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

Heejung Yu [a], Taejoon Kim [b,*]

[a] Department of Electronics and Information Engineering, Korea University, 2511 Sejong-ro, Sejong 30019, Republic of Korea
[b] School of Information and Communication Engineering, Chungbuk National University, 1 Chungdae-ro, Seowon-Gu, Cheongju, Chungbuk 28644, Republic of Korea

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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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* Corresponding author.
E-mail addresses: heejungyu@korea.ac.kr (H. Yu), ktjcc@chungbuk.ac.kr (T. Kim).

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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.

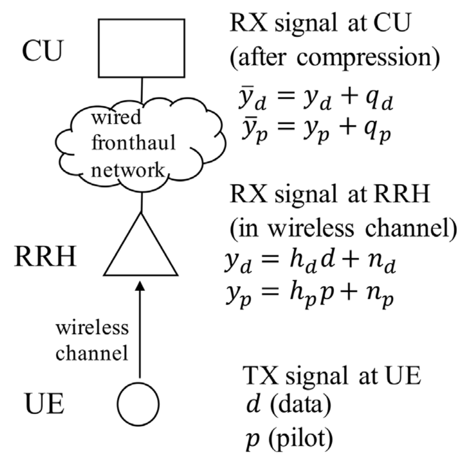

Fig. 1. Uplink system and signal models in C-RAN.

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