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Optimization of uplink rate and fronthaul compression in cloud radio access networks☆

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ABSTRACT

In cloud radio access networks (C-RANs), a central unit (CU) and remote radio heads (RRHs) are connected with a wired fronthaul, e.g., a common public radio interface (CPRI). Due to the limitations of the fronthaul bandwidth in 5G systems, some digital baseband processing blocks are moved from the CU to the RRHs. In this case, the uplink data and pilot symbols after digital processing are delivered from the RRHs to the CU for further processing to decode transmitted information. We consider compression of the data and pilot signals at different compression rates. In the compression of signals, as the compression rate is higher (i.e., the fronthaul rate after the compression is lower), the signal is more distorted. Moreover, compression will affect both the uplink user throughput and the fronthaul rate. The effects of the pilot and data signals on uplink throughput are formulated with an achievable rate considering channel estimation. We formulate an optimization problem to address the tradeoff, and find the optimal distortion variances for the data and pilot signals under high signal-to-noise ratio (SNR) conditions. We show that the optimal signal distortion variance is proportional to the number of data and pilot symbols. We provide numerical results that verify our analytical derivations.

1. Introduction

Cloud radio access networks (C-RANs) were introduced as one of the key technologies to improve network performance and provide 5G services with high throughput [1–3]. As a way to provide high throughput, even for cell-edge users, the deployment of a large number of small cells was proposed under the term *network densification* [4]. For cost-effective deployment of small cells, a C-RAN architecture where multiple remote radio heads (RRHs) are connected with a central unit (CU) has been proposed. The RRHs exchange signals with the CU via wired fronthaul network, e.g., a common public radio interface (CPRI) [5].

For C-RANs in 4G networks, base station (BS) functionality is splitted between the RRH and the CU. Radio frequency (RF) and analog blocks are included in the RRH, and the remaining digital blocks, i.e., digital baseband processing and higher layers, are included in the CU. The required capacity of the fronthaul, which connects the RRH and CU, is calculated with the number of antennas, the signal bandwidth (sampling frequency), and the number of bits for I/Q samples. For example, when a 20 MHz bandwidth (30.72 Msps), eight antennas, and 16-bit quantization are assumed, the required throughput for the fronthaul is about 10 Gbps [4]. If signal bandwidth and the number of antennas increase for 5G networks, the required fronthaul capacity increases to several hundreds gigabits per second. To mitigate the fronthaul capacity requirement, alternative functional split options have been investigated. An enhanced CPRI (eCPRI) is an example [6]. In the eCPRI standards, a part of the digital baseband processing is moved back to the RRH. Additionally, compression of signals to be delivered from the RRH to the CU via fronthaul has been considered. [7].

CPRI is a high-speed serial communications protocol to deliver quantized radio data and control information between the CU and the RRH. In 5G networks with small cells, the density of RRHs will significantly increase. Although the RRHs need to be located over a wide area, the CU can be located in a common area to reduce deployment and maintenance costs. A CPRI based on dedicated optical fiber links is neither practical nor economical. To overcome limitations of CPRIs in 5G networks, the eCPRI was proposed. With eCPRI, information between the CU and the RRH is packetized and sent over Ethernet. In addition

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to point-to-point and point-to-multipoint setups, an eCPRI also supports multipoint-to-multipoint logical connections. Another change from CPRI to eCPRI is that several functional split options in the physical (PHY) layer are allowed, because the eCPRI aims to reduce the required bandwidth by tenfold and allow the required bandwidth to scale flexibly with user traffic.

1.1. Previous work

C-RANs with fronthaul constraints have been investigated from various aspects [8,9]. In [10], the authors proposed an adaptive compression approach for minimizing fronthaul transmission rates with a constraint on the block error rate (BLER). Additionally, a fronthaul rate allocation was proposed to minimize the system BLER. A maximization problem for the achievable sum rate in uplink of a C-RAN with the finite-capacity fronthaul links was considered in [11] and [12] with consideration for correlation between RRHs. Extensions to multiple-antenna beamforming were investigated in [13] and [14] for uplink and downlink transmissions, respectively. In [15], a joint quantization mapping across all fronthaul links that adapts to the channel condition for the C-RAN downlink was proposed. In [16], a method for Long Term Evolution (LTE) downlink point-to-point signal compression based on linear prediction and Huffman coding was proposed. An improved method with an adjustable compression factor was proposed in [17].

