Interference Alleviation for Time-Reversal Cloud Radio Access Network

Hang Ma[†], Beibei Wang[*†], Yan Chen[*‡] and K. J. Ray Liu[*†]
[†]Department of Electrical and Computer Engineering, University of Maryland, College Park, MD, USA
[*]Origin Wireless Inc., 7500 Greenway Center Drive, Greenbelt, MD, USA
[‡]School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan, China
E-mail: {hangma,bebewang,kjrliu}@umd.edu, chenyanumd@gmail.com

***Abstract*—Due to the unique spatial and temporal focusing effects, time-reversal (TR) communication can be utilized in the cloud radio access network, where it creates a tunneling effect such that the traffic load in the front-haul links can be alleviated in both downlink and uplink. Although the basic TR waveforms are simple to use, they cannot provide the optimal performance in some cases. While the cloud radio access network (C-RAN) is usually expected to serve massive wireless devices, the severe inter-user interference (IUI) might limit the performance of the system. In this paper, we propose to optimize both downlink and uplink transmissions so as to alleviate the interference. In the downlink transmission, optimal content-aware waveform design is proposed so that the baseband units (BBUs) are able to combine both the channel information and the symbol information to suppress the interference. In the uplink transmission, an optimal receiver design algorithm is proposed such that the BBUs can detect the symbols transmitted by the terminal devices (TDs) more accurately by leveraging the channel information. We study the BER performance of the proposed algorithm based on extensive measurements of the wireless channel in a real-world environment. Numerical results demonstrate the significant performance improvement over basic TR transmission techniques.**

I. Introduction

Time-reversal (TR) communication [1] is proposed recently as a new broadband wireless communication technique. Due to the unique spatial and temporal focusing effects of the TR communications in a rich-scattering environment, all the terminal devices (TDs) are naturally separated by their location-specific signatures in both downlink [2] and uplink [3]. These facts make TR a promising candidate in the future broadband wireless communication solutions, which has been illustrated in the cognitive radio networks [4], the internet of things (IoT) [5], and more recently cloud radio access networks (C-RAN) [6].

The C-RAN is a radio access network (RAN) architecture which has the advantage of providing high quality wireless services to massive terminal devices (TDs) over traditional RANs [7]. Nevertheless, in this system, the limited front-haul link capacity between the baseband unit (BBU) and the remote radio head (RRH) is a bottleneck that may prevent the C-RAN from fully utilizing the benefits made possible by concentrating the processing intelligence [8]. Due to this unique focusing features, the TR communication creates a unique "tunneling effect" such that more information can be transmitted with the same amount of traffic load when there are more TDs to be served [6], which is efficient in addressing the front-haul deficit.

However, with massive TDs, the severe inter-user interference (IUI) becomes the limiting factor that impairs both the spectral and energy efficiency. Therefore, it is very important to design effective interference management schemes. In [3], [9], [10], several interference mitigation schemes are proposed for both uplink and downlink. Nevertheless, these works only considered the case with single access point (AP), which might not be applicable to the C-RAN architecture where multiple RRHs are expected to work together to deliver information. Other than TR based C-RAN, works on the downlink and uplink optimizations in general C-RAN include [11]–[14].

In this work, we aim to leverage all the available information and computing power at the BBUs to better manage the interference so that the transmissions in the TR based C-RAN become more reliable and efficient. In the downlink, since the instantaneous channel impulse responses (CIRs) as well as the intended symbols of all the TDs are available at the BBUs, we propose algorithms that combine these information to optimally determine the power allocation and transmitting waveforms to minimize the mean square error (MSE) of the signal received by the TDs. In the uplink, since only the CIRs of all the TDs are available at the BBUs, we propose to utilize such information to optimize the receiver design as well as the transmitting power of all the TDs. All the proposed algorithms are guaranteed to converge. To illustrate the effectiveness of the proposed schemes, we conduct experiments to measure the multipath channel information in a real-world environment, based on which we show that the proposed schemes can significantly reduce the bit error rate (BER) of both downlink and uplink transmissions compared with using the basic TR waveforms. Moreover, since all these optimizations are performed in the BBUs, the asymmetric architecture of the TR communications are preserved, and the performance is improved without any change at the TD side.

The rest of the paper is organized as follows: in section II, both downlink and uplink transmission optimization problems are formulated; the downlink waveform design is optimized in section III; the uplink detector and power control is optimized in section IV; numerical results are shown in section V and

978-1-5090-1328-9/16/$31.00 ©2016 IEEE

section VI concludes this paper.

