IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 3 March 2023, accepted 15 May 2023, date of publication 25 May 2023, date of current version 1 June 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3280059

RESEARCH ARTICLE

Joint Blocklength and Power Optimization in High-Speed Railway Relay Communication Systems

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This work was supported by the Key Programs of Technological Research and Development of China Academy of Railway Sciences under Grant 2021YJ101.

ABSTRACT For a high-speed railway relay downlink communication system based on short-packet transmission, the problem of maximizing the minimum user throughput by jointly optimizing the transmission packet length and the transmission power control of the relay device is investigated in this paper. The optimization problem is a nonconvex and mixed-integer one that is difficult to obtain an optimal solution, and a low-complexity algorithm is proposed to obtain the solution to the joint optimization problem. First, a closed-form expression of the optimal blocklength is derived by fixing the transmission power; Secondly, in the case of fixed blocklength, the non-convex optimization subproblem of transmission power is transformed into a convex problem by introducing auxiliary variables and using the successive convex approximation method. Finally, the feasibility and effectiveness of the proposed algorithm in this paper are verified by simulation.

INDEX TERMS High-speed railway communication, short-packet transmission, packet length, power control, continuous convex approximation.

I. INTRODUCTION

In order to meet the demand of high-speed data transmission, the application of 5G technology in high-speed railway (HSR) scenarios is gaining more and more attention. To ensure the safe operation and the high quality of experience of the users, the wireless communication technology plays an important role in HSR system [1]. The downlink resource allocation problem in HSR downlink orthogonal frequency division multiple access (OFDMA) system with a cellular/relay integrated network architecture was investigated and an equivalent one-stage programming was proposed in [2]. The secure transmission from the roadside base stations to the vehicle stations on the top of the train was considered, and the eavesdropping user is a mobile unmanned aerial vehicle in [3], where the objective is to maximize the sum of the minimum security rate of each time slot. The transmission performance of wireless links between the base station and the access point on the roof of the train was considered in [4], and the quality of service (QoS) distinguished power allocation algorithm was derived to achieve the largest achievable rate region. These works mainly concern the direct communication between the base station and the vehicle stations. However, the penetration losses caused by train carriage and Doppler shift are more severe at millimeter wave frequencies. Therefore, it is widely accepted that a mobile relay-based network architecture is one of the most desirable solutions to the above problem [5].

In the mobile relay network, the link between the base station and relay device uses frequencies below 6 GHz, while the link between the relay device and user uses millimeter wave frequencies [6]. There are several advantages of mobile relay in HSR communication compared with the conventional direct point to point communication [7], [8]. Firstly, HSR has sufficient power and a large space to support the mobile relay stations with multiple antennas. Secondly, mobile relay offers

The associate editor coordinating the review of this manuscript and approving it for publication was Di Zhang.

new chance for performance enhancement by the higher frequency (e.g., millimeter wave), especially for a large number of passengers in the carriage in a static environment. Thirdly, the lower frequency in the link between the train and ground can reduce Doppler shift, which makes the mobile relay stations stronger processing power and the link more reliable.

There are many researches on mobile relay network in the existing literature. When mobile relay nodes cooperated, the system-level simulation of HSR was given in [9], the results showed that the cooperation of relay nodes could significantly improve the user rate. In [10], the system performance of average symbol error rate for the two relays railway networks was analyzed, and decode-and-forward (DF) protocol was adopted by partial differential modulation. The simulation results showed that the system had the best performance, when two relay nodes were in the same location. In [11], the HSR communication system with mobile relay technology and OFDMA to serve users was considered, and how to minimize the total power consumption of base stations and relay nodes under the desired QoS of users was investigated. The optimal subcarrier and power allocation scheme was derived by the Lagrange dual method, then a low-complexity sub-optimal algorithm based on the Hungarian algorithm was proposed. A novel two-hop mobile relay architecture for high-speed trains was considered in [12], two relay structures (several relay nodes in a railway carriage and a single relay node with multiple antennas) and two relay modes (amplify-and-forward and DF) were studied. A new broadband data access technology using multiple input and multiple output (MIMO) technology, mobile relay and millimeter wave band was proposed to provide service for train passengers in high-speed environment. The HSR communication system based on relay was considered in [13], and the relay node operated in full duplex mode. The goal was to maximize the network capacity by allocating spectrum resources, and the formulated problem was a non-convex optimization one about the spectrum resource allocation. A sequential quadratic programming algorithm based on Lagrange function was proposed, which could effectively solve the bandwidth allocation problem of base stations and relay nodes.

The 5G-based Internet of Things technology can provide ultra-reliable low-latency communication (URLLC) for HSR system, and improve the QoS of the passengers [14], [15]. For URLLC, ultra-reliable means high stability of the network, and low-latency requires minimal end-to-end time delay. In the URLLC scenario, the latency is generally 1-10 milliseconds [16]. At present, most physical layer designs rely largely on long blocklengths, which make the transmission rate close to Shannon capacity. To support low-latency communication, the shor-packet data with finite blocklength codes is considered to reduce the transmission latency [17]. Compared with Shannon capacity for infinite blocklength, the decoding error probability of the receiver for finite blocklength transmission can not be ignored due to the short blocklength [18]. The accurate approximate value of the information rate of the limited blocklength in the additive white Gaussian noise (AWGN) channel was derived in [19], which considered error probability and blocklength. Non-orthogonal multiple access (NOMA) in short-packet communications was compared with orthogonal multiple access (OMA) in [20], which could reduce the transmission latency of physical layer. The closed-form expression for the block error rate in NOMA was derived, and the near-optimal scheme about power allocation and blocklength was given. A multiuser downlink network model in the finite blocklength regime was considered, the optimal power allocation algorithm was proposed to maximize the normalized sum throughput under statistical QoS constraints [21]. In [22], a downlink multiple-input single-output (MISO) OFDMA URLLC system with short packet transmission was considered, the proposed resource allocation algorithm was used to maximize the weighted sum throughput with QoS constraints regarding the number of transmitted bits and delay.