Extensions from various aspects have also been studied. In [18], joint optimization to maximize the fairness-aware quality-of-service (QoS) in terms of coordinated multipoint (CoMP) cell selection and time–frequency resource allocation among cells in orthogonal frequency division multiple access (OFDMA) systems was investigated under a limited fronthaul capacity. Fronthaul rate allocation for non-orthogonal multiple access (NOMA) systems was considered in [19]. In [20], Qin et al. minimized the maximum load on all fronthaul links, i.e., they balanced the fronthaul loads under the constraints of QoS and harvested energy. Xia et al. considered an uplink heterogeneous C-RAN where macro BSs and distributed units (DUs) are connected to a CU with a coexisting wireless fronthaul, and user access links and fronthaul links share the spectrum [21]. In such an environment, maximization of the sum rate with respect to fronthaul compression and bandwidth allocation was investigated.

1.2. Contributions of this paper

Previously, a throughput maximization with a constraint on the fronthaul was investigated. If the fronthaul is a dedicated network for point-to-point connection between an RRH and a CU, the optimal solution is to fully utilize the fronthaul capacity. In eCPRI, however, an Ethernet-based protocol is defined, and the fronthaul is regarded as a shared medium [6]. Therefore, the minimization of the frounthaul rate, as well as the maximization of the user throughput, is considered an objective of system design in C-RANs.

In this paper, we consider optimization of the user throughput and fronthaul compression based on a rate–distortion theory. The compression rate of the fronthaul signal determines the quality of the received signal and the throughput of the fronthaul. To improve the quality of the received signal, i.e., to reduce signal distortion, higher fronthaul throughput is required. Therefore, there is a tradeoff between signal distortion and the fronthaul rate. By optimizing the compression rate, we can achieve a balance between user throughput maximization and fronthaul rate minimization.

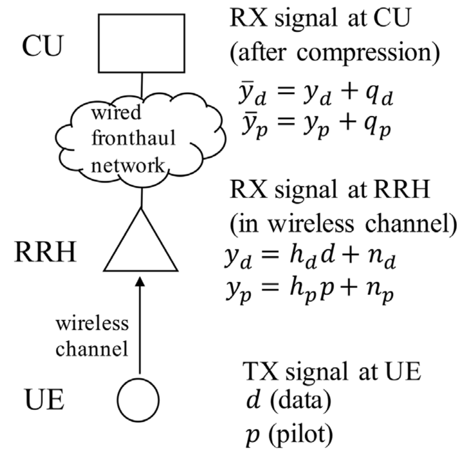

Fig. 1. Uplink system and signal models in C-RAN.

1.3. Notations

The notation $x \sim \mathcal{CN}(\mu, \sigma)$ means that x is a complex Gaussian distributed random variable with mean μ and variance σ. $\mathbb{E}(\cdot)$ denotes the expectation of a random variable.

2. System model

We consider a simple C-RAN structure where one RRH is connected with a CU via wired fronthaul, as shown in Fig. 1. As seen in the figure, UEs send an uplink signal to the associated RRH, and the RRH forwards the received signal to the CU. Therefore, the functions in the conventional base station (BS) are divided into two parts: the functions in the lower layers are implemented in the RRH, and the remaining functions in the upper layers are placed in the CU. In the conventional CPRI standard, the split option E in Fig. 2 was adopted. In this case, RF and analog blocks are in the RRH, and the digital baseband and upper layers are in the CU. Even though this split option demands high fronthaul throughput, implementation of the C-RAN is simple, with low cost, because most of the complex functions are implemented in the CU.

In emerging 5G networks and services, signal bandwidth and the number of antennas at the BS increase, and the required capacity of the fronthaul cannot be met with the conventional CPRI. Therefore, eCPRI adopts split option I_U for uplink, as shown in Fig. 2. In this case, the RRH includes OFDM demodulation (cyclic prefix removal, fast Fourier transform (FFT), and resource element (RE) demapping) as well as RF and analog functions. It means that the RRH sends data and pilot symbols in subcarriers of OFDM systems to the CU through the fronthaul. In this process, signal compression between RRH and CU can be considered to reduce the fronthaul throughput requirement.

In this paper, for simplicity, we consider frequency flat fading channels, e.g., a single subcarrier in OFDM symbols. The received signal for data and pilot symbols at the RRH can be expressed as follows:

$$y_d = h_d d + n_d, \text{ for data symbol,} \tag{1}$$

$$y_p = h_p p + n_p, \text{ for pilot symbol,} \tag{2}$$

where d and p denote data and pilot symbols with unit power, and $h_d(\sim \mathcal{CN}(0,1))$ and $h_p(\sim \mathcal{CN}(0,1))$ are channel coefficients for data and pilot symbols, respectively. Also, $n_d(\sim \mathcal{CN}(0,\sigma^2))$ and $n_p(\sim \mathcal{CN}(0,\sigma^2))$ are additive white Gaussian noise added to the data and pilot, respectively. The transmit data are assumed

