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Improvement of the Spatial Channel Matrix Mapping and Precoding Algorithm in the Forest Environment

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ABSTRACT Few studies have been conducted on the forest spatial channel matrix, most of which were conducted by experts and scholars in the field of communications. The mature cellular network channel coding matrix was ‘‘transplanted’’ to the vegetation-covered space, and the effects of the various vegetation dielectric constants, the forest canopy density and other objective factors on the traditional cellular channel were ignored. To overcome this problem, this paper built a relay network that is suitable for forest environments. This network was an effective complement to the existing cellular communication network for expanding the coverage of signals in the forest. On this basis, this paper analysed the multi-antenna relay transmission protocol and proposed an additional spatial channel matching (mapping) matrix between the forward and backward filters. This matrix was designed to consider the effect of the complex forest environment on the channel to reduce the relaying noise power. Then, under the forest cellular relay network topology, a spatial channel matrix structure (based on unitary matrix) that is suitable for the forest environment is proposed. This matrix can be incorporated into various relay protocols and considers the source node preprocessing operation and the destination node equalizer. The forest relay cooperative network that is proposed in this paper can effectively expand the coverage of signals in forest areas; however, due to the inherent limitations of the relay network, many problems will be encountered in practical applications. For example, the precoding scheme that is based on phase correction requires the terminal node to feed the phase correction factor back to the forest base station node; however, the system performance is substantially affected by the feedback accuracy and the arrival delay difference. Due to the uncertain rank of the integrated channel in the forest base station precoding scheme, it was necessary to adapt to a variety of antenna ports, which rendered the design of the precoding codebook highly difficult. In addition, when the number of transmission layers was greater than 1, the local precoding scheme also encountered the problem of inter-layer interference (ILI). Based on a detailed analysis of the shortcomings of the previous scheme and the strategy of partial coherence transmission, this paper proposes an improved algorithm of incoherent joint transmission technology and an improved precoding scheme that are suitable for forest relay systems. The signal that is transmitted by the relay node and the feedback signal is corrected via layer exchange between cells and via phase correction. By changing the layer’s exchange information and phase information, it can be adapted to various forest environments, such as artificial forests, natural forests, and virgin forests. Finally, the outage probability is considered as a performance indicator in the simulation of the forest environment wireless relay system. The theoretical analysis and simulation results demonstrate the satisfactory performance of the proposed spatial channel mapping matrix and the forest relay precoding scheme.

INDEX TERMS Forest environment, forest channel matrix mapping, relay system, phase correction, ILI.

I. INTRODUCTION

The base stations of operators mainly cover hot spots such as cities and suburbs; however, there remain many communication blind areas in special environments such as forests and forest farms [1], [2]. This paper studies communication blind areas in the forest environment, returns to traditional ground wireless communication theory, investigates the adaptive environmental factors in the forest environment, and constructs spatial channel matrices in forest areas.

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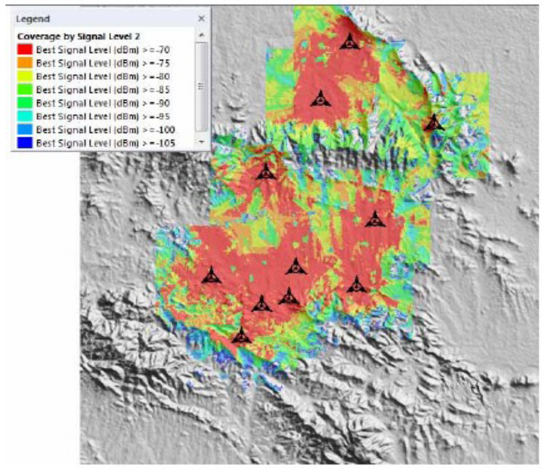
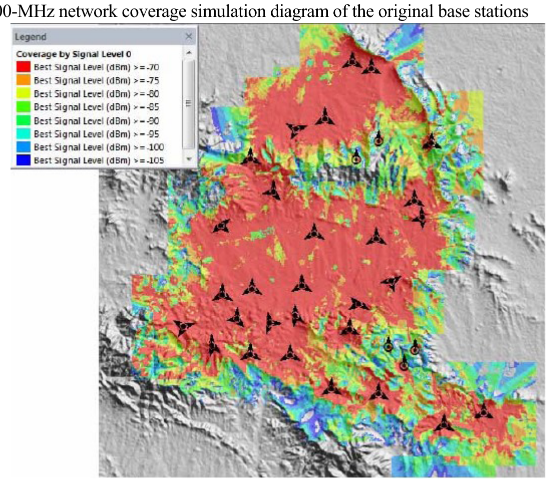
Wireless communication depends on wireless channels. The quality of the wireless channel environment will directly affect the quality of communication. The forest environment has a substantial impact on the propagation of radio waves. The loss of radio waves in the forest is much greater than that in the atmosphere [3], [4]. The wireless signal is affected by the topography, vegetation, weather and other factors during the propagation process and reflection, scattering, absorption and other phenomena may cause signal attenuation [5], [6]. The electromagnetic signal transmission model has always been the focus of scholars in the field of electromagnetics. It currently includes the Okumura-Hata [7] model, the Egli model [8], the ITU-R model [9] and the COST231 model [10]. These models are simple in form and are electromagnetic models. The environment (e.g., city, suburb, or ocean) has a single spatial distribution and regularly shaped objects. However, these theoretical models do not accurately predict the law of radio wave transmission in complex forest environments. Considering the 5G communication system as an example, the constructed wireless channel is based on the Rayleigh channel model and according to the author's preliminary research, the electromagnetic channel in the artificial forest environment is a special channel that is similar to the Rayleigh model [11] and for the forest environment, the channel must be analysed in terms of the electromagnetic signal transmission mechanism.

In implementation, the accuracy of the wireless channel determines the stability of the data flow in the communication network; hence, a high-precision channel transfer matrix is also necessary. Matrix encoding of the forest channel and the design of adaptive environmental factors yield the mathematical equations that are used to determine the channel transmission law of the forest environment; hence, they constitute a key mechanism for expanding the coverage of forest signals [12], [13]. Increasing the number of base stations is often regarded as a solution to the problem of blind areas in forest signals and the base stations serve as carriers of the channel model and the coding matrix [14], [5]. As shown in Fig. 1, the long-term evolution (LTE) communication system is considered as an example. Under the communication frequency, after designing the regular channel model and coding matrix, by increasing the number of communication base stations the simulation effect maps of forests and mountains are obtained.