In this paper, a relay downlink communication system for HSR based on short packet is considered, where the relay device deployed on the top of the train provides communication services for multiple users in the carriage using DF mode. Downlink information transmission is divided into two phases. The first phase is the transmission from the base station to the relay device, and the second phase is the transmission from the relay device to the users. The sum of the blocklengths of the two phases is fixed. The contributions are mainly summarized as follows:

(1) Maximizing the throughput of the minimum user by jointly optimizing the blocklength and the transmission power of the relay device is studied, The constraints include the amount of data from the base station to the relay device is greater than that from the relay device to the user, the maximum blocklength, the minimum blocklength, and the transmit power of the on-board relay device.

(2) The formulated joint optimization problem is non-convex, an alternate iteration algorithm is proposed in this paper. With fixed transmission power, the original optimization problem is transformed into an optimization subproblem about blocklength. Through variable substitution and the first-order Taylor expansion, the closed expression of blocklength can be obtained. By fixing the blocklength, the original problem is transformed into a non-convex optimization subproblem about transmission power. By introducing auxiliary variables and the first-order Taylor expansion, the non-convex optimization problem about transmission power is solved. On this basis, an alternate iteration algorithm for the joint optimization problem is proposed.

(3) The HSR relay communication system is simulated in detail, and the detailed simulation results are given to verify the effectiveness of the proposed algorithm. In addition, the simulation results also show the influence of the packetlength, the transmission power, the train speed and the channel error probability on the system transmission performance.

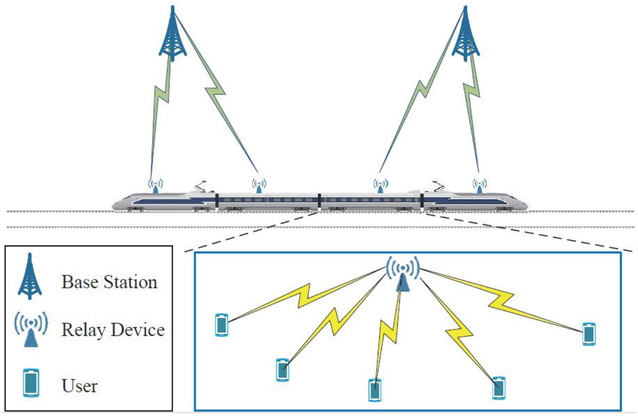

FIGURE 1. The model of HSR relay communication system.

The rest of this paper is organized as follows. Section II introduces the HSR communication relay downlink system based on short packet, and the joint optimization problem of maximizing the minimum user throughput is given under the constraints of data transmission blocklength and relay transmission power. In Section III, a subproblem about the other variable is solved by fixing another variables, then an alternate iteration algorithm is proposed. Section IV gives numerical simulation. Section IV concludes this paper.

II. SYSTEM MODEL AND PROBLEM STATEMENT

The model of relay collaborative downlink system based on short-packet communication is shown in Figure 1. It is assumed that there is an operator's base station deployed at a certain distance from each other on the side of the HSR, and there is an on-board relay device deployed in each carriage of the train, which receives information from the roadside base station and serves multiple users in the carriage by DF. It is assumed that the base station, on-board relay device and subscriber are equipped with a single antenna. If the set of K users served in the compartment is denoted as $\mathcal{K}$, where the user $k \in \mathcal{K} = \{1, 2, \cdots, K\}$. In order to ensure highly reliable and low latency communication, we use short-packet communication, and the decoding error rate does not become zero even if the signal to interference plus noise ratio (SINR) is very high in this transmission, which leads to the Shannon formula no longer being applicable in this case. Let L^{max} denote the maximum channel blocklength, the downlink information transmission is divided into two phases. The first phase is the transmission phase from the base station to the vehicular relay device, and the second phase is the transmission phase from the vehicular relay device to the user. The corresponding blocklength of each stage are L_1 and L_2, respectively, and $L_1 + L_2 = L^{max}$. Under the finite channel blocklength constraint, the channel is considered as a quasi-static flat fading channel during transmission. In this paper, we only consider the joint optimization strategy design of blocklength and power allocation in short-packet transmission time period, so the system transmission model is quasi-static.

Let h_{vs} denote the channel gain from the base station to the on-board relay device and h_k denote the channel gain from the relay to the user k. The transmitting power of the base station and the transmitting power of the on-board relay device to user k are denoted as p_b and p_k, respectively. Then the SINR γ_{vs} and γ_k received by the relay and user k are expressed as follows,

$$\begin{cases} \gamma_{vs} = \dfrac{p_b h_{vs}}{p_{b'} g_{vs} + \sigma_{vs}^2}, \\ \gamma_k = \dfrac{p_k h_k}{\sum_{l=1, l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2}, \end{cases} \tag{1}$$

where $p_{b'}$ denotes the transmitting power of the adjacent base station, g_{vs} denotes the channel gain from the neighboring base station to the on-board relay device. σ_{vs}^2 and σ_k^2 denote the variance of AWGN.

In this paper, a new formulation is used to portray the tradeoff between achievable rate of data transmission, decoding error probability and transmission delay under the transmission condition of shorter blocklength. For a given finite blocklength $L^{max}(L^{max} < 100)$, the channel decoding rate can be described by,

$$R\left(L^{max}, \epsilon\right) = C - \sqrt{\frac{V}{L^{max}}} Q^{-1}(\epsilon) + \mathcal{O}\left(\frac{\log L^{max}}{L^{max}}\right), \tag{2}$$

where C is based on the Shannon capacity at infinite blocklength, V denotes the channel discretization, which measures the randomness of the channel relative to a deterministic channel with the same capacity, ϵ denotes the expected decoding error probability, and Q^{-1} is the inverse function of the Gaussian Q-function, $Q(x) \triangleq \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$.

