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JOINT ENERGY AND MUTUAL INFORMATION ACCUMULATION FOR COOPERATIVE MULTI-RELAY HIGH-SPEED RAILWAY MOBILE COMMUNICATION SYSTEM WITH FOUNTAIN CODES

[1]XIAOFEI DI, [2*]KE XIONG, [3]YU ZHANG, [4]DANDAN LI, [5]ZHENGDING QIU

[1,3,4]School of Computer and Information Technology, Beijing Jiaotong University, Beijing, China

[2]Asstt Prof., School of Computer and Information Technology, Beijing Jiaotong University, Beijing, China

[5]Prof., School of Computer and Information Technology, Beijing Jiaotong University, Beijing, China

E-mail: [1]xiaofeidi.bjtu@gmail.com, [2]kxiong@tsinghua.edu.cn

ABSTRACT

In this paper, we investigate how to design effective strategy to improve the transmission data rate for high-speed railway mobile communication system with fountain codes. We consider a cooperative multi-relay architecture, where each relay is equipped with one antenna and the destination is with multiple antennas deployed. To this end, a new information receiving method at the destination is proposed, which combines the energy accumulation and mutual information accumulation together. To evaluate the performance of the proposed method, we derive the probability density function of the transmission rate in Rayleigh fading channels, and based on this, we give the average transmission rate of our method. Since the considered multi-relay architecture with multi-antenna destination can be regarded as a virtual MIMO system, we compare our proposed information receiving method with traditional MIMO detection in terms of transmission rate. Numerical results show that our method achieves higher transmission rate than using traditional MIMO information detection in multi-path fading channels. This work also gives some insights that the proposed information receiving method on the basis of multi-relay multi-antenna architecture with fountain codes has great potential in improving the system performance of high-speed railway mobile communications.

Keywords: *Fountain Codes, Cooperative Multi-Relaying, Energy Accumulation, Mutual Information Accumulation*

1. INTRODUCTION

In recent years, the high-speed railway in China has attracted much attention and it has stepped into a new era with rapid development. In the meantime, the high-speed railway mobile communication system is required to provide broadband service for railway managers and passengers on the train. However, high mobility of trains raises some new problems and challenges to the communication between the base station and the running train, which is also referred as the train-ground communication. Firstly, high mobility of trains results in a very fast time varying channel for the train-ground communication, so it is impossible for the receiver to precisely track, to capture and to estimate the instantaneous channel state information (CSI), and then to feed it back to its transmitter in real-time. Secondly, Doppler Effect caused by high mobility leads to severe inter-carrier interference, which remarkably deteriorates the information receiving performance and then leads to very poor communication quality. Thirdly, compared with low-speed mobile scenarios, multipath fading becomes much worse in high-speed mobile scenarios, because in high mobility scenarios, wireless channels often experience more sophisticated space effect within a very short time. Just because of these problems mentioned above, it is difficult to attain reliable train-ground communications, consequently, resulting in very low spectral efficiency. In order to provide higher transmission rate with good reliability for high-speed railway mobile communication system, new technologies have to be explored. Very recently, some works have begun to respectively introduce fountain codes and cooperative relay into high-mobility systems, e.g., see [1] and [2].

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Fountain codes [3], also referred as rateless codes, have attracted much attention and been studied widely. It's shown that fountain codes have good performance in various channels, including erasure channels, AWGN channels, and Rayleigh-fading channels. Due to their following advantages, fountain codes are considered to have huge potential to be applied in high-speed railway mobile communication system. Firstly, in fountain codes, the transmitter does not need to know CSI, so they adapt to the fast time-varying fading characteristic of high-speed mobile channels, where the receiver is hard to acquire and feed CSI back to its transmitter. Secondly, the rateless property of fountain codes, by which the transmitter can generate infinitely long code-stream of the source data, makes it easier for the receiver to successfully decode and recover the information transmitted from its source by accumulating mutual information. Once the total mutual information is accumulated from any received subset of the code-stream marginally exceeds the entropy of the source information, the successful decoding can be achieved. Thirdly, fountain codes need little feedback, only when the receiver has successfully decoded data, it sends one bit to notify the transmitter that the current information has been successfully decoded and it can transmit new information.