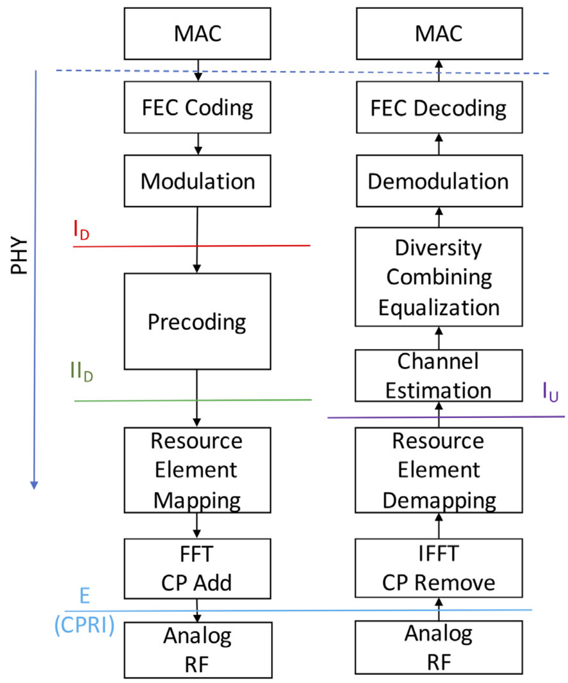

Fig. 2. PHY split options in eCPRI.

to be drawn from a Gaussian codebook. The numbers of data and pilot symbols in the transmit signal are given by N_d and N_p, respectively, and their sum is $N_t(=N_d+N_p)$ symbols. It is also assumed that the channel gain in each block with N_t symbols is constant, and the channel gain in different blocks is statistically independent. That is, quasi-static block fading channels are assumed. If a fronthaul link has no capacity limit, the received signals of (1) and (2) can be delivered without any compression (distortion). However, the fronthaul network is shared with other RRHs, CUs, and even other Ethernet connections, i.e., a wired network used for a fronthaul is not a dedicated network but a shared network. Therefore, it is important to reduce the required fronthaul throughput. To this end, the compression of fronthaul signals is considered. The compressed signals are expressed by

$$\bar{y}_d = y_d + q_d = h_d d + n_d + q_d, \tag{3}$$

$$\bar{y}_p = y_p + q_p = h_p p + n_p + q_p, \tag{4}$$

where q_d and q_p are distortions of data and pilot signals, respectively. It is assumed that the distortions are independent of the original signals and follow a Gaussian distribution, that is $q_d \sim \mathcal{CN}(0,\theta_d^2)$ and $q_p \sim \mathcal{CN}(0,\theta_p^2)$. After compression, the RRH sends compressed data and pilot symbols $\bar{y}_d$ and $\bar{y}_p$ to the CU for further processing to recover the transmitted data.

3. Uplink/Fronthaul throughput optimization

With compressed data and pilot signals, a CU can estimate the channel and decode the uplink data. Because we assume that the channel gain of pilot symbols is identical to that of data symbols (i.e., block fading channels), the channel estimate obtained by the pilot symbols can be directly used for decoding the data symbols. Hereafter, we define $h = h_p = h_d$. The effective signal-to-noise ratio (SNR) of N_p pilot symbols is given by

$$\Gamma_p = \frac{N_p}{\sigma^2+\theta_p^2}. \tag{5}$$

If minimum mean square error (MMSE) channel estimation is employed, the variances in channel estimate, $\hat{h}$, and its error, $\tilde{h}(=h-\hat{h})$, are given as follows [22]:

$$\mathbb{E}\{|\hat{h}|^2\} = \frac{\Gamma_p}{1+\Gamma_p} = \frac{N_p}{N_p+\sigma^2+\theta_p^2}, \tag{6}$$

$$\mathbb{E}\{|\tilde{h}|^2\} = \frac{1}{1+\Gamma_p} = \frac{\sigma^2+\theta_p^2}{N_p+\sigma^2+\theta_p^2}. \tag{7}$$

The compressed data signal can be rewritten as

$$\bar{y}_d = \hat{h}d + \tilde{h}d + n_d + q_d. \tag{8}$$

In the right-hand side (RHS) of (8), the first term is the desired signal, and the remaining ones are the effective noise. Therefore, an achievable rate with channel estimation is given by

$$\begin{aligned} R_u &= \frac{N_d}{N_t}\mathbb{E}\left[\log\left(1+\frac{|\hat{h}|^2}{|\tilde{h}|^2+\sigma^2+\theta_d^2}\right)\right] \\ &\overset{(a)}{\approx} \log\left(1+\frac{\mathbb{E}[|\hat{h}|^2]}{\mathbb{E}[|\tilde{h}|^2]+\sigma^2+\theta_d^2}\right) \\ &= \log\left(1+\frac{N_p}{\sigma^2+\theta_p^2+(\sigma^2+\theta_d^2)(N_p+\sigma^2+\theta_p^2)}\right). \end{aligned} \tag{9}$$

where $\frac{N_d}{N_t}$ is the fraction of data symbols. In approximation (a) above, we use $\mathbb{E}\left[\log(1+\frac{x}{y})\right] \approx \log\left(1+\frac{\mathbb{E}[x]}{\mathbb{E}[y]}\right)$. The accuracy of this approximation can be discussed based on the following lemma [23,24].