According to the above equation, the approximate decoding rates $R(\gamma_{vs})$ and $R(\gamma_k)$ of the information received by the on-board relay device and user k can be obtained as follows,

$$\begin{cases} R(\gamma_{vs}) = \log_2(1+\gamma_{vs}) - \sqrt{\dfrac{V(\gamma_{vs})}{L_1}} \dfrac{Q^{-1}(\varepsilon_{vs})}{\ln 2}, \\ R(\gamma_k) = \log_2(1+\gamma_k) - \sqrt{\dfrac{V(\gamma_k)}{L_2}} \dfrac{Q^{-1}(\varepsilon_k)}{\ln 2}, \end{cases} \tag{3}$$

where $V(\gamma_{vs}) = \left(1 - (1+\gamma_{vs})^{-2}\right)(\log_2 e)^2$, $V(\gamma_k) = \left(1 - (1+\gamma_k)^{-2}\right)(\log_2 e)^2$. Obviously, this approximation adds a rate penalty term compared with the channel capacity to keep the maximum channel error probability ε at a finite blocklength L^{max}, which is proportional to $\frac{1}{\sqrt{L^{max}}}$. ε_{vs} denotes the maximum channel error probability from the base station to the on-board relay, and ε_k denotes the maximum channel error probability from the on-board relay to the user.

In this paper, we maximize the throughput of the minimum user by jointly optimizing the blocklength and power, and the specific optimization problem is expressed as follows,

$$P: \max_{L_1,L_2,p_k} \min_{k\in\mathcal{K}} L_2 (1-\varepsilon_k) R(\gamma_k) \tag{4}$$

$$\text{s.t. } L_1 (1-\varepsilon_{vs}) R(\gamma_{vs}) \geq L_2 \sum_{k=1}^{\mathcal{K}} (1-\varepsilon_k) R(\gamma_k), \tag{5a}$$
$$L_1 + L_2 = L^{max}, \tag{5b}$$
$$L_1 \geq L^{min}, L_2 \geq L^{min}, L_1, L_2 \in \mathbb{N}, \tag{5c}$$
$$0 \leq \sum_{k=1}^{K} p_k \leq P^{max}\ k \in \mathcal{K}. \tag{5d}$$

The constraint (5a) is to ensure that the data from the base station to the on-board relay device in the first phase can all be decoded and forwarded to the user in the relay in the second phase. The constraint (5b) ensures that the blocklength of the two phases is equal to the maximum blocklength. The constraint (5c) ensures that the minimum blocklength L^{min} is satisfied in each phase, and constraint (5d) is the transmit power constraint of the on-board relay device. The problem P is a nonconvex optimization problem, which is solved by the alternating iterative method in this paper.

III. PROBLEM SOLVING

A. FIXED TRANSMISSION POWER TO OPTIMIZE BLOCKLENGTH

By fixing the transmitting power p_k, $k \in \mathcal{K}$, the problem P is transformed into an optimization problem with respect to the blocklengths L_1, L_2 as follows,

$$P1: \max_{L_1,L_2} \min_{k\in\mathcal{K}} \Delta_k L_2 - \Lambda_k L_2^{\frac{1}{2}} \tag{6}$$

$$\text{s.t. } \Phi_{vs} L_1 - \Psi_{vs} L_1^{\frac{1}{2}} \geq \sum_{k=1}^{\mathcal{K}} \left(\Delta_k L_2 - \Lambda_k L_2^{\frac{1}{2}}\right), \tag{7a}$$
$$L_1 + L_2 = L^{max}, \tag{7b}$$
$$L_1 \geq L^{min}, L_2 \geq L^{min}, L_1, L_2 \in \mathbb{N}. \tag{7c}$$

where $\Lambda_k = (1-\varepsilon_k)\sqrt{1-(1+\gamma_k)^{-2}}\frac{Q^{-1}(\varepsilon_k)}{\ln 2}$, $\Delta_k = (1-\varepsilon_k)\log_2(1+\gamma_k)$, $\Phi_{vs} = (1-\varepsilon_{vs})\log_2(1+\gamma_{vs})$, $\Psi_{vs} = (1-\varepsilon_{vs})\sqrt{1-(1+\gamma_{vs})^{-2}}\frac{Q^{-1}(\varepsilon_{vs})}{\ln 2}$.

It follows from the constraint (7b) that $L_1 = L^{max} - L_2$ is substituted into P1, as well as such that $\Delta = \sum_{k=1}^{\mathcal{K}} \Delta_k$ and $\Lambda = \sum_{k=1}^{\mathcal{K}} \Lambda_k$, then problem P1 is rewritten as follows,

$$P1.1: \max_{L_2} \min_{k\in\mathcal{K}} \Delta_k L_2 - \Lambda_k L_2^{\frac{1}{2}} \tag{8}$$

$$\text{s.t. } (\Phi_{vs}+\Delta) L_2 - \Lambda L_2^{\frac{1}{2}} + \Psi_{vs}\left(L^{max} - L_2\right)^{\frac{1}{2}} \leq \Phi_{vs} L^{max}, \tag{9a}$$
$$L^{min} \leq L_2 \leq L^{max},\ L_2 \in \mathbb{N}. \tag{9b}$$

Introducing the variable τ, problem P1.1 is transformed into the following equivalence problem,

$$P1.2: \max_{L_2,\ \tau} \tau \tag{10}$$

$$\text{s.t. } (\Phi_{vs}+\Delta) L_2 - \Lambda L_2^{\frac{1}{2}} + \Psi_{vs}\left(L^{max} - L_2\right)^{\frac{1}{2}} \leq \Phi_{vs} L^{max}, \tag{11a}$$
$$\Delta_k L_2 - \Lambda_k L_2^{\frac{1}{2}} \geq \tau\ k \in \mathcal{K}, \tag{11b}$$
$$L^{min} \leq L_2 \leq L^{max},\ L_2 \in \mathbb{N}. \tag{11c}$$