II. System Models and Problem Formulations

In the time-reversal (TR) based cloud radio access network (C-RAN) [6], the terminal devices (TDs) communicate with the remote radio heads (RRHs) powered by the baseband units (BBUs). The channel impulse response (CIR) information is available in the BBUs through the channel probing phase prior to data transmissions. The CIR is considered as the transmitting waveform of the corresponding TD, and used by the BBUs for the downlink and uplink data transmissions. In the downlink data transmission, the BBUs simply use the time-reversed version of the CIR as the symbol waveform to transmit the data symbols. After receiving the signal, the TD detects the transmitted symbols by looking at one sample of the received signal for each symbol. As a consequence, the complexity at the TD side can be very low while most of the computational burden is shifted to the BBUs. In the uplink data transmission, the TDs directly transmit the symbols through the multipath channel to the RRHs. The RRHs transmit the received signal through the front-haul links to the BBUs and the BBUs then convolve the received signal with the time-reversed version of the CIR of corresponding TDs to detect the symbols transmitted by the TDs.

Although using the basic TR waveform above is simple and straightforward, it cannot achieve the optimal performance, especially in the dense network where the inter-user interference (IUI) becomes the limiting factor. In this work, we focus on the problem to optimize both downlink and uplink data transmissions. The downlink and uplink waveform design problem will be formulated separately in the following.

A. Downlink Problem Formulation

We will first analyze the case that a single RRH serves multiple TDs. Let $h_{i,k}$ denote the multipath channel between the i-th RRH and the k-th TD, which is a vector of length L with L being the maximum channel length of all the N TDs. Let X_k and $g_{i,k}$ denote the information symbols and the transmit waveform for user k at RRH i. $g_{i,k}$ can be basic TR waveform or more advanced waveform. The length of $g_{i,k}$ is also L. In this work, we consider the frame-based transmission and reception schemes. The frame of symbols for user k is denoted by $X_k = [x_{k,1}, x_{k,2}, \cdots x_{k,F_k}]$ where F_k is the frame length of TD k. As shown Fig. 1, at RRH i, the X_k will be first upsampled by the backoff factor D_k for inter-symbol interference (ISI) alleviation. The upsampled symbol frame is denoted as $X_k^{[D_k]}$. After that, a blank sub-frame is appended to the end of the up-sampled signal to prevent the interference between frames. The length of the sub-frame is no less than L taps. Then, the entire frame is convolved with the downlink transmission signature $g_{i,k}$, after which the convoluted signal for all the TDs are summed up together and transmitted over the air to multiple TDs simultaneously.

The signal received at TD k can be represented as

$$S_k = h_{i,k} * \sum_{v=1}^{N} g_{i,v} * X_v^{[D_v]} + n_k, \tag{1}$$

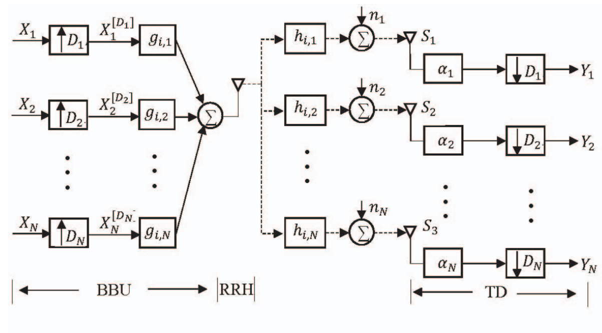

Fig. 1: The Downlink Transmission Diagram

where n_k is the noise vector with appropriate length. Without loss of generality, we assume $E[\|n_k[j]\|^2] = \sigma^2, \forall k, j$.

The k-th TD will first amplify the S_k with α_k and then down-sample it with the backoff factor D_k, obtaining the receiced sequence Y_k, based on which it will try to detect X_k. The received sequence Y_k can be represented as

$$Y_k = \alpha_k M_k \cdot h_{i,k} * \sum_{v=1}^{N} g_{i,v} * X_v^{[D_v]} + \alpha_k M_k n_k, \tag{2}$$

where M_k is a masking matrix for TD k since only the sampled taps of the received signal are considered. More specifically,

$$M_k = [\mathbf{e}_L; \quad \mathbf{e}_{L+D_k}; \quad \cdots \quad \mathbf{e}_{L+(F_k-1)D_k}], \tag{3}$$

where $\mathbf{e}_i$ denotes the i-th row of the $(2L-1+(F_k-1)D_k) \times (2L-1+(F_k-1)D_k)$ identity matrix.