Lemma 1. *For given positive random variables x and y, there exists positive numbers, c_1, c_2, δ_1, and δ_2, such that*

$$\begin{aligned} &\left|\mathbb{E}\left[\log\left(1+\frac{x}{y}\right)\right] - \log\left(1+\frac{\mathbb{E}[x]}{\mathbb{E}[y]}\right)\right| \\ &\leq \log\left(\left(1+c_1\frac{\mathbb{VAR}[x+y]}{\mathbb{E}^2[x+y]}\right)\left(1+c_2\frac{\mathbb{VAR}[y]}{\mathbb{E}^2[y]}\right)\right), \end{aligned} \tag{10}$$

when $\frac{\mathbb{VAR}[x+y]}{\mathbb{E}^3[x+y]} < \delta_1$ *and* $\frac{\mathbb{VAR}[y]}{\mathbb{E}^3[y]} < \delta_2$.

The proof of the lemma can be found in [23].

To evaluate the fronthaul rate, the rate–distortion theory is adopted with a test channels of (3) and (4). We denote the rate–distortion function of the data with $R(\theta_d^2)$. It can be derived as follows:

$$R(\theta_d^2) = \frac{N_d}{N_t}\log\left(1+\frac{1+\sigma^2}{\theta_d^2}\right). \tag{11}$$

The above equation can be obtained by modifying Eq. (8) in [13] and Eq. (7) in [14]. In [13] and [14], the fronthaul rate was evaluated for multiple input multiple output (MIMO) cases. By changing the MIMO channel capacity formula to single input single output (SISO) capacity formula, e.g., neglecting the determinant operation and changing matrices to scalars, we can obtain (11).

Similarly, we define $R(\theta_p^2)$ for the pilot as follows:

$$R(\theta_p^2) = \frac{N_p}{N_t}\log\left(1+\frac{1+\sigma^2}{\theta_p^2}\right). \tag{12}$$

Then, minimum data rate R_d will be $R(\theta_d^2)$ in (11). Similarly, minimum pilot rate R_p will be $R(\theta_p^2)$ in (12). The tradeoff between signal distortion and fronthaul rate is obvious from the rate–distortion functions. When the fronthaul rate after compression is low, the signal is more distorted to meet the limited fronthaul bandwidth.

Based on the uplink and fronthaul rates, we can formulate an optimization problem. If the fronthaul is a shared medium as a wireless channel (uplink channel), minimization of the fronthaul rate, as well as maximization of the uplink rate, is an important objective in designing a C-RAN. The two objectives of the optimization are as follows:

- maximization of the uplink throughput with the compressed (distorted) data and pilot symbols
- minimization of the fronthaul rate by using signal compression of data and pilot symbols

That is, the optimization increases the uplink throughput while decreasing the fronthaul usage (a resource shared with others). To combine the two opposite directions of optimization, i.e., one is maximization and the other is minimization, we employ a positive weight for uplink throughput and a negative weight for the fronthaul rate. By adjusting the weights, we can control the priority on both objectives. The optimization problem can be formulated as follows:

$$\max_{\theta_d^2,\,\theta_p^2} wR_u-(1-w)(R_d+R_p) \tag{13a}$$

$$\text{subject to } \theta_d^2 \geq 0 \tag{13b}$$

$$\theta_p^2 \geq 0 \tag{13c}$$

where w is a weight to determine the priority of the uplink rate over the fronthaul rate. In general, w is greater than 0.5, because the uplink rate affects the end-users' experience more directly. To simplify the objective function, i.e., the weighted sum of the uplink and fronthaul rates, and to obtain an insight for C-RAN design, we assume a high effective SNR and rewrite objective function (13a) as follows:

$$\begin{aligned} R_t &\triangleq wR_u-(1-w)(R_d+R_p)\\ &\approx \hat{R}_t\\ &= w\frac{N_d}{N_t}\log\left(\frac{N_p}{(1+N_p)\sigma^2+N_p\theta_d^2+\theta_p^2}\right)\\ &\quad-(1-w)\left\{\frac{N_d}{N_t}\log\left(\frac{1}{\theta_d^2}\right)+\frac{N_p}{N_t}\log\left(\frac{1}{\theta_p^2}\right)\right\}. \end{aligned} \tag{14}$$

Optimization problem (13) can be rewritten as

$$\max_{\theta_d^2,\,\theta_p^2} \hat{R}_t(\theta_d^2,\theta_p^2) \tag{15a}$$

$$\text{subject to (13b) and (13c).} \tag{15b}$$

4. Optimal compression for data and pilot signals in fronthaul

A closed-form solution to optimization problem (15) can be obtained as follows.

