Uplink Transmission Scheme Based on Rateless Coding in Cloud-RAN

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Abstract. We consider a Cloud Radio Access Network (C-RAN) uplink system composed of single user, multiple remote radio heads (RRH) and baseband unit (BBU) pool. The user encodes the messages with rateless code which are then modulated and sent. Each RRH which covers the user quantizes the received signals and transfers them to the BBU pool through the high rate fronthaul link. The BBU pool applies belief propagation (BP) algorithm for joint decompression and decoding for the user information. In order to further improve the performance of the system, we resort to the extrinsic mutual information transfer (EXIT) analysis to optimize the degree profile of the rateless code. The numerical simulation shows that the BER performance of the proposed rateless coded scheme is close to the theoretical upper bound.

Keywords: Cloud Radio Access Network (C-RAN) · Rateless code
Extrinsic mutual information transfer (EXIT)

1 Introduction

With the rapid growth of mobile Internet, the next generation communication system will face a huge number of users and a huge amount of data transmission [1]. Under this situation, current Radio Access Network (RAN) has potential problems such as low quality of wireless coverage and a large number of sites leading to high energy consumption. For these problems, IBM and China mobile have proposed a new type of access network architecture: Cloud Radio Access Network (C-RAN) [2]. Compared with the traditional cellular networks, C-RAN network status and channel condition are more complex and changeable, and each user may access through multiple remote radio head (RRH) and interfere each other. During transmission, the RRHs via which the user accesses may also change. These characteristics bring challenge to the application of traditional fixed-rate channel coding (such as LDPC code, turbo code) in C-RAN. However, with rateless code [3] (such as LT code, Raptor code), the rate changes adaptively with the experienced channel. Moreover, the optimized rateless code can still approach the channel capacity even when the channel information is unknown to the transmitter [4]. In addition, the rateless code does not need to use hybrid automatic repeat request (HARQ) mechanism in the case of decoding failure. It

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can effectively alleviate the system loss caused by ACK\NACK signal feedback which is a severe problem in C-RAN due to the long fronthaul. Therefore, rateless code is suitable for C-RAN architecture naturally.

When each RRH is regarded as a relay, the C-RAN network has an internal relation with the relay systems. In [5], rateless coded transmission was considered and optimized for the three-node decode-and-forward relay system and the compress-and-forward relay system respectively. References [6–8] focused on the problem of resource allocation for the C-RAN network. The authors in [9, 10] studied the rateless coding in a two-way and multiple access relay network. The above works mainly focus on the rateless network coding design for multi-point coordination. Note that in these works, the relay has a complete set of baseband signal processing and decoding functions. It is not the case for the C-RAN system because the RRH in C-RAN does not have or has limited signal processing capability so that it is unable to implement complex signal processing and decoding. Besides, rateless codes with optimized degree profiles can also approach the channel capacity like the fixed rate channel code. Rateless coded transmission have been studied for various communication systems including wireless broadcast systems, relay systems and distributed antenna systems [11, 12].

This paper proposes a rateless coded uplink transmission scheme for the single user scenario in C-RAN. The user encodes the messages with rateless code which are then BPSK modulated and sent. Each RRH that covers the user preprocesses the received signal to obtain baseband signals. Then the RRH quantizes the baseband signals and transfers them to the BBU pool through the high rate link. The BBU pool applies belief propagation (BP) algorithm for joint decompression and decoding for the user information. In addition, we resort to the extrinsic mutual information transfer (EXIT) analysis to optimize the degree profile of the rateless code.

The remaining of this paper is organized as follows. In Sect. 2, we introduce the system model. In Sect. 3, we present the C-RAN uplink rateless coded transmission strategy. In Sect. 4, we optimize the output degree of the rateless code used at the user to improve the system performance and gives the numerical simulation. We conclude in Sect. 5.

2 System Model

As shown in Fig. 1, the C-RAN system consists of single user S, remote single-antenna radio frequency unit $RRH_j,\ j = 1, 2, \ldots, L$ and BBU pool. The channel gain of the link between user S and RRH_j is defined as $h_j, j = 1, 2, \ldots, L$ which is randomly distributed. The variance of Gaussian noise at each RRH is σ_0^2. The link SNR from user S to RRH_j is expressed as: $\gamma_j = \left|h_j\right|^2 P/\sigma_0^2$, where P is the transmit power of the user, and for simplicity we normalize it as $P = 1$.

