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PAPER

Random Access Identifier-Linked Receiver Beamforming with Transmitter Filtering in TDD-Based Random Access*

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SUMMARY This paper proposes a novel random access identifier (RAID)-linked receiver beamforming method for time division duplex (TDD)-based random access. When the number of receiver antennas at the base station is large in a massive multiple-input multiple-output (MIMO) scenario, the channel estimation accuracy per receiver antenna at the base station receiver is degraded due to the limited received signal power per antenna from the user terminal. This results in degradation in the receiver beamforming (BF) or antenna diversity combining and active RAID detection. The purpose of the proposed method is to achieve accurate active RAID detection and channel estimation with a reasonable level of computational complexity at the base station receiver. In the proposed method, a unique receiver BF vector applied at the base station is linked to each of the M RAIDs prepared by the system. The user terminal selects an appropriate pair comprising a receiver BF vector and a RAID in advance based on the channel estimation results in the downlink assuming channel reciprocity in a TDD system. Therefore, per-receiver antenna channel estimation for receiver BF is not necessary in the proposed method. Furthermore, in order to utilize fully the knowledge of the channel at the user transmitter, we propose applying transmitter filtering (TF) to the proposed method for effective channel shortening in order to increase the orthogonal preambles for active RAID detection and channel estimation prepared for each RAID. Computer simulation results show that the proposed method greatly improves the accuracy of active RAID detection and channel estimation. This results in lower error rates than that for the conventional method performing channel estimation at each antenna in a massive MIMO environment.

key words: *NOMA, random access, multi-packet reception, mMTC, URLLC, TDD, active user detection, channel estimation, beamforming, transmitter filtering*

1. Introduction

Compared to scheduling-based access methods, random access methods [1]–[5] implementing multi-packet reception [6] based on non-orthogonal multiple access (NOMA) with an advanced transceiver [7] can reduce the control-signaling overhead and transmission delay. As such, there is a need to investigate an advanced random access protocol that accommodates uplink transmission for massive machine-type communications (mMTC) and ultra-reliable low latency communications (URLLC) in the fifth-generation mobile communication system (5G NR) [8], [9] and beyond [10].

Since random access-based grant-free data transmission [4] is considered in this investigation, users transmit a preamble and data jointly within a random-access packet, which is referred to as two-step random access in [11] and [12]. In such a random access scheme employing multi-packet reception, the system prepares multiple random access identifiers (RAIDs) in advance to identify users who transmit uplink data simultaneously and separately decode the received multiple packets based on the NOMA receiver. The transmitting user sends uplink random access packets generated using a (randomly) selected RAID [4], [11], [12]. The RAID can be a scrambling code in 4G LTE/LTE-Advanced and 5G NR [9], [13], [14], a channel interleaver in interleave division multiple access (IDMA) [2], [15], or a generation matrix of sparse transmitted signals in low density signature (LDS)- and sparse code multiple access (SCMA)-based approaches [16], [17].

In random access, to suppress the packet loss due to collision and to achieve multi-packet reception, accurate active RAID (user) detection, in which the set of RAIDs that are used in the transmitted packets is identified, and channel estimation for detected RAIDs are essential [18]. The active RAID detection and channel estimation are conducted by using a preamble attached to the packet. In this paper, multiple preamble sequences, each of which has a one-to-one relationship with the RAID pattern prepared in the system, are generated by applying a cyclic time shift to Zadoff-Chu (ZC) sequences [19], [20].

Meanwhile, massive multiple-input multiple-output (MIMO) [21] with a large number of antennas at the base station is a promising technology in 5G and beyond. Therefore, it is important to investigate an advanced random access method considering massive MIMO scenarios as the baseline. When the number of receiver antennas at the base station is increased in a massive MIMO scenario in order to extend the cell coverage by utilizing the beamforming (BF) gain from multiple antenna transmission, the channel estimation accuracy per receiver antenna at the base station receiver is degraded due to the limited received signal power per antenna from the user terminal. This results in degradation in receiver BF or antenna diversity combining and active RAID detection.

In [3], [22]–[25], the active RAID (user) detection and

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channel estimation methods based on compressive sensing such as using the approximate message passing (AMP) algorithm are investigated. Reference [26] investigates a deep learning-based approach. In [27] and [28], an iterative channel estimation method based on the data decision feedback is investigated. These methods can certainly improve the accuracy in active RAID detection and channel estimation. However, since these methods rely fully on advanced signal processing at the base station, the level of computational complexity for the base station receiver becomes very high especially in an mMTC scenario where the number of candidate RAIDs is very large.

This paper proposes a novel RAID-linked receiver BF method for time division duplex (TDD)-based random access. The purpose of the proposed method is to achieve accurate active RAID detection and channel estimation with a reasonable level of computational complexity at the base station receiver by eliciting a small amount of aid from the transmitting users, i.e., the downlink channel estimation before conducting uplink random access. In the proposed method, a unique receiver BF vector applied at the base station is linked to each of the M RAIDs prepared by the system. The user terminal selects in advance an appropriate pair comprising a receiver BF vector and RAID based on the channel estimation results in the downlink assuming channel reciprocity in the TDD system. Therefore, the base station can perform receiver BF for each RAID candidate before performing channel estimation. Consequently, the per-receiver antenna channel estimation for receiver BF is not necessary in the proposed method. When we assume the per-receiver antenna channel estimation approach, correlation detection between the received signal and each candidate preamble sequence is necessary for all antennas. The proposed method does not need the correlation detection at each antenna. Only the correlation detection after the BF combining is needed. Therefore, the proposed method reduces the computational complexity required for correlation detection by the factor of the number of receiver antennas.

Furthermore, in order to utilize fully the knowledge of the channel at the user transmitter, we propose applying transmitter filtering (TF) to the proposed method. This shortens the effective channel and increases the orthogonal preambles for active RAID detection and channel estimation prepared for each RAID. Based on computer simulations, we show that the proposed method greatly improves the accuracy of active RAID detection and channel estimation. As a result, the proposed method reduces the error rate compared to that for the conventional method, which performs channel estimation at each antenna in a massive MIMO environment.

The remainder of the paper is organized as follows. First, Sect. 2 describes the basic random access procedure with multi-packet reception assumed in this paper. Section 3 describes the proposed method. Then, Sect. 4 presents numerical results based on computer simulations. Finally, Sect. 5 concludes the paper.

