Optimal Antenna Installation Position Analysis for Wireless Networks in Underground Tunnels

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Abstract—**Field coverage is strongly affected by the antenna position because of the multimode waveguide characteristics in the underground tunnel. This is critical for the wireless system to have a satisfied performance. In order to investigate the optimal installation location of the antenna in tunnel, the coupling relation between the antenna current distribution and the propagation modes in the underground tunnel is derived. On this basis, the best excited modes, the coupling loss and the radio coverage for antenna at different positions are compared and discussed. Results show that the most suitable installation location for the non-mobile wireless nodes such as AP is the middle of the tunnel ceiling.**

Keywords— field coverage; antenna position; multimode waveguide theory; underground tunnel; wireless network

I. INTRODUCTION

Small fading and uniform field coverage not only reduce data retransmissions, enhance the reliability of the link, but also reduce the power consumption and cost of the wireless devices. The existing measurements [1,2] and simulations [3~5] make more and more people realize that the wireless coverage of the system is very sensitive to antenna position in the underground tunnel which is a kind of narrow and limited environment. However, the current measurements are still very limited, and the theoretical explanation and mechanism analysis of this phenomenon are not detailed enough.

In order to better guide the design and deployment of wireless communication devices, the theory of multimode waveguide [6,7] is used to deduce the coupling relation between the antenna current distribution and the propagation modes in the roadway. Then the effectively coupled modes and their propagation loss, and the overall coupling loss versus different antenna locations are analyzed and compared. Based on the above, the best installation position of the antenna with a small fading and uniform coverage is studied.

II. THEORY

Suppose the width of a rectangular hollow and straight tunnel is w, height is h, and rectangular coordinate system is adopted. The origin is located at the center of the cross-section of the tunnel, x, y and z are respectively along the width, height and length of the tunnel.

The electromagnetic field of antenna in the tunnel is positively or negatively radiated along the z axis[6, 7], which is a superposition of multiple wave field values. Normalize the power of all wave modes, the electric field $\boldsymbol{E}$ and magnetic field $\boldsymbol{H}$ in the roadway for horizontal polarized wave are

$$\boldsymbol{E} = \frac{1}{\sqrt{M}}\sum_m\sum_n \boldsymbol{E}_{mn} = \frac{1}{\sqrt{M}}\sum_m\sum_n E_{0mn}\boldsymbol{e}_{mn}\ ;$$
$$\boldsymbol{H} = \frac{1}{\sqrt{M}}\sum_m\sum_n \boldsymbol{H}_{mn} = \frac{1}{\sqrt{M}}\sum_m\sum_n \frac{E_{0mn}}{Z_{mn}}\boldsymbol{h}_{mn} \tag{1}$$

$$\boldsymbol{e}_{mn} \approx \boldsymbol{i}_x \cos k_{xmn}x \cos k_{ymn}y \exp\left[-ik_{zmn}\left(z-z_0\right)\right];$$
$$\boldsymbol{h}_{mn} \approx \boldsymbol{i}_y \cos k_{xmn}x \cos k_{ymn}y \exp\left[-ik_{zmn}\left(z-z_0\right)\right] \tag{2}$$

in which $1 \le |m| \le 2w/\lambda$ and $1 \le |n| \le 2h/\lambda$ are the order of the wave modes. M is the number of modes in the tunnel. $M = 8\left(w+h\right)/\lambda$. $\boldsymbol{E}_{mn}$ and $\boldsymbol{H}_{mn}$ respectively denote the electric field and magnetic field of the (m, n) mode. k_{xmn}, k_{ymn} and k_{zmn} are the wave vector components of the (m, n) order mode, Z_{mn} is (m, n) mode impedance. E_{0mn} is the excitation intensity of the (m, n) mode at the excitation surface. If the maximum current of the antenna in the roadway is I_0, the current density is $\boldsymbol{J}$ in area V, and the antenna size is very small relative to the tunnel section, we obtain

$$\begin{aligned} E_{0mn} &= Z_{mn}\iiint_V (\boldsymbol{i}_z \times I_0\boldsymbol{J})\bullet\boldsymbol{h}_{mn}dV \\ &\cong I_0 Z_{mn}\iiint_V \boldsymbol{J}dV\cdot\cos k_{xmn}x_0 \cos k_{ymn}y_0 \end{aligned} \tag{3}$$