Proposition 1. *Under a high effective SNR assumption, the optimal distortion variances of data and pilot signals, which maximize the approximation of the weighted sum of the uplink user and fronthaul rates, $\hat{R}_t$, are given by*

$$\theta_d^{2*}=\frac{\sigma^2 w(1-w)N_d(1+N_p)}{(2w-1)(wN_t-N_p)-(1-w)^2N_p^2} \tag{16}$$

and

$$\theta_p^{2*}=\frac{\sigma^2 w(1-w)N_p(1+N_p)}{(2w-1)(wN_t-N_p)-(1-w)^2N_p^2}, \tag{17}$$

respectively.

Proof. To find the optimal solution to (15), we form a Lagrangian to derive the Karush Kuhn Tucker (KKT) conditions:

$$\begin{aligned} L(\theta_d^2,\theta_p^2,\lambda_d,\lambda_p)&=w\frac{N_d}{N_t}\log\left(\frac{N_p}{(1+N_p)\sigma^2+N_p\theta_d^2+\theta_p^2}\right)\\ &\quad-(1-w)\left\{\frac{N_d}{N_t}\log\left(\frac{1}{\theta_d^2}\right)+\frac{N_p}{N_t}\log\left(\frac{1}{\theta_p^2}\right)\right\}+\lambda_d\theta_d^2+\lambda_p\theta_p^2, \end{aligned} \tag{18}$$

where λ_d and λ_p are Lagrangian dual variables associated with (13b) and (13c), respectively. Because the optimal solution, θ_d^{2*} and θ_p^{2*}, cannot be zero, $\lambda_d=\lambda_p=0$ to satisfy the complementary slackness conditions, i.e., $\lambda_d\theta_d^{2*}=0$ and $\lambda_p\theta_p^{2*}=0$. Therefore, the solution is obtained by solving $\frac{\partial\hat{R}_t}{\partial\theta_d^2}=0$ and $\frac{\partial\hat{R}_t}{\partial\theta_p^2}=0$ when θ_p^2 and θ_d^2, respectively, are fixed.

With a given θ_p^2, the optimal variance of distortion for data signal is obtained by solving the following equation:

$$\frac{\partial\hat{R}_t}{\partial\theta_d^2}=-\frac{wN_dN_p}{N_t\left((1+N_p)\sigma^2+N_p\theta_d^2+\theta_p^2\right)}+\frac{(1-w)N_d}{N_t\theta_d^2}=0. \tag{19}$$

By rewriting the above equation with respect to θ_d^2, we can obtain the optimal solution as follows:

$$\theta_d^{2*}=\frac{(1-w)\left((1+N_p)\sigma^2+\theta_p^2\right)}{(2w-1)N_p}. \tag{20}$$

Similarly, the optimal θ_p^2 can be obtained:

$$\frac{\partial\hat{R}_t}{\partial\theta_p^2}=-\frac{wN_d}{N_t\left((1+N_p)\sigma^2+N_p\theta_d^2+\theta_p^2\right)}+\frac{(1-w)N_p}{N_t\theta_p^2}=0, \tag{21}$$

$$\theta_p^{2*}=\frac{(1-w)N_p\left((1+N_p)\sigma^2+N_p\theta_d^2\right)}{wN_d-(1-w)N_p}. \tag{22}$$

Solutions (20) and (22) are functions of θ_p^2 and θ_d^2, respectively. By inserting (22) into (20), we have a fixed-point equation. The converged solution of θ_d^{2*} can be obtained by solving the following fixed-point equation:

$$\begin{aligned}\theta_d^{2*}&=\frac{(1-w)\left((1+N_p)\sigma^2+\theta_p^{2*}\right)}{(2w-1)N_p}\\ &=\frac{(1-w)\left((1+N_p)\sigma^2+\frac{(1-w)N_p\left((1+N_p)\sigma^2+N_p\theta_d^{2*}\right)}{wN_t-N_p}\right)}{(2w-1)N_p}.\end{aligned} \tag{23}$$

