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Research and analysis of OSTBC in the mine tunnel

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Abstract

This paper builds three dimensions GBSB tunnel model, and analyses the performance of OSTBC in coal mine underground on the basis. The correlation of MIMO channel is very strong in a tunnel. The capability of OSTBC symbol error and the effect of the channel correlation are analyzed on the assumption that there are multi transmitted antennas and only one received antenna. The simulation results show that OSTBC symbol error rate could be decreased obviously by increasing the number of the transmitted antennas, and that change the placing angle of the antennas could also improve the upper bound of OSTBC symbol error rate.

Keywords: mine tunnel; MIMO; OSTBC

1. Introduction

MIMO is the technology breakthrough of modern wireless mobile communication. To make use of transmitted channel increased in space, the signal is transmitted by multi-antenna. For the signals sent out simultaneously by the transmitted antennas occupy the same frequency band, the system capacity will increase multiplied by contrast of single in single out system if the frequency band stay the same.

Wireless mobile communication remains the problem hard to resolve in coal mine underground. However, the technology developed so slowly that the breakthrough of it is cried out for. Research on MIMO technology is still limited on the ground and indoor, but the research on MIMO used in coal mine is rarely [1-2].

This paper depends on GBSB(Geometrically Based Single-Bounce) method, builds MIMO channel model in three dimensions coal mine for the first time, and researches the property of OSTBC (Orthogonal Space-Time Block Codes), then analyses the feasibility of MIMO technology applied to coal mine underground.

2. Three dimensions GBSB model in tunnel

In coal mine the long and narrow space, the configuration of the tunnel walls in coal mine is complex, and the walls in tunnel are rougher than indoor [3-4]. So there will be biggish dispersion in tunnels. Different from geometrical distribution in microcell and indoor environment, the scattering objects in the tunnel always distribute...
on both sides and the top and the bottom wall. The pitching angles arrived to receiver should not be neglected. From
the above, MIMO models in microcell and indoor environment are unsuitable for tunnel environment.

The differences of MIMO model between ground and tunnel are as follows:

1) The geometrical distribution of scattering objects in the ground model is different from that in the tunnel very
much, which is decided by the especially situation in tunnels.

2) The size of tunnel model is smaller than any ground model, so approximate arithmetic is unfit for some
deductions.

3) The loss of the electromagnetic waves in the coal mine tunnel is too large to consider multi-dispersion.

Fig. 1 and Fig. 2 show GBSB models, in which the transmission between dual omni-directional antenna arrays is
considered.

Suppose that $2a$ and $2b$ is the width and height of the tunnel respectively. The coordinate system is with $x$
horizontal, $y$ vertical, and $z$ along the tunnel. The transmitter and the receiver are immobility. The antenna arrays are
both equidistant linear arrays, and all the antennas are omni-directional. Define $D_B$ as the distance between the
antennas in the base station, and $D_r$ as the as the distance between the antennas in the mobile station. $T_p$ and $T_q$
denote the antennas which centered in $(x_t, y_t, 0)$ in the base station, and the horizontal angel of them is $\alpha_\parallel$ which
expressed by $(\alpha_\parallel, \alpha_\perp)$. $R_m$ and $R_n$ denote the antennas which centered in $(x_r, y_r, z)$ in the mobile station, and the
horizontal angel of them is $(\alpha_\parallel, \alpha_\perp)$. $S$ is the scattering object distributed on the side walls of the tunnel random
evenly.

$h_{pm}(t)$ is the equivalent impulse response on the path from $T_p$ to $R_m$. Then the transmitted power is

$$\Omega_{pm} = E[h_{pm}(t)]|^{\leq 1}. \text{ We consider } h_{pm}^{\text{DIFF}}(t) \text{ and } h_{pm}^{\text{LOS}}(t) \text{ is the equivalent impulse response of the scattering component and the line-of-sight component, and } \frac{1}{N} \sum_{n=1}^{\infty} E[g_n^2] = 1, \text{ in which } N \text{ is the number of the independent scatterers, and } g_n,$$

is the gain introduced by the scatterer $S$. The influence of Doppler shift is not considered because of the slow
mobile rate of the objects in coal mine. Then

$$h_{pm}(t) = h_{pm}^{\text{DIFF}}(t) + h_{pm}^{\text{LOS}}(t) \quad (1)$$

$$h_{pm}^{\text{DIFF}}(t) = \left[ \frac{\Omega_{pm}}{K_{pm}+1} \right] \lim_{N \to \infty} \frac{1}{N} \sum_{n=1}^{\infty} g_n \exp[j2\pi \frac{d_{pm}}{\lambda}] \quad (2)$$

$$h_{pm}^{\text{LOS}}(t) = \left[ \frac{\Omega_{pm}K_{pm}}{K_{pm}+1} \right] \exp[-j2\pi \frac{d_{pm}}{\lambda}] \quad (3)$$

where the path distances $d_{ps}, d_{sm}, d_{pm}$ are showed as Fig. 1 and Fig. 2. $\phi$ that subjects to $[0, 2\pi]$ of the uniform
distribution is the random phase shift introduced by scatterer $S$. $g_n, \Phi_n$ are all the independent random variables.