2. Basic Procedure of Random Access with Multi-Packet Reception

This section describes the basic random access procedure with NOMA-based multi-packet reception assumed in the paper. The base station periodically broadcasts a set of available RAID patterns, $\mathbf{s}_m$, along with dedicated preamble sequence $\mathbf{p}_m$, $(\mathbf{s}_m, \mathbf{p}_m)$, $m = 1, \ldots, M$, via the downlink. Term M denotes the total number of RAIDs prepared by the base station of interest. As M is increased, the probability of selected RAID collision between simultaneously transmitting users is reduced at the cost of computational complexity at the base station receiver, since the base station needs to perform active RAID detection and channel estimation for all M RAID candidates. The user terminals that have uplink information to be transmitted randomly select one set comprising a RAID and preamble from the informed set. They then generate packets using the selected RAID and transmit the packets. Finally, the base station decodes the received packets using an interference canceller and feeds back acknowledgement information to the user terminals whose packets are correctly decoded. In the following explanation and performance evaluation, we assume scrambling code-based NOMA and $\mathbf{s}_m$ represents the m-th scrambling code sequence. However, we note that the proposed method can use any kind of NOMA and corresponding RAID in principle.

In the following, we assume that a set of users, $\mathcal{K}$, transmits packets simultaneously. Here, the number of simultaneously transmitting users, $|\mathcal{K}|$, is denoted as K. A single transmitter antenna per user is assumed in the paper. User $k \in \mathcal{K}$ selects the $m(k)$-th RAID - preamble set $(\mathbf{s}_{m(k)}, \mathbf{p}_{m(k)})$. At each user transmitter, the transmission information bit sequence is processed with turbo coding and repetition coding. The coded bit sequence of user k is scrambled by $\mathbf{s}_{m(k)}$ and data symbol mapping is applied. We assume quadrature phase shift keying (QPSK) data modulation in the paper. We assume single-carrier transmission and the data symbol sequence is block-wised (hereafter denoted as a discrete Fourier transform (DFT) block) with the block size of N. We also assume that a cyclic prefix (CP) is appended to each DFT block [13], [14], [29] in the single-carrier transmission and the CP length is sufficiently long so that it covers the entire multipath delay spread and the difference in the received signal timings among users. One packet comprises data and a preamble. The preamble signal of user k, $\mathbf{p}_{m(k)}$, is generated using ZC sequences because they have good correlation properties. ZC sequences of length N can be represented as

$$a_u(i) = \exp\left(\frac{-j2\pi u}{N} \cdot \frac{i(i+1)}{2}\right), \quad i = 0, 1, \ldots, N-1, \tag{1}$$

where u denotes the ZC sequence index, which is an arbitrary integer relatively prime to N. When N is a prime number, the number of available sequences is $N-1$. Note that N is basically the same as the DFT size, and a preamble based on ZC sequences of length N is transmitted in one DFT block.

In order to increase the number of orthogonal preamble sequences, a cyclic time shift is applied to the ZC sequences. Since the autocorrelation of the ZC sequence of length N is an ideal delta function, we can generate $\lfloor N/\Delta \rfloor$ orthogonal preamble sequences from one ZC sequence by applying a cyclic time shift with an integer multiple of Δ samples. We note that Δ should be greater than the received timing difference among user terminals to distinguish the received multipath from those of different users. If $\lfloor N/\Delta \rfloor$ is less than the number of RAIDs equaling that of the preambles, M, multiple ZC sequences that are non-orthogonal to each other are needed to be used to generate M preamble sequences.

We assume L receiver antennas at the base station in the paper. Denoting the frequency domain transmitted signal component of user k at frequency n ($n = 1, \ldots, N$) as $X_{k,n}$, the frequency domain received signal at frequency n at receiver antenna l, $Y_n^{(l)}$, is represented as

$$Y_n^{(l)} = \sum_{k \in \mathcal{K}} H_{k,n}^{(l)} X_{k,n} + Z_n^{(l)}, \tag{2}$$

where $H_{k,n}^{(l)}$ is the channel frequency response of user k at frequency n at receiver antenna l. Term $Z_n^{(l)}$ represents the i.i.d. additive white Gaussian noise (AWGN) term at frequency n at receiver antenna l.

The base station receiver performs active RAID detection and channel estimation using the received preamble signals. We assume in this paper the active RAID detection and channel estimation schemes described in [30]. In the baseline method, channel estimation is conducted at each receiver antenna. Subsequently, the packet using $m(k)$-th RAID $\mathbf{s}_{m(k)}$, which corresponds to user k's packet, is detected in the received signal based on the decision if the preamble signal of $\mathbf{p}_{m(k)}$ is detected at the base station and receiver BF is performed to obtain the received signal after receiver antenna diversity combining to detect the packet generated using $\mathbf{s}_{m(k)}$, $\tilde{Y}_n^{[m(k)]}$. This is represented as

$$\tilde{Y}_n^{[m(k)]} = \sum_{l=1}^{L} \left(B_{m(k),n}^{(l)} \right)^* Y_n^{(l)}, \tag{3}$$

where $B_{m(k),n}^{(l)}$ is the receiver BF coefficient for RAID m at frequency n at receiver antenna l. In the following, this method is referred to as the per-antenna channel estimation-based receiver BF (PACE-RBF) method. Figure 1 illustrates the transmission and reception flow of the PACE-RBF method.