We define $H_{i,k}$ as the Toeplitz matrix of size $(2L-1) \times L$ with the first column being $[h_{i,k}^T \quad \mathbf{0}_{1\times(L-1)}]$, then Y_k can be further written as

$$Y_k = \alpha_k \cdot \tilde{B}_{i,k} g_i + \alpha_k \cdot M_k n_k, \tag{4}$$

where $g_i = (g_{i,1}^T, g_{i,2}^T, \cdots, g_{i,N}^T)^T$ is the aggregation of all the downlink transmission signature $g_{i,k}$'s of the RRH i. $\tilde{B}_{i,k}$ is the equivalent channel matrix combining both the channel information $h_{i,k}$'s and content information X_k's. More specifically,

$$\tilde{B}_{i,k} = M_k[\tilde{B}_{i,k}^{(1)} \quad \tilde{B}_{i,k}^{(2)} \quad \cdots \quad \tilde{B}_{i,k}^{(N)}], \tag{5}$$

where

$$\tilde{B}_{i,k}^{(t)} = \sum_{j=1}^{F_k} X_t[j] \cdot H_{i,k}^{(j)}, \tag{6}$$

and

$$H_{i,k}^{(j)} = \begin{pmatrix} \mathbf{0}_{(j-1)D_k \times L} \\ H_{i,k} \\ \mathbf{0}_{(F_k-j)D_k \times L} \end{pmatrix} \tag{7}$$

is the augmented matrix of $H_{i,k}$ with size $(2L-1+(F_k-1)D_k) \times L$.

In the TR communication system, due to the asymmetric architecture [2], [3], all the computation complexity are migrated to the BBUs and the TDs have low complexity. Due to this constraint, we aim to make the received signal Y_k close to X_k so that TD k could directly get the transmitted information based on the received signal.

It can be seen in (4) that we combine the channel information $h_{i,k}$'s and the content information X_k's in the matrix $\tilde{B}_{i,k}$, which are readily available at the BBUs, and the BBUs can instantaneously compute the $\tilde{B}_{i,k}$'s and utilize them to optimize the downlink data transmission. Since all the TDs simultaneously work at the same spectrum, each TD suffers from the inter-symbol interference (ISI) and the inter-user interference (IUI), which are significantly affected by the design of g_i. We aim to find the optimal g_i and $\alpha = [\alpha_1, \alpha_2, \quad \cdots \quad \alpha_N]$ to minimize the mean square error (MSE) of the received signal without violating the transmitting power constraints. More specifically, the optimization problem becomes

$$\begin{aligned} \min_{\alpha, g_i} \quad & \sum_{k=1}^{N} E[\|Y_k - X_k\|^2] \\ \text{s.t.} \quad & g_i' g_i \leq P_{max}^{(dl)}, \end{aligned} \tag{8}$$

where $P_{max}^{(dl)}$ is the maximum transmitting power allowed for each RRH in the downlink transmission.

B. Uplink Problem Formulation

In the uplink of the TR based C-RAN system, All the TDs simultaneously transmit the information through the RRHs to the BBUs. The BBUs collect the information received by all the RRHs and then detect the transmitted symbols by processing the received signal. We will first analyze the case that a single RRH serves multiple TDs. Similar to the downlink case, the uplink will also be using the frame based transmission. The frame of symbols of TD k is denoted by $X_k = [x_{k,1}, x_{k,2}, \cdots x_{k,F_k}]$ where F_k is the frame length of TD k. As shown in Fig. 2, at TD k, the X_k will be first upsampled by the backoff factor D_k for ISI alleviation. After that, a blank sub-frame is appended to the end of the up-sampled signal to prevent the interference between frames. The length of the sub-frame is no less than L taps. Then, the entire frame is amplified element-wisely by $\beta_k = [\beta_{k,1}, \beta_{k,2}, \cdots, \beta_{k,F_k}]$ and then transmitted over the air to the RRH, i.e., the symbol $x_{k,j}$ is amplified by $\beta_{k,j}$. The signal received at the i-th RRH is the summation of the frame transmitted by each TD convoluted with its corresponding multipath channel. Similar to the downlink case, we use matrix notations to represent the received signal, which is

$$Z_i = R_i \beta X + n_i, \tag{9}$$

where $X = (X_1^T, X_2^T, \cdots, X_N^T)^T$ is the aggregation of the frames of all the TDs,