Since the constraints (11a) and (11b) in P1.2 are both nonconvex, by calculating the first-order Taylor expansions of $\Psi_{vs}(L^{max}-L_2)^{\frac{1}{2}}$ and $-\Lambda_k L_2^{\frac{1}{2}}$ at the feasible point L_2^t, the upper and lower bounds at the feasible point L_2^t can be obtained, respectively,

$$\begin{cases} \Psi_{vs}\left(L^{max}-L_2\right)^{\frac{1}{2}} \leq \Psi_{vs}\left(L^{max}-L_2^t\right)^{\frac{1}{2}} - \frac{1}{2}\Psi_{vs}\left(L^{max}-L_2^t\right)^{-\frac{1}{2}}\left(L_2 - L_2^t\right), \\ -\Lambda_k L_2^{\frac{1}{2}} \geq -\Lambda_k\left(L_2^t\right)^{\frac{1}{2}} - \frac{1}{2}\Lambda_k\left(L_2^t\right)^{-\frac{1}{2}}\left(L_2 - L_2^t\right). \end{cases} \tag{12}$$

Let $\Theta_1 = \Phi_{vs} + \Delta - \frac{1}{2}\Psi_{vs}\left(L^{max}-L_2^t\right)^{-\frac{1}{2}}$ and $\Theta_2 = \Phi_{vs}L^{max} - \Psi_{vs}\left(L^{max}-L_2^t\right)^{\frac{1}{2}} - \frac{1}{2}L_2^t\Psi_{vs}\left(L^{max}-L_2^t\right)^{-\frac{1}{2}}$, then P1.2 translates into the following optimization problem,

$$P1.3: \max_{L_2,\ \tau} \tau \tag{13}$$

$$\text{s.t. } \Theta_1 L_2 - \Lambda L_2^{\frac{1}{2}} \leq \Theta_2, \tag{14a}$$
$$\left(\Delta_k - \frac{1}{2}\Lambda_k\left(L_2^t\right)^{-\frac{1}{2}}\right) L_2 - \frac{1}{2}\Lambda_k\left(L_2^t\right)^{\frac{1}{2}} \geq \tau,\ k \in \mathcal{K}, \tag{14b}$$
$$L^{min} \leq L_2 \leq L^{max},\ L_2 \in \mathbb{N}. \tag{14c}$$

The upper bound condition on L_2 can be obtained from constraints (14a) and (14c) as follows,

$$L_2 \leq \min\left(L^{max}, \left(\frac{\Lambda + \sqrt{\Lambda^2 + 4\Theta_1\Theta_2}}{2\Theta_1}\right)^2\right). \tag{15}$$

According to the constraint (14b), the optimization objective τ is maximized when L_2 takes the maximum value. At the same time, combining constraints $L_1 \geq L^{min}$ and $L_1 + L_2 = L^{max}$, the following solution can be obtained by,

(1) If $L^{max} - \min\left(L^{max}, \left(\frac{\Lambda+\sqrt{\Lambda^2+4\Theta_1\Theta_2}}{2\Theta_1}\right)^2\right) \geq L^{min}$,

$$\begin{cases} L_1^* = L^{max} - \min\left(L^{max}, \left(\frac{\Lambda + \sqrt{\Lambda^2 + 4\Theta_1\Theta_2}}{2\Theta_1}\right)^2\right), \\ L_2^* = \min\left(L^{max}, \left(\frac{\Lambda + \sqrt{\Lambda^2 + 4\Theta_1\Theta_2}}{2\Theta_1}\right)^2\right). \end{cases} \tag{16}$$

(2) If $L^{max} - \min\left(L^{max}, \left(\frac{\Lambda+\sqrt{\Lambda^2+4\Theta_1\Theta_2}}{2\Theta_1}\right)^2\right) < L^{min}$,

$$\begin{cases} L_1^* = L^{min}, \\ L_2^* = L^{max} - L^{min}. \end{cases} \tag{17}$$

B. FIXED BLOCKLENGTH TO OPTIMIZE TRANSMITTING POWER

By fixing the blocklengths L_1, L_2, the problem P is transformed into an optimization problem on the transmitting power p_k, $k \in \mathcal{K}$, as follows,

$$P2: \max_{p_k} \min_{k\in\mathcal{K}} L_2 (1-\varepsilon_k) R(\gamma_k) \tag{18}$$

$$\text{s.t.} \quad L_1(1-\varepsilon_{vs}) R(\gamma_{vs}) \geq L_2 \sum_{k=1}^{\mathcal{K}} (1-\varepsilon_k) R(\gamma_k), \tag{19a}$$

$$0 \leq \sum_{k=1}^{K} p_k \leq P^{max} \; k \in \mathcal{K}. \tag{19b}$$

By introducing the variable ρ, ψ_k, φ_k, $k \in \mathcal{K}$, problem P2 is transformed into the following equivalent problem,

$$P2.1: \max_{p_k,\rho,\psi_k,\varphi_k} \rho \tag{20}$$

$$\text{s.t.} \quad L_1(1-\varepsilon_{vs}) R(\gamma_{vs}) \geq L_2 \sum_{k=1}^{\mathcal{K}} (1-\varepsilon_k) R(\gamma_k, \psi_k), \tag{21a}$$

$$L_2(1-\varepsilon_k) R(\gamma_k, \varphi_k) \geq \rho, \tag{21b}$$

$$\frac{p_k h_k}{\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2} \geq \psi_k, k \in \mathcal{K}, \tag{21c}$$

$$\frac{p_k h_k}{\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2} \leq \varphi_k, k \in \mathcal{K}, \tag{21d}$$

$$0 \leq \sum_{k=1}^{K} p_k \leq P^{max} \; k \in \mathcal{K}. \tag{21e}$$

The constraints (21a)-(21d) in P2.1 are all nonconvex. We will deal with them separately and convert them into the form of convex constraints.