In the paper, the maximum ratio combining (MRC) criterion is assumed in receiver BF in the PACE-RBF method. In this case, $B_{m(k),n}^{(l)}$ is represented using $\tilde{H}_{k,n}^{(l)}$, which is the estimate of $H_{k,n}^{(l)}$, as

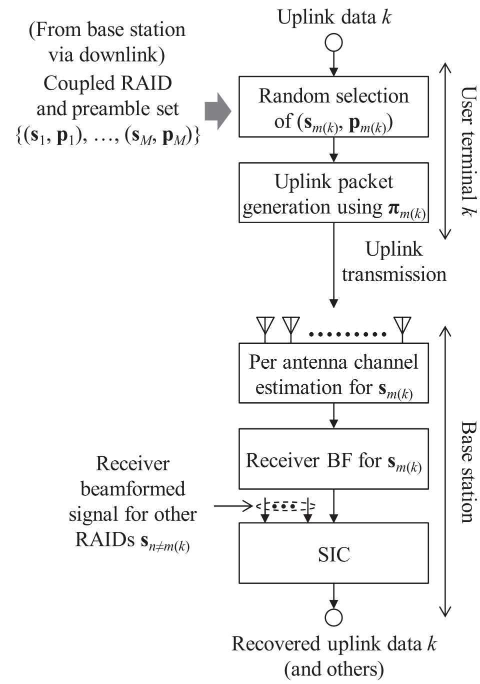

Fig. 1 Transmission and reception flow of PACE-RBF method.

$$B_{m(k),n}^{(l)} = \frac{\tilde{H}_{k,n}^{(l)}}{\sqrt{\sum_{l=1}^{L} \left| \tilde{H}_{k,n}^{(l)} \right|^2}}. \tag{4}$$

After obtaining $\tilde{Y}_n^{[m(k)]}$, the frequency-domain successive interference canceller (SIC) described in [4] is applied to decompose the simultaneously received packets to achieve multi-packet reception. As the number of receiver antennas, L, increases, the received signal power per antenna decreases assuming the same received signal power after receiver BF. This results in deterioration in the accuracy of the active RAID detection and channel estimation in the PACE-RBF method.

3. Proposed Method

3.1 IDL-RBF Method

The issue in channel estimation accuracy in the PACE-RBF method is addressed if the receiver BF can be performed before the channel estimation (and active RAID detection). To achieve this, we propose a RAID-linked receiver BF method, which is referred to as the IDL-RBF method hereafter.

Figure 2 illustrates the transmission and reception flow of the proposed IDL-RBF method. The IDL-RBF method assumes the TDD system where channel reciprocity between the downlink and uplink is established. In the IDL-RBF method, a unique receiver BF vector applied at the base station is linked to each RAID prepared by the system. Thus, the available RAID pattern, $\mathbf{s}_m$, has not only preamble sequence $\mathbf{p}_m$ but also receiver BF vector $\mathbf{b}_m$ in a one-to-one

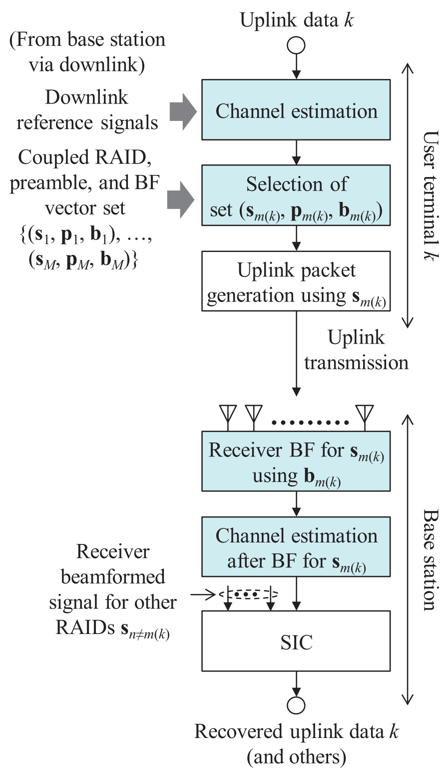

Fig. 2 Transmission and reception flow of IDL-RBF method.

relationship. The base station periodically broadcasts the set of available RAIDs, $\mathbf{s}_m$, along with dedicated unique preamble sequence $\mathbf{p}_m$ and receiver BF vector $\mathbf{b}_m$, $(\mathbf{s}_m, \mathbf{p}_m, \mathbf{b}_m)$, $m = 1, \ldots, M$, via the downlink. User terminal k that has uplink information estimates the channel accurately using the downlink reference signals whose transmission power is much higher than that of the uplink signal. Then, user k selects the best receiver BF vector, $\mathbf{b}_{m(k)}$, from the prepared M candidates along with the linked $\mathbf{s}_{m(k)}$ and $\mathbf{p}_{m(k)}$. Finally, user k sends the packet using $\mathbf{s}_{m(k)}$ and $\mathbf{p}_{m(k)}$.

The base station receiver uses $\mathbf{b}_{m(k)}$ to obtain $\tilde{Y}_n^{[m(k)]}$ in (3) without relying on the per-antenna uplink channel estimation. Thus, in the IDL-RBF method, $B_{m(k),n}^{(l)}$ is the l-th element of $\mathbf{b}_{m(k)}$. The effective channel of user k, who selected the $m(k)$-th RAID $\mathbf{s}_{m(k)}$, after receiver BF at frequency n in $\tilde{Y}_n^{[m(k)]}$ is represented as

$$H_{k,n}^{\mathrm{RBF}} = \sum_{l=1}^{L} \left(B_{m(k),n}^{(l)} \right)^* H_{k,n}^{(l)}. \tag{5}$$

The channel estimation (estimation of $H_{k,n}^{\mathrm{RBF}}$) and active RAID detection for $m(k)$-th RAID $\mathbf{s}_{m(k)}$ are performed directly on the received signal after receiver BF $\tilde{Y}_n^{[m(k)]}$. Therefore, the per-receiver antenna channel estimation for receiver BF is not necessary in the proposed IDL-RBF method.

Since the IDL-RBF method selects one of the prepared receiver BF vectors, optimal receiver BF that perfectly matches the channel is not possible. However, since the error in the receiver BF due to the channel estimation error can be reduced, the transmission performance of the IDL-RBF method can be better than that for the PACE-RBF method, especially in a massive MIMO scenario where L is very large.

