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Modeling the Leaky Feeder as a Multi Antenna Array

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***Abstract*—Reliable communication in underground mines and tunnels has always been an issue. The leaky feeder (LF) is the most widely used medium for radio wave transmission in the underground environment. The LF has carefully designed radiating slots along its length that act as bidirectional antennas. Since there will be a finite phase shift between the RF signals radiated from the slots, that depends on the radio frequency and slot separation, modeling the LF as a single radiating element is not accurate. In this paper, the LF is modeled as a multi antenna array supporting a multi-input-single-output (MISO) system. The received signal of this MISO system is estimated under various conditions assuming a Binary Phase Shift Keying signal (BPSK) modulation.**

***Index Terms*—Leaky feeder, MISO, BPSK, Fading, Channel gain.**

I. Introduction

Reliable communication is essential for underground mines and tunnels for multiple reasons including safety and productivity. This communication system is needed to distribute video information, radio telephony and digital control information within the network of tunnels. Video signals originating from the cameras mounted on the moving mining machinery or at fixed locations are transmitted to a remote control room allowing operators to monitor and exert control via a return radio data link. Moveable radio telephony is frequently employed by miners for real-time communication [1].

However, there is no easy way to achieve this. Mines can be tens of hundreds of meters deep and terrestrial radio signals don't propagate to deep underneath. Mine topographies keep changing rapidly; a mine can grow up to 50 m in one day. Often unused areas are closed down. Typically mines have open areas interconnected with tunnels; pillars and obstructions are very common and the wall will be rough absorbing RF signal. Installing large number of antennas to maintain a well covered wireless network is not practical.

The leaky feeder (LF) is the most widely used transmission medium in underground mines and tunnels. The LF has dual functionality; it not only transmits RF signal as a cable but also radiates the RF signal along its length via carefully designed slots. The leaky feeder radio system is almost noise free and has enough bandwidth to support multiple RF signals carrying voice and data simultaneously. The LF system is also able to transfer the DC power which is required to power up amplifiers and active nodes. Many types of leaky feeder cables with low loss desired radiation and coupling properties have been introduced in the mining industry [1]. Although most studies consider the LF as a single radiating element, it is an interesting task to consider the LF as a multiple antenna array. This will pave way to model the entire system as a multiple-input-single-output (MISO) wireless communication system.

Let us briefly review the previous work. Emami et al. studied the emergence of the technology and its applications, analytical, numerical and measurement based propagation modeling techniques, and the implications of the physical environment, antenna placement and radiation characteristics on LF based wireless communication system design [2]. They have considered multiple systems including narrowband, wideband and ultra-wideband (UWB) systems. Fan et al. [3] studied the radiation characteristics of leaky co-axial cable field and compared it with the characteristics of the helical antenna and provided a formula for electric field distribution at the receiver. Wang et al. [1] studied the frequency band and coupling loss; the parameters of leaky coaxial cables with periodic slots. Wang used the finite-difference time-domain (FDTD) method to calculate the electric field distribution in the slot cut in the