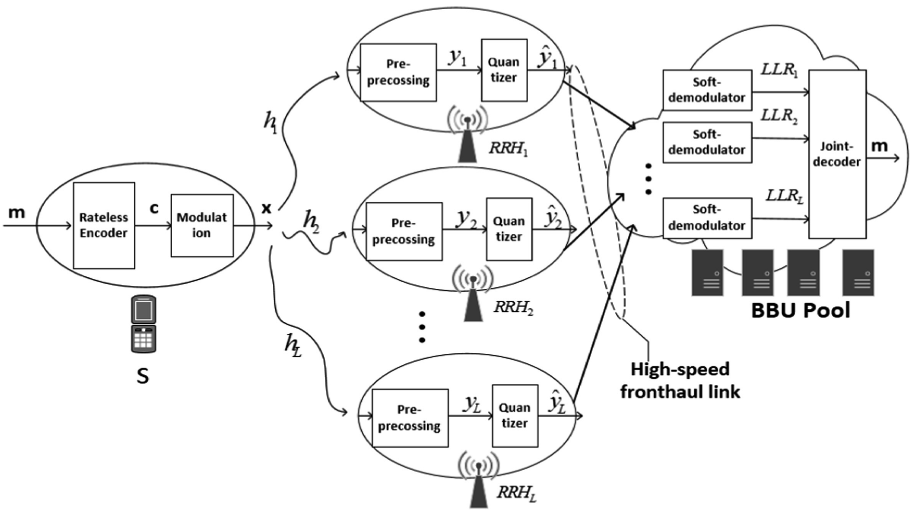

Fig. 1. The C-RAN single user uplink transmission system.

The Firstly, the user S encodes k bit message m to obtain rateless codeword $c[i], i = 1, \ldots, k$. Then it do modulation and send the modulated symbol $x[i], i = 1, \ldots, N$ to each RRH that covers the user. Each RRH pre-processes the received signal to obtain the baseband signal:

$$y_j[i] = h_j x[i] + n_j[i], j = 1, 2, \ldots, L \tag{1}$$

where $n_j[i]$ is Gaussian white noise at RRH_j. Next, the RRH quantizes the signal $y_j[i]$, and the quantized signal $\hat{y}_j[i]$ is transmitted to the BBU pool through the high rate fronthaul link. Then BBU performs joint decompression and demodulation on the receives signals from all the RRHs. Finally, the joint decoder applies belief propagation (BP) algorithm for joint decoding the user information. After successful decoding, the ACK signal is fed back by the RRH through the downlink to inform the user to stop sending the information.

3 Rateless Codes Uplink Transmission Scheme

3.1 Rateless Coding at User

The user encodes the information by Raptor code [3] and use LDPC code as its precoding. The message m passes through the LDPC encoder and LT encoder. The output of the LT encoder is derived by:

$$\Omega(x) = \sum_{d=1}^{d_c} \Omega_d x^d \tag{2}$$

where Ω_d denotes the probability that the output node with degree d appears in the output node, d_c denotes the maximum degree of the output node. For the output node with degree d, d bits are randomly and equally probabilistically selected from the input node for XOR operation, and the result of the operation is taken as the corresponding output bit value. Through the above encoding process, a steady stream of rateless codes c is generated. Next, rateless code adopts binary phase shift keying (BPSK) modulation, where bits 0 and 1 are mapped to +1 and −1 respectively. The user continuously sends the modulated signal x until the BBU pool recovers the user information correctly and feeds back the ACK signal.

