Transmitter Filtering-aided Sparse Activity Detection for TDD-based Random Access

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***Abstract*—We investigate active user detection (AUD) for time-division duplexing (TDD)-based random access using transmitter filtering (TF). The main purpose of TF is to reduce the delay spread in a frequency-selective channel (channel shortening), resulting in the sparseness of the effective channel. In particular, the effective channel after zero-forcing (ZF)-based TF can be regarded as a one-tap channel, enhancing the sparsity in a channel. Thus, we propose a compressed-sensing-based AUD making full use of the feature of ZF-based TF. We further introduce an approximated received signal model in which the number of unknown variables is reduced compared to the original formulation. Simulation results demonstrate the superiority of the proposed method over the conventional methods.**

I. Introduction

Future wireless communications systems will be required to satisfy heterogeneous requirements from wide-ranging applications [1], [2]. In particular, massive ultra reliable and low latency communications (URLLC), in which URLLC is integrated with massive access, will be a key usage scenario to support time-sensitive applications such as robot control, which require massive short-packet communications [2]–[4]. Due to sporadic data traffic in such scenarios, conventional multiple access schemes employing grant-based approaches suffer from the inevitable significant control-signaling overhead required for resource assignments ahead of uplink data transmission [5].

To overcome this problem, grant-free random access schemes in which the base station (BS) does not exclusively assign radio resources to active users for data transmission have attracted a significant amount of attention [5], [6]. Although each active user in grant-free random access schemes is allowed to directly transmit its packets to the BS without waiting for permission, the BS must cope with active user detection (AUD) and channel estimation (CE) to recover the transmitted packets accurately. In this context, a large number of studies have addressed these challenges by sparse signal processing such as compressed sensing (CS), in which the inherent sparsity due to sporadic traffic is exploited [5].

A number of approaches for multiple-antenna BS have been actively investigated to handle the aforementioned challenges [7]–[17]. These schemes formulate challenges, e.g., AUD, CE, and data detection, into a sparse recovery problem, making full use of the enhanced sparsity due to the measurements taken by multiple antennas. Subsequently, the BS solves the problem utilizing sparse signal processing techniques. It is worth noting that, in these schemes, neither active users nor the BS needs any extra processing to address the challenges in grant-free random access schemes.

On the other hand, in [18], [19], our research group proposed a sophisticated time division duplex (TDD)-based (grant-free) random access scheme, which is based on two-step random access [20]. In this scheme, a pre-designed receiver beamforming (BF) vector applied at the BS is linked to each of the random access identifiers (RAIDs) prepared by the system to identify users who transmit uplink data simultaneously, which is referred to as the IDL-RBF method [19]. Each active user selects in advance an appropriate pair comprising a receive BF vector and RAID based on the CE results in the downlink assuming channel reciprocity in the TDD system. The BS can thus perform receiver BF for each RAID candidate before performing CE. Moreover, the active users utilize the transmitter filtering (TF) method, which shortens the effective channel, to further improve the accuracy of AUD (RAID detection) and CE.

It is worth noting that the channel-shortening effect achieved by TF remains unaffected by whether BF is applied or not. Furthermore, the effective channel after the zero forcing (ZF)-based TF method can be regarded as a one-tap channel [21]. This implies that the effective channel becomes sparse, enhancing the inherent sparsity in grant-free random access schemes. Nevertheless, the conventional method in [18], [19] does not fully use this benefit since it performs the correlation-based AUD [22], which does not exploit the sparsity. Therefore, there is room for improving the accuracy of AUD in the random access with the ZF-based TF method.

To this end, we propose a CS-based AUD method that exploits the feature of ZF-based TF. Concretely, we introduce a tailored signal model reflecting the channel-shortening effect achieved by the ZF-based TF method. This signal model results in the dimension reduction of the desired signal compared to the original formulation. To perform AUD efficiently, the proposed method utilizes the generalized multiple measurement vector approximate message passing (GMMV-AMP) algorithm [12] as the sparse signal processing technique. Simulation results demonstrate the superiority of the proposed method over the conventional method.