$K_{pm}$ is Rice factor from transmit antenna $T_p$ to received antenna $R_m$. $K_{pm} = |h_{pm}^{\text{LOS}}(t)|^2 / E[|h_{pm}^{\text{DIFF}}(t)|^2]. \lambda$ is the
wavelength. As the scatterers are independent to each other, then based on central limit theorem, $h_{pm}^{\text{DIFF}}(t)$ is the zero-mean complex Gaussian random variable when the scattering number $N \to \infty$.

The related feature of the channels is so important to the performance of the MIMO system that it is inevitable to
consider and study the space-time correlation when modeling MIMO channel. The space-time correlation function of two transmission links $h_{pm}(t)$ and $h_{qn}(t)$ is defined as
\[ \rho_{pm,qn}(\tau, t) = \rho_{pm,qn}(\tau) = E[h_{pm}(t)h_{qn}^*(t + \tau)]/\sqrt{\Omega_{mp}\Omega_{nq}} \]

where * is the complex conjugate.

Work over scattering component and the line-of-sight component respectively, then the corresponding space-time correlation functions are

\[ \rho_{pm,qn}^{\text{DIF}}(\tau, t) = \rho_{pm,qn}^{\text{DIF}}(\tau) = E[h_{pn}^{\text{DIF}}(t)h_{qn}^{\text{DIF}*}(t + \tau)]/\sqrt{\Omega_{mp}\Omega_{nq}} \]

\[ \rho_{pm,qn}^{\text{LOS}}(\tau, t) = \rho_{pm,qn}^{\text{LOS}}(\tau) = E[h_{los}(t)h_{qn}^{\text{LOS}*}(t + \tau)]/\sqrt{\Omega_{mp}\Omega_{nq}} \]

Hypothesis that the links of scattering component and the line-of-sight component are independent to each other, then the space-time correlation function between \( h_{pm}(t) \) and \( h_{qn}(t) \) is

\[ \rho_{pm,qn}(\tau) = E[h_{pm}(t)h_{qn}^*(t + \tau)]/\sqrt{\Omega_{mp}\Omega_{nq}} = E[(h_{pm}^{\text{DIF}}(t) + h_{pm}^{\text{LOS}}(t))(h_{qn}^{\text{DIF}*}(t + \tau) + h_{qn}^{\text{LOS}*}(t + \tau))]/\sqrt{\Omega_{mp}\Omega_{nq}} \]

\[ = E[h_{pn}^{\text{DIF}}(t)h_{qn}^{\text{DIF}*}(t + \tau)]/\sqrt{\Omega_{mp}\Omega_{nq}} + E[h_{los}(t)h_{qn}^{\text{LOS}*}(t + \tau)]/\sqrt{\Omega_{mp}\Omega_{nq}} = \rho_{pm,qn}^{\text{DIF}}(\tau) + \rho_{pm,qn}^{\text{LOS}}(\tau) \]

On substituting for Eq. (2) into Eq. (5), we obtain

\[ \rho_{pm,qn}^{\text{DIF}}(\tau) = \frac{1}{\sqrt{[1 + K_{pm}][1 + K_{qn}]}} \lim_{N \to \infty} \frac{1}{\sqrt{N}} \sum_{i=1}^{N} E(g_{i}^{2}) \exp\{-j \frac{2\pi}{\lambda}(d_{ps} + d_{sm} - d_{qs} - d_{sn})\} \]

Because the cross section of the tunnel is relatively small, and the distances between antennas and tunnel walls are nearly, the path length \( d_{ps} - d_{qs} \), \( d_{sm} - d_{sn} \) could not be approximated as ground model but obtained by analytical method.

From (3) and (5), correlation coefficient between direct inter-components is get,

\[ \rho_{pm,qn}^{\text{LOS}}(\tau) = \frac{K}{K + 1} \exp\{-j \frac{2\pi}{\lambda}(d_{pm} - d_{qn})\} \]

Thus the MIMO channel model in tunnel is finished, meanwhile the correlation coefficient between direct inter-components.

3. OSTBC

OSTBC is brought forward by Tarokh, etc. based on Alamouti code. The signals sent out by each antenna are orthogonal to each other. Thus, it can guarantee to get the largest diversity gain in slow flat fading channel, and to reduce the difficulty of decoding [5-6].

Suppose that there are \( n_{T} \) antennas at transmitter and \( n_{R} \) antennas at receiver. \( (x_{1}, x_{2}, \ldots, x_{k}) \) is the information symbol sequence need to send. The space-time code matrix of \( n_{T} \times p \) is

\[ C = \begin{bmatrix} C_1^1 & C_2^1 & \cdots & C_p^1 \\ C_1^2 & C_2^2 & \cdots & C_p^2 \\ \vdots & \vdots & \ddots & \vdots \\ C_1^n & C_2^n & \cdots & C_p^n \end{bmatrix} \]

where \( C_i^j \) \( (i = 1, 2, \ldots, p; j = 1, 2, \ldots, n_T) \) is the signal sent out from the \( n_{T} \) th antenna at \( i \) moment, and the linearity combination between \( x_1, x_2, \ldots, x_k \) and its conjugate \( x_1^*, x_2^*, \ldots, x_k^* \).