3.2 Signal Quantization Scheme at RRH

The quantizer of RRH compresses the received signal to satisfy the forward link capacity requirement. In order to reduce the complexity, we use a scalar quantization compression algorithm. In addition, the quantization interval and threshold of quantizer at RRH are fixed and do not change during the transmissoin. This will further reduce RRH complexity. The RRH receives the signals sent by the user which are given by (for simplicity, we omitted the time subscript):

$$y = hx + n \tag{3}$$

The expectation of y (for the probability density space of channel gain h, signal x and noise n) is derived by:

$$E(y) = E(hx + n) = E(h) \cdot E(x) + E(n) = 0 \tag{4}$$

The variance of y is derived as:

$$D(y) = E(y^2) - (E(y))^2 = E(h^2x^2) + 2E(hx) + E(n^2) = 2\sigma_h^2 + \sigma_0^2 \tag{5}$$

where σ_h^2 is the variance of the channel gain coefficient. According to the $''3\sigma''$ criterion [13], it can be considered that almost all the values of y are distributed in the interval $(-3\sqrt{D(y)}, +3\sqrt{D(y)})$. Let the quantizer uses b-bit quantization, then the number of quantization levels satisfies $2M = 2^b$. We use the uniform quantization, through the following rules:

$$\hat{y} = Q(y) = \begin{cases} q_{-M} & -\infty < y < (-M+1)\Delta \\ q_k & k < 0\text{时}\mathrm{k}\Delta < y < (k+1)\Delta, k > 0\text{时（k}-1\text{）}\Delta \le y < k\Delta \\ q_M & (M-1)\Delta \le y < \infty \end{cases} \tag{6}$$

to quantify y into a quantized signal $\hat{y}$. Where $\Delta = \frac{3\sqrt{D(y)}}{M}$ is the quantization interval and $q_k = \left(j - \frac{\mathrm{sgn}(j)}{2}\right)\Delta$, $k = \pm1, \pm2, \ldots, \pm M$ is the quantized value.

3.3 Iterative Decoding at BBU Pool

The BBU pool first performs soft decompression and demodulation on the quantized signals sent by the RRH before iterative decoding. For the rateless code, the ith coding bit $c[i]$ is made of 0 or 1 equiprobably. Assuming that the quantized signal which the jth RRH uploads to the BBU pool is $\hat{y}_j[i] = q_k$, then the corresponding Log Likelihood Ratio (LLR) is:

$$LLR_j[i] = \ln \frac{\Pr(\hat{y}_j[i] = q_k | c[i] = 0)}{\Pr(\hat{y}_j[i] = q_k | c[i] = 1)}, j = 1, 2, \ldots, L \tag{7}$$

The LLR of the i th bits when considering the compressed signals from all RRHs is given by:

$$LLR[i] = \ln \frac{\Pr(\hat{y}_1[i], \hat{y}_2[i], .., \hat{y}_L[i] | c[i] = 0)}{\Pr(\hat{y}_1[i], \hat{y}_2[i], .., \hat{y}_L[i] | c[i] = 1)} = \sum_{j=1}^{L} \ln \frac{\frac{1}{2}\int_{\Delta_k} \frac{1}{\sqrt{2\pi\sigma_0^2}} e^{-\frac{(x-h_j)^2}{2\sigma_0^2}} dx}{\frac{1}{2}\int_{\Delta_k} \frac{1}{\sqrt{2\pi\sigma_0^2}} e^{-\frac{(x+h_j)^2}{2\sigma_0^2}} dx},$$
$$k \in \{-M, \ldots, M\} = \sum_{j=1}^{L} LLR_j[i] \tag{8}$$

where Δ_k is the quantization interval corresponding to the quantization level q_k, σ_0^2 is the Gaussian noise variance at each RRH, and h_j is the link channel gain.

Next, the BBU performs iterative decoding using the LLRs given in (8). Using BP decoding algorithm [14] based on Factor diagram, the decoding process is divided into two steps. The first step, as shown in Fig. 2, is to perform decoding iterations over the entire graph. The message updates sequence between input nodes and output nodes are: from the input node to the LDPC check node, then the LDPC check node returns the input node, then from the input node to the output node, and finally returns the input node. In details, the message passing process is as follows (in the lth iteration): The message sent from input node i to LDPC check node c is:

$$m_{ic}^{(l)} = \sum_{o} m_{oi}^{(l-1)} \tag{9}$$

where $m_{oi}^{(l-1)}$ is the input node i connected to the output node o in the previous round of transmission to the input node message. LDPC check node c back to the input node messages is:

$$\tanh\left(\frac{m_{ci}^{(l)}}{2}\right) = \prod_{i' \neq i} \tanh\left(\frac{m_{i'c}^{(l)}}{2}\right) \tag{10}$$

where $i'c$ is the input node connected to the LDPC check node c (except i). Then, the message from input node i to output node o is:

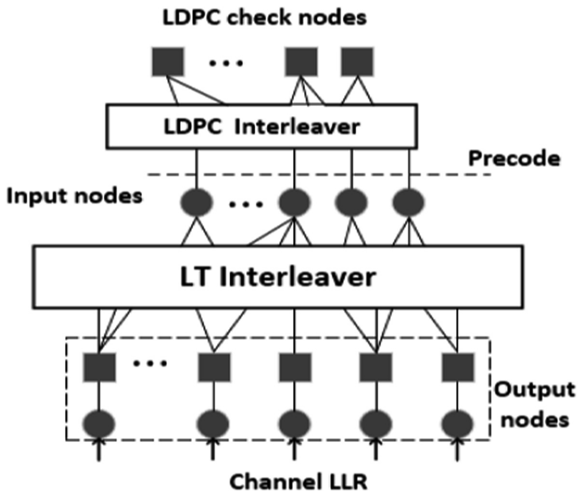

Fig. 2. The Raptor code decoding Factor graph.

$$m_{io}^{(l)} = \sum_{o' \neq o} m_{o'i}^{(l-1)} + \sum_{c} m_{ci}^{(l)} \tag{11}$$

where $m_{o'i}^{(l-1)}$ is the message that the output node (except o) connected to input node i transmitted to the input node in the previous round, $m_{ci}^{(l)}$ is the message transmitted from LDPC check node c to input node i. Finally, the message which the output node o return back to the input node i can be expressed as:

$$\tanh\left(\frac{m_{oi}^{(l)}}{2}\right) = \tanh\left(\frac{Z_o}{2}\right) \prod_{i' \neq i} \tanh\left(\frac{m_{i'o}^{(l)}}{2}\right) \tag{12}$$

where $m_{oi}^{(l)}$ is the message transmitted by the output node o to the input node i in the iteration l, $m_{i'o}^{(l)}$ is the message sent by input node i to output node o in iteration l, Z_o is the channel LLR calculated by Eq. (7) based on the quantized value of the corresponding bit at the output node. After each round of iteration, the LLR of the input node is updated as:

$$m_{i}^{(l)} = \sum_{o} m_{oi}^{(l)} \tag{13}$$

When the mean value of the input node LLR (or equivalently, the corresponding amount of external information) exceeds a certain threshold, the second step of joint coding is performed.

3.4 Degree Profile Optimization

To further improve the performance of the rateless coded scheme, the degree profile in Eq. (2) deployed at the user is optimized. We resort to extrinsic information transfer (EXIT) analysis to do the optimization. Explicitly, we maximize the achievable rate under the constraint that the average extrinsic information transferred from the input nodes to the output nodes increases for each iteration until it reaches a threshold during the decoding. The detailed degree profile optimization procedure is not given here due to the limited space, for which the readers can refer to [9].

4 Numerical Simulation

4.1 Theoretically Achievable Rates

We use the case that the RRH does not quantify the signal, and directly transmitting the baseband signal (3) to the BBU pool as theoretical upper bound. It is easy to prove that when the quantization interval of RRH tends to 0 and the quantization threshold tends to be infinite, the LLR combination (8) of the BBU pool is equivalent to the maximum ratio combination. Therefore, the BBU pool receives the SNR as:

$$\gamma_{MRC} = \frac{P(\sum_{j=1}^{L} |h_j|^2/\sigma_0^2)^2}{E\left[\left|\sum_{j=1}^{L} (h_j^*/\sigma_0^2)n_j\right|^2\right]} = \frac{P(\sum_{j=1}^{L} |h_j|^2/\sigma_0^2)^2}{\sum_{j=1}^{L} |h_j|^2/\sigma_0^2} = \sum_{j=1}^{L} \gamma_j \tag{14}$$

When the RRH is not quantized, the theoretical channel capacity of C-RAN single-user uplink system is C. Due to BPSK modulation, the theoretical capacity of binary input symmetric Gaussian channel with a SNR of γ_{MRC} [15] can be derived as follows:

$$C(\gamma_{MRC}) = 1 - \frac{1}{2\sqrt{2\pi\gamma_{MRC}}}\int_{-\infty}^{\infty} \log_2(1+e^{-x}) \cdot e^{-\frac{(x-2\gamma_{MRC})^2}{8\gamma_{MRC}}} dx \tag{15}$$

which is the theoretical upper bound of the studied C-RAN system.