The remainder of the paper is organized as follows. First, Section II describes the system model and the ZF-based TF method. Section III describes the proposed AUD method.

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Section IV shows the numerical results based on computer simulations. Finally, Section V concludes the paper.

II. System Model

We consider the random access based on the IDL-RBF method, where a common BS equipped with L antennas and a large number of single-antenna users exist. Throughout the paper, we assume that M RAIDs are prepared by the system and that K users transmit packets simultaneously. In the following subsections, we describe the basic procedure of the random access in this paper and the TF operation.

A. Basic Procedure of TDD-based Random Access

The transmission and reception flow of TDD-based random access is illustrated in Fig. 1. In the downlink, the BS periodically broadcasts the set of available RAIDs $\mathbf{s}_m$, along with dedicated unique preamble sequence $\mathbf{p}_m$ and linked receiver BF vector $\mathbf{b}_m$[1], namely $\{(\mathbf{s}_1, \mathbf{p}_1, \mathbf{b}_1)\}, \ldots, \{(\mathbf{s}_M, \mathbf{p}_M, \mathbf{b}_M)\}$. In the following explanation and performance evaluation, we assume scrambling code-based non-orthogonal multiple access (NOMA), and $\mathbf{s}_m$ also represents the m-th scrambling code sequence [23]. Besides, the preamble sequence, $\mathbf{p}_m \in \mathbb{C}^{N\times 1}$, is generated by applying a cyclic time shift to Zadoff-Chu (ZC) sequences [24] of length N. Meanwhile, user k that has uplink information estimates the channel using the downlink reference signal. After that, user k selects the best receiver BF vector, $\mathbf{b}_m \in \mathbb{C}^{L\times 1}$, from the prepared M candidates along with the linked $\mathbf{s}_m$ and $\mathbf{p}_m$. Throughout the paper, when $\mathbf{s}_m$, $\mathbf{p}_m$, and $\mathbf{b}_m$ are selected by user k, they are denoted as $\mathbf{s}_{m(k)}$, $\mathbf{p}_{m(k)}$, and $\mathbf{b}_{m(k)}$, respectively.

The packets of user k are generated using $\mathbf{s}_{m(k)}$ and $\mathbf{p}_{m(k)}$. Concretely, the uplink information bit sequence of user k is first encoded by channel coding and is then scrambled by $\mathbf{s}_{m(k)}$. Subsequently, data symbol mapping is applied to the scrambled coded bit sequence. Note that one packet comprises data and a preamble, and the preamble signal of user k is the same as $\mathbf{p}_{m(k)}$. We assume single-carrier transmission and the data symbol sequence is block-wised, which is hereafter referred to as a discrete Fourier transform (DFT) block, with the block size of N. Furthermore, a cyclic prefix (CP) is appended to each DFT block, where the CP length is sufficiently long to cover the entire multipath delay spread and the difference in the received signal timings among users.

In the uplink, active user k transmits the packets generated through the above process to the BS after TF using $Q_{k,n}$. The TF operation will be detailed in the next subsection. Let $\mathcal{K}$ and $X_{k,n}$ denote the set of active users and the frequency domain transmitted component of user k at frequency n ($n = 1, 2, \ldots, N$), respectively. Then, the frequency domain received signal at frequency n is represented by

$$\mathbf{y}_n = \sum_{k\in\mathcal{K}} \mathbf{h}_{k,n} X_{k,n} + \mathbf{z}_n, \tag{1}$$

[1]Unlike [19], the BF vector is not utilized at the BS for AUD and CE in this paper. The design of the sophisticated AUD for random access using both TF and receiver BF is beyond the scope of this paper and therefore left for future work.