We note that we can consider the use of downlink directional synchronization signal block (SSB) transmission, which is assumed in 5G NR [9], with the IDL-RBF method. In this case, each $\mathbf{b}_m$ corresponds to a sweeping beam of the downlink SSB, and the best $\mathbf{b}_{m(k)}$ corresponds to the $\mathbf{b}_m$ experiencing the highest received SSB power for user k. In 5G NR, random access attempts corresponding to different beams (receiver BF vectors) are mainly performed on different channels (time and frequency blocks). This is partly owing to the assumption of analog BF. In contrast, the proposed IDL-RBF method allows random access attempts corresponding to different receiver BF vectors to be performed on the same channel using BF vector-specific RAIDs and preambles. This can be achieved by using digital BF. The basis for this reasoning is that the proposed method is a two-step random access process where the data are sent simultaneously with the preamble to reduce control overhead and the delay time. In the case of random access where data are also sent simultaneously, as described in [4], as the transmission bandwidth of a random-access attempt increases, the frequency diversity effect and channel coding gain increase. Furthermore, a wider transmission bandwidth increases the statistical multiplexing effect, which has the effect of reducing the probability of the number of simultaneous transmitting users exceeding the tolerance range of the interference canceller based on the law of large numbers. These effects significantly improve the transmission performance of the NOMA-based two-step random access process with multi-packet reception. The proposed method in this paper takes the approach of multiplexing random-access packets applying different receiver BF vectors into the same wideband channel in order to obtain the above effects.

3.2 IDL-RBF Method with TF

It is expected that a sufficiently large M is necessary in the IDL-RBF method so that the selected receiver BF vector from the prepared ones sufficiently matches the actual channel. When considering the increase in M, a possible bottleneck is preparing the orthogonal preamble sequences that have one-to-one relationships with the respective total M RAIDs and BF vectors. In the ZC sequence-based preamble design assumed in the paper, one way to increase the number of orthogonal preamble sequences is to decrease Δ. However, if Δ is shorter than the delay time spread of the multipath, the paths between users cannot be separately identified, and the channel estimation accuracy deteriorates.

To address this problem by utilizing fully the knowledge of the channel at the user transmitter, we propose applying TF operation in the IDL-RBF method for channel shortening [31], [32] in order to increase the orthogonal preambles for active RAID detection and channel estimation prepared for each set of RAID and BF vector. Hereafter, this method is referred to as the IDL-RBF with TF method. We note that the IDL-RBF with TF method also contributes to better channel estimation accuracy at the base station since the received signal power per path is expected to be increased.

The TF operation on $H_{k,n}^{\mathrm{RBF}}$ is assumed to be performed in the frequency domain. User k knows its effective channel after receiver BF, $H_{k,n}^{\mathrm{RBF}}$, prior to the uplink transmission based on the channel estimation in the downlink. The TF coefficient of user k at frequency n is denoted as $Q_{k,n}$. The transmission signal of user k at frequency n is now represented as $Q_{k,n}X_{k,n}$, instead of $X_{k,n}$. For the total transmission power constraint, $Q_{k,n}$ should satisfy

$$\sum_{n=1}^{N}\left|Q_{k,n}\right|^2 = N. \tag{6}$$

For channel shortening purposes, a zero forcing (ZF)-based TF, channel equalization in other words, is optimal, since the transmitter filtered (TFed) channel has only a single path in this case. However, pure ZF results in excessive transmission power loss at the equalization in the frequency experiencing low channel power gain $\left|H_{k,n}^{\mathrm{RBF}}\right|^2$. Therefore, a modified ZF-based TF (mZF-TF) based on the method in [33], is investigated for the IDL-RBF method.

With mZF-TF, $Q_{k,n}$ is represented as

$$Q_{k,n} = \begin{cases} \dfrac{A_k}{H_{k,n}^{\mathrm{RBF}}}, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 \geq G_{\mathrm{th}} \\ \dfrac{A_k\left(H_{k,n}^{\mathrm{RBF}}\right)^*}{\sqrt{G_{\mathrm{th}}}\left|H_{k,n}^{\mathrm{RBF}}\right|}, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 < G_{\mathrm{th}} \end{cases}. \tag{7}$$

Here, G_{th} is the threshold. Term A_k is a power normalization coefficient that satisfies the power constraint of $Q_{k,n}$ in (6).

$$A_k = \sqrt{\frac{N}{\sum_{n=1}^{N} P_{k,n}}}, \tag{8}$$

where

$$P_{k,n} = \begin{cases} 1/|H_{k,n}^{\mathrm{RBF}}|^2, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 \geq G_{\mathrm{th}} \\ 1/G_{\mathrm{th}}, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 < G_{\mathrm{th}} \end{cases}. \tag{9}$$

For a frequency where $\left|H_{k,n}^{\mathrm{RBF}}\right|^2$ is lower than G_{th}, channel equalization is not performed so that power loss is avoided and only channel phase compensation is performed during TF. As G_{th} is increased, power allocated to a frequency experiencing good channel conditions can be increased at the expense of deterioration in the delay-spread reduction (channel shortening) effect by TF. The G_{th} value of zero corresponds to pure ZF-TF.

In this paper, we also investigate the minimum mean squared error (MMSE)-based TF (MMSE-TF). The MMSE-TF can achieve a high power gain and an appropriate reduction in multipath interference. Based on [34], MMSE-TF for the IDL-RBF method is represented as

$$Q_{k,n} = \frac{\left(H_{k,n}^{\mathrm{RBF}}\right)^*}{\left|H_{k,n}^{\mathrm{RBF}}\right|}\sqrt{\max\left(A_k\sqrt{\frac{N_0}{\upsilon P_{\mathrm{d}}\left|H_{k,n}^{\mathrm{RBF}}\right|^2}} - \frac{N_0}{\upsilon P_{\mathrm{d}}\left|H_{k,n}^{\mathrm{RBF}}\right|^2}, 0\right)}, \tag{10}$$

where P_{d} and N_0 denote the power levels of the data symbols and noise, respectively. Power normalization coefficient A_k is determined so that the power constraint of $Q_{k,n}$ in (6) is satisfied. Parameter υ ($0 \leq \upsilon \leq 1$) represents the target intersymbol interference level due to multipaths.

