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Power allocation and mode selection methods for cooperative communication in the rectangular tunnel

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ABSTRACT

For the multipath fading on electromagnetic waves of wireless communication in the confined areas, the rectangular tunnel cooperative communication system was established based on the multimode channel model and the channel capacity formula derivation was obtained. On the optimal criterion of the channel capacity, the power allocation methods of both amplifying and forwarding (AF) and decoding and forwarding (DF) cooperative communication systems were proposed in the limitation of the total power to maximize the channel capacity. The mode selection methods of single input single output (SISO) and single input multiple output (SIMO) models in the rectangular tunnel, through which the higher channel capacity can be obtained, were put forward as well. The theoretical analysis and simulation comparison show that, channel capacity of the wireless communication system in the rectangular tunnel can be effectively enhanced through the cooperative technology; channel capacity of the rectangular tunnel under complicated conditions is maximized through the proposed power allocation methods, and the optimal cooperative mode of the channel capacity can be chosen according to the cooperative mode selection methods given in the paper.

1. Introduction

Tunnel wireless communication is the bottleneck which restricts the information transmission in the mines, underground facilities and other complex environments [1–3]. The space-limited tunnels, which are not only narrow but also with lots of branches, corners, ramps, greatly differ from free space [4,5], shown as Fig. 1. Propagating in the tunnels, the electromagnetic waves would frequently reflect and scatter, which leads to the multipath fading effect in tunnel communication and results in the propagation loss of electromagnetic waves [6–8]. The transmission distance is shortened and the direct information transmission between two nodes is even prevented in the complex environments, such as tunnel branches, corners and ramps moreover.

Cooperative communication technology utilizes the broadcast nature of the wireless communication. The nodes share the antenna of each other through a certain way and a virtual multiple input multiple output (VMIMO) system is formed [9,10]. Based on different processing modes for the receipt signals at the relay node, cooperative communication is mainly divided into two categories: AF and DF [11,12]. With cooperative communication, the wireless communication channel capacity can be improved without increasing the number of antennas in tunnels. Especially coming to the complex environments in the confined areas, such as branches, corners and ramps, efficient information transmission could not be achieved directly between nodes, which will be solved through the relay cooperative.

Channel capacity is an important performance indicator of cooperative communication system. From the perspective of information theory, the channel capacity of different cooperative modes were analyzed [12]. Based on Complex Gaussian random distribution channel, the ergodic capacity expression and its upper bound of AF system were deduced; the approximately optimal power allocation scheme, regarding the upper bound of the ergodic capacity as the objective function, was proposed [13]. On account of the Rayleigh channel model, the relay selection of multiple-source multiple-relay cooperative communication system was studied and the problem on maximizing the minimum channel capacity was resolved through standard branch boundary algorithm [14]. Yu et al. modeled the multiple-relay-assisted communication system as a two-hop communication link, and the relationship between the upper bound of the system channel capacity and the number of the cooperative relays was given in

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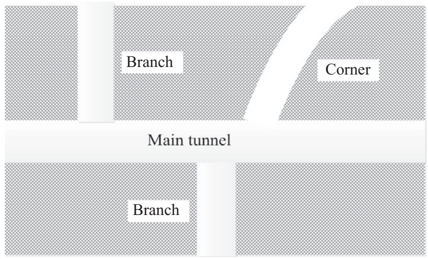
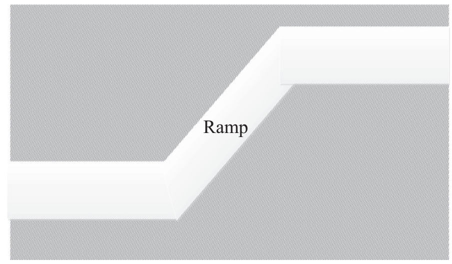


(a) Branches and corners



(b) Ramps

Fig. 1. Schematic diagram of the branches, corners and ramps in the rectangular tunnel.

two special cases [15]. Guo et al. studied the optimization of channel capacity of the multiple-user cooperative communication network and system reliability, and optimize the tradeoff relationship of the cooperative communication system by selecting the appropriate partners and power allocation schemes [16]. However, there is no systematic study on the channel capacity of the cooperative communication at the background of the tunnel environments.

For the study on the existing tunnel channel models, lots of theoretical derivation and simulation analysis were based on the Rice distribution, Rayleigh distribution and other random channel models. Because of the complexity of the tunnel environments, the propagation properties of the electromagnetic waves in the rectangular tunnel, described by the random channel models, have large deviations, compared to the actual measurements. Nevertheless, the simulation results have much higher agreement with the actual measurements while the multimode channel model is used to research the electromagnetic wave propagation in the rectangular tunnel [7,17].