As for cooperative relay, it has been widely explored for increasing the capacity and decreasing the outage probability of wireless networks. In cooperative relaying system, relays process the received data from their sources and then forward them to the destinations by using some relaying protocols (e.g., decode-and forward (DF) and amplify-and forward (AF)), so that the destinations can receive several signal samples of each data. By using some advanced information combing methods, cooperative diversity gains can be achieved.

In order to improve the quality of wireless communication in fading channels, recently, some new results on combining fountain codes into cooperative relaying systems can be found in the literatures, see e.g., [4] [5]. In [4], a novel coding framework based on rateless codes for wireless relay channels was presented and it was shown that theoretical rate limits can be approached across a wide variety of channels. Authors in [5] studied the performance of the fountain codes in multi-relay cooperative networks, where the rateless property of fountain codes was fully utilized and the DF cooperative protocol was employed. A mutual

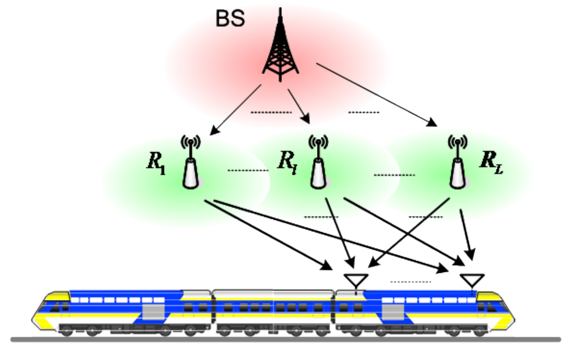

Fig. 1. System Model

information accumulation (IA) method was also proposed in their work, which was very different from conventional energy accumulation (EA) methods [6]-[8], including maximum ratio combining (MRC), equal gain combining (EGC) and selection combining (SC), etc. In the conventional EA method, all relays use the same fountain code, that is, repetition code, and to re-encode and transmit, so the destination can combine the received signals by MRC, while in the IA method, each relay uses different and independent fountain code and orthogonal channel respectively, so the destination can separate each relay's information and then decode and recover the information by accumulating mutual information of all relays. The performance of IA and EA was compared in [5] [9], where it was shown that IA method outperforms EA method in many aspects, such as the mean transmission time, the transmission rate and energy expenditure.

In this work, we also consider the multi-relay cooperative architecture with fountain codes, and we aim to use it to improve the train-ground transmission data rate for high-speed railway mobile communication systems. To this end, we propose a mixed information receiving method by jointly combining the IA and EA, which can remarkably improves the transmission rate.

Our contributions are summarized as follows: (1) We present the multi-relay cooperative architecture and the mixed information receiving method. (2) We analyze the information receiving method, and derive the probability density function of the transmission rate in Rayleigh fading channels, and based on which, obtain the average transmission rate. (3) The considered multi-relay architecture with multi-antenna destination can be regarded as a virtual MIMO system. We compare the transmission rate of our proposed information receiving method with that of the MIMO channel. Numerical results show that our method achieves

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higher average transmission rate than using traditional MIMO detection method in multi-path fading channels.

The rest of the paper is organized as follows: In section II, the system model is presented and the new information receiving method is introduced. In Section III, the performance of the information receiving method is analyzed in term of average transmission rate. The transmission rates of this virtual MIMO system and the general MIMO channel are compared in section IV. Finally, conclusions are drawn in section V.

2. SYSTEM MODEL

We consider a train-ground communication model as shown in Fig. 1 consisting of a base station (BS, source), L relays denoted as R_1, R_2, …, R_L, and a high speed train (destination). The source wishes to transmit data to a destination via the L relays. Relays are placed closely to BS so as that relays can rapidly and correctly acquire BS's data and then spatial diversity can be constructed and fully used. The source and each of relays are only deployed with one antenna respectively while the destination is equipped with N antennas.