If R_r is the radiation resistance of the antenna, the power radiated by the antenna is $P_{antenna}=0.5I_0^{\,2}R_r$. When the position coordinates of the transmitting antennas in the laneway is $\left(x_0, y_0, z_0\right)$, the total antenna power coupled into the (m, n) mode is $P_{0mn} = \frac{1}{2}\frac{\left|E_{0mn}\right|^2}{Z_{mn}}$. Then the fraction of the antenna power coupled to the (m, n) mode is

$$\eta_{mn} = \frac{P_{0mn}}{P_{antenna}} \cong \frac{1}{R_r}Z_{mn}\left(\iiint_V \boldsymbol{J}dV\right)^2 \cos^2 k_{xmn}x_0 \cos^2 k_{ymn}y_0 \tag{4}$$

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The total coupling loss in dB of the antenna in the roadway under the action of multimode synthesis is,

$$\eta \cong -10\log 10\left(\frac{1}{M}\sum_{m}\sum_{n}\eta_{mn}\right) \tag{5}$$

III. RESULTS AND ANALYSIS

The roadway wall is composed of coal and rock medium, and the electric parameter is 10-j0.18. The shape of the roadway section is a rectangle with a width of 4m and a height of 3m. The antennas are horizontally polarized half-wave dipoles. The receiver is in the center of the tunnel. The carrier frequency is 915MHz.

A. Significant Modes

In a rectangular hollow and straight tunnel, if the initial strength of all the modes is approximately the same, the first modes are always determine the significant amount of the total signal, because of their lowest attenuation rate. By $\alpha_{mn} = 10\log 10(\mathrm{Re}(\exp(-jk_z z)))$ in [7], Table I calculates the propagation loss of the first modes in dB.

According to Table I, the first ten modes which have significant power are (1,1), (1,2), (1,3), (2,1), (1,4), (2,2), (2,3), (1,5), (2,4), (3,1)。

B. Optimal Coupling Position

According to equation (4), the best position of the antenna which can effectively excite (m, n) mode is

$$\begin{cases} x_0 \cong k_1 w/m & , \text{ for } m \neq 0 \\ x_0 \text{ is any value in the interval} \left(-w/2, w/2\right) & , \text{ for } m=0 \end{cases}$$

where $k_1 = 0, \pm 1, \pm 2, \ldots, \pm\lfloor m/2 \rfloor$

$$\begin{cases} y_0 \cong \dfrac{k_2 h}{n} & , \text{ for } n \neq 0 \\ y_0 \text{ is any value in the interval} \left(-h/2, h/2\right) & , \text{ for } n=0 \end{cases}$$

where $k_2 = 0, \pm 1, \pm 2, \ldots, \pm\lfloor n/2 \rfloor$ (6)

Table II calculates the antenna positions that minimum the coupling loss of each critical wave mode.

When the antenna is in the center of the roadway section, all the wave modes can get maximum excitation. In the vicinity of roadway walls, the optimal coupling positions of critical modes are mainly concentrated in: (1) the middle of the ceiling, where (1,2), (1,4), (2,2) and (2,4) modes can be best excited; (2) the middle of the side walls, in which (2,1), (2,2) and (2,4) modes can be best excited. At the corner of roadway cross section, the key modes with optimal coupling are the least, which are (2,2) and (2,4) modes.

TABLE I. PROPAGATION LOSS (IN DB/M) OF THE FIRST MODES

Modes	$m=1$	$m=2$	$m=3$	$m=4$
$n=1$	0.280 λ^2	0.959 λ^2	2.090 λ^2	3.673 λ^2
$n=2$	0.441 λ^2	1.119 λ^2	2.250 λ^2	3.834 λ^2
$n=3$	0.709 λ^2	1.387 λ^2	2.518 λ^2	4.101 λ^2
$n=4$	1.084 λ^2	1.763 λ^2	2.894 λ^2	4.477 λ^2
$n=5$	1.567 λ^2	2.245 λ^2	3.376 λ^2	4.960 λ^2

TABLE II. THE BEST ANTENNA COUPLING POSITION OF EACH SIGNIFICANT MODES

Significant Modes	**Optimal Antenna Positions**
EM_{11}	$x_0 = 0; y_0 = 0$
EM_{12}	$x_0 = 0; y_0 = 0, \pm h/2$
EM_{13}	$x_0 = 0; y_0 = 0, \pm h/3$
EM_{21}	$x_0 = 0, \pm w/2; y_0 = 0$
EM_{14}	$x_0 = 0; y_0 = 0, \pm h/4, \pm h/2$
EM_{22}	$x_0 = 0, \pm w/2; y_0 = 0, \pm h/2$
EM_{23}	$x0 = 0, \pm w/2; y0 = 0, \pm h/3$
EM_{15}	$x_0 = 0; y_0 = 0, \pm h/5, \pm 2h/5$
EM_{24}	$x_0 = 0, \pm w/2; y_0 = 0, \pm h/4, \pm h/2$
EM_{31}	$x_0 = 0, \pm w/3; y_0 = 0$