4. Numerical Results

4.1 Simulation Parameters

The performance of the proposed IDL-RBF method is evaluated based on computer simulations. We assume DFT-spread OFDM-based single-carrier transmission [13], [14], [29]. We assume scrambling code-based NOMA and RAID $\mathbf{s}_m$ represents the m-th scrambling code sequence. The number of subcarriers (= DFT size), N, is 307 with the subcarrier spacing of 15 kHz, which corresponds to a 4.6-MHz transmission bandwidth. One packet comprises seven DFT blocks and the packet length is 0.5 ms including the CP. One DFT block is used for preamble transmission comprising a ZC sequence of length $N = 307$. The cyclic shift width of the ZC sequence, Δ, is parameterized. From one root ZC sequence, $M_{\mathrm{orth}} = \lfloor N/\Delta \rfloor$ orthogonal preamble sequences are generated by cyclic-shifting operation. Then, $\lceil M/M_{\mathrm{orth}} \rceil$ ZC sequences that are non-orthogonal to each other are used to generate the total of M preamble sequences. As the channel coding, we use a combination of the turbo and repetition codes. The coding rate for the turbo code is 1/3, which is used in LTE [13]. The number of repetitions in the repetition coding is set to 10. QPSK data modulation is assumed. Ten users transmit packets simultaneously. We assume that there is no collision in the selected RAIDs among simultaneous transmitting users in order to assess the fundamental performance of the proposed method with comparison to that of the conventional method.

As the channel model, six-path block Rayleigh fading with the rms delay spread of 1 µs is assumed. This corresponds to the delay spread of multipaths of 16 samples. The L receiver antennas are arranged linearly at half-wavelength intervals, and the received signals of all six paths for each user k are assumed to be received as ideal plane waves from the same angle of arrival, $\theta(k)$. Therefore, a fixed phase rotation of $e^{j\pi\cos\theta(k)}$ is observed between the faded channels of adjacent antennas. The arrival angle, $\theta(k)$, of each user k is uniformly distributed in the range of $\pi/6$ to $5\pi/6$. According to this channel model, BF vector $\mathbf{b}_m$ is set to match the channel whose angle of arrival is $2\pi(m-1)/3(M-1) + \pi/6$ and represented as

$$\mathbf{b}_m = \begin{bmatrix} \frac{1}{\sqrt{L}} \\ \frac{1}{\sqrt{L}} e^{j\pi \cos\left\{\frac{2\pi(m-1)}{3(M-1)} + \frac{\pi}{6}\right\}} \\ \vdots \\ \frac{1}{\sqrt{L}} e^{j\pi(L-1) \cos\left\{\frac{2\pi(m-1)}{3(M-1)} + \frac{\pi}{6}\right\}} \end{bmatrix}. \quad (11)$$

Max-Log MAP (maximum *a posteriori*) decoding with eight iterations is used to decode the turbo code. The maximum number of iterations in the SIC process is set to eight. Active RAID detection and channel estimation are performed using a preamble based on the method described in [30], where the thresholds for the active RAID detection and channel estimation are denoted as C_{ID} and C_{CE}, respectively. We note that C_{ID} is denoted as C_{UD} in [30]. Based on the time-domain correlation between the received signal and each preamble replica for each RAID, when the correlation power level exceeds C_{ID}, the corresponding RAID is detected as active. Similarly, C_{CE} is used for effective path detection for the detected RAIDs to alleviate the negative impact of noise and interference on the channel estimate. As C_{ID} is set larger, the probability of the miss detection of active RAID (MDP) increases while the probability of a false alarm of an inactive RAID (FAP) is suppressed.

4.2 Simulation Results

First, we evaluate the performance of the proposed IDL-RBF method without TF compared to that of the conventional PACE-RBF method. Figure 3 shows the average packet error rate (PER) as a function of the number of base station receiver antennas, L. The number of available RAIDs, M, is parameterized. Ideal active RAID detection and real channel estimation using the received preamble signal are assumed. The signal-to-noise ratio (SNR) per receiver antenna is set to −22 dB. The cyclic shift width of the ZC sequence, Δ, is set to 20. The value of M is fixed at 200 in the conventional PACE-RBF method. We note that the PER of the PACE-RBF method is not dependent on M since we assume no RACH collision among users. As a reference, the PER when ideal receiver BF is conducted in the IDL-RBF method is also shown. Overall, the IDL-RBF method achieves a lower PER than that for the PACE-RBF method. This is due to the improvement in the channel estimation accuracy. The PACE-RBF method improves the PER mainly due to the power gain of the receiver BF as L increases, but the improvement is relatively small due to the increased channel estimation error per receiver antenna, which becomes larger as L increases. In contrast, in the IDL-RBF method, the effect of decreasing the PER as L is increased is more pronounced. This is because the effect of channel estimation error when L is increased is small. When L is set to an excessively large value for a given number of RAIDs, M, the PER of the IDL-RBF method degrades. The L value at which the PER starts to increase becomes smaller as M is set smaller. This is because, in the IDL-RBF method, the receiver BF vectors are restricted such that they are selected from a set of pre-defined M candidates. Therefore, as L is increased, the probability that the pre-defined M receiver BF vectors do not match a given user channel increases. In other words, by using a sufficient M value for a given L, the proposed IDL-RBF method achieves a significantly reduced PER compared to that for the conventional PACE-RBF method especially when L is large. It is also confirmed that the PER of the IDL-RBF method is very close to that of the ideal case of the receiver BF, except for the range where L is too large for the given M.

Figure 4 shows the average PER as a function of the number of RAIDs, M. Term L is parameterized in the proposed IDL-RBF method. Ideal active RAID detection and real channel estimation using the received preamble signal are assumed. The SNR is set to −22 dB and Δ is set to 20. Term L is fixed at 100 in the conventional PACE-RBF method since Fig. 3 shows that the PER of PACE-RBF is not largely dependent on L. As a reference, the PER assuming

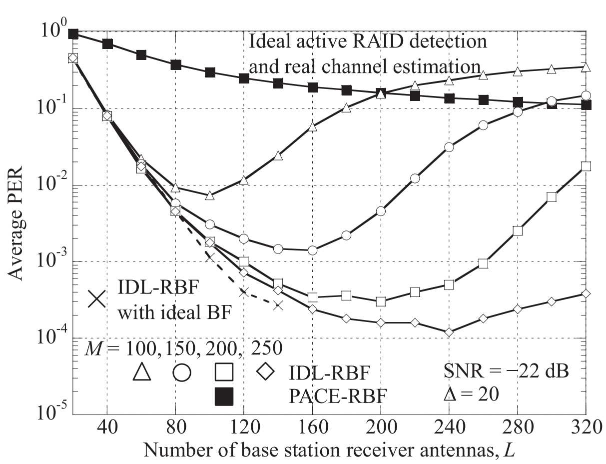

Fig. 3 Average PER as a function of number of base station receiver antennas, L.