$$R_i = \begin{pmatrix} R_{i,1} & R_{i,2} & \cdots & R_{i,N} \end{pmatrix}, \tag{10}$$

and β is a diagonal matrix with the diagonal elements being $\beta_{1,1}, \cdots \beta_{1,F_1}, \beta_{2,1}, \cdots \beta_{2,F_2}, \cdots, \beta_{N,1}, \cdots \beta_{1,F_N}$. $R_{i,j}$ is the Toeplitz matrix of size $(D_j \cdot (F_j - 1) + L) \times F_j$ with the j-th column being $[\mathbf{0}_{(j-1)*D_j}; h_{i,j}^T; \mathbf{0}_{(F_j - j)\times D_j}]$.

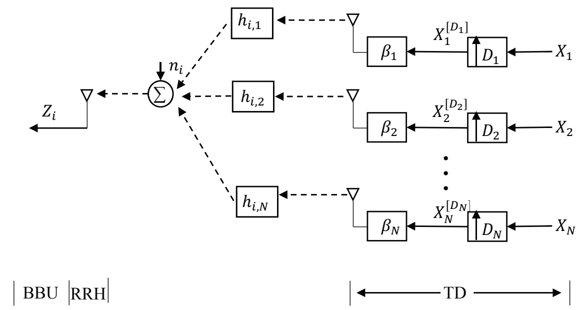

Fig. 2: The Uplink Transmission Diagram

In this work, we aim to design the linear minimum mean square error (LMMSE) detector W_i to detect the symbols transmitted by the TDs. Moreover, the BBUs need also determine the power control factor $\beta_{k,j}$'s in order to avoid the strong-weak effect. The problem can be formulated as

$$\begin{aligned} \min_{\beta, W_i} \quad & E[\|W_i Z_i - X\|^2] \\ \text{s.t.} \quad & \beta_{k,j}^2 E[\|x_{k,j}\|^2] \leq P_{max}^{(ul)}, \qquad \forall k, j, \end{aligned} \tag{11}$$

where $P_{max}^{(ul)}$ is the maximum transmitting power allowed for each TD in the uplink transmission.

III. Downlink Waveform Design

In this section, we will start with the single RRH multiple TD case. Since the problem in (8) is a non-convex problem, we propose to use iterative algorithms to solve it. Eventually, we extend the problem to the coordinated waveform design such that multiple RRHs can work together to focus the signal at the intended locations.

A. Single RRH Waveform Design and Power Allocation

In this subsection, we will analyze the waveform design problem in the case that a single RRH serves multiple TDs.

The Lagrangian of the problem in (8) can be written as

$$\begin{aligned} L(\alpha, g_i, \lambda) = & g_i' (\sum_{k=1}^{N} \|\alpha_k\|^2 \tilde{B}_{i,k}' \tilde{B}_{i,k}) g_i \\ & - g_i' (\sum_{k=1}^{N} \alpha_k' \tilde{B}_{i,k}' X_k) - (\sum_{k=1}^{N} \alpha_k X_k' \tilde{B}_{i,k}) g_i \\ & + \sum_{k=1}^{N} \|\alpha_k\|^2 F_k \sigma^2 + \lambda (g_i' g_i - P_{max}^{(dl)}). \end{aligned} \tag{12}$$

Given g_i, optimizing α is an unconstrained optimization problem, which can be solved by

$$\frac{\partial L}{\partial \alpha_k} = 0 \Rightarrow \alpha_k = (F_k \sigma^2 + g_i' \tilde{B}_{i,k}' \tilde{B}_{i,k} g_i)^{-1} g_i' \tilde{B}_{i,k}' X_k'. \tag{13}$$

From (13), we are able to calculate the optimal α_k given g_i, from which the MSE of the k-th TD can be expressed as

$$MSE_k = X_k' X_k - \frac{g_i' \tilde{B}_{i,k}' X_k X_k' \tilde{B}_{i,k} g_i}{g_i' \tilde{B}_{i,k}' \tilde{B}_{i,k} g_i + F_k \sigma^2}. \tag{14}$$

The total MSE of all the TDs can be represented as

$$\sum_{k=1}^{N} MSE_k = \sum_{k=1}^{N} (X_k' X_k - \frac{g_i' \tilde{B}_{i,k}' X_k X_k' \tilde{B}_{i,k} g_i}{g_i' \tilde{B}_{i,k}' \tilde{B}_{i,k} g_i + F_k \sigma^2}). \quad (15)$$