We assume that there is no direct link between the source and the destination, and all information transmitted from the source to the destination must be forwarded by the relays. Half duplex constraint is considered so that each node cannot transmit and receive signals at the same time. Decode-and-forward (DF) relaying protocol is deployed at the relay node. It is also assumed that only the receivers know channel state information (CSI) while the senders don't know the CSI. All relays are allocated with equal transmission power. Moreover, suppose that the inter-carrier interference caused Doppler Effect can be perfectly eliminated by using some advanced technologies, see e.g., [10] [11], so the effect of Doppler Shift is not considered in our work. As mentioned previously, multipath fading is a severe problem in high mobility scenario, so all the channels are modeled as Rayleigh fading channels.

Then, our designed transmission protocol can be described as follows. At first the source segments its data into k packets with equal length, and then all data are transmitted packet by packet over the wireless links. Then the transmission process of each packet is divided into two phases: the source transmission phase and relay transmission phase.

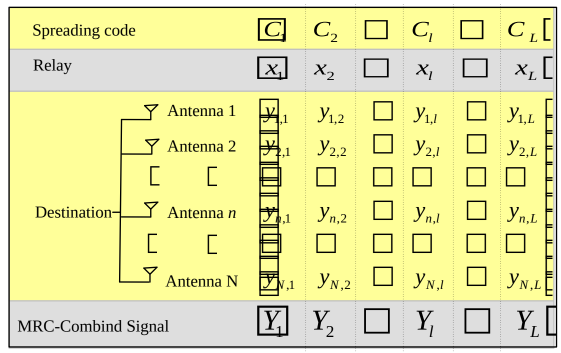

Fig. 2. The Relay Transmission Protocol And Signal Model.

In the source transmission phase, the source encodes an original packet to infinitely symbols with fountain codes and broadcasts the coded symbols to the relays. All the relays collect the transmitted symbols from the source. Compared with the channels between the relays and the receiver on the train, the quality of the channels between the BS and the relays may be much better. Moreover, since we place the relays closely to the BS, the channels between the BS and the relays can be regarded as good enough for the relays to successfully and correctly decode and recover the original packets. So, in this paper, we assume that the transmissions from the source to the relays are always successful. Once all relays successfully decode the original data, the transmission will step into the relay transmission phase.

In the relay transmission phase, the relays re-encode the original data with a different and independent fountain code respectively and then send infinitely coded symbols to the destination. In addition, the relays are required to use a group of orthogonal channels to transmit in order that the destination can separate their information. DS-CDMA technology is adopted to acquire the ground of orthogonal channels. The orthogonality of spreading codes is assumed to be guaranteed and thus interference problem is avoided.

The relay transmission protocol and signal model are shown in Fig. 2, where each column shows the communication between a relay and the destination. Each relay uses its spreading code to send its fountain-coded symbols, for example, the relay R_l sends coded symbol x_l with spreading code C_l.

The received signal on the n-th antenna of destination can be expressed as

$$y_n = \sum_{l=1}^{L} \sqrt{P_l}\, h_{l,n} x_l + z_n ,$$

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where x_l is the transmitted coded symbol by the relay R_l with unit power constraint, $h_{l,n}$ is channel coefficient between the l-th relay node and the n-th antenna of the destination, P_l is the transmission power of the l-th relay, and the additive white Gaussian noise (AWGN) z_n at each antenna of destination has the same variance N_0 for simplicity.

Based on the orthogonality of spreading codes, each antenna of the destination despreads and separates L signals of the relays from the received signal, for example, antenna n can obtain signals $[y_{n,1}, y_{n,2}, ..., y_{n,L}]$ of L relays from y_n. And then the destination respectively combines the separated signals of each relay by MRC method and stores the combined signal, for example, the destination can combine N signals $[y_{1,l}, y_{2,l}, ..., y_{N,l}]^T$ of l-th relay by MRC and then store the combined signal Y_l. The process can be seen in Fig. 2.

One can find that after each relay sends a symbol, the destination will store L MRC-combined symbols $[Y_1, Y_2, \cdots, Y_l, \cdots, Y_L]$ into its buffer. Because these relays use a different and independent fountain code respectively to encode the packet and thus each coded symbol from these relays contains independent mutual information, the destination can accumulate the mutual information by IA method in order to decode and recover the data. Due to the rateless property, the destination can continually accumulate mutual information. Until the destination successfully decodes the source's information by using the buffered symbols, it sends an **acknowledgment** to the relays and the relays inform the source to transmit the next packet. Since the destination jointly uses maximum ratio combining (a kind of EA) and IA to recover the original information, we call the proposed method as a mixed information receiving method.