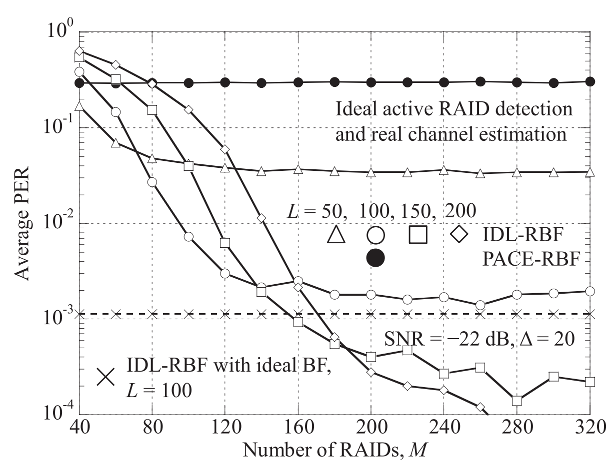

Fig. 4 Average PER as a function of number of RAIDs, M.

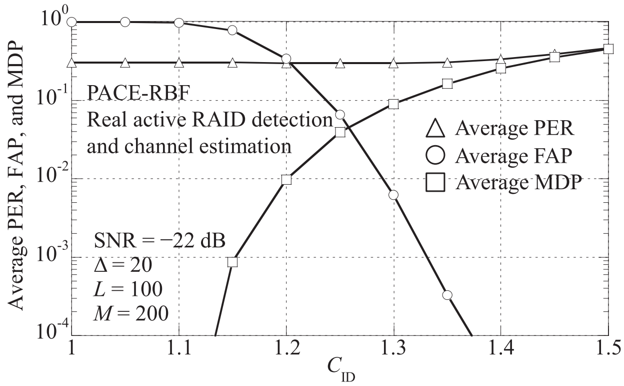

Fig. 5 Average PER, FAP, and MDP of PACE-RBF method as a function of active RAID detection threshold, C_{ID}.

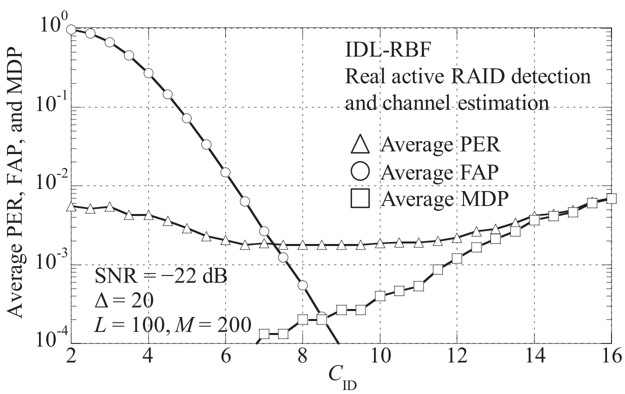

Fig. 6 Average PER, FAP, and MDP of IDL-RBF method as a function of active RAID detection threshold, C_{ID}.

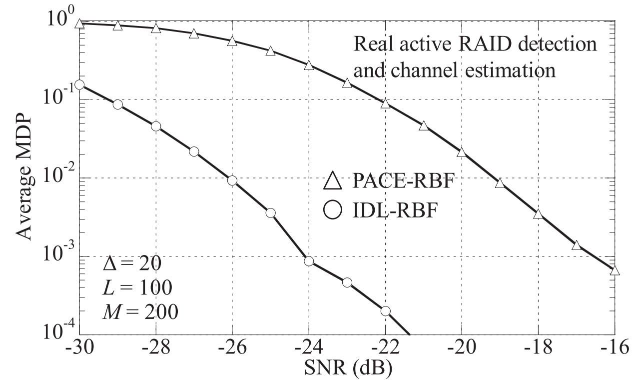

Fig. 7 Average MDP as a function of SNR.

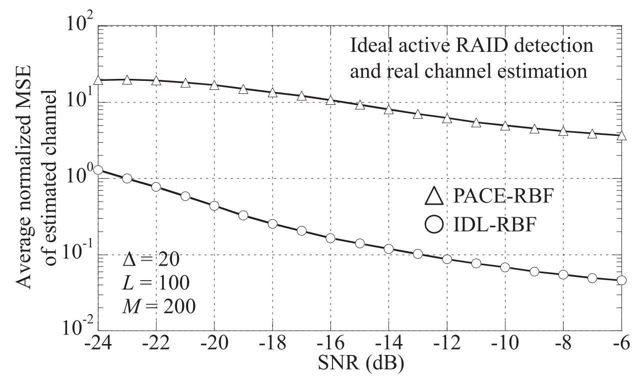

Fig. 8 Average normalized MSE of estimated channel as a function of SNR.

ideal receiver BF in the IDL-RBF method when L is 100 is also shown. Since we assume no RAID collisions among users due to random RAID selection, the average PER of the PACE-RBF method is not dependent on M. On the other hand, the average PER of the IDL-RBF method is greatly reduced as M is increased. This is because the number of candidate BF vectors is increased as M increases, and each user can select a receiver BF vector that better matches the channel of that user. As L increases, the required M for obtaining a sufficiently reduced PER increases. We also confirm that when $L = 100$, the PER of the IDL-RBF method with a sufficiently large M is close to that assuming ideal receiver BF. Based on the results in Figs. 3 and 4, L and M are set to 100 and 200, respectively, in the following evaluations.

Figure 5 shows the average PER, FAP, and MDP in the active RAID detection in the PACE-RBF method as a function of the active RAID detection threshold, C_{ID}. Figure 6 shows those of the IDL-RBF method. The SNR is set to -22 dB and Δ is set to 20. Both in Figs. 5 and 6, as C_{ID} is set larger, FAP decreases while MDP increases. We see that the resultant PER is more affected by MDP rather than FAP, since the received packet of the miss detected RAID is directly discarded. In the proposed IDL-RBF method, the received signal power increases during active RAID detection since the received signal after the receiver BF is utilized. As a result, the C_{ID} that minimizes the PER in the IDL-RBF method is higher than that in the conventional PACE-RBF method and a much lower PER, MDP, and FAP are achieved simultaneously with the IDL-RBF method. In the following evaluation, the C_{ID} level is selected such that the resultant PER is minimized for the respective methods.