In Fig. 1, the warm-colour area corresponds to strong signal, namely, the network coverage area, and the cold-colour area corresponds to the signal dead zone. According to Fig. 1, with the increased number of base stations, the network coverage is expanded; however, there are blue regions in the coverage area of the base stations in both (a) and (b), which correspond to regions that are not covered by the signal. These regions occur due to the channel model and the channel transfer matrix of the traditional cellular network, which are not suitable for the forest environment. The spatial channel matrix design directly affects the coverage of a cellular network. The main objective of this paper is to design a forest spatial channel matrix that can adapt to specified standards and to define a matrix coding and adaptive environmental factors under a unified framework.



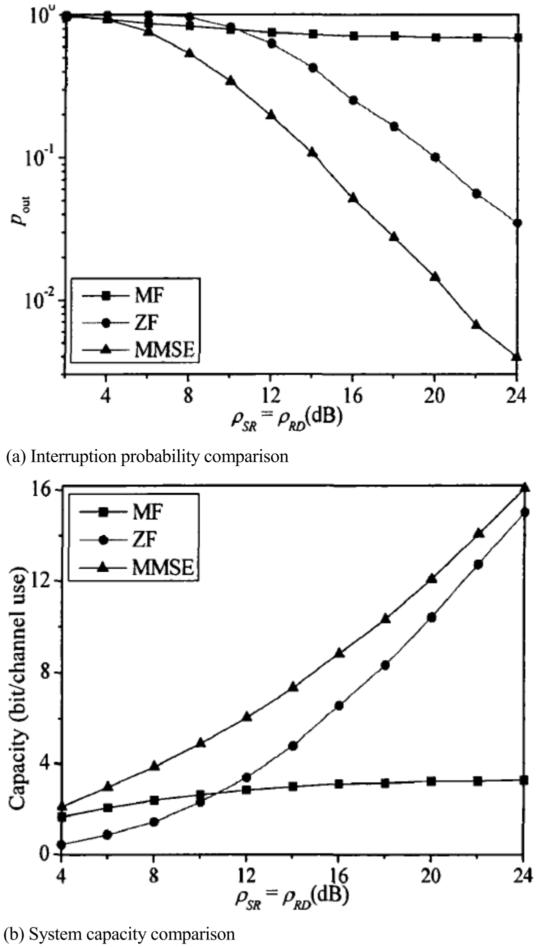
(a) 600-MHz network coverage simulation diagram of the original base stations



(b) 600-MHz network coverage simulation diagram after the addition of new mobile base stations

FIGURE 1. Simulation of the LTE network coverage in a forest environment.

After reviewing the literature [26]–[31], the authors summarize the existing wireless spatial channels. The energy efficiency of the channel matrix coding design that is closest to the forest environment space is shown in Fig. 2, which reflects the current mainstream channel coding schemes of matching filter (MF) [16], zero forcing (ZF) [17], and minimum mean square error (MMSE) [18] and these channel coding schemes reflect the development status of forest wireless cellular networks in terms of the link outage probability and the system capacity. Fig. 2(a) plots the signal coverage success rate of the coding matrix in the cell. The traditional MMSE channel coding scheme is more suitable for transmission in the forest environment; however, based on the channel model scheme that is proposed in this project, the traditional scheme requires further adjustments, especially regarding the authors' proposal of adaptive environmental factors [19], which will substantially improve the dynamic changes of traditional channel matrix coding in forest areas. The system capacity analysis of Fig. 2(b) is consistent with the results in Fig. 2(a) and



(a) Interruption probability comparison

(b) System capacity comparison

FIGURE 2. Channel coding matrix protocol in a forest environment space.

the link connectivity is positively correlated with the system capacity.

In channel matrix coding that is based on the environment of a forestry district, Chen *et al.* [20] and others in the United States studied a new multi-channel sparse data compression sensing model, in which each channel can be represented as a vegetation layer. This study encountered the problem of layered uncertainty in forest vegetation modelling. Spain's Quintano Carmen *et al.* [21] and others used the land ground temperature (LST) of images and terrestrial satellite data to observe forest fire burns via the space-ground channel matrix. This study used a typical approach to transfer traditional communication means to the forest environment, in which a large error was made. In China, Professor Shu *et al.* [22] of Fujian Agricultural and Forestry University and others used artificial noise projection, phase alignment/beamforming, and orthogonal frequency division. The multiplexed random subcarrier selection technique was used to adjust the directional modulation transmitting antenna array. The coded result of this beamforming can be incorporated into the forest channel transfer matrix. These studies all yielded improvements over the traditional communication channel; however, they neglected the influence of the forest environment on the matrix parameters (e.g., the antenna array and the environmental noise) [23]–[25].

In past research on forest relay systems, the downlink cooperative transmission technology of the relay system is studied. The local precoding incoherent joint transmission scheme, the phase-correction-based precoding scheme and the global precoding scheme were analysed [32]–[34]. The strategies of local precoding and single-frequency network (SFN) precoding are simple and easy to implement. There is no need for large amounts of information exchange among multiple transmission nodes and the control channel information requirement of the system is low. The precoding scheme that is based on phase correction follows the strategy of local precoding. By introducing phase correction compensation between transmission nodes, the coherent reception of user signals can be realized and the quality of the received signals can be improved. Global precoding is based on channel information between all transmission nodes and all users and it can theoretically realize the optimal performance gain [35], [36].

These schemes provide promising strategies for the implementation of relay transmission; however, due to the inherent limitations of the algorithms, many problems were encountered in practical application [37]–[39]. For example, the precoding that is based on phase correction required the user to feed the phase correction factor back to the sending node, during which the system performance was substantially affected by the feedback accuracy and the arrival delay difference. Global precoding schemes must adapt to a variety antenna ports because of the uncertain rank of the integrated channel; this was a substantial challenge for the design of the precoding codebook. In addition, when the number of transmission layers was greater than 1, there was also the problem of ILI in the precoding of the forest relay system [40].