Consider \( h_{ji} \) \( (i = 1, 2, \ldots, n_T; j = 1, 2, \ldots, n_R) \) as the attenuation coefficient from the \( i \) th transmitted antenna to the \( j \) th received antenna. The signal received by the \( j \) th antenna at No. \( t \) slot \( r_j^t = \sum_{i=1}^{n_T} h_{ji}C_i^t + n_i^t \). Received signal matrix is obtained by the received antenna array, and then the receiver computes and adjudges the pairs of code words \( C \).
The code character set that makes the value of the decision formula smallest is got. Then the maximum likelihood decoding is finished.

To the classical two antenna space-time block codes, its matrix is

\[
\begin{bmatrix}
-1 & 1 \\
0 & -1 \\
1 & 1 \\
0 & 0
\end{bmatrix}
\]

When there is single received antenna, if the receiver could fully restored the channel state information, then the statistics of the judgments of the received signal and the state of the channel are [7-8].

\[
\tilde{x}_1 = h_1^* r_1 + h_2^* r_2
\]

\[
\tilde{x}_2 = h_2^* r_1 + h_1^* r_2
\]

Suppose that each source symbol sent the same transmitted power which is \( E_S \). Then from Eqs. (11) and (12), receiver output could be equivalent to two times the output of independent slip with the same received signal to noise.

\[
R_{\text{SNR}} = \sum_{i=1}^{2} |h_i|^2 \frac{E}{E_0}
\]

The same, in MIMO OSTBC system, the received signal to noise of each slip is

\[
R_{\text{SNR}} = \sum_{i=1}^{2} \sum_{i=1}^{2} |h_i|^2 \frac{E_i}{N_0}
\]

The transmitted information symbol sequence is \( \{x_1, x_2, \ldots, x_k\} \), then its general power is \( E_{\text{tot}} = n E_s \).

So, Eq. (14) converted to,

\[
R_{\text{SNR}} = \sum_{i=1}^{2} \sum_{i=1}^{2} |h_i|^2 \frac{E_i}{n_i N_0}
\]

When the general power of the transmitted signals is limited, the instantaneous symbol error rate adopted of the minimum distance between a ball circles can not larger than [9-10]

\[
P_{\text{err}}(h_{ji}) \leq \exp\left(-\frac{d^2}{4P_n}\right) = \exp\left(-\frac{1}{4P_n} \sum_{i=1}^{2} |h_i|^2 \frac{E_i}{n_i N_0}\right)
\]

4. Simulation and analysis

4.1. Relevant characteristics of simulation

The parameters selected refer to document [11], in which the tunnel with 5 m width and 3 m height, and the antenna arrays are configured for 2x2. Suppose that the frequency of the carrier wave is 900 MHz, and the distance between the base station and the mobile station is 300 m, and the transmitter antenna spacing is \( 7\lambda \), while the received antenna spacing is \( 0.0 \). The mobile terminal antenna angle placed to \( 0 \), and \( K=0 \).the relationship between the correlation coefficient \( \rho_{pm,qt} \) and the placing angle of the base station antenna is shown in Fig. 3.

As shown in Fig. 3, the influence of the horizontal angle of the antenna is large to the correlation coefficient, while it will reduce slowly with the increase of the pitching angle only if the horizontal angle is 0. From the simulation result, if the antennas placed to the same horizontal, and the horizontal angle is \( \pi / 2 \), namely vertical to the side walls, the space-time correlation coefficient is the smallest. The conclusion is consisted with Reference [11], in which only measured the multi-antenna system placed on the same horizontal.
4.2. Performance analysis of OSTBC

The simulated circumstance is the same as the above. The MIMO system antennas configured for 1×1, 2×1, 4×1, respectively. Adopted BPSK modulate. Then in Eq. (16), $\mu = 1/4$. Fig. 4 depicts the simulated result of STBC symbol error rate upper bound. It can be concluded that the performance of STBC symbol error rate could be improved obviously by increase the number of the transmitted antennas.

![Fig. 4. Symbol error rate curve](image)

![Fig. 5. The relationship of symbol error rate and the antenna angle](image)

Fig. 5 depicts the relationship of symbol error rate and the antenna angle. It shows that the placing angle could affect the symbol error rate very much. The symbol error rate decreases with the increase in the angle with the antennas and the side wall. This means indirectly that the placing angle of antennas in coal mine underground influences the correlation of each slip of MIMO channel.

5. Conclusion

1) The antenna placing angle could influence the corresponding correlation directly. The larger the angle, the smaller the correlation.
2) The upper bound of OSTBC symbol error rate could be improved obviously by increase the number of the transmitted antennas.
3) Change the placing angle of the antennas also could improve the upper bound of OSTBC symbol error rate, as a result of the effect of the channel correlation on the OSTBC performance.

So the correlation between links could be reduced as long as placing the antennas reasonable. MIMO OSTBC could improve the reliability obviously, so it is feasible to use MIMO technology in coal mine underground.
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