TABLE III. COUPLING LOSS

Frequency	**Antenna Positions**			
	Center	***Middle of the Side Wall***	***Middle of the Ceiling***	***Corner***
915MHz	13.51	15.30	16.46	18.23

C. Coupling Loss

Table III calculates the coupling loss of antenna in the roadway by (5) and (6). Considering that wireless Access Point (AP) is mainly installed near the roadway wall, we choose four locations to compare. They are the middle of the ceiling, the middle of the side walls, the corner and the center of the tunnel cross section. Their horizontal coordinates in the laneway are (0, 1.49), (1.99, 0), (1.99, 1.49) and (0, 0), respectively.

It can be seen from Table III that the coupling loss of the antenna is the lowest when it is in the center of the roadway, and highest when it is at the corner. Besides, the coupling loss is similar when the antenna is installed on the middle of the side walls or the ceiling. Actually, the coupling loss reflects the number of the modes excited by the antenna.

D. Coverage Effect

Fig.1 shows the field coverage generated by the 915MHz antenna at different locations. When the transmitting antenna is in the center of the tunnel, the electromagnetic field have the lowest attenuation and the maximum power. When the antenna

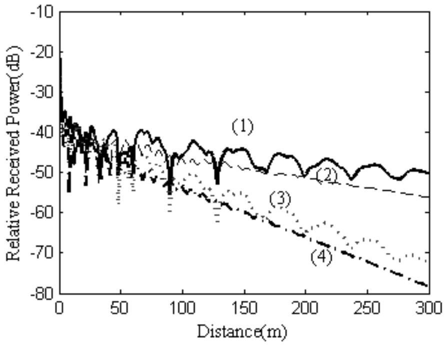

Fig. 1. Path loss analysis of different antenna positions: (1) the center of the tunnel cross section; (2) the middle of the ceiling; (3) the middle of the side walls; (4)the corner of the tunnel cross section.

is installed at the corner of the tunnel cross section, the electromagnetic field is the minimum. The simulation results are in accordance with the measurement results of [2]. From Table I, II and III, this phenomenon can be explained: when the antenna is in the center of the roadway, it can realize the optimal coupling of all guided wave modes, and then the coupling loss is the lowest, so the signal can not only obtain the maximum intensity of excitation, but also achieve the maximum power coverage; when the antenna is located at the corner, the coupling efficiency of the antenna is the lowest, and the number of the effectively excited key modes is the least, and their attenuation rate is larger, so the intensity of signal excitation is the weakest and the field coverage is the minimum.

In Fig.1, the coverage power of the antenna mounted in the middle of the roof is larger than in the middle of the side wall. This is consistent with the measured results of [1]. From Table I, II and III, this phenomenon can be interpreted: for former, the coupling loss is the same as the later, but the number of the first key modes effectively coupled is larger, and their attenuation rate is smaller. Consequently, even though its excitation intensity is the same as the later but can obtain stronger field coverage.

Besides, Fig.1 shows that more uniform field coverage can be got when the antenna is located at the ceiling middle or corner positions. For the former, it can be seen from Table I, II that the strength difference between the modes effectively coupled is larger than other cases, so the multipath interference is weaker. For the later, the uniform field coverage is formed because the number of the effectively excited modes is the least from Table III.

IV. Conclusion

To achieve efficient design and deployment of the wireless systems, the distribution of the electromagnetic field generated by the antenna with different installation location is studied in this paper. The coupling relation between the antenna current distribution and the propagation modes in the underground tunnel is analyzed based on the theory of multimode waveguide. The results indicate that the optimal antenna coupling positions of the first critical modes are mainly concentrated in the center of the roadway section, the middle of the ceiling, the middle of the side walls, and the corner of the roadway cross section. It is shown, by comparison and analysis, that a smaller path loss and a more uniform field distribution can be obtained when the antenna is mounted on the middle of the roadway top wall. Such position would be the preferred location for the non-mobile wireless nodes such as AP in the coalmine roadway.

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