Therefore, this paper hypothesizes that since the existing electromagnetic signal transmission model does not consider the mechanism of the forest vegetation environment, which causes dead zones in the existing forest areas, even though there are base stations, the wireless communication theory must be improved and further expanded in the unknown space. Therefore, this paper attempts to construct a relay system model and a spatial channel matrix that are suitable for the special forest environment. Based on a detailed analysis of the shortcomings of the previous scheme and the strategy of partial coherence transmission, this article proposes an improved algorithm of incoherent joint transmission technology and an improved precoding scheme that are suitable for forest relay systems. The signal that is transmitted by the relay node and the feedback signal are corrected via layer exchange between cells and via phase correction. By changing each layer's exchange information and phase information, it can adapt to various forest environments, such as artificial forest, natural forest, and virgin forest. Then, we select representative forest farms for scientific evaluation of the model, in which we demonstrate the validity of the hypothesis. This research has important scientific significance and academic

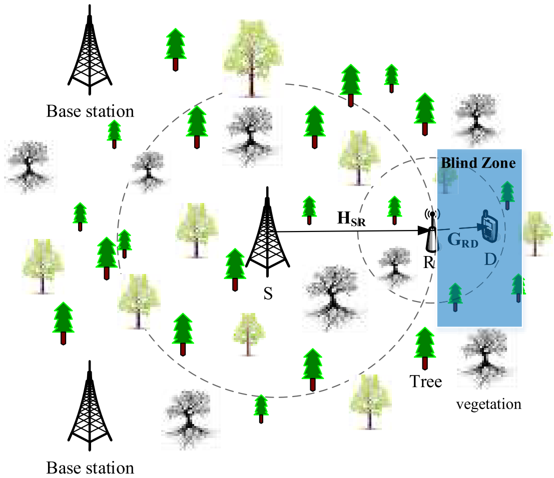


FIGURE 3. Channel model that is suitable for forest transmission—a cellular relay network.

value for improving future wireless communication theory and forest informatics.

Notations: A^H, A^{-1} and $||A||_F$ denote the conjugate-transpose, the inverse and the Frobenius norm, respectively, of A. $[A]_{i,j}$ denotes the element in the ith row and the jth column of A. I_m is the $m \times m$ identity matrix and $0_{m,n}$ denotes an all-zero matrix. $\varepsilon(\cdot)$ denotes the mathematical expectation. u_m is the set of $m \times m$ unitary matrices.

II. SYSTEM MODEL

The forest electromagnetic signal transmission model was established and the forest wireless signal channel was constructed. On this basis, a suitable channel model and a relay network model for forest transmission are established, as illustrated in Fig. 3.

Fig. 3 is a model of relay system suitable for forest environment proposed by the authors. From Fig. 3, we can see that relay node (R) is built on the edge of base station (S) coverage. The reason for this is that in the forest, the area of forest is huge (hundreds of square kilometers or more), and the number of base stations of tradition operator networks is not so large. More coverage of the entire forest environment, the base station is only based on the needs of people gathered and power supply, then the S on the right side (in Fig. 3) is the operator's furthest base station in the forest, from it to the depths of forest, there is no network coverage, then, we add a relay to the edge covered by the farthest base station, the relay is used to extend the extension radius of the operator's network signal. It is also true that PICO base station is not used in this paper, because PICO base station is a micro base station added to expand the capacity of the cell, its location should be inside the S's dotted line circle, and the problem solved is not the network's capacity, but the coverage radius and signal extension of the cell. Therefore, one relay is established at the edge of the cell, of which instead building a PICO base station inside the cell.

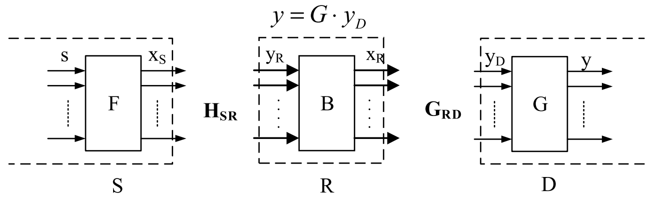


FIGURE 4. Signal transmission sequence of the forestry relay network.

In addition, because the forest relay described in this paper is a small base station itself, it is assumed that the relay will not fail. If the relay base station fails, it is equivalent to the loss of one base station, and a relay base station needs to be redeployed. As can be seen from Fig. 3, the relay base station is located at the radius of coverage of base station farthest from the forest, i.e. the dotted circle covered by S, so as to expand the extension range of signal.

H_{SR} is a channel matrix between the S and R and G_{RD} is a channel matrix between R and the receiving node (D). The communication range of S is indicated by a large dotted circle. To extend the signal to the blind area of the existing network (the blue area in Fig. 3), R is used to communicate with D. Here, we use a non-regenerative relay (AF) protocol. $N_S(N_{R_i}, N_D)$ antennas are equipped in $S(R_i, D)$, respectively. There is no direct link between S and D; the signals must be transmitted through the relay node.

The system model is illustrated in Fig. 1 and the signal transmission sequence diagram is shown in Fig. 4. According to the signal transmission sequence in the system model, the sending signal of S is $s \in \mathbb{C}^{N_{ds}\times 1}$, where N_{ds} is the number of data streams, with the power constraint $E(s \cdot s^H) = I_{N_{ds}}$. Hence, the transmitted signal of S is expressed as follows:

$$x_S = F \cdot s \in \mathbb{C}^{N_{ds}\times 1} \tag{1}$$

In phase 1, S sends and R receives. The transmitted signal of S is x_S, with the power constraint $E(||x_S||_F^2) = E_S$, where $E(\cdot)$ is the mathematical expectation and $||\cdot||_F$ is the Frobenius norm. Therefore, in phase 1, the received signal at R can be expressed as follows:

$$y_R = H_{SR}x_S + n_R \tag{2}$$

where H_{SR_i} is the channel matrix of the $S - R$ link, n_{R_i} is the additive white Gaussian noise (AWGN) of R, and $n_R \sim CN(0, \sigma_R^2 \cdot I)$. S uses the spatial multiplexing (SM) protocol; hence, $E(x_S x_S^H) = E_S/N_S \cdot I_{N_S}$, in which I_{N_S} is the unit matrix. After transmission by R, the signal is:

$$x_R = B \cdot y_R \tag{3}$$

where B is the transmitted matrix and the transmitted signal is subject to the power constraint $E(x_R^H x_R) = E_R$. After the relay node, in phase 2, R sends and D receives. The transmitted signal of R is x_S; hence, the received signal at D can be expressed as follows:

$$y_D = G_{RD}x_R + n_D \tag{4}$$

where G_{RD} is the channel matrix of the $R - D$ link, n_D is the received noise (AWGN) of D, and $n_D \sim CN(0, \sigma_D^2 \cdot I)$.