4.2 BER Performance of the System

We consider a scenario with single user and two RRHs. The user uses the LDPC code with a rate of 0.95 and a length of 10000 as a pre-coding of the rateless code. The correct decoding threshold of LDPC code is $x_u^{th} = 0.9818$. Let the noise variance at each RRH be $\sigma_0^2 = 1.4^2$. The channel fading coefficients of the users S to RRH_1 and RRH_2 are respectively $h_1 = 0.7$ and $h_2 = 1.1$. The decoding overhead is defined as:

$$overhead = \frac{C \cdot N}{k} - 1 \tag{16}$$

where C is the theoretical channel capacity of the uplink system given by Eq. (15), N is the actual transmitted code length when decoding is successful, and k is the user original information length. According to the EXIT analysis in article [9], we optimize the user's rateless code degree profile $\Omega(x)$ in Gaussian channels. The optimized degree profile $\Omega_{opt}(x)$ is given in the following:

$$\Omega_1 = 0.004715, \Omega_2 = 0.436706, \Omega_3 = 0.272642, \Omega_6 = 0.127585, \Omega_7 = 0.085293,$$
$$\Omega_{19} = 0.055493, \Omega_{20} = 0.011292, \Omega_{60} = 0.006274;$$

As a benchmark, we use the optimized degree profile for BEC given in [15]. Under different overhead, we compare the system BER achieved by degree profile $\Omega_{BEC}(x)$ and degree profile $\Omega_{opt}(x)$ respectively. Simulation results are shown in Fig. 3. It can be seen from that when the RRH applies 4-bit quantization, the degree profile $\Omega_{opt}(x)$ is about 5% better than the degree profile $\Omega_{BEC}(x)$. With 8-bit quantization, the degree profile $\Omega_{opt}(x)$ is about 3% better than the degree profile $\Omega_{BEC}(x)$ and about 4% better than the degree profile $\Omega_{opt}(x)$ with 4-bit quantization. When the RRH is quantized with 10-bits, the performance of the degree profile $\Omega_{opt}(x)$ tends to be the same as when using the 8-bit quantization, and the overhead is only about 11% more than the theoretical limit under the assumption of no signal compression at the RRH.

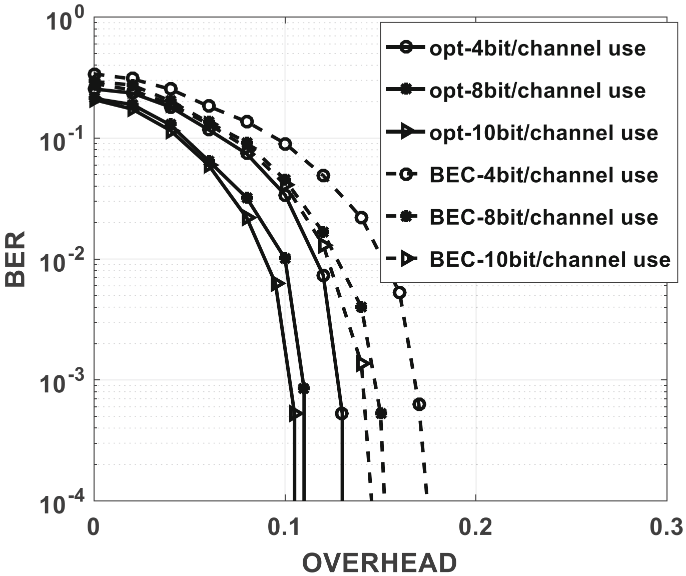

Fig. 3. System BER with different output degree profiles.

5 Conclusion

This paper mainly studies the transmission scheme based on rateless code in single-user uplink access scenario in C-RAN. A scalar quantization algorithm with lower complexity at RRH and a joint decompression, demodulation and decoding algorithm at BBU pool are designed. In order to further improve the performance, we optimized the degree profile based on the EXIT analysis for the rateless code. The simulation results show that the optimized is better than the BEC degree profile in bit error rate and its performance is close to the theoretical limit.

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