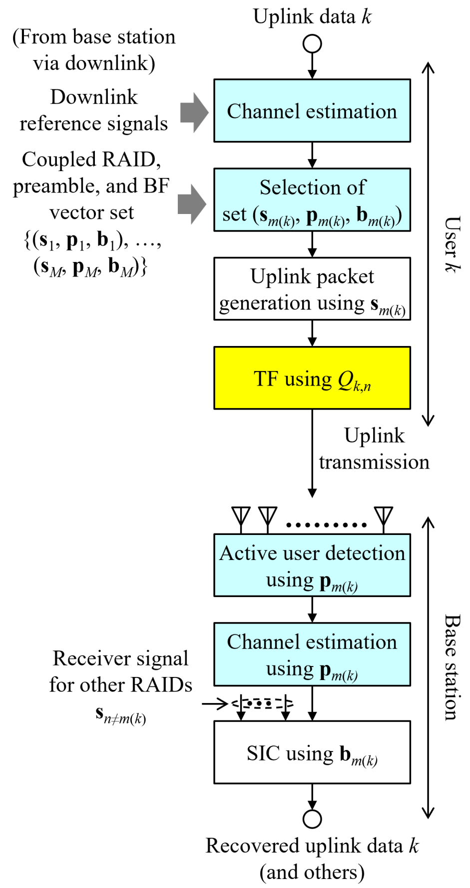

Fig. 1. Transmission and reception flow of TDD-based Random Access.

where $\mathbf{h}_{k,n} \in \mathbb{C}^{L\times 1}$ is the channel frequency response vector of user k at frequency n, and $\mathbf{z}_n \in \mathbb{C}^{L\times 1}$ represents the independently and identically distributed (i.i.d.) additive white Gaussian noise (AWGN) vector at frequency n. The BS first performs active RAID detection, namely AUD, using the received preamble signals in the time domain. Subsequently, the BS attempts to obtain the channel state information of users (RAIDs) that are detected as active by the CE scheme of [22]. Finally, the transmitted packets are decoded by the frequency-domain successive interference canceller (SIC) in [25], which can achieve multi-packet reception. In this paper, receiver BF based on the maximum ratio combining criterion is performed using the BF vector that is linked to the RAID, which is detected as active. This receiver BF for detecting the packet generated using $\mathbf{s}_{m(k)}$ can be expressed as

$$\tilde{y}_n^{[m(k)]} = \frac{\hat{\mathbf{h}}_{k,n}^{\mathrm{H}}}{\left\|\hat{\mathbf{h}}_{k,n}\right\|_2} \mathbf{y}_n, \tag{2}$$

where $\hat{\mathbf{h}}_{k,n}$ denotes the estimate of $\mathbf{h}_{k,n}$.

B. TF Operation

In this paper, we use a modified ZF-based TF (mZF-TF) [19] as the TF method. This TF operation is performed in the frequency domain, where user k is assumed to ideally know its effective channel after receiver BF prior to the uplink transmission based on the CE in the downlink. The effective channel after receiver BF of user k at frequency n, $H_{k,n}^{\mathrm{RBF}}$, is calculated by

$$H_{k,n}^{\mathrm{RBF}} = \mathbf{b}_{m(k)}^{\mathrm{H}} \mathbf{h}_{k,n}. \tag{3}$$

For the TF operation, we need to calculate the TF coefficient of user k at frequency n, $Q_{k,n}$. Note that the transmitted signal of user k at frequency n with TF is given by $Q_{k,n}X_{k,n}$. Therefore, to meet the total transmission power constraint, $Q_{k,n}$ must satisfy

$$\sum_{n=1}^{N} |Q_{k,n}|^2 = N. \tag{4}$$

In light of the above, $Q_{k,n}$ for the mZF-TF method is obtained by [19]:

$$Q_{k,n} = \begin{cases} \frac{A_k}{H_{k,n}^{\mathrm{RBF}}}, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 \geq G_{\mathrm{th}} \\ \frac{A_k \left(H_{k,n}^{\mathrm{RBF}}\right)^*}{\sqrt{G_{\mathrm{th}}}\left|H_{k,n}^{\mathrm{RBF}}\right|}, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 < G_{\mathrm{th}} \end{cases}, \tag{5}$$

where G_{th} is the predetermined threshold, and A_k is a power normalization coefficient that satisfies the power constraint in (4) and is given by

$$A_k = \sqrt{\frac{N}{\sum_{n=1}^{N} P_{k,n}}}, \tag{6}$$

with

$$P_{k,n} = \begin{cases} \frac{1}{\left|H_{k,n}^{\mathrm{RBF}}\right|^2}, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 \geq G_{\mathrm{th}} \\ \frac{1}{G_{\mathrm{th}}}, & \left|H_{k,n}^{\mathrm{RBF}}\right|^2 < G_{\mathrm{th}} \end{cases}. \tag{7}$$