By solving (23) with respect to θ_d^{2*}, we have (16). Similarly, a fixed-point equation for the converged solution of θ_p^{2*} is given by

$$\begin{aligned}\theta_p^{2*}&=\frac{(1-w)N_p\left((1+N_p)\sigma^2+N_p\theta_d^{2*}\right)}{wN_t-N_p}\\ &=\frac{(1-w)N_p\left((1+N_p)\sigma^2+\frac{(1-w)\left((1+N_p)\sigma^2+\theta_p^{2*}\right)}{(2w-1)N_p}\right)}{wN_t-N_p}.\end{aligned} \tag{24}$$

By rearranging (24), the solution in (17) can be obtained. □

With Proposition 1, the characteristics of the optimal distortion variances in data and pilot signals are found. Both variances of data- and pilot-signal distortions variances are decreasing functions of weight factor w. Because w denotes the priority of an uplink user rate over a fronthaul rate, the less distortion, which leads to higher user and fronthaul rates, can be optimal when w increases. Both distortion variances are linearly increasing functions of σ^2. As expected, as σ^2 decreases (i.e., the SNR at the RRH increases), the optimal distortion variances decrease.

Even a small amount of distortion can significantly increase the uplink rate under a high SNR condition.

Corollary 1. *With a given w and σ^2, the ratio between the optimal data and pilot distortion variances are the same as the ratio between the number of data and pilot symbols:*

$$\frac{\theta_d^{2*}}{\theta_p^{2*}} = \frac{N_d}{N_p}. \tag{25}$$

Proof. By checking both (16) and (17), we can easily prove the corollary. □

Based on Corollary 1, since N_d is greater than N_p, the data signal is compressed more than the pilot signal. This can also be considered a rate allocation between the data and pilot signals.

Corollary 2. *When N_d approaches infinity with a fixed N_p (i.e., the data portion in the transmit signal increases without bound), the optimal variances of data and pilot distortion variances are given by*

$$\theta_d^{2*} = \frac{\sigma^2(1-w)(1+N_p)}{2w-1}, \tag{26}$$

$$\theta_p^{2*} = 0. \tag{27}$$

Proof. Because $N_t = N_d + N_p$, N_t increases with N_d. With (16) and (17), we have

$$\begin{aligned}\lim_{N_t\to\infty} \theta_d^{2*} &= \lim_{N_t\to\infty} \frac{\sigma^2 w(1-w)(N_t-N_p)(1+N_p)}{(2w-1)(wN_t-N_p)-(1-w)N_p} \\ &= \frac{\sigma^2(1-w)(1+N_p)}{2w-1},\end{aligned} \tag{28}$$

and

$$\begin{aligned}\lim_{N_t\to\infty} \theta_p^{2*} &= \lim_{N_t\to\infty} \frac{\sigma^2 w(1-w)N_p(1+N_p)}{(2w-1)(2N_t-N_p)-(1-w)N_p} \\ &= 0. \quad \square\end{aligned} \tag{29}$$

The pilot signal should not be compressed when the pilot portion in a signal structure is negligible. That is because the increment in the fronthaul rate due to a non-compressed pilot signal is much less significant than the improvement of the uplink user rate due to an accurate channel estimation.

5. Numerical results

In this section, the analytical results in the above section are verified. First, we investigate the accuracy of the weighted sum of user and fronthaul rates, $\hat{R}_t$.

In Fig. 3, the exact weighted sum rates and their approximations, with an assumption of high effective SNR, are evaluated. Fig. 3(a) shows the weighted sum rates with respect to pilot signal distortion, θ_p^2, when $N_d = 9$, $N_p = 1$, $N_t = 1$, $\sigma^2 = 0.01$, $w = 0.9$, and $\theta_d^2 \in \{0.1, 0.01, 0.0032, 0.00032\}$. Additionally, Fig. 3(b) shows the weighted sum rates with respect to data signal distortion, θ_d^2, when $N_d = 9$, $N_p = 1$, $N_t = 1$, $\sigma^2 = 0.01$, $w = 0.9$, and $\theta_p^2 \in \{0.1, 0.01, 0.0032, 0.00032\}$. As shown in both figures, the accuracy of the approximation is high enough for the approximated sum rate to be used as an objective function instead of the exact one. In detail, the approximated rates are very close to the exact values when signal distortion is less than 0.01, i.e., under a high effective SNR. Even when data (pilot) signal distortion is 0.1, the behavior of the approximated sum rate is very similar to that of the exact one with respect to pilot (data) signal distortion. It means that the optimal solution with the approximated objective function is well matched to the optimal solution with the exact objective function. The figures also show that the exact and approximated weighted sum rates are concave functions of θ_p^2 (θ_d^2) when θ_d^2 (θ_p^2) is fixed.