Figure 7 shows the average MDP as a function of the SNR. Term Δ is set to 20. This figure clearly shows that the proposed IDL-RBF method achieves a lower MDP than that for the conventional PACE-RBF method.

Figure 8 shows the average normalized mean squared error (MSE) of the estimated channel in the frequency domain as a function of the SNR. Ideal active RAID detection and real channel estimation using the received preamble signal are assumed. Term Δ is set to 20. From the figure, the proposed IDL-RBF method significantly improves the channel estimation accuracy compared to that for the conventional PACE-RBF method thanks to the receiver BF on the received signal vector conducted before the channel estimation.

Figure 9 shows the average PER as a function of the SNR for various conditions for active RAID detection and channel estimation. The conventional PACE-RBF and the proposed IDL-RBF method are evaluated. Term Δ is set to 20. When assuming ideal active RAID detection and channel estimation, the PER of the proposed IDL-RBF method

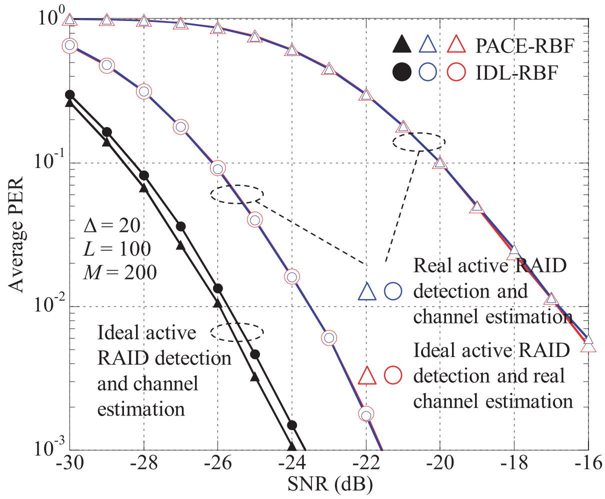

Fig. 9 Average PER as a function of SNR for various active RAID detection and channel estimation conditions.

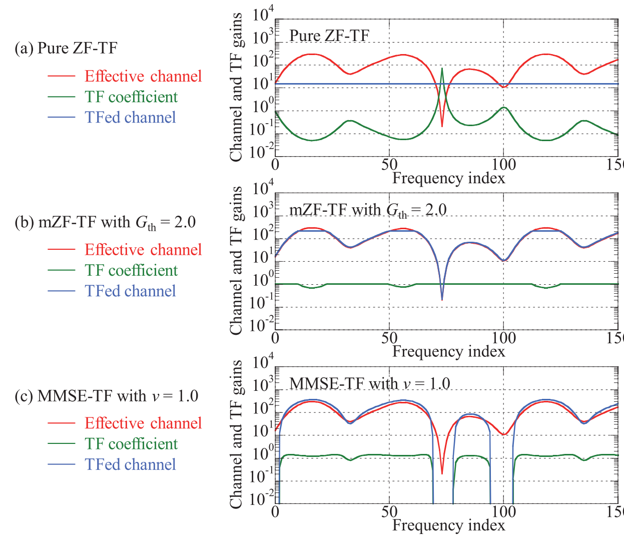

Fig. 10 Example of TF operation in frequency domain.

is slightly degraded compared to that for the conventional PACE-RBF method. This is due to imperfect receiver BF selected from the pre-defined $M = 200$ candidate BF vectors. However, when we assume real channel estimation using a preamble, the IDL-RBF method significantly decreases the PER compared to that for the PACE-RBF method thanks to more accurate channel estimation. We also see that for the respective methods, the PER levels assuming the ideal active RAID detection and the real one are almost identical when we assume real channel estimation. This means that the impact of error in real active RAID detection on the resultant PER is much smaller than that in real channel estimation.

Hereafter, we evaluate the performance of the proposed IDL-RBF method with TF. Figure 10 shows examples of TF in the frequency domain. The pure ZF-TF, mZF-TF, and MMSE-TF are tested. The first 150 frequency components from the total of $N = 307$ components are shown for better visibility. Figure 11 shows the corresponding channel impulse response of the effective channel and TFed channel of the respective TF methods. In Fig. 11, the path gain is normalized by that of the first path in the effective channel. Figure 11 shows that the pure ZF-TF makes the effective channel a perfect single path, while the TFed channel gain is clearly reduced. This is due to the large power allocation to the faded frequency components as shown in Fig. 10. In contrast, a significant power loss is mitigated when using mZF-TF and MMSE-TF. However, Fig. 11 shows that there are many small paths after TF in mZF-TF and MMSE-TF. These small paths are difficult to detect in the active RAID detection and channel estimation, and cause multipath interference. The tradeoff of these factors determines the resultant PER of the respective TF methods.

Figure 12 shows the average PER of the IDL-RBF method with various TF operations as a function of the cyclic shift width of the ZC sequences, Δ. The SNR is set to −22 dB. The average PER of the IDL-RBF method without TF increases when Δ is set to less than 16. This

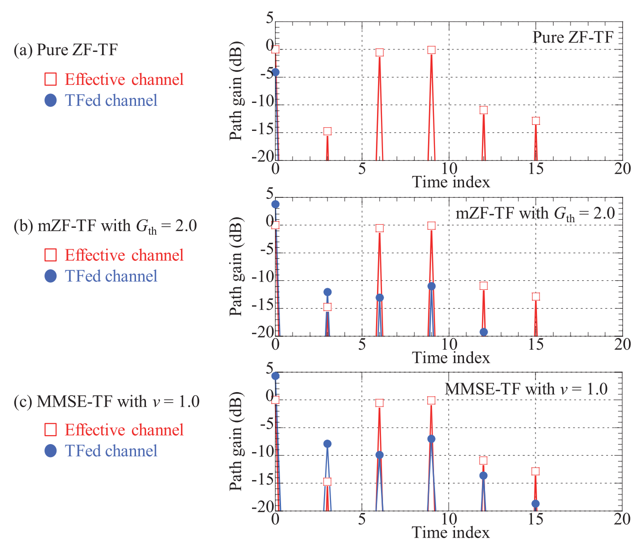

Fig. 11 Example of channel impulse response in time domain.

is because the received paths from different users cannot be separated for Δ of less than the multipath delay spread of 16 samples and the accuracy of the channel estimation is degraded. Actually, the PER when not using TF shows a step function-like shape and each of the Δ values that gives the breaking point of the PER corresponds to each delay time of 6 paths assumed in the simulation. The use of mZF-TF or MMSE-TF mitigates the degradation in the PER when Δ is shortened beyond 16 samples. This is due to the channel shortening effect of TF. Increasing Δ decreases the number of orthogonal preambles that can be generated from one ZC sequence. As the number of mutually non-orthogonal ZC sequences used to generate M preambles increases, the accuracy in the active RAID detection and channel estimation deteriorates. Based on the results in Fig. 12, Δ for the IDL-RBF method without TF is set to 20, while that for the case with TF is set to 5 in the following evaluation.