In this paper, based on the multimode channel model, SISO and SIMO rectangular tunnel cooperative communication systems in the complex tunnel environments are established, and the channel capacity is deduced. Considering the channel capacity maximization as the optimal criterion, the optimal power allocation methods and mode selection methods of cooperative communication in rectangular tunnel are proposed and validated by simulating analysis under the limited total power.

2. Rectangular tunnel cooperative communication systems

2.1. Multimode channel model

It was beneficial for the electromagnetic waves to propagate in the UHF band in tunnels, since the propagating attenuation was much smaller based on the study on the propagation of the electromagnetic waves [7,18]. Therefore, the tunnel was regarded as lossy dielectric wave guide [7,18,19], and the channel gain could be calculated by the multimode channel model in the rectangular tunnel [17,19].

The cross-section of the tunnel is modeled as a rectangular whose width is $2a$ and height is $2b$, as shown in Fig. 2. Cartesian

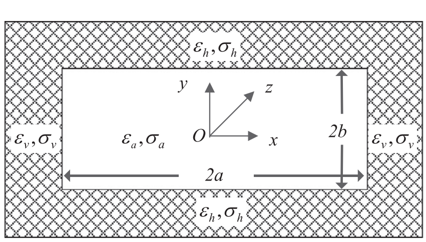


Fig. 2. Schematic diagram of the rectangular tunnel.

coordinate system is established, regarding the center of the rectangular as the origin of the coordinate.

In Fig. 2, x, y, z directions are along the width, height and length of the tunnel respectively. ε_v, ε_h and ε_a are the relative permittivity of the side walls, the floor and ceiling of the tunnel and the air in the tunnel respectively; σ_v, σ_h and σ_a are the conductivity of the side walls, the floor and ceiling of the tunnel and the air in the tunnel respectively.

Based on the multimode theory, the channel gain between the transmitting antenna Tx and the receiving antenna Rx in the tunnels is as Eq. (1) [17,19]:

$$h_{TxRx} = \sqrt{G_{Tx}G_{Rx}}\sum_{m,n}[E^{eign}_{mn,(x_{Rx},y_{Rx})} \cdot C_{mn,Tx} \cdot e^{-(\alpha_{mn}+j\beta_{mn})z_{TxRx}}] \tag{1}$$

where G_{Tx} and G_{Rx} are the gains of the transmitting antenna Tx and receiving antenna Rx; m and n represent the order of the wave mode; $E^{eign}_{mn,(x_{Rx},y_{Rx})}$ is the field distribution of (m, n) wave mode at the receiving antenna Rx; $C_{mn,Tx}$ is the intensity of (m, n) wave mode at the transmitting antenna Tx; α_{mn} is attenuation coefficient and β_{mn} is phase coefficient of (m, n) wave mode, which are determined by the frequency f, relative permittivity (ε_v, ε_h and ε_a)and conductivity (σ_v, σ_h and σ_a); Z_{TxRx} is the distance between transmitting antenna Tx and receiving antenna Rx; $e^{-(\alpha_{mn}+j\beta_{mn})\cdot z_{TxRx}}$ is the attenuation along z.

2.2. Cooperative communication model

The cooperative communication systems in the tunnel environments, which are shown as Fig. 1a and b, can be abstracted to SISO and SIMO cooperative communication models, displayed as Fig. 3a and b. There are three kinds of nodes in the models: source node S, relay node R and destination node D.

Cooperative communication in the rectangular tunnel includes two stages. During the first stage, the source node S broadcasts signals while the relay node R and destination node D receive signals. During the other stage, the relay node R processes and forwards the signals, and the destination node D receives signals.

In the first stage, the receipt signals of the relay node R and the destination node D are

$$y_r = \sqrt{P_s}h_{sr}x + n_r \tag{2}$$

$$y_{d1} = \sqrt{P_s}h_{sd}x + n_{d1} \tag{3}$$

In the second stage, the destination node D receives signal

$$y_{d2} = \sqrt{P_r}h_{rd}q(y_r) + n_{d2} \tag{4}$$

Among Eqs. (2)–(4), P_s is the transmission power of the source node S and P_r is the transmission power of the relay node R; h_{sd}, h_{sr} and h_{rd} denote the channel gains between the source node S and destination node D, the source node S and relay node R, the relay node R and destination node D respectively. x denotes the