Without loss of generality (w.l.o.g.), assume $\sigma_{R_i}^2 = \sigma_D^2 = \sigma^2$, $E_S = E_R = 1$, $[H_{SR}]_{i,j} \sim CN(0, h_{SR}^2)$ for $i \in \{1, 2, \cdots, N_S\}$ and $j \in \{1, 2, \cdots, N_R\}$, and $[G_{RD}]_{i,j} \sim CN(0, g_{RD}^2)$ for $i \in \{1, 2, \cdots, N_R\}$ and $j \in \{1, 2, \cdots, N_D\}$. The SNR offsets are defined as follows:

$$\rho_{SR} = \frac{h_{SR}^2}{\sigma^2}, \quad \rho_{RD} = \frac{g_{RD}^2}{\sigma^2}. \tag{5}$$

From equations (2)~(3), equation (4) can be reexpressed as:

$$y_D = G_{RD}BH_{SR}Fs + G_{RD}Bn_R + n_D \tag{6}$$

The equivalent noise can be expressed as:

$$\hat{n} = G_{RD}Bn_R + n_D \tag{7}$$

The D's equalizer is G and the final received signal can be estimated as:

$$y = G \cdot y_D \tag{8}$$

Thus, we complete the single source, multi-relay and single-destination system model with multiple antenna. The objective is to design the spatial channel mapping matrix B to reduce the system outage probability.

Power allocation of relay nodes: relay is located within the coverage of macro base station with high transmission power, and their users are vulnerable to downstream interference from macro cells. The macro base station can enable users to access the relay cell earlier by controlling the offset value during handover. The commonly used cell selection method is to compare the size of Reference Signal Received Power (RSRP). If the offset value is introduced to control the handover, the users outside the relay cell can access the relay cell even when the RSRP value of the relay base station is slightly lower than that of the macro base station, which is equivalent to expanding the coverage of relay cells. The extended area is called Cell Range Expansion (CRE). In the relay cell, users located in the CRE region are vulnerable to downstream interference from the macro cell. In addition, interference with the control channel may also lead to user access failure. In such environment, if the relay transmission technology is used for users, the power allocation problem between users can be effectively solved.

III. IMPROVED CHANNEL PRECODING ALGORITHM FOR THE FOREST RELAY SYSTEM

In this section, based on the shortcomings of previous schemes and the strategy of coherent transmission, three improved algorithms of incoherent joint transmission technology are proposed, which including an improved local precoding algorithm. On the basis of theoretical research, the improved algorithm is simulated to further evaluate the feasibility.

A. PROBLEMS IN PRECODING ALGORITHMS FOR FOREST RELAY SYSTEMS

For analysis, the model of the forest relay system in Eq. (6) is extracted and analysed. The final logical channel is acquired by the terminal node as follows:

$$H_e = G_{RD}BH_{SR}F \tag{9}$$

with order:

$$H_1 = G_{RD}BH_{SR} \tag{10}$$

where the precoding matrix F matches the forest channel H_1. When the ranks of the base station cell and the relay cell are greater than 1, the number of layers that are used by the cell to transmit data is greater than 1. After the terminal node is superimposed, the signal is transmitted by the relay node and ILI occurs. The analysis is as follows:

If the relay node is not used to transmit data, namely, if only a single cell transmits data to the user, the channel between the base station and the terminal is assumed to be H. The singular value decomposition (SVD) of H is:

$$H = U\Delta V^H \tag{11}$$

where U and V are unitary matrices and Δ is a diagonal matrix that has the same rank as H. Considering zero-forcing (ZF) precoding as an example, precoding matrix satisfies $F = V$. The demodulation of data by the user's receiver is realized via a left-multiplied normalized receiving weight or matrix $(FH)^H$. Ideally:

$$(HF)^H H = F^H \Delta^H \Delta \tag{12}$$

This is a diagonal array and the ILI can be eliminated. When relay nodes are cooperating:

$$(G_{RD}BH_{SR} \cdot F)^H H = (G_{RD}BH_{SR} \cdot F)^H \cdot G_{RD}BH_{SR} \tag{13}$$

From the analysis of a single-cell scenario, $G_{RD}BH_{SR} \cdot F$ is a diagonal array, $G_{RD}BH_{SR}$ is not necessarily a diagonal matrix, and the ILI comes from this item.

Due to the particularity of the forest environment, factors such as the absorption of electromagnetic waves by trees and signal occlusion must be considered. The original orthogonality characteristics between layers of merged logical channel $G_{RD}BH_{SR}$ are difficult to guarantee, which are influenced by many factors such as feature vectors and eigenvalues. At present, the ILI that is caused by this method is uncontrollable; therefore, when considering optimization based on local precoding, the ILI should be eliminated as much as possible. In addition, considering the signal phase problem, the gain of useful signal after merging should be considered in the improvement.

B. CAUSES AND TECHNICAL ANALYSIS OF ILI IN FOREST ENVIRONMENT

1) CAUSES OF SIGNAL'S ILI IN FOREST ENVIRONMENT

As mentioned in the previous section, $G_{RD}BH_{SR}$ is not necessarily a diagonal matrix. ILI comes from this term. So, what

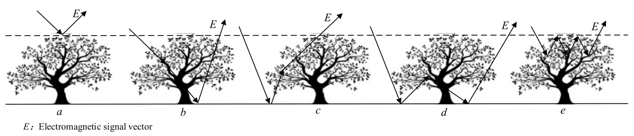


FIGURE 5. Electromagnetic signal transmission mechanism in vegetation.

are the causes of signal's ILI in forest? This section will focus on the discussion.

The characteristics of vegetation stratification in typical forest farms are studied. When electromagnetic wave passes through vegetation cover such as grassland, forest and mountain, the scattering and absorption of electromagnetic wave by vegetation various components (mainly dielectric constant) will cause amplitude attenuation, phase shift and even distortion of the transmitted signal.

In order to solve this problem, the motion and radiation characteristics of one single electromagnetic particle in free space are analyzed. The scattering field expression is calculated from the scattering plane and amplitude, and then the electromagnetic beam is formed by the integral superposition of the scattering plane and amplitude. Then the forest vegetation is equivalent to the rough surface model of incident light. According to the scattering theory of random rough surface, the propagation law of vegetation electromagnetic wave (high frequency) is obtained when the electromagnetic wave is incident on the vegetation surface. Secondly, the vegetation cover in forest is modeled and simulated randomly. The stem of vegetation is equivalent to a finite cylinder, the leaves are represented by ellipsoidal particles approximating a disk, and the whole forest field is equivalent to an electromagnetic signal transmission model. According to the distribution characteristics of forest vegetation, the reflection and folding of high frequency wave in vegetation are considered. In the case of radiation and diffraction, several transmission mechanisms are established. As shown in Fig. 5a∼5e, each mechanism establishes a signal vector transmission equation and forms a set of equations to solve it.