The gradient can be calculated as

$$\begin{aligned} \nabla g_i \triangleq & \quad \frac{\partial}{\partial g_i} (\sum_{k=1}^{N} MSE_k) \\ &= \sum_{k=1}^{N} [\frac{2\tilde{B}_{i,k}' \tilde{B}_{i,k} g_i (g_i' \tilde{B}_{i,k}' X_k X_k' \tilde{B}_{i,k} g_i)}{(g_i' \tilde{B}_{i,k}' \tilde{B}_{i,k} g_i + F_k \sigma^2)^2} \\ &- \frac{2\tilde{B}_{i,k}' X_k X_k' \tilde{B}_{i,k} g_i}{g_i' \tilde{B}_{i,k}' \tilde{B}_{i,k} g_i + F_k \sigma^2}]. \end{aligned} \quad (16)$$

Once the gradient is calculated, we use it to update the waveform in order to minimize the MSE. Moreover, we project it to the constraint set $g_i' g_i = P_{max}^{(dl)}$ by normalization to comply with the transmitting power constraint. Specifically,

$$g_i^{new} = g_i - \delta_n \cdot \nabla g_i \quad (17)$$

$$g_i^{new,p} = \frac{\sqrt{P_{max}^{(dl)}}}{\|g_i^{new}\|} \cdot g_i^{new}, \quad (18)$$

where the first equation is to determine the shape of the new waveform by line search. The second equation is to project the waveform into the space satisfying the transmitting power constraint. The gradient optimization algorithm can be summarized in Algorithm 1.

Algorithm 1 Gradient Optimization Algorithm

```
1  Initialize g_i as the basic TR waveform
2  loop:
3      Calculate ∇g according to (16)
4      Set n = 1
5      Update g_i^{new,p} according to (17) and (18)
6      if MSE_new < MSE_current
7          g_i = g_i^{new,p}
8      else
9          n = n + 1, go to step 5
10 until g_i and α_k's converge or the maximum number
       of iterations is reached
```

In this algorithm, g_i is updated in step 7 only when the MSE is reduced by the update. Therefore, the MSE is non-increasing in this algorithm. Since the MSE is lower bounded, the gradient algorithm is guaranteed to converge.

B. Extension to multi-RRH Joint Waveform Design and Power Allocation

We extend the problem in (8) to the multiple RRH case. When multiple RRHs work together to serve the TDs distributed in the area, each TD simultaneously receives and combines the signal transmitted by all the serving RRHs. Suppose there are totally M RRHs serving N TDs in the area. The signal received by TD k can be represented as

$$\begin{aligned} Y_k &= \alpha_k \sum_{i=1}^{M} \tilde{B}_{i,k} g_i + \alpha_k \cdot M_k n_k \\ &= \alpha_k \cdot \tilde{B}_k g + \alpha_k \cdot M_k n_k, \end{aligned} \quad (19)$$

where $g = (g_1^T, g_2^T, \cdots, g_M^T)^T$ is the aggregation of all the downlink transmission signature g_i's of the RRH i, and

$$\tilde{B}_k = [\tilde{B}_{1,k} \quad \tilde{B}_{2,k} \quad \cdots \quad \tilde{B}_{M,k}]. \quad (20)$$

Since the transmitting power at each of the RRHs cannot exceed $P_{max}^{(dl)}$, the projection in (18) is modified by normalizing the maximum transmitting power of all the RRHs to $P_{max}^{(dl)}$, while the transmitting power of all the other RRHs are scaled down accordingly. Specifically, the projection step is

$$g^{new,p} = \frac{\sqrt{P_{max}^{(dl)}}}{\max_i \|g_i\|} \cdot g_{new}. \quad (21)$$

IV. Uplink Joint Power Control and Detector Design

In this section, we will first analyze the single RRH case where RRH i determines the transmitting power of all the TDs and then processes the received signal to extract the uplink information. Then we extend it to the multiple RRH case where the BBUs can leverage the signal collected by more than one RRHs.