For constraint (21a), $L_2(1-\varepsilon_k) R(\gamma_k, \psi_k)$ can be written in the following form,

$$\begin{aligned} &L_2(1-\varepsilon_k) R(\gamma_k, \psi_k) \\ &= L_2(1-\varepsilon_k)\log_2\left(\sum_{l=1}^{\mathcal{K}} p_l h_l + \sigma_k^2\right) \\ &\quad - L_2(1-\varepsilon_k)\log_2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2\right) \\ &\quad - L_2^{\frac{1}{2}}(1-\varepsilon_k)\sqrt{1-(1+\psi_k)^{-2}}\frac{Q^{-1}(\varepsilon_k)}{\ln 2}. \end{aligned} \tag{22}$$

In the above equation, where $\log_2\left(\sum_{l=1}^{\mathcal{K}} p_l h_l + \sigma_k^2\right)$ is a concave function, its first-order Taylor expansion at the feasible point p_l^t, $l \in \mathcal{K}$ yields the upper bound as follows,

$$\begin{aligned} \log_2\left(\sum_{l=1}^{\mathcal{K}} p_l h_l + \sigma_k^2\right) &\leq \log_2\left(\sum_{l=1}^{\mathcal{K}} p_l^t h_l + \sigma_k^2\right) \\ &\quad + \sum_{l=1}^{\mathcal{K}} \frac{h_l\left(p_l - p_l^t\right)}{\ln 2\left(\sum_{l=1}^{\mathcal{K}} p_l^t h_l + \sigma_k^2\right)}. \end{aligned} \tag{23}$$

Let

$$\begin{aligned} A &= L_1(1-\varepsilon_{vs}) R(\gamma_{vs}) \\ &\quad - \sum_{k=1}^{\mathcal{K}}\left(L_2(1-\varepsilon_k)\left(\log_2\left(\sum_{l=1}^{\mathcal{K}} p_l^t h_l + \sigma_k^2\right)\right.\right. \\ &\quad \left.\left. - \sum_{l=1}^{\mathcal{K}} \frac{h_l p_l^t}{\ln 2\left(\sum_{l=1}^{\mathcal{K}} p_l^t h_l + \sigma_k^2\right)}\right)\right), \end{aligned} \tag{24}$$

$$B_k = L_2(1-\varepsilon_k), \tag{25}$$

$$C_k = L_2^{\frac{1}{2}}(1-\varepsilon_k)\frac{Q^{-1}(\varepsilon_k)}{\ln 2}, \tag{26}$$

$$D_{k,l} = \frac{h_l}{\ln 2\left(\sum_{l=1}^{\mathcal{K}} p_l^t h_l + \sigma_k^2\right)}. \tag{27}$$

Constraints (21a) is transformed into the following inequality,

$$\begin{aligned} &\sum_{k=1}^{\mathcal{K}} B_k \sum_{l=1}^{\mathcal{K}} D_{k,l} p_l - \sum_{k=1}^{\mathcal{K}}\left(B_k \log_2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2\right)\right) \\ &\quad - \sum_{k=1}^{\mathcal{K}} C_k\sqrt{1-(1+\psi_k)^{-2}} \leq A. \end{aligned} \tag{28}$$

For constraints (21b), $L_2(1-\varepsilon_k) R(\gamma_k, \varphi_k)$ can be written as follows,

$$\begin{aligned} &L_2(1-\varepsilon_k) R(\gamma_k, \varphi_k) \\ &= L_2(1-\varepsilon_k)\log_2\left(\sum_{l=1}^{\mathcal{K}} p_l h_l + \sigma_k^2\right) \\ &\quad - L_2(1-\varepsilon_k)\log_2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2\right) \\ &\quad - L_2^{\frac{1}{2}}(1-\varepsilon_k)\sqrt{1-(1+\varphi_k)^{-2}}\frac{Q^{-1}(\varepsilon_k)}{\ln 2}. \end{aligned} \tag{29}$$

In the above equation, $-\log_2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2\right)$ is convex function. Calculate its first-order Taylor expansion at the feasible point p_l^t, $l \in \mathcal{K}$ and yield the following lower bound,

$$-\log_2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2\right) \geq -\log_2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2\right) - \sum_{l=1,l\neq k}^{\mathcal{K}} \frac{h_l}{\ln 2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2\right)}\left(p_l-p_l^t\right). \quad (30)$$

Similarly, calculate the first-order Taylor expansion of $-L_2^{\frac{1}{2}}\left(1-\varepsilon_k\right)\sqrt{1-\left(1+\varphi_k\right)^{-2}}\frac{Q^{-1}(\varepsilon_k)}{\ln 2}$ at the feasible point φ_k^t, $k\in\mathcal{K}$ and obtain the following lower bound,

$$\begin{aligned} &-L_2^{\frac{1}{2}}\left(1-\varepsilon_k\right)\sqrt{1-\left(1+\varphi_k\right)^{-2}}\frac{Q^{-1}\left(\varepsilon_k\right)}{\ln 2} \\ &\geq -L_2^{\frac{1}{2}}\left(1-\varepsilon_k\right)\sqrt{1-\left(1+\varphi_k^t\right)^{-2}}\frac{Q^{-1}\left(\varepsilon_k\right)}{\ln 2} \\ &\quad -L_2^{\frac{1}{2}}\left(1-\varepsilon_k\right)\left(1-\left(1+\varphi_k^t\right)^{-2}\right)^{-\frac{1}{2}}\left(1+\varphi_k^t\right)^{-3} \\ &\quad \times\frac{Q^{-1}\left(\varepsilon_k\right)}{\ln 2}\left(\varphi_k-\varphi_k^t\right). \end{aligned} \quad (31)$$