In the signal transmission process of Fig. 5a-e, the vegetation layer in the forest is a non-uniform dielectric layer, which will cause the problems of electromagnetic beam cancellation and attenuation. These five situations will cause the ILI in the signal transmission process in the forest. The simulation platform includes parameters such as high frequency electromagnetic wave, coherent wave, incident angle and amplitude, which are built to establish the attenuation equation of multi-layer medium model signal link. The result is that the channel matrix $G_{RD}BH_{SR}$ is not diagonal array, that is, the phenomenon of ILI will occur.

2) ILI ANALYSIS OF SIGNALS IN FOREST ENVIRONMENT

The causes of ILI can be further explained qualitatively by the schematic diagram. As shown in Fig. 6, the ranks of both cell channels are set 2.

$s_l^{(i)}$ $(i, l \in \{1, 2\})$ represents the l layer of the cell i, the two layers of one cell are orthogonal to each other, and the first layer of both cells is transmitted s_1, the second layer is transmitted s_2. As can be seen from the Fig. 6, after channel merging, the distance between s_1 and s_2 is very close, which is difficult to distinguish, and there is a great deal of ILI. The actual eigenvector space is a multi-dimensional complex space, and the eigenvalues and the elements of the eigenvector are complex numbers. Therefore, the phase problem should be considered when merging, which is not shown in Fig. 6.

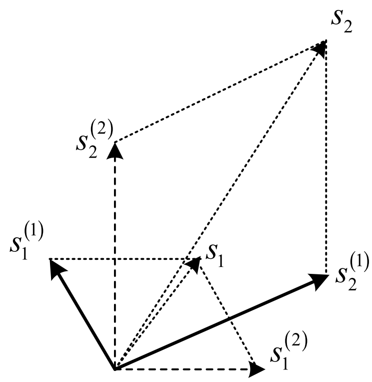


FIGURE 6. ILI schematic diagram of local precoding.

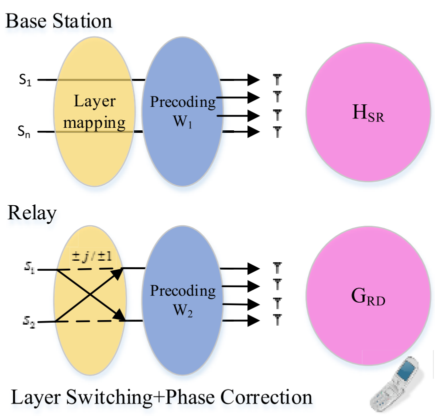


FIGURE 7. Precoding schematic diagram of the forest relay system that is based on layer-switching.

Generally, the original orthogonal characteristics between layers of merged logical channel $G_{RD}BH_{SR}$ are difficult to guarantee, which are influenced by many factors such as feature vector, eigenvalue and so on. At present, the ILI caused by this method is uncontrollable, so when considering the optimization based on local precoding, the ILI should be eliminated as far as possible. In addition, considering the signal phase problem, the gain of useful signal after merging should also be considered in the improvement.

C. IMPROVED PRECODING ALGORITHM FOR FOREST RELAY SYSTEMS

To overcome the ILI of the forest channel that is described above, an improved precoding algorithm for forest relay systems that is based on layer exchange and phase correction is proposed in this section and is illustrated in Fig. 7. The modulated signal is divided into several channels and mapped

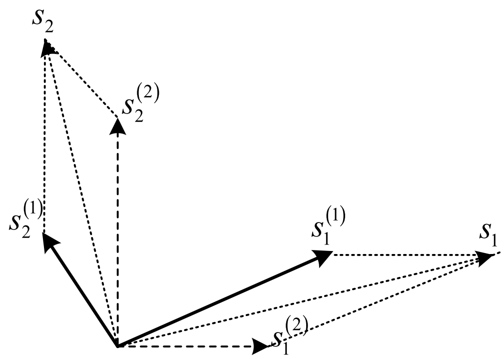


FIGURE 8. Schematic diagram of the layer switching strategy.

to each layer in a layered form. Each signal is sent to the transmitting antenna through the radio frequency circuit via the precoding module, resource allocation, power control and other steps. Layer switching, which is proposed in this section, occurs when each signal is mapped to each layer. The base station cell is considered as the criterion for changing the mapping relationship of the relay node cells to eliminate ILI. The whole process can exchange data not only between layers but also between data streams and layers. As an improvement, we multiply various phases for each layer, such as $\pm j$ or ± 1.

The layer switching strategy in Fig. 7 is further elaborated by Fig. 8. Based on the single relay node of a single cell, the two-layer data exchange of a base station cell can be effectively suppressed via relay node forwarding; however, the superimposed signal remains distorted due to the shadow of the forest tree environment when the relay node forwards each signal. The system also has the problem of signal phase offset; therefore, we use the method of "layer switching + phase correction" to design the forest environment channel matrix mapping, namely, the transmitted signal source (s_i) is to be designed. By adjusting s_i's phase and mapping it to each layer, we can transmit the subsequent intermediate protocol, which can increase the combined signal power and effectively eliminate the forest-to-forest interaction and, therefore, the signal ILI.

If the layer mapping matrix (including layer switching and phase correction) of the base station cell and the relay node coverage area is the relay node forwarding matrix B, then according to Eqs. (1-4), (6), and (8), the precoding scheme of the forest relay system that is based on layer switching is obtained as follows:

$$y = G \cdot G_{RD} B H_{SR} \cdot Fs + G \cdot G_{RD} B n_R + G \cdot n_D \tag{14}$$

with order

$$n = G\hat{n} = G \cdot G_{RD} B n_R + G \cdot n_D \tag{15}$$

Eq. (14) can be reexpressed as follows:

$$y = G \cdot H \cdot Fs + n = G \cdot G_{RD} H_{SR} F \cdot Bs + n \tag{16}$$

where n is the noise interference of the whole link from the base station to the relay node and, subsequently, to the terminal node in the forest. In Eq. (16), G_{RD}, H_{SR}, and F are known and fixed; therefore, the relay node forwarding matrix is designed based on the forest base station. Because the AF relay protocol is used, B is a diagonal matrix:

$$B = \begin{pmatrix} e^{j\theta_1} & 0 \\ 0 & e^{j\theta_2} \end{pmatrix} \tag{17}$$

Next, the layer mapping matrix G of the terminal node is designed. It represents the layer mapping scheme of layer switching and phase correction that is adopted in the relay coverage area, the results that are transmitted by forest relay system channel $G_{RD} H_{SR} F \cdot B$, and the multiplication characteristics of the matrix. We transform G into a diagonal matrix of the same rank:

$$G = \begin{pmatrix} 0 & e^{j\alpha_1} \\ e^{j\alpha_2} & 0 \end{pmatrix} \tag{18}$$

where $\alpha_1, \alpha_2 \in \left\{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\right\}$. This matrix uses the operations of layer switching and phase correction. At this time, G has $4^2 \times 2 = 32$ codewords from which to choose. In the actual design of the matrix, the layer mapping matrix can be determined according to the criterion of maximizing the SIR of the MMSE receiver.