III. Proposed Method

In this paper, we assume that the BS performs AUD using the time domain received preamble signals. When the cyclic shift width of the ZC sequence is Δ, the time domain received preamble signals, $\mathbf{Y} \in \mathbb{C}^{N \times L}$, can be expressed by

$$\mathbf{Y} = \mathbf{P}\mathbf{X} + \mathbf{Z}, \tag{8}$$

where $\mathbf{P} = [\mathbf{p}_{1,0}, \mathbf{p}_{1,1}, \ldots, \mathbf{p}_{1,\Delta-1}, \ldots, \mathbf{p}_{M,\Delta-1}] \in \mathbb{C}^{N \times \Delta M}$ is the measurement matrix comprising preambles and their cyclic shift version. $\mathbf{p}_{m,d}$ denotes m-th preamble sequence with d symbol cyclic shift, which satisfies $\mathbf{p}_{m,0} = \mathbf{p}_m$. $\mathbf{X} \in \mathbb{C}^{\Delta M \times L}$ is the desired signal matrix whose rows correspond to the channel impulse responses in the time domain. $\mathbf{Z} \in \mathbb{C}^{N \times L}$ is the i.i.d. AWGN matrix. Note that both $\mathbf{P}$ and $\mathbf{X}$ can be considered in blocks, each of the size Δ, for all M RAIDs. Moreover, for non-active RAIDs (users), all entries in the Δ rows of $\mathbf{X}$ are zero.

When the mZF-TF method is applied, the effective channel can be regarded as a one-tap channel whose first tap has a considerably high path-gain [19]. However, in the conventional CS-based approaches, sparse signal processing techniques are directly applied to (8), regardless of whether the TF operation is applied or not.

To perform AUD more efficiently, the proposed method introduces a tailored signal model with the proper approximation based on the channel-shortening effect. Only considering the first tap in the channel for all users, the signal model in (8) can be approximated as follows:

$$\mathbf{Y} \approx \tilde{\mathbf{P}}\tilde{\mathbf{X}} + \mathbf{Z}, \tag{9}$$

where $\tilde{\mathbf{P}} = [\mathbf{p}_1, \mathbf{p}_2, \ldots, \mathbf{p}_M] \in \mathbb{C}^{N \times M}$ is the matrix that only consists of the original preambles $\mathbf{p}_m$, and $\tilde{\mathbf{X}} \in \mathbb{C}^{M \times L}$ is the approximated desired signal, which comprises the first rows of each block of $\mathbf{X}$ in (8). The model in (9) enables the proper dimension-reduction of the desired signal when the mZF-TF method is applied. This can also improve the estimation accuracy in sparse signal processing techniques while significantly reducing the computational complexity. Such an improvement will be verified by computer simulations in Section IV.

In the proposed method, the AUD is performed by applying the GMMV-AMP algorithm [12] to (9). In this paper, we assume that all entries in $\tilde{X}$ follow the Bernoulli-Gaussian distribution, which is given by

$$p_0(\tilde{x}_{m,l}) = (1 - \gamma_{m,l})\delta_0(\tilde{x}_{m,l}) + \gamma_{m,l}\mathcal{CN}(\tilde{x}_{m,l}; 0, \tau_{m,l}), \tag{10}$$

where $\tilde{x}_{m,l}$, $\gamma_{m,l}$, $\delta_0(\cdot)$, and $\tau_{m,l}$ denote the element at the m-th row and l-th column of $\tilde{\mathbf{X}}$, the sparsity ratio, the Dirac delta function, and the variance of $\tilde{x}_{m,l}$, respectively. In this paper, we assume that the BS ideally knows the noise variance, σ_{z}^2, while estimating $\gamma_{m,l}$ and $\tau_{m,l}$ by the expectation maximization (EM)-based hyperparameter updates as in [12]. Besides, we initialize $\gamma_{m,l}$ and $\tau_{m,l}$ for all m and l, as follows:

$$\gamma_{m,l} = 0.5, \tag{11}$$

$$\tau_{m,l} = \frac{\sum_{n=1}^{N} \left|y_{n,l}\right|_2^2}{\sum_{n=1}^{N} \sum_{m=1}^{M} |p_{n,m}|}, \tag{12}$$

where $y_{n,l}$ and $p_{n,m}$ represent the element at the n-th row and l-th column of $\mathbf{Y}$ and the n-th element of the m-th preamble sequence, respectively.

We herein discuss the computational complexity in AUD. When the GMMV-AMP algorithm is applied to (8), the computational complexity order is $O(\Delta LMN)$. On the other hand, the computational complexity order can be reduced to $O(LMN)$ when the algorithm is applied to (9). As (massive) grant-free random access schemes considered in the related literature assume the use of non-orthogonal preamble (pilot) sequences, Δ is naturally set to be more than 1. Therefore, our proposed method has the potential to realize a low-complexity CS-based AUD.

We use the belief indicators $\pi_{m,l} \in [0, 1]$, which are calculated by the GMMV-AMP algorithm, for AUD. For $m = 1, 2, \ldots, M$, we calculate the sum of $\pi_{m,l}$ as $\pi'_m = \sum_{l=1}^{L} \pi_{m,l}$.

After that, we determine the threshold for AUD, T_{AUD}, as follows:

$$T_{\mathrm{AUD}} = \frac{C}{M} \sum_{m=1}^{M} \pi'_m, \tag{13}$$

where C is a non-negative threshold factor. The m-th user (RAID) is detected as active if $\pi'_m > T_{\mathrm{AUD}}$ and non-active otherwise.

IV. Numerical Results

A. Simulation Parameters

The performance of the proposed method is evaluated based on computer simulations. We assume DFT-spread orthogonal frequency division multiplexing (OFDM)-based single-carrier transmission. The number of subcarriers (=DFT size), N, is 151 with the subcarrier spacing of 30 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 $N = 151$. The number of available RAIDs (preamble sequences), M, is 120. The cyclic shift width of the ZC sequence, Δ, is set to 5. From one root ZC sequence, $M_{\mathrm{orth}} = \lfloor N/\Delta \rfloor$ orthogonal preamble sequences are generated by cyclic-shifting operation, where $\lfloor \cdot \rfloor$ denotes the floor operation. Then, M/M_{orth} 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/LTE-Advanced [26]. The number of repetitions in the repetition coding is set to 10. As data modulation scheme, quadrature phase-shift keying (QPSK) is employed. We assume that there is no collision in the selected RAIDs among simultaneous transmitting users to assess the fundamental performance of the proposed method with comparison to that of the conventional methods. The signal-to-noise ratio (SNR) is defined as $1/\sigma_z^2$ and is set to -18 dB.

As the channel model, six-path block Rayleigh fading with the rms delay spread of 1 μs is assumed. The L receiver antennas are arranged linearly at half-wavelength intervals, and the received signals of all six paths for each user are assumed to be received as ideal plane waves from the same angle of arrival, θ_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, θ_k, is uniformly distributed in the range of $\pi/6$ to $5\pi/6$. Max-Log maximum a posteriori (MAP) 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 [22]. The threshold for CE was set to the value with the lowest average packet error rate (PER) when AUD was assumed to ideally succeed. The TF threshold, G_{th}, is set to be 190.