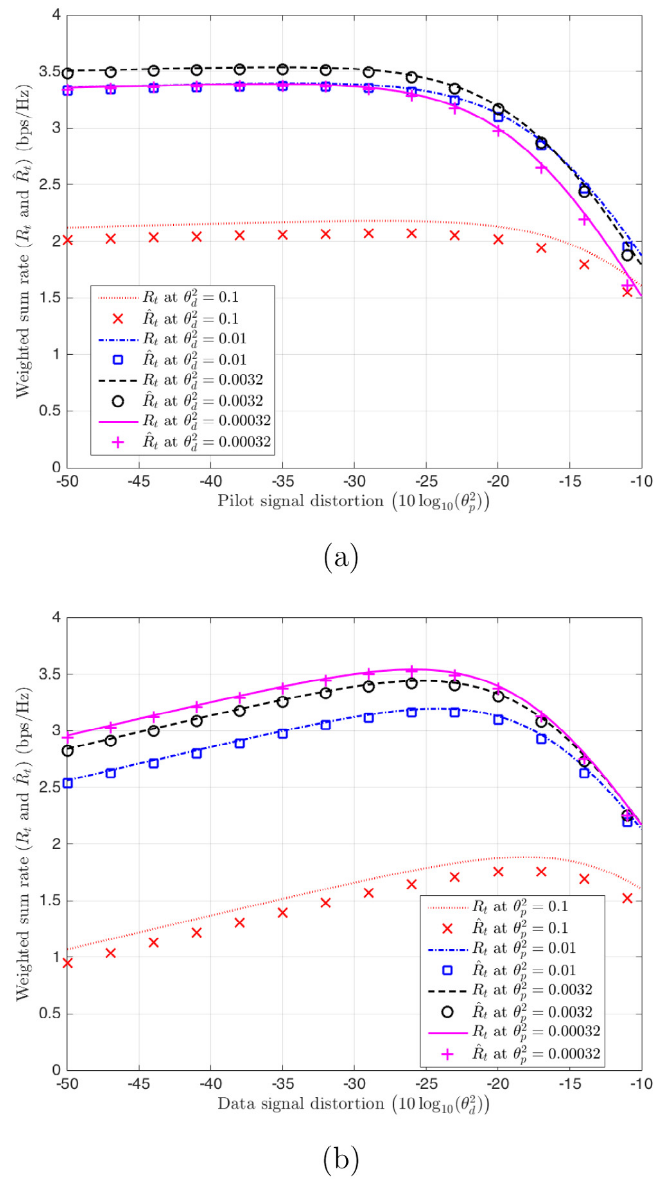

Fig. 3. Exact and approximated sum rate (R_t and $\hat{R}_t$), when $N_d = 9$, $N_p = 1$, $N_t = 10$, $\sigma^2 = 0.01$, and $w = 0.9$, with respect to (a) pilot signal distortion, θ_p^2, and (b) data signal distortion, θ_d^2.

Fig. 4 shows the exact weighted sum rate with respect to both data and pilot distortion variances. In the figure, the optimal distortion variances, obtained by exhaustive search, are also marked. When $N_d = 9$, $N_p = 1$, $N_t = 10$, $\sigma^2 = 0.01$, and $w = 0.9$, the optimal distortion variances are given by $10\log_{10}(\theta_p^{2*}) = -35.5$ dB and $10\log_{10}(\theta_d^{2*}) = -26$ dB. This figure can show that the closed-form solutions of (16) and (17) are identical to those of the numerical solutions in Fig. 4.

Fig. 5 shows the optimal distortion variances, θ_d^{2*} and θ_p^{2*}, and the corresponding maximum sum rate, $\hat{R}_t$, with respect to weight factor w when $N_p = 1$, $N_d = 9$, and $\sigma^2 = 0.01$. As weight factor w increases, uplink user throughput has priority over fronthaul throughput. Therefore, the increase in uplink throughput is more