In the above method, the core mechanism is to adjust the phase of the signal by adjusting the forwarding matrix on the relay node and the mapping matrix of the terminal node. At the same time, it can effectively suppress the ILI of multiple channels. Although this method will incur CSI feedback information overhead (approximately 32 bits), these bit codes eliminate the ILI between cells and improve the performance of the precoding scheme for forest relay systems.

IV. TRANSMISSION ANALYSIS OF FOREST RELAY SYSTEMS

The previous chapter analyses the signal transmission of the base station, a single relay node and a single terminal node. The system has only one terminal user at each time point. On this basis, this section analyses the general scenario of multi-terminal and multi-relay-node transmission, which will introduce a series of problems, such as modulation and coding scheme (MCS) prediction, resource management, and multiple access. Next, this paper discusses and analyses these problems.

A. SCENARIO ANALYSIS OF COLLABORATIVE TRANSMISSION IN FOREST RELAY SYSTEMS

The forest environment is complex in terms of topography, plant distribution, plant density and other objective factors. Therefore, if the existing mobile base station is placed in the forest, the traditional networking technology cannot cover the hot areas. Hence, at the edge of the base station, we add relay nodes to expand the network in the forest. These relay nodes and macrocell base stations use the same frequency to form a larger coverage area of the relay network.

A relay network has been adopted by LTE R10 [41], which has become a necessary co-frequency networking technology for improving the system throughput and the overall network

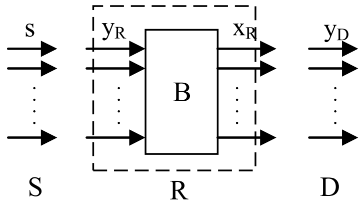


FIGURE 9. Forest relay node forwarding matrix (B matrix).

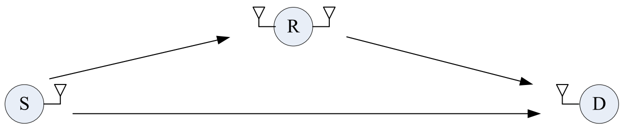


FIGURE 10. Category 1: Single forwarding node topology.

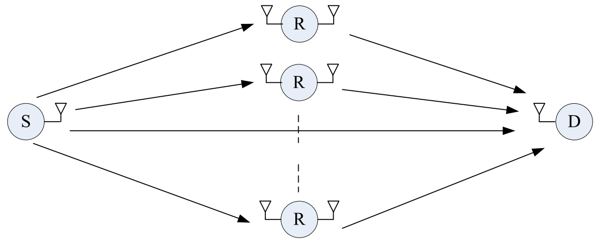


FIGURE 11. Category 2: Multi-relay node topology.

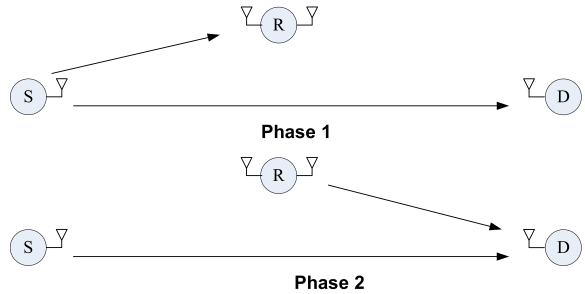


FIGURE 12. Category 3: Phased forwarding topology (transport flow).

efficiency. However, in the process of networking, we find that the ILI between a cell that is covered by relay nodes and the base station is substantial. Since there are many possibilities in terms of the locations of the relay nodes and the cooperative communication, this paper will study the joint transmission of relay nodes in forest areas.

The coverage of relay nodes is a hot area and provides a low-power base station within the coverage of the macro base station. Since the coverage area of the base station and the relay node overlap, the relay node is within the coverage area of the macro base station with high transmission power; hence, the terminal node is vulnerable to downstream interference from the macro cell. In such an environment, if cooperative transmission is adopted, the problem of intercell interference can be effectively solved. There are three scenarios for the joint transmission of a forest relay system: single forwarding node topology, multi-relay node forwarding topology and staged forwarding topology.

These three types of network topology are deployed. Category 1 and Category 2 mainly differ in terms of the system topology. The precoding method of a Category 2 cooperative forwarding node depends on multiple relay nodes and the virtual antenna array that is formed at the time of transmission. In Category 1, a single forwarding node is applied to the local antenna array of the source and relay nodes in a single relay system, while the main difference between the Category 3 topology and the Category 1 and 2 topologies is that the node source coding operation involves multiple time-domain sending symbols (vectors), rather than only space-domain coding operations.

B. ANALYSIS OF THE TRANSMISSION PRECODING SCHEME FOR FOREST RELAY SYSTEMS

The precoding scheme of forest relay systems is studied and improved to adapt the channel transmission matrix of the existing cell to the complex environment in the forest area. The relay node enlarges the coverage of the existing cellular cell. The precoding scheme in the preceding section will be demonstrated in scenario 3.

The precoding and improvement scheme of the forest relay system can adapt to all forest relay scenarios in Figs. 10-12. Consider scenario 3 as an example: The base station and the relay node jointly serve terminal node D and the base station can also provide services to non-relay cell and terminal nodes that are within its coverage.

In the special forest environment, due to objective factors such as trees and the topography, terminal node D can only feed limited CSI information back to R, and the channel is $G_{RD}^{(m)}$. Similarly, the channel that the R feeds back to S is $H_{SR}^{(m)}$. When R sends data to D, precoding is performed according to G_{RD} and B forwarding matrices in a single-user cooperative manner. When the cell base station transmits data to users and relay nodes, precoding is conducted via multi-user cooperation based on the feedback information from $H_{SR}^{(m)}$ and $G_{RD}^{(m)}$. Furthermore, if a node has parameter feedback regarding phase correction, coherent merging can be considered at the relay node and the terminal. The precoding of D by the R and S, namely, the precoding of the forest relay system, is conducted separately.