A. Single RRH Power Control and Detector Design

Suppose the RRH i collects the uplink signal transmitted by N TDs and forward it to the BBUs for further processing. The MSE in (11) can be written as

$$E[\|W_i Z_i - X\|^2] = E[\|W_i R_i \beta X + W_i n_i - X\|^2]. \quad (22)$$

In this work, we use the LMMSE detector to detect X. By [15], the LMMSE detector can be written as

$$W_i = \Sigma_x \beta' R_i' (R_i \beta \Sigma_x \beta' R_i' + \Sigma_e)^{-1}, \quad (23)$$

where

$$\begin{aligned} \Sigma_x &= E[XX'] \\ \Sigma_e &= E[n_i n_i']. \end{aligned} \quad (24)$$

It can be seen that if β is available, the LMMSE detector can be determined. The MSE can be written as

$$MSE^{(ul)} = trace[(\beta' R_i' \Sigma_e^{-1} R_i \beta + \Sigma_x^{-1})^{-1}], \quad (25)$$

which is affected by β. Moreover, β is also limited by the transmitting power constraints of the TDs. Since the R_i, Σ_x and Σ_e are available at the BBUs, the BBUs are able to optimize over β in order to further minimize the MSE, and signal them to the TDs through the control/feedback links. The problem becomes

$$\min_{\beta} \quad trace[(\beta' R_i' \Sigma_e^{-1} R_i \beta + \Sigma_x^{-1})^{-1}]$$
$$\text{s.t.} \quad \beta_{k,j} \leq \sqrt{\frac{P_{max}^{(ul)}}{E[\|x_{k,j}\|^2]}}, \qquad \forall k, j, \tag{26}$$

which is a non-convex problem. Since the global optimal solution is hard to find, in the following, we use a gradient algorithm to find the optimal β to minimize the MSE while satisfying the transmission power constraint of each TD.

Let $A \triangleq \Sigma_e^{-\frac{1}{2}} R_i$. Note that β is a diagonal matrix. By [16], we have

$$\nabla\beta(s,s) \triangleq \frac{\partial MSE^{(ul)}}{\partial \beta(s,s)}$$
$$= -trace[(\beta' A' A \beta + \Sigma_x)^{-2}(\psi_s' A' A \beta + \beta' A' A \psi_s)], \tag{27}$$

where ψ_s is a matrix the same size with β. All elements in ψ_s are zeros except that $\psi_s(s,s) = 1$. We define $\nabla\beta$ to be the diagonal matrix the same size with β, and the i-th item in the diagonal is $\nabla\beta(i,i)$, i.e.,

$$\nabla\beta = \begin{pmatrix} \nabla\beta(1,1) & 0 & \cdots & 0 \\ 0 & \nabla\beta(2,2) & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & \nabla\beta(U,U) \end{pmatrix}, \tag{28}$$

where $U = \sum_{i=1}^{N} F_i$.

After we obtain the gradient for each $\beta(s,s)$, we update each $\beta(s,s)$ by line search and projection similar to the downlink gradient algorithm. Specifically,

$$\beta^{new} = \beta - \delta_n \cdot \nabla\beta, \tag{29}$$

$$\beta^{proj} = \frac{\sqrt{P_{max}^{(ul)}}}{\max_s(\beta^{new}(s,s)\sqrt{\Sigma_x(s,s)})}\beta^{new}, \tag{30}$$

where we choose $\delta_n = \frac{1}{n}$. The algorithm can be summarized in Algorithm 2. In this algorithm, β is updated in step 7 only when the MSE is reduced by the update. Therefore, the MSE is non-increasing in this algorithm. Since the MSE is lower bounded, the gradient algorithm is guaranteed to converge.

Algorithm 2 Gradient Optimization Algorithm for Optimal Power Control in Uplink

1 Initialize $\beta(s,s) = \sqrt{\frac{P_{max}^{(ul)}}{\Sigma_x(s,s)}}, \ \forall s$
2 **loop:**
3   Calculate $\nabla\beta$ according to (27) and (28)
4   Set $n = 1$
5   Update β^{proj} according to (29) and (30)
6   **if** $MSE_{new} < MSE_{current}$
7         $\beta = \beta^{proj}$
8   **else**
9         $n = n + 1$, go to step 5
10 **until** β converges or the maximum number of iterations is reached