3. PERFORMANCE ANALYSIS

In this section, we analyses the performance of the proposed mixed information receiving method which is measured as the average transmission rate $\bar{r}$ of the destination. The average transmission rate $\bar{r}$ can be expressed as

$$\bar{r} = \int_0^\infty r \cdot f_r(r)dr ,$$

where $f_r(r)$ is the probability density function (pdf) of transmission rate r. Obviously, to obtain average transmission rate $\bar{r}$, we only need to compute $f_r(r)$. In the following, we will derive the expression of $f_r(r)$.

For obtaining the expression of $f_r(r)$, firstly a simple special case is considered, in which the destination and all relays are only deployed with one antenna respectively. In this simple case, we know the transmission rate of EA (MRC) (Nat/s/Hz) is given as

$$r = \ln(1+\sum_l g_l) ,$$

where g_l is the channel gain between the i-relay and the destination. Here due to the summation of the channel gains, it is so-called energy accumulation. And the transmission rate of IA is given as

$$r = \sum_l \ln(1+g_l) ,$$

where the mutual information from the L relays is added, so it is so-called mutual information accumulation.

The two transmission rates in this simple case have been studied in many literatures [5] [9] and results show the transmission rate of IA is higher than EA. In the following work, we study the case that the destination is equipped with multiple antennas.

When the multi-antenna destination is deployed, according to the description of the proposed mixed information receiving method, the transmission rate of the mixed information receiving method (Nat/s/Hz) can be expressed as

$$r = \sum_{l=1}^{L} \ln(1+\sum_{n=1}^{N} g_{l,n}) , \qquad (1.1)$$

where $g_{l,n} = |h_{l,n}|^2 P_l / N_0$ is the channel gain between the l-th relay node and the n-th antenna of the destination. Here due to the orthogonality of spreading codes, interference part is ignored. By defining $SNR_l = \sum_{n=1}^{N} g_{l,n}$, (1.1) can be rewritten as

$$r = \sum_{l=1}^{L} \ln(1+SNR_l) , \qquad (1.2)$$

obviously, SNR_l is the MRC-combined signal-to-noise ratio of the separated signals which N antennas at the destination receive from the l-th relay.

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Since the channels are assumed to be Rayleigh-distributed, the channel gain $\gamma_{l,n}$ between the l-th relay node and the n-th antenna of the destination must be exponential random variable and its probability density function (pdf) is

$$f_{\gamma_{l,n}}(\gamma)=\frac{1}{\overline{\gamma_{l,n}}}\exp(-\gamma/\overline{\gamma_{l,n}}), \quad \text{for } \gamma \ge 0,$$

where $\overline{\gamma_{l,n}}$ is the mean channel gain between the l-th relay node and the n-th antenna of the destination.

Because the probability density function (pdf) of $\gamma_{l,n}$ is exponentially distributed and all $\gamma_{l,n}$ are assumed to be independent, the pdf of the transmission rate r can be computed by using equation (1.1).

To obtain the pdf of the rate r, we first consider MRC-combined signal-to-noise ratio SNR_l in equation (1.2). Since SNR_l is the result of maximum ratio combining, the probability density function (pdf) of SNR_l is known. Then the pdf of the rate r can be calculated.

In the following, we consider two channel cases, one case is that all channels are of equal mean channel gains, and the other case is that channels are of different mean channel gains, because the pdf of SNR_l in the two cases is different.

A. Equal mean channel gains (EMG)

In this case, all channel gains between relays and destination are equal and are assumed to be independent, so all channels are independent and identical distributed (i.i.d), and the pdf of SNR_l is given as in [5]

$$f_{SNR_l}(\gamma)=\frac{1}{(L-1)!}\frac{\gamma^{L-1}}{\overline{\gamma_{l,n}}}\exp\left(-\frac{\gamma}{\overline{\gamma_{l,n}}}\right), \quad \text{for } \gamma \ge 0.$$

Let $r_l = \ln(1+SNR_l)$, the pdf of r_l is easily computed as

$$f_{r_l}(r)=\frac{1}{(L-1)!}\frac{(e^r-1)^{L-1}}{\overline{\gamma_{l,n}}}\exp\left(-\frac{e^r-1}{\overline{\gamma_{l,n}}}+r\right), \quad \text{for } r \ge 0.$$

Due to all paths from relays to destination are independent, all r_l ($l = 1, 2, \ldots, L$) are also independent. The sum of the independent random variables $r=\sum_{l=1}^{L} r_l$ is easily computed via its Characteristic Function (CF), which is defined as the Fourier transform of the pdf.