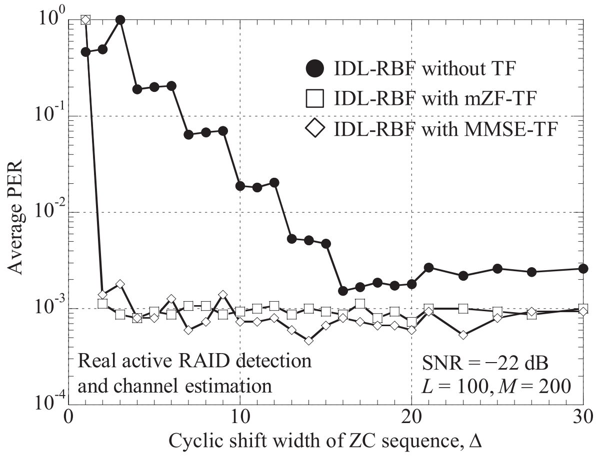

Fig. 12 Average PER of IDL-RBF method with various TF operations as a function of cyclic shift width of ZC sequence, Δ.

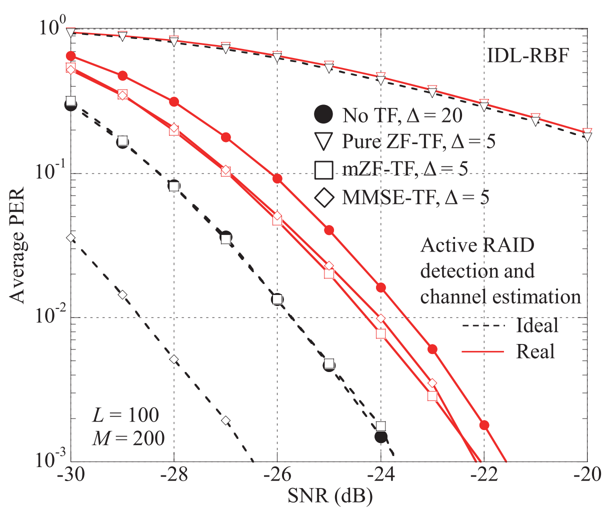

Fig. 13 Average PER of IDL-RBF method with various TF operations as a function of SNR.

Figure 13 shows the average PER as a function of the SNR for the IDL-RBF method with various TF operations. The pure ZF-TF, mZF-TF, and MMSE-TF are tested. As a reference, the performance level assuming no TF is also plotted. Regarding the active RAID detection and channel estimation, both the ideal and real cases are evaluated. When we use pure ZF-TF, the achievable PER is rather degraded compared to the case without TF due to significant transmission power loss for channel equalization. Using the mZF-TF and MMSE-TF, a lower average PER than that without TF is achieved. This is because the transmitter power gain is improved and the channel estimation accuracy is further improved by the TF since the received signal power per path is increased. Furthermore, the number of orthogonal preambles is increased thanks to the reduced Δ value. The PER degradation in MMSE-TF assuming real active RAID detection and channel estimation compared to the ideal case is greater than that with the mZF-TF. A possible reason for this is that since many small paths are observed in a channel to which MMSE-TF is applied as shown in Fig. 11, the accuracy in path detection and channel estimation is degraded compared to that for mZF-TF considering a realistic channel estimation using the received preamble signals. This offsets the maximization effect in the signal-to-interference plus noise ratio (SINR) by using MMSE-TF.

5. Conclusion

We proposed a novel RAID-linked receiver BF method in TDD-based random access for a massive MIMO scenario assumed in 5G and beyond. In the proposed IDL-RBF method, a unique receiver BF vector applied at the base station is linked to each of the RAIDs prepared by the system. The user terminal selects an appropriate receiver BF vector and RAID pair in advance based on the channel estimation results in the downlink assuming channel reciprocity in the TDD system. Therefore, the per-receiver antenna channel estimation for receiver BF is not necessary in the proposed method. This brings about accurate active RAID detection and channel estimation as well as reduced computational complexity at the base station receiver. Furthermore, we proposed the application of TF to the IDL-RBF method for effective channel shortening in order to increase the orthogonal preambles for active RAID detection and channel estimation prepared for each RAID. Computer simulations showed that the proposed methods greatly improve the accuracy of active RAID detection and channel estimation and reduce the PER compared to that for the conventional method in which channel estimation is performed at each antenna in a massive MIMO environment. A potential disadvantage of the proposed IDL-RBF over PACE-RBF is a longer transmission latency, which is similar to the 5G SSB-based random access. This is caused by the downlink channel estimation process with BF selection before random access packet transmission. We note that the proposed method multiplexes random-access packets applying different receiver BF vectors in the same channel, which is different from the 5G SSB-based random access. Therefore, the potential increase in transmission latency is only due to the channel estimation step in downlink and the uplink transmission of random-access packet in the proposed method does not cause extra delay in principle. As a future research topic on the proposed method, an actual channel estimation procedure in the downlink should be investigated while considering the transmission latency. This paper assumes a single transmitter antenna per user. Transmitter BF (precoding) assuming multiple transmitter antennas at the user terminal to enhance the TF performance is also a possible issue to be investigated in the future.

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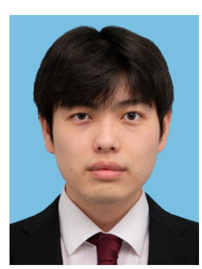

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