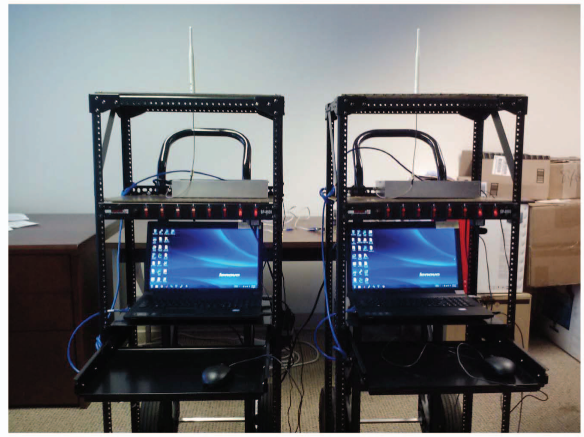

Fig. 3: The TR Radio Prototype

B. Extension to the Multiple RRH Joint Power Control and Detector Design

In the multiple RRH case, we assume the M RRHs simultaneously observe the transmitted signal from the N TDs and forward the collected signal to the BBUs for processing. The BBUs collect the aggregation of the signal received by all the RRHs, which can be represented as

$$Z = R\beta X + n, \tag{31}$$

where $Z = [Z_1^T, Z_2^T, \cdots Z_M^T]^T$, $R = [R_1^T, R_2^T, \cdots R_M^T]^T$, $n = [n_1^T, n_2^T, \cdots n_M^T]^T$.

The LMMSE detector design in (23) and the gradient power control algorithm can be readily extended to the multiple RRH case by replacing R_i by R and n_i by n, respectively.

V. Numerical Results

In this section, we will use some numerical results to illustrate the effectiveness of the proposed waveform design algorithms.

We build a TR radio prototype to measure the multipath channel. A snapshot of the radio stations of our prototype is illustrated in Fig. 3, where a single antenna is attached to a small cart with RF board and computer installed on the cart. The tested signal bandwidth spans from 5.3375 GHz to 5.4625 GHz, centered at 5.4 GHz. An office room in the J. H. Kim Engineering Building at the University of Maryland is considered, from which 4800 independent multi-path channel measurements are obtained. In the following, the performance of the proposed waveform design schemes are evaluated using the measured channels.

In Fig. 4, we show the BER performance of the algorithm in section III-B for the multiple RRH settings. The BER of the basic TR waveform goes down very slowly with the increase

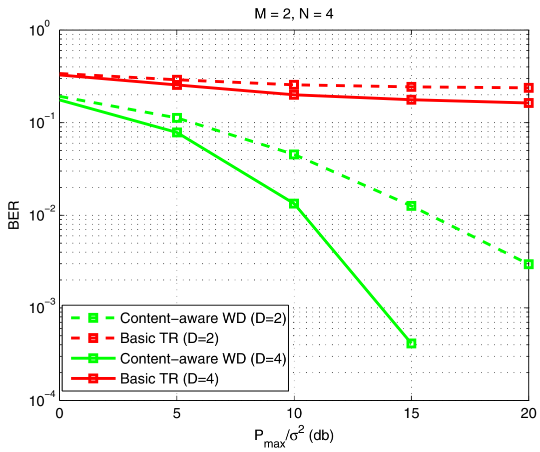

Fig. 4: The BER Performance of Downlink Transmission in a Multiple RRH Case

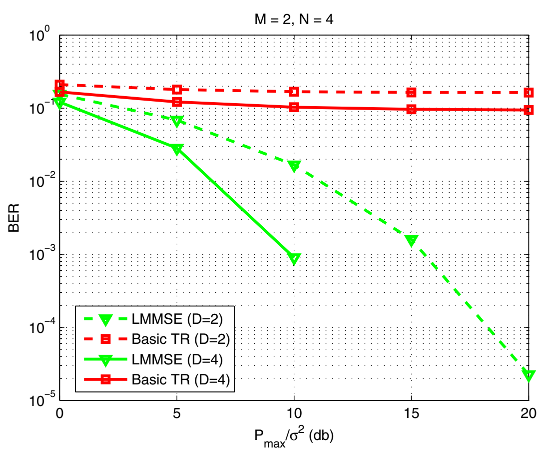

Fig. 5: The BER Performance of Uplink Transmission in a Multiple RRH Case

of $\frac{P_{max}^{(dl)}}{\sigma^2}$. On the other hand, in the proposed content-aware waveform design schemes, multiple RRHs work together to determine the transmitting power and waveform and thus achieve good interference management. As a result, the extra RRHs not only brings in more transmitting power, but also the additional degree of freedom that can be utilized to better focus the signal at the intended locations.

For the uplink case, we show the BER performance of the proposed algorithm in the multiple RRH setting. The curves labeled "LMMSE" stand for the performance of the proposed LMMSE estimator design, and the curves labeled "TR" stand for the performance of the basic TR waveforms in [3]. As shown in Fig. 5, The BER of the basic TR waveform goes down very slowly as $\frac{P_{max}^{(ul)}}{\sigma^2}$ increases. On the other hand, by using the proposed algorithm, the observations from multiple RRHs are gathered and processed to detect the symbols transmitted by the TDs. Additional RRHs provide extra observations of the symbols transmitted by the TDs, which can be utilized to improve the accuracy of the detection.