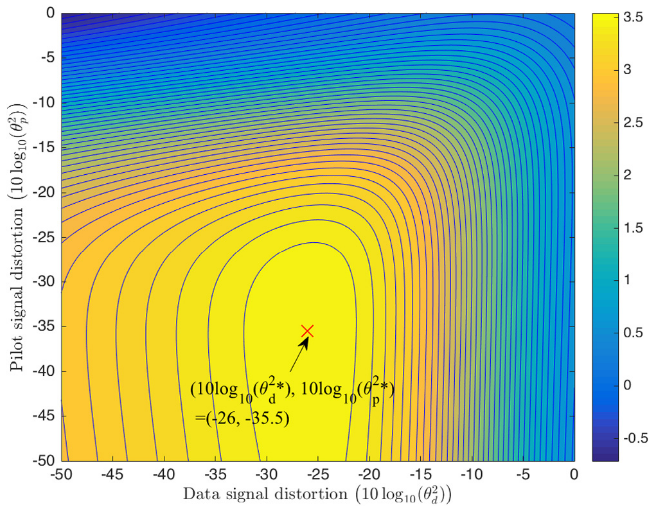

Fig. 4. Exact weighted sum (R_t) with respect to data- and pilot-signal distortions when $N_d = 9$, $N_p = 1$, $N_t = 10$, $\sigma^2 = 0.01$, and $w = 0.9$.

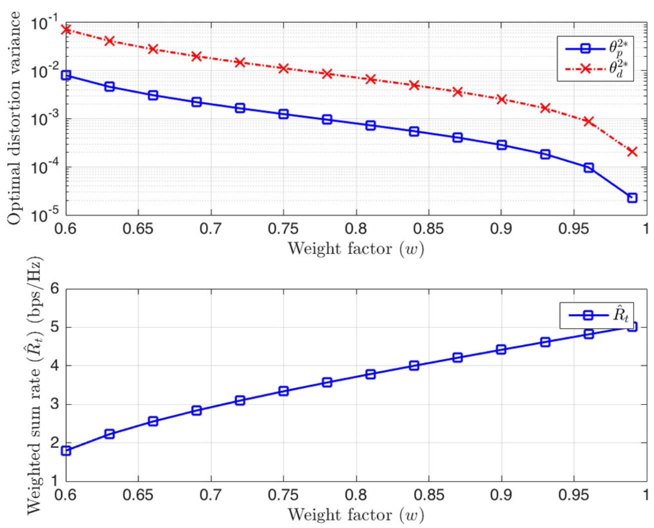

Fig. 5. Optimal distortion variances and weighted sum rate with respect to w when $N_d = 9$, $N_p = 1$, and $\sigma^2 = 0.01$.

important than the reduction of the fronthaul rate, even with a higher compression, i.e., a lower signal distortion.

In Fig. 6, θ_d^{2*}, θ_p^{2*}, and $\hat{R}_t$, with respect to N_d are shown when $N_p = 1$, $\sigma^2 = 0.01$, and $w = 0.9$. As expected from Corollary 2, θ_d^{2*} and θ_p^{2*} converge to 0.0025 and 0. Additionally, the ratio between θ_d^{2*} and θ_p^{2*} is given by N_d, as mentioned in Corollary 1. The weighted sum rate is an increasing function of N_d, because the increment in the uplink rate is more significant than the decrease in the fronthaul rate.

6. Conclusions

In an uplink C-RAN scenario where a CU and an RRH are connected via fronthaul that is not a dedicated link but a shared medium, a maximization problem for the weighted sum rate with respect to compression rate has been considered. More compression leads to higher distortion, i.e., additional noise, and a lower fronthaul rate, according to the rate–distortion theory. Minimization of the fronthaul rate, as well as maximization of the uplink rate, with respect to both data and signal distortions has been

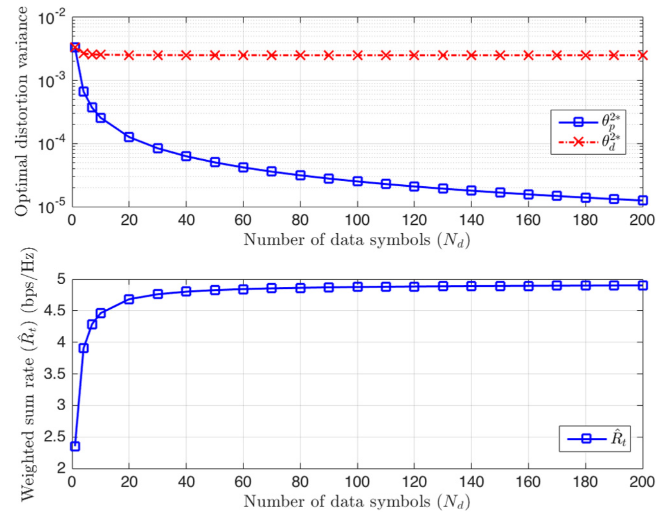

Fig. 6. Optimal distortion variances and weighted sum rate with respect to N_d when $N_p = 1$, $\sigma^2 = 0.01$, and $w = 0.9$.

formulated. The closed-form expressions for the optimal data- and pilot-signal distortion variances are derived, and their characteristics are investigated. As future work, frequency-selective and time-varying channel conditions with multiple antennas and multiple RRHs can be considered.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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