average SNR | 0.97 | 0.94 | 0.92 | 0.89 | 0.87 | 0.87 | 0.86 |
| MER | 0.97 | 0.95 | 0.93 | 0.90 | 0.89 | 0.88 | 0.88 |
| ARF (S=100) | 1 | 1 | 1 | 0.99 | 0.90 | 0.87 | 0.86 |
| **ARF (S=1000)** | **1** | **1** | **1** | **1** | **0.99** | **0.99** | **0.92** |

## 7. Conclusion

We have presented the new variable wordlength method for power reduction that can preserve high communication

†Although the methods of average SNR and MER request the cost of measuring signal quality as well as the proposed method, their costs in power consumption are omitted.

quality in an OFDM receiver. The conventional variable wordlength methods induce communication performance degradation when compared with a floating-point representation in time-varying fading channels. To solve this issue, we have discussed rapid wordlength control that an OFDM receiver can apply short wordlength as long as a packet error does not occur. Since the proposed method based on monitoring subcarrier SNRs is more sensitive to signal quality of an OFDM receiver including bit rounding error, it is suitable for the rapid wordlength control. In the evaluation, the proposed method has showed almost the same PERs compared with the floating-point representation and reduced power consumption by up to 17% compared with the fixed wordlength. Rapid wordlength control for a MIMO-OFDM receiver will be studied in our future work.

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