VI. Conclusion

In this work, we studied the optimization on the downlink and uplink transmission in TR based C-RAN. The content/channel information and the computing power in the BBU pool is utilized to optimize the waveform design in the downlink and receiver design in the uplink. The asymmetric architecture of TR communication is preserved in the optimization and no change in the TD is needed. In this way, the performance of the TR based C-RAN can be improved while keeping the low cost of the TDs. We built a TR radio prototype to measure the wireless channel in the real-world environment, with which we illustrated that the proposed algorithms can significantly improve the downlink and uplink transmission reliability over basic TR waveforms.

References

[1] B. Wang, Y. Wu, F. Han, Y.-H. Yang, and K. J. R. Liu, "Green wireless communications: A time-reversal paradigm," *Selected Areas in Communications, IEEE Journal on*, vol. 29, no. 8, pp. 1698–1710, September 2011.

[2] F. Han, Y.-H. Yang, B. Wang, Y. Wu, and K. J. R. Liu, "Time-reversal division multiple access over multi-path channels," *Communications, IEEE Transactions on*, vol. 60, no. 7, pp. 1953–1965, July 2012.

[3] F. Han and K. J. R. Liu, "A multiuser trdma uplink system with 2d parallel interference cancellation," *Communications, IEEE Transactions on*, vol. 62, no. 3, pp. 1011–1022, March 2014.

[4] H. Ma, F. Han, and K. J. R. Liu, "Interference-mitigating broadband secondary user downlink system: A time-reversal solution," in *Global Communications Conference (GLOBECOM), 2013 IEEE*, Dec 2013, pp. 884–889.

[5] Y. Chen, F. Han, Y.-H. Yang, H. Ma, Y. Han, C. Jiang, H.-Q. Lai, D. Claffey, Z. Safar, and K. J. R. Liu, "Time-reversal wireless paradigm for green internet of things: An overview," *Internet of Things Journal, IEEE*, vol. 1, no. 1, pp. 81–98, Feb 2014.

[6] H. Ma, B. Wang, Y. Chen, and K. J. R. Liu, "Time-reversal tunneling effects for cloud radio access network," *Wireless Communications, IEEE Transactions on*, to appear. [Online]. Available: http://sigport.org/571

[7] ChinaMobile, "C-ran: The road towards green ran," *White Paper*, October 2011.

[8] R. Wang, H. Hu, and X. Yang, "Potentials and challenges of c-ran supporting multi-rats toward 5g mobile networks," *Access, IEEE*, vol. 2, pp. 1187–1195, 2014.

[9] Y.-H. Yang, B. Wang, W. Lin, and K. J. R. Liu, "Near-optimal waveform design for sum rate optimization in time-reversal multiuser downlink systems," *Wireless Communications, IEEE Transactions on*, vol. 12, no. 1, pp. 346–357, January 2013.

[10] E. Yoon, S.-Y. Kim, and U. Yun, "A time-reversal-based transmission using predistortion for intersymbol interference alignment," *Communications, IEEE Transactions on*, vol. 63, no. 2, pp. 455–465, Feb 2015.

[11] S.-H. Park, O. Simeone, O. Sahin, and S. Shamai, "Joint precoding and multivariate backhaul compression for the downlink of cloud radio access networks," *Signal Processing, IEEE Transactions on*, vol. 61, no. 22, pp. 5646–5658, Nov 2013.

[12] B. Dai and W. Yu, "Sparse beamforming and user-centric clustering for downlink cloud radio access network," *Access, IEEE*, vol. 2, pp. 1326–1339, 2014.

[13] Y. Zhou and W. Yu, "Optimized backhaul compression for uplink cloud radio access network," *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 6, pp. 1295–1307, June 2014.

[14] S. Luo, R. Zhang, and T. J. Lim, "Downlink and uplink energy minimization through user association and beamforming in c-ran," *Wireless Communications, IEEE Transactions on*, vol. 14, no. 1, pp. 494–508, Jan 2015.

[15] B. Hajek, "An exploration of random processes for engineers," *Department of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign, Urbana, Illinois*, 2009.

[16] K. B. Petersen, M. S. Pedersen *et al.*, "The matrix cookbook," *Technical University of Denmark*, vol. 450, pp. 7–15, 2008.