So far, this paper has presented a brief and comprehensive analysis of an improvement precoding scheme for forest relay systems. Considering one of the scenarios as an example, it describes how the signal expands its coverage in the forest via relay nodes. The analyses of the other scenarios are similar; only the transmission order of the signal changes. Compared with the traditional cellular cell, the increased number of relay nodes can participate in the expansion of the network coverage as cooperative transmission nodes. In addition to the change of precoding, the cooperative multi-point transmission scheme of forest relay systems also involves resources. The simulation platform must be built more carefully for management, multiple access allocation, antenna pairing, and MCS prediction, among other tasks. However, the research results of this paper are not limited to forest relay system transmission.

TABLE 1. Simulation parameter settings.

Parameter	Value
Carrier	3.5 GHz
Working bandwidth	10 MHz
User mobile speed	3 km/h
Channel model	ITU-UMa, Umi
Base station antenna configuration	Base station: 8 transmitting antennas (two nodes, with four antennas per node)
Base station antenna spacing	Half wavelength
User antenna configuration	Two receiving antennas
User antenna spacing	Half wavelength
Antenna polarization angle	Base station: +/-45°; User: 90/0°
Feedback scheme	LTE PMI feedback
Link adaptation	Rank adaptation, AMC, HARQ
Receiver	MMSE receiving
Rank of Base Station Cell	2
Rank of Relay Cells	2

V. SIMULATION RESULTS AND ANALYSIS

MATLAB is used to simulate the performance of the proposed relay selection method. The parameters are as follows: a forest environment of 1000 m × 1000 m is simulated, the source node (S) is located at (0, 0), the terminal node (D) is located at (1000, 1000), and relay nodes are distributed in a central region that is defined by (400, 600), (600, 600), (400, 400), and (600, 400). The *MonteCarlo* simulation method is adopted—at every time, a new relay node can quickly be regenerated. The decline factor of the line-of-sight transmission between S and R is 2.35. R and D, along with S and D, adopt non-line-of-sight transmission; according to the calculation of forest environmental factors, the decline factor is 3.75. The wireless channel is a frequency-selective channel and a model with 6 similar Rayleigh [11] flat fading channels is adopted. The packet length is 1024 bits and the packet interval is 50 ms. The simulation parameters are listed in Table 1.

Considering an SNR from -10 dB to 10 dB, the signal undergoes fast fading. Users use PMI feedback, namely, the index number that represents the precoding matrix is fed back to the transmission node.

Without loss of generality, this paper simulates and analyses the scenarios that correspond to the following factors:

(1) The rank of both plots is 2;

(2) Channel correlation/non-correlation;

(3) The system adopts the precoding of the original local or the improved forest relay system;

(4) The average received powers by the user from two cells are equal or differ by 5 dB.

A. SIMULATION AND ANALYSIS OF THE IMPROVED PRECODING ALGORITHM FOR FOREST RELAY SYSTEMS

Since the improved precoding algorithm for forest relay systems aims at overcoming the ILI with more than one transmission layer, our simulation considers a non-correlated forest

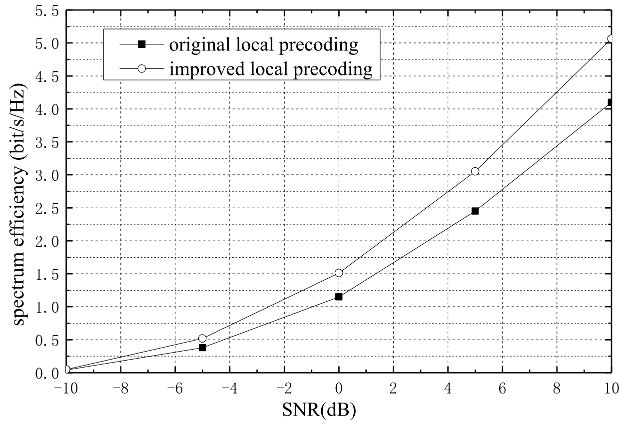


FIGURE 13. Performance of the improved precoding algorithm for forest relay systems with received power balance (uncorrelated channel with rank 2).

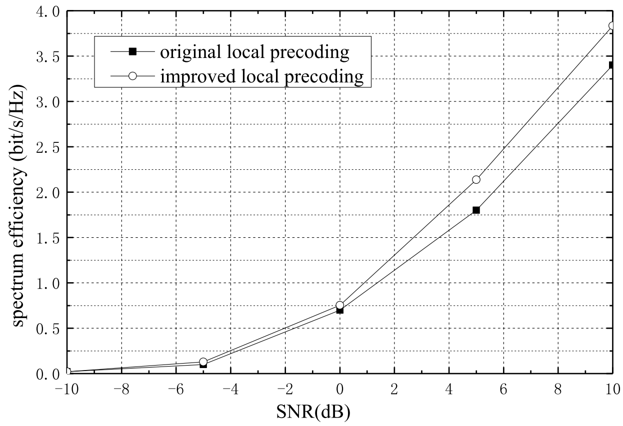


FIGURE 14. Performance of the improved precoding algorithm for forest relay systems with unbalanced receiving power (uncorrelated channel and rank 2).

channel with rank 2. Considering the coverage area of the base station cell and the relay node, there are two cases: received signal power balance and received signal powers that differ by 3 dB between these two cells. The simulation results are plotted in Fig. 13 and Fig. 14. According to the plots, the improved precoding algorithm of forest relay systems, which is based on layer switching, has substantial performance advantages with the increase of SNR. For comparison, a relay system precoding scheme without layer switching is adopted here.

According to Fig. 13, when SNR is -10 dB, the original local precoding algorithm is consistent with the forest relay transmission method that is proposed in this paper and the spectral efficiency is almost zero. This demonstrates that in the case of very low SNR, the useful signal is completely submerged in noise, while the cooperative relay transmission technology mainly eliminates ILI. With the increase of SNR, the spectral efficiency of the terminal nodes in blind areas of the cell edge increases gradually and the improved forest relay transmission scheme grows faster. When the SNR is 10 dB, the efficiency of the user spectrum at the edge of the cell in our proposed forest relay transmission scheme is approximately 1 bit/s/Hz higher than that of the original local precoding scheme. This is because the proposed forest relay system cell introduces layer switching and phase correction operations while improving the distribution of the precoding matrix. The objective of this operation is not only to improve the mapping relationship between the data flow and the layer based on the complex channel environment in the forest but also to refer to the phase. The strategy of phase correction in coherent joint transmission can eliminate the ILI of the original local precoding algorithm more effectively, which will incur CSI information feedback overhead; however, it is acceptable to sacrifice spectrum resources to eliminate the ILI.