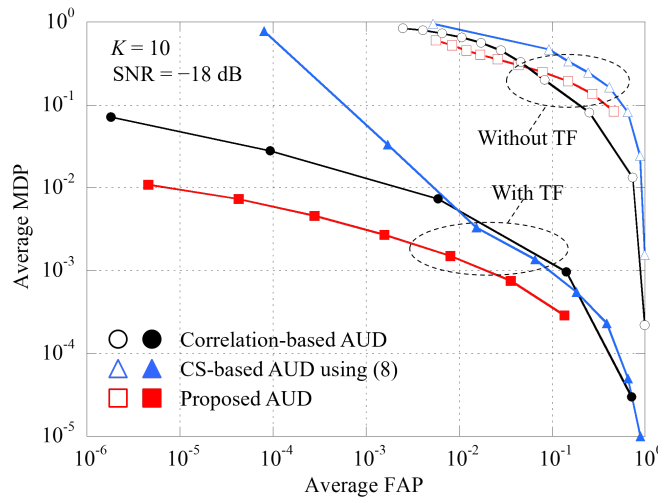

Fig. 2. Average MDP as a function of average FAP.

B. Simulation Results

In the following, we evaluate the proposed method and the two conventional methods; 1) the correlation-based AUD [22] and 2) the CS-based AUD applying the GMMV-AMP algorithm to (8), which is referred to as "CS-based AUD" in the following figures.

To evaluate the AUD performance, Fig. 2 shows the probability of the false alarm of an inactive RAID (FAP) as a function of the probability of the miss detection of active RAID (MDP). $K = 10$ users transmit packets simultaneously. The threshold factor C in the correlation-based method varies from 1.0 to 2.0 in steps of 0.1, while that in the CS-based method[2] and the proposed method does from 0.5 to 5.0 in steps of 0.5. As shown from Fig. 2, when TF is used, the proposed method achieves a lower MDP than the conventional methods. This is because the proposed method can properly focus on estimating the effective channels after TF thanks to the signal model in (9), making full use of the channel-shortening effect. Moreover, the results shown in Fig. 2 indicate that the use of TF can improve the estimation performance of the (classical) CS-based methods.

Fig. 3 shows the average PER as a function of the number of active users, K. For each method, the threshold factor C is set to the value at which FAP is nearly equal to MDP. As a lower bound, we also evaluate the average PER under the ideal AUD, in which TF is used and the BS ideally knows the active users ahead of CE and data detection. This figure demonstrates that the PERs of all methods without TF are very high, whereas all methods with TF achieve the PER below 10^{-2}. In particular, the PER of the proposed method is close to that of the ideal case.

[2]This conventional method also utilizes the belief indicators for AUD, like the proposed method.

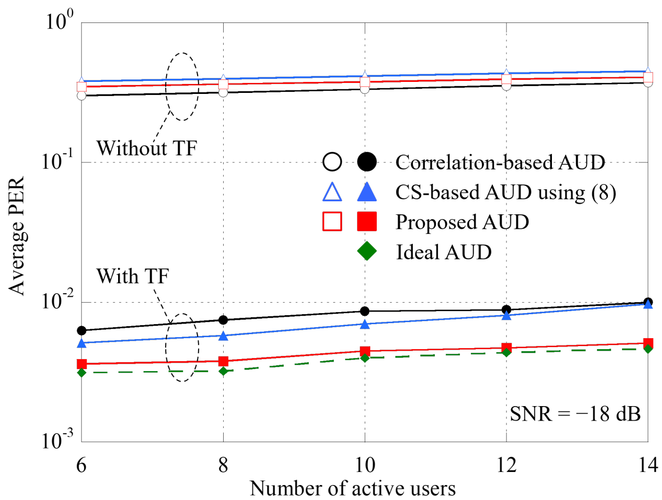

Fig. 3. Average PER as a function of number of active users, K.

V. Conclusion

In this paper, we proposed a CS-based AUD for grant-free random access with the ZF-based TF method. To realize an efficient AUD, we introduced a tailored signal model that makes full use of channel shortening due to the ZF-based TF method, which leads to highly accurate estimation performance while reducing computational complexity. Numerical results indicate that the proposed method is superior to the conventional methods.

Although the original IDL-RBF method in [19] uses not only TF but receiver BF before AUD, this paper does not consider the BF. The design of a sophisticated AUD method that integrates both TF and BF is challenging; however, it is an interesting open problem. Therefore, we leave this design consideration for future work.

Acknowledgment

This work was partially supported by JSPS KAKENHI Grant Number JP23K13337.

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