Define the following symbols:

$$E_{k,l}=\frac{h_l}{\ln 2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2\right)}, \quad (32)$$

$$\begin{aligned} F_k &= L_2\left(1-\varepsilon_k\right)\left(\log_2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2\right) - \sum_{l=1,l\neq k}^{\mathcal{K}} \frac{h_l p_l^t}{\ln 2\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2\right)}\right) \\ &\quad + L_2^{\frac{1}{2}}\left(1-\varepsilon_k\right)\sqrt{1-\left(1+\varphi_k^t\right)^{-2}}\frac{Q^{-1}\left(\varepsilon_k\right)}{\ln 2}, \end{aligned} \quad (33)$$

$$G_k = L_2^{\frac{1}{2}}\left(1-\varepsilon_k\right)\left(1-\left(1+\varphi_k^t\right)^{-2}\right)^{-\frac{1}{2}} \times\left(1+\varphi_k^t\right)^{-3}\frac{Q^{-1}\left(\varepsilon_k\right)}{\ln 2}. \quad (34)$$

Constraints (21b) are transformed into the following inequalities,

$$B_k\log_2\left(\sum_{l=1}^{\mathcal{K}} p_l h_l+\sigma_k^2\right) - B_k\sum_{l=1,l\neq k}^{\mathcal{K}} E_{k,l}p_l - G_k\varphi_k \geq \rho + F_k - G_k\varphi_k^t. \quad (35)$$

For constraints (21c), $\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2\right)\psi_k$ is rewritten as follows,

$$\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2\right)\psi_k = \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2+\psi_k\right)^2}{4} - \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2-\psi_k\right)^2}{4}. \quad (36)$$

For $-\frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2-\psi_k\right)^2}{4}$, calculate the first-order Taylor expansion at the feasible point ψ_k^t, p_l^t, $l\in\mathcal{K}$ and obtain the following upper bound,

$$\begin{aligned} &-\frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2-\psi_k\right)^2}{4} \\ &\leq -\frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2-\psi_k^t\right)^2}{4} + \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2-\psi_k^t\right)}{2}\left(\psi_k-\psi_k^t\right) \\ &\quad - \sum_{l=1,l\neq k}^{\mathcal{K}} \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2-\psi_k^t\right)h_l}{2}\left(p_l-p_l^t\right). \end{aligned} \quad (37)$$

Let $I_k=\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l+\sigma_k^2-\psi_k^t$, the constraint (21c) can be transformed into the following inequality,

$$\frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2+\psi_k\right)^2}{4} - \sum_{l=1,l\neq k}^{\mathcal{K}}\frac{I_k h_l}{2}p_l + \frac{I_k}{2}\psi_k \leq p_k h_k + \frac{I_k{}^2}{4} + \frac{I_k\psi_k^t}{2} - \sum_{l=1,l\neq k}^{\mathcal{K}}\frac{I_k h_l p_l^t}{2}. \quad (38)$$

For constraint (21d), $\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2\right)\varphi_k$ is rewritten as follows,

$$\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2\right)\varphi_k = \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2+\varphi_k\right)^2}{4} - \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2-\varphi_k\right)^2}{4}. \quad (39)$$

For the first-order Taylor expansion of $\frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l+\sigma_k^2+\varphi_k\right)^2}{4}$ at the feasible point ψ_k^t, p_l^t, $l\in\mathcal{K}$, the

Algorithm 1 Blocklength Optimization Algorithm

Initialization: Fix the transmitting power $p_l, l \in \mathcal{K}$, initialize L_2^0, make $t = 0$ and threshold $\epsilon = 10^{-3}$.
For every time slot $t = 1, 2, \cdots$,
Step 1:
Calculate the optimal solutions L_1^* and L_2^* according to equations (7) or (11).
Step 2:
$t = t + 1$, update $L_2^t = L_2^*$.
Until:
The change in the optimization objective of P1.3 is below the threshold ϵ, stop the loop and output L_1^{opt} and L_2^{opt}.

upper bound is obtained as follows,

$$\frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2 + \varphi_k\right)^2}{4} \geq \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l + \sigma_k^2 + \varphi_k^t\right)^2}{4} + \sum_{l=1,l\neq k}^{\mathcal{K}} \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l + \sigma_k^2 + \varphi_k^t\right) h_l}{2} (p_l - p_l^t) + \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l + \sigma_k^2 + \varphi_k^t\right)}{2} (\varphi_k - \varphi_k^t). \tag{40}$$

Let $J_k = \sum_{l=1,l\neq k}^{\mathcal{K}} p_l^t h_l + \sigma_k^2 + \varphi_k^t$, the constraint (21d) can be transformed into the following inequality,

$$\sum_{l=1,l\neq k}^{\mathcal{K}} \frac{J_k h_l}{2} p_l + \frac{J_k}{2}\varphi_k - \frac{\left(\sum_{l=1,l\neq k}^{\mathcal{K}} p_l h_l + \sigma_k^2 - \varphi_k\right)^2}{4} \geq p_k h_k + \sum_{l=1,l\neq k}^{\mathcal{K}} \frac{J_k h_l p_l^t}{2} + \frac{J_k \varphi_k^t}{2} - \frac{{J_k}^2}{4}. \tag{41}$$

Problem P2.1 can be written in the following form,

$$P2.2: \max_{p_k,\rho,\psi_k,\varphi_k} \rho \tag{42}$$

$$\text{s.t. } (15), (22), (25), (28), \tag{43a}$$

$$0 \leq \sum_{k=1}^{K} p_k \leq P^{max} \; k \in \mathcal{K}. \tag{43b}$$

The problem P2.2 is convex and can be solved by using the convex optimization toolkit CVX.

C. JOINT BLOCKLENGTH AND TRANSMISSION POWER ITERATIVE OPTIMIZATION ALGORITHM DESIGN

According to the above analysis, the blocklength optimization subproblem can be solved using Algorithm 1 when the transmission power is fixed. When the transmission blocklength is fixed, the power control problem can be solved using Algorithm 2, and the total joint iterative optimization algorithm is described in Algorithm 3.

Algorithm 2 Power Control Algorithm

Initialization: Fix the blocklengths L_1 and L_2, initialize the transmitted power p_l^0, $l \in \mathcal{K}$ and parameters $\psi_k^0, \varphi_k^0, k \in \mathcal{K}$, make $t = 0$ and threshold $\epsilon = 10^{-3}$.