Fig. 14 and Fig. 13 differ in terms of whether the receiving power is balanced or not. The trends of these two plots are consistent: With the increase of SNR, the performance advantage of improved precoding scheme for forest relay systems increases over the original precoding scheme in terms of the user spectrum efficiency at the edge of the cell. When the SNR is 10 dB, the improved algorithm improves the user spectrum efficiency by approximately 13% compared with the original algorithm. When the receiving powers differ, the system performance is typically lower compared to the scenario of receiving power balance.

The schemes of precoding layer switching and phase correction for forest relay systems that are proposed in this paper correspond to several schemes at the transmitter and receiver, which can be selected according to the criterion of maximum SNR. In addition, in the simulations, only the case in which the rank of the cell and the relay node is 2 is considered; however, this approach is not limited to this case in practice. When the number of relay nodes that are cooperating increases, the base station cell is used as the benchmark to change other relay node layer mapping schemes that are cooperating; however, the terminal must coordinate the impact of overlapping coverage of multiple relay nodes. As the number of transmission layers increases, the dimension of the layer mapping matrix also increases and the number of available codewords increases to $4^l \times 2$ (l is the layer number).

B. OVERALL PERFORMANCE ANALYSIS OF THE FOREST RELAY SYSTEM

Now, we incorporate the precoding scheme that is discussed above into the existing relay protocol and apply it to the forest environment for evaluation. First, we simulate the spatial channel mapping under the MMSE relay protocol. The independent and identically distributed (i.i.d.) similar Rayleigh fading channel is assumed in this section. Without loss of generality, the average SNR is defined by Eq. (5). The average outage probability is considered as the criterion, which is defined as:

$$P_{out} = \frac{1}{N_S} \sum_{i=1}^{N_S} \Pr(\gamma_i < \gamma_{th}), \gamma_{th} = 1 \tag{19}$$

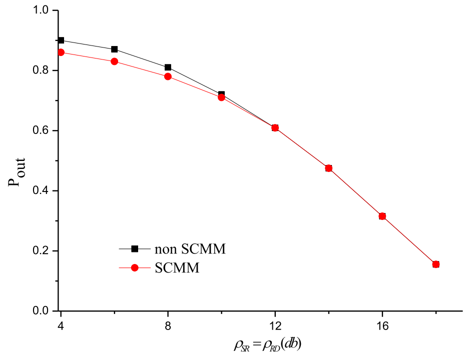


FIGURE 15. $N_S = N_R = N_D = 2$, $\rho_{SR} = \rho_{RD} = 16dB$, **and outage probability** B.

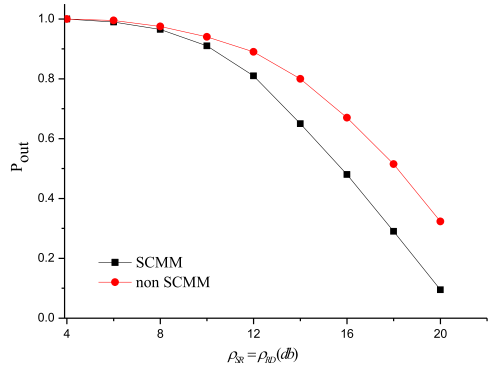


FIGURE 16. $N_S = N_R = N_D = 2$, $\rho_{SR} = \rho_{RD} = 16dB$, **and outage probability.**

The reliability and performance of the system can be improved by incorporating the inter-layer channel mapping matrix. In this chapter, we consider various single-source single-relay and single-destination systems and assess the universality of the forest spatial channel mapping matrix. In the results in this section, "non SCMM" indicates that B does not have the forest inter-layer channel mapping incorporated into the relay protocol and "SCMM" indicates that B has the forest inter-layer channel mapping incorporated into the relay protocol.

1) MMSE RELAY PROTOCOL

In this part, we consider the forest inter-layer channel mapping matrix under the MMSE relay protocol [34]–[36]. The source node's precoder F is constituted by the right singular vector N_S in H_{SR}. We set $N_S = N_R = N_D = 2$ and $\rho_{SR} = \rho_{RD}$ and the receiver D uses G as the MIMO equalizer.

The forest inter-layer channel mapping matrix should be designed via Eq. (17). According to Fig. 15, since we consider B in the relay node, the performance enhancement with B is larger. This result is consistent with the theoretical analysis.

2) MMSE+ I

In this section, the spatial channel mapping under the MMSE relay protocol is considered with the reverse filter unchanged. The feedback overhead matrices $H_{SR}^{(m)}$ and $G_{RD}^{(m)}$ are also used and the channel precoding matrix of the base station is set as a unit array, namely, $F = I$. According to Section 3, the matrix B should be designed via Eqs. (17) and (18). Set $N_S = N_R = N_D = 2$ and $\rho_{SR} = \rho_{RD}$. D uses M as the equalizer.

The MIMO equalizer is necessary even if B is not used; therefore, the use of B does not increase the complexity at D under this assumption. According to Fig. 16, B is designed via Eq. (17), G is designed via Eq. (18), the total noise power is reduced at D and the system reliability and the spectral efficiency performance are both improved. If the backward filter uses the ZF equalizer and D uses an identity matrix, then the forest inter-layer channel mapping matrix does not further change the performance.

VI. CONCLUSION

Based on matrix theory and linear algebra, via theoretical calculation and deduction, this paper innovatively deploys the existing relay cooperative network to the cell base station in a forest environment to overcome the problem of lack of signal on the edge of the forest environment coverage are. It is proposed that a spatial channel mapping moment that is suitable for the forest environment be added to the relay node. The additional space channel mapping matrix is based on a matrix of the same rank, which, according to matrix theory, can be added and multiplied and the row and column factors in each matrix can be changed via multiplication by several matrices. To overcome the problem of ILI in the precoding algorithm of the forest relay system, a layer-switching-based method is proposed. Layer switching acts on the layer mapping module prior to precoding the data in the actual system. It has no effect on the original precoding mode. The objective is to avoid ILI while maximizing the received signal power of the terminal. The layer switching strategy must be determined from the channel information of each layer according to user feedback.

This paper is based on the research on single relay node transmission; however, the presented research results are not limited to this scenario. For generality, this paper also analyses several possible scenarios of multi-user cooperative multipoint transmission and demonstrates the application and the improved performance of the precoding scheme. Finally, several possible scenarios are simulated and compared with the original scenario. The simulation results demonstrate that the improved scheme that is proposed in this paper substantially improves the performance and can be applied to coherent/incoherent channels, low/high rank channel and other scenarios.

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