Firstly, the characteristic function expression of r_l can be calculated as

$$\begin{aligned}M(j\omega)&=\frac{1}{(L-1)!}\sum_{i=0}^{L-1}C_{L-1}^{i}(-1)^{L-i-1}\overline{\gamma_{l,n}}^{\,i-j\omega}\Gamma(i-j\omega+1,1/\overline{\gamma_{l,n}})\\&=\sum_{i=0}^{L-1}\frac{(-1)^{L-i-1}}{i!(L-i-1)!}\overline{\gamma_{l,n}}^{\,i-j\omega}\Gamma(i-j\omega+1,1/\overline{\gamma_{l,n}}),\end{aligned}$$

where $\Gamma(a,x)=\int_x^{\infty}e^{-t}t^{a-1}dt$ is the incomplete Gamma function.In computation process, the binomial theorem is used to transform integral operation to definite summation operation.

Then according to the property of CF, the CF expression of r is given by

$$M(j\omega)=\prod_{l=1}^{L}\left[\sum_{i=0}^{L-1}\frac{(-1)^{L-i-1}}{i!(L-i-1)!}\overline{\gamma_{l,n}}^{\,i-j\omega}\Gamma(i-j\omega+1,1/\overline{\gamma_{l,n}})\right]. \quad (2)$$

From this equation, using Inverse Fourier transform, lastly we derive the pdf of the transmission rate r as

$$\begin{aligned}f_r(r)&=\frac{1}{2\pi}\int_{-\infty}^{+\infty}e^{j\omega r}M(j\omega)d\omega\\&=\frac{1}{2\pi}\int_{-\infty}^{+\infty}e^{j\omega r}\prod_{l=1}^{L}\left[\sum_{i=0}^{L-1}\frac{(-1)^{L-i-1}}{i!(L-i-1)!}\overline{\gamma_{l,n}}^{\,i-j\omega}\Gamma(i-j\omega+1,1/\overline{\gamma_{l,n}})\right]d\omega.\end{aligned} \quad (3)$$

Then, the average transmission rate $\bar{r}_{EMG}$ of the equal mean channel gain case can be calculated by

$$\bar{r}_{EMG}=\int_0^{\infty}r\cdot f_r(r)dr.$$

B. Different mean channel gains (DMG)

In this case, all channels between relays and destination are with different mean channel gains, but independently distributed. Thus, according to the result in [5], the pdf of SNR_l can be given by

$$f_{SNR_l}(\gamma)=\frac{1}{\prod_{n=1}^{N}\overline{\gamma_{l,n}}}\sum_{n=1}^{N}\frac{\exp(-\gamma/\overline{\gamma_{l,n}})}{\prod_{k\ne n}\left[\frac{1}{\overline{\gamma_{l,k}}}-\frac{1}{\overline{\gamma_{l,n}}}\right]} \quad \text{for } \gamma \ge 0.$$

Now, let us discuss the pdf of the transmission rate r for DMG case as follows. To do so, we use the similar method in section A.

Since $r_l = \ln(1+SNR_l)$, then we can derive the pdf expression of r_l as

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$$f_{r_l}(r)=\frac{1}{\prod_{n=1}^{N}\bar{g}_{l,n}}\sum_{n=1}^{N}\frac{\exp(-(e^{r}-1)/\bar{g}_{l,n}+r)}{\prod_{k\neq n}\left[\frac{1}{\bar{g}_{l,k}}-\frac{1}{\bar{g}_{l,n}}\right]},\quad \text{for } r\geq 0 .$$