For every time slot $t = 1, 2, \cdots$,
Step 1:
Use CVX to solve problem P2.2 and obtain the optimal solution $p_k^*, \rho^*, \psi_k^*, \varphi_k^*, k \in \mathcal{K}$.
Step 2:
$t = t + 1$, update $p_k^t = p_k^*, \psi_k^t = \psi_k^*, \varphi_k^t = \varphi_k^*, k \in \mathcal{K}$.
Until:
The change in the optimization objective of P2.2 is below the threshold ϵ, stop the loop and output $p_l^{opt}, l \in \mathcal{K}$.

Algorithm 3 Joint Blocklength and Power Control Iterative Optimization Algorithm

Initialization: Initialize the transmitting power p_l^0, $l \in \mathcal{K}$, make $t = 0$ and threshold $\epsilon = 10^{-3}$.
For every time slot $t = 1, 2, \cdots$,
Step 1:
Fixed transmitting power p_l^t, $l \in \mathcal{K}$, Optimal blocklengths L_1^{opt} and L_2^{opt} are obtained by optimizing according to Algorithm 1.
Step 2:
Update $L_1^t = L_1^{opt}, L_2^t = L_2^{opt}$.
Step 3:
Fix the blocklengths L_1^t and L_2^t and according to Algorithm 2 to obtain the optimal power $p_l^{opt}, l \in \mathcal{K}$.
Step 4:
$t = t + 1$.
Step 5:
Update $p_l^t = p_l^{opt}, l \in \mathcal{K}$.
Until:
The change in the optimization objective of P is below the threshold ϵ, stop the loop.

IV. SIMULATION EXPERIMENTS

Consider a 500 meters long section of railroad with two roadside base stations and one on-board relay at the top of the train, and the train passes through this section at a uniform speed of 100m/s. Each time slot is divided into 2.5s and the total number of time slots is 4. As shown in Figure 2, assuming that the starting point is coordinate zero, when $t = 0$, the coordinates of the two roadside base stations are (100, 100, 10) and (500, 100, 10), respectively, and the coordinates of the on-board relay device are (310, 0, 5). At the same time, we provide location coordinates (140, 0, 1), (210, 0, 1), and (270, 0, 1) for three users respectively. The path loss between the base station and the relay is $PL^{vs} = 70.9 + 10.8 \log 10(d_{vs}[km])$, where d_{vs} denotes the distance between them. The path loss between the on-board relay and user k is $PL^{k} = 80.3 + 16.8\, log10(d_k[km])$, where d_k denotes the

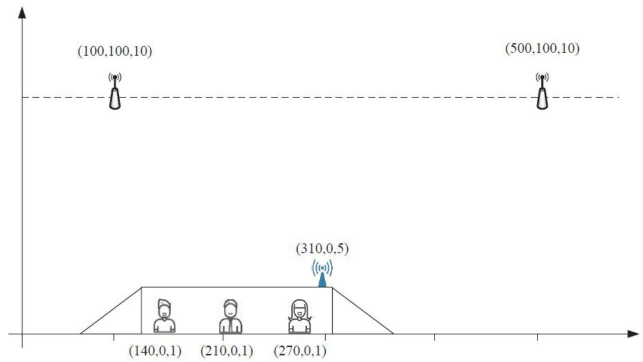

FIGURE 2. Deployment location of base station, relay and users.

distance between the two. The noise power $\sigma_{vs}^2 = \sigma_k^2 = -110$ dBm and the transmission power of the base station $p_b = 40$ dBm. Assume that the on-board relay device is always associated to the nearest roadside base station with maximum blocklength $L^{max} = 100$ and minimum blocklength $L^{min} = 20$. The maximum transmission power of the relay is $P^{max} = 30dBm$.

Figure 3 depicts the relationship of the received data by user with data blocklength under three algorithms: fixed blocklength optimized transmitting power, fixed transmitting power optimized blocklength, and the proposed joint iterative optimization algorithm. The transmitting power of the base station is 40 dBm, and the maximum transmission power of the on-board relay device is 30 dBm. it can be seen from the figure that the data received by the user under all three algorithms gradually increases as the data blocklength increases. In the case of fixed data blocklength, the proposed joint iterative optimization algorithm has the best performance, followed by the fixed blocklength optimized transmitting power algorithm, and the fixed transmitting power optimized blocklength algorithm has the worst performance. The performance of the fixed transmitting power optimized blocklength algorithm is much worse than the other two algorithms in the case of fixed data blocklength, and the performance of the fixed blocklength optimized transmitting power algorithm is not very different from the performance of the joint iterative optimization algorithm. When the maximum data blocklength is 100, the user receives 300bits of data by the joint iterative optimization algorithm, 295bits of data by the fixed blocklength optimized transmitting power algorithm, and only 265bits of data by the fixed transmitting power optimized blocklength algorithm.

Figure 4 shows the relationship between the received data of the users and the transmitting power of the on-board relay device by three different algorithms with a data blocklength 100. It can be seen from the figure that the received data for both the joint iterative optimization algorithm and the fixed blocklength optimized power algorithm increase with the maximum transmitting power of the relay device, while the received data for the fixed transmitting power optimized blocklength algorithm increases first and then decreases

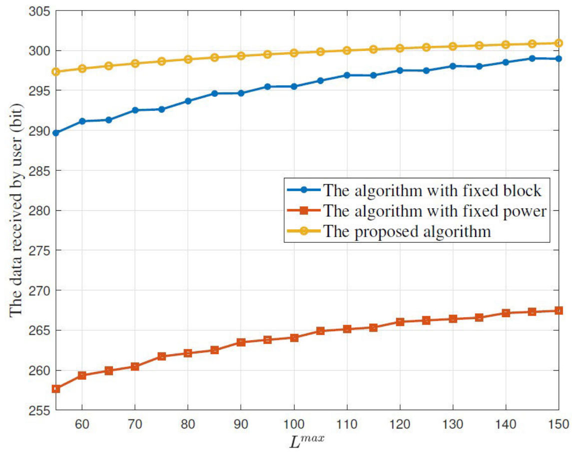

FIGURE 3. Given the transmitting power, the relationship between the received data and the data blocklength for different algorithms.