Then we obtain CF expression of r_l

$$M(j\omega)=\frac{1}{\prod_{n=1}^{N}\bar{g}_{l,n}}\sum_{n=1}^{N}\frac{\left[\frac{1}{\bar{g}_{l,n}}\right]^{j\omega-1}\exp\left[\frac{1}{\bar{g}_{l,n}}\right]\Gamma(1-j\omega,1/\bar{g}_{l,n})}{\prod_{k\neq n}\left[\frac{1}{\bar{g}_{l,k}}-\frac{1}{\bar{g}_{l,n}}\right]}$$

Then the CF expression of $r=\sum_{l=1}^{L}r_l$ can be given as

$$M(j\omega)=\prod_{l=1}^{L}\left[\frac{1}{\prod_{n=1}^{N}\bar{\lambda}_{l,n}}\sum_{n=1}^{N}\frac{\left[\frac{1}{\bar{g}_{l,n}}\right]^{j\omega-1}\exp\left[\frac{1}{\bar{g}_{l,n}}\right]\Gamma(1-j\omega,1/\bar{g}_{l,n})}{\prod_{k\neq n}\left[\frac{1}{\bar{g}_{l,k}}-\frac{1}{\bar{g}_{l,n}}\right]}\right]. \quad (4)$$

At last, using (4) and Inverse Fourier transform, the pdf of transmission rate r can be calculated by

$$f_r(r)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}e^{j\omega r}\prod_{l=1}^{L}\left[\frac{1}{\prod_{n=1}^{N}\bar{\lambda}_{l,n}}\sum_{n=1}^{N}\frac{\left[\frac{1}{\bar{g}_{l,n}}\right]^{j\omega-1}\exp\left[\frac{1}{\bar{g}_{l,n}}\right]\Gamma(1-j\omega,1/\bar{g}_{l,n})}{\prod_{k\neq n}\left[\frac{1}{\bar{g}_{l,k}}-\frac{1}{\bar{g}_{l,n}}\right]}\right]d\omega .$$

So the average transmission rate $\bar{r}_{DMG}$ of the different mean channel gain case can be deduced in terms of

$$\bar{r}_{DMG}=\int_{0}^{\infty}r\cdot f_r(r)dr .$$

4. NUMERICAL RESULTS AND DISCUSSIONS

This section will present some numerical results to show the performance of our proposed scheme. Since the system architecture considered in this paper, which consists of multiple single-antenna relays and a multi-antenna destination, can be regarded as a virtual MIMO system, thus we can use the information receiving performance of MIMO detection as a benchmark to show the performance of our proposed joint EA and IA information receiving method.

The well-known instantaneous channel capacity (Nats/s/Hz) of $n_r\times n_t$ MIMO system is

$$C=\sum_{i=1}^{n_{\min}}\ln\left(1+\frac{P_i\lambda_i^{2}}{N_0}\right),$$

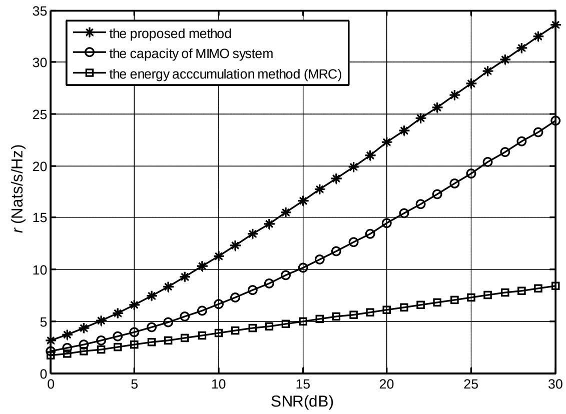

Fig. 3. Transmission Rate R Vs. SNR With The Number Of Relays L=5 And The Number Of Antennas At The Destination N=5.

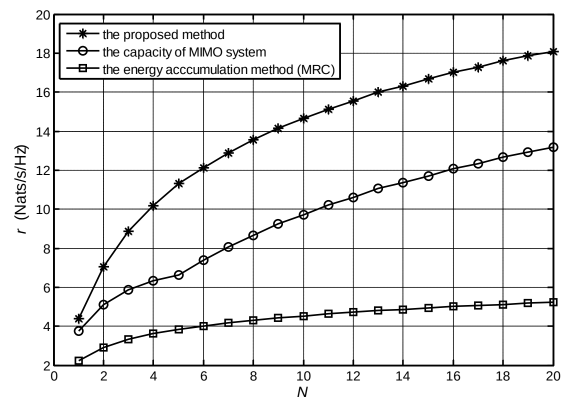

Fig. 4. R Vs. N With SNR=10db And L=5.

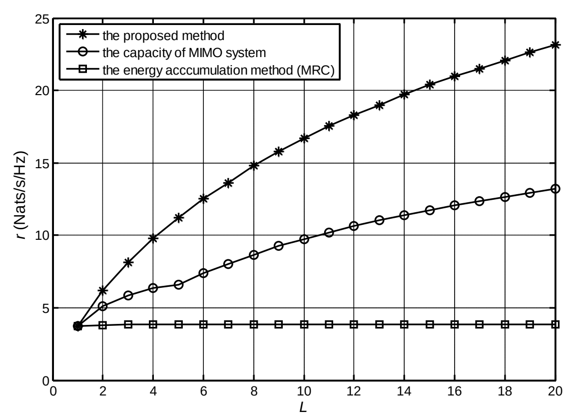

Fig. 5. R Vs. L With SNR=10db And N=5.

where $n_{\min}=\min(n_r,n_t)$, P_i is the power of each transmitting antenna. λ_i is i-th element of singular value vector $\boldsymbol{\lambda}=[\lambda_1,\lambda_2,\ldots,\lambda_{n_{\min}}]$ of the channel matrix H between the relays and the destination. In the simulations, the channel fading coefficient is

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Rayleigh-distributed with variance of 0.2. If we apply traditional MIMO detection, the MIMO ergodic channel capacity can be calculated. With the Monte Carl method, we present the performance of our proposed method and traditional MIMO detection as well as the method of MRC, where the information collected at each antenna by using MRC and then the total information extracted from multi-antenna is also obtained by MRC. All the results are averaged over 10,000 times of instantaneous channel simulations.

Firstly, we set both the number of relays L and the number of the antennas N at the destination to 5. Fig. 3 compares the transmission rate using the proposed information receiving method to the traditional MIMO detection. The transmission rate of virtual MIMO system obviously surpasses the capacity of the traditional MIMO channel and the difference between them becomes larger with the increase of signal to noise ratio. This is mainly because the relays utilize CDMA and each antenna of the destination can distinguish and separate different information streams from the relays, and the transmission rate of IA is higher than that of EA [5] [9]. In addition, the rate of the EA method is also compared. In EA method, the destination combines all signals by using MRC method. Obviously, the method cannot achieve the capacity of the MIMO channel.

Secondly, we set L to 5 and then change the value of N. Fig. 4 shows the relation of transmission rate and the number of antennas of the destination for signal to noise ratio (SNR) = 10dB. With the increase of the number of antennas of the destination, the transmission rates increase and the transmission rate of virtual MIMO system outperforms the ergodic capacity of the MIMO channel. It is noticed that when the destination has only one antenna (N=1), the proposed method corresponds to the IA and the capacity of the MIMO channel to EA. It can be found the transmission rate of IA is higher than the rate of EA. This is consistent with the result in [5].

Lastly, we set N to 5 and then change the value of L. Fig. 5 plots the relation of transmission rate and the number of relays and we find it has the similar result with Fig. 4. But it is found that when the number of relays is one (L=1), the destination only uses energy accumulation, so three rates are the same at this point.

From the numerical results presented above, we can state that the transmission rate of the proposed information receiving method is superior to that of the MIMO detection.

5. CONCLUSION

This paper designed a multi-relay based strategy to improve the transmission data rate for high-speed railway mobile communication system with fountain codes. In order to do this, novel information receiving method was presented, which receives the information at the destination by jointly using IA and EA. We derived the explicit expression of the pdf of the transmission rate of our method in Rayleigh fading channels and then presented the average transmission rate. In addition, since the considered multi-relay architecture with multi-antenna destination can be treated as a virtual MIMO system, we compared our method with traditional MIMO detection in terms of average transmission rate. Numerical results showed that our method achieves higher transmission rate than using traditional MIMO detection method.

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