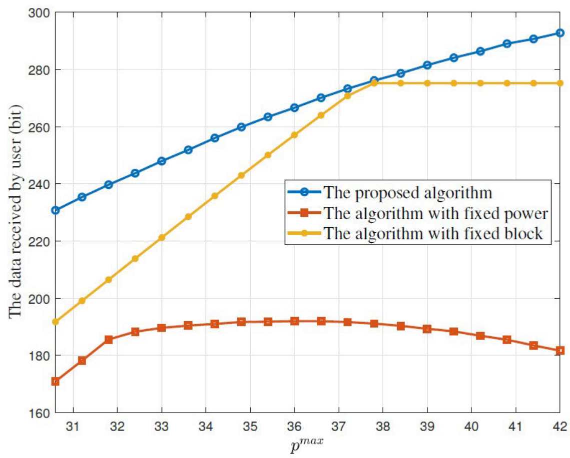

FIGURE 4. Given the data blocklength, the relationship between the received data and the transmitting power of the relay node for different algorithms.

gradually. The maximum received data for the fixed transmitting power optimized blocklength algorithm is 190bits, and the received data of the joint iterative optimization algorithm and the fixed blocklength optimized power algorithm are almost equal when the transmitting power of the relay device is about 38dBm, which is about 275bits, while the received data for the fixed transmitting power optimized blocklength algorithm is about 190bits.

Figure 5 gives the relationship between the data received by the user and the driving speed when the data blocklength and the transmitting power of the on-board relay device are fixed. It can be seen that under the conditions of fixed data blocklength and fixed driving speed, the higher the transmitting power of the on-board relay device, the larger the received data. The performance of the proposed joint iterative optimization algorithm decreases first and then increases with the increase of driving speed in all three cases. The received data is minimized at a driving speed of 75m/s. This is due to the fact that when the train travels at 75m/s, the train

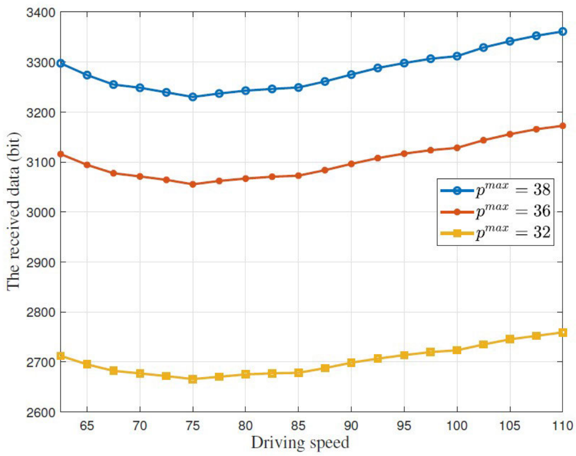

FIGURE 5. Given the data blocklength and the transmitting power of the on-board relay device, the relationship between the received data and driving speed.

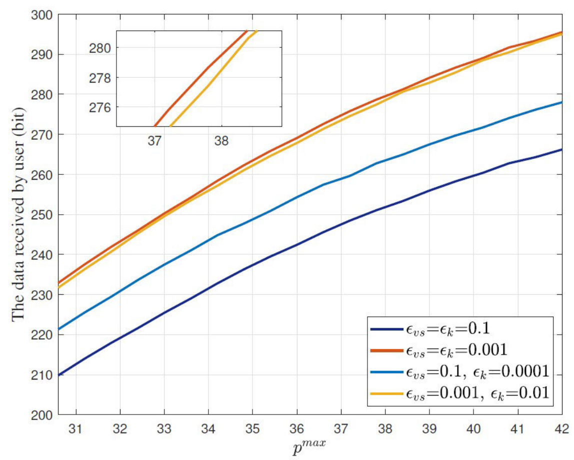

FIGURE 6. The relationship between the received data and the transmitting power of the on-board relay device under different channel error probabilities.

travels in the middle of the two base stations for a long period of time and receives stronger interference, which affects the communication performance between the base station and the relay. In this case, the rate from the base station to the on-board relay is smaller, which will result in the receiving less data for the user. When the train speed is accelerated, the on-board relay device has a greater chance to associate with a closer base station, the on-board relay device always associates with the base station closest to it. Therefore, the user's ability to receive data gradually becomes larger.

Figure 6 depicts the relationship between the amount of data received by the user and the transmitting power of on-board relay device under different channel error probabilities. It can be seen that the performance of data received by user is best when the maximum channel error probability ϵ_{vs} from the base station to the relay device and the maximum channel error probability ϵ_k from the relay device to the user are both 0.001. When $\epsilon_k = \epsilon_k = 0.1$, the data received by user is the smallest. When $\epsilon_{vs} = 0.1$, the performance with $\epsilon_k = 0.001$ is significantly better than that with $\epsilon_k = 0.1$. When $\epsilon_{vs} = 0.001$, the difference in performance can be negligible if ϵ_k is changed from 0.001 to 0.01. Therefore, both the maximum channel error probability ϵ_{vs} from the base station to the relay device and the maximum channel error probability ϵ_k from the device relay to the user all have an impact on the performance of data received by users.

V. CONCLUSION

In this paper, we considered a relay downlink system for HSR communication based on short-packet transmission, and studied the optimization problem of maximizing the minimum user throughput under the constraints of transmission blocklength and transmitting power of relay device. The formed optimization problem was nonconvex, and two optimization subproblems were solved by fixing one variable and solving the other variable. Based on solving the subproblems, an alternating iteration algorithm was proposed. Finally, the effectiveness of the proposed algorithm was verified by simulation. In the next step of research, the effect of multiple relay node diversity or collaboration on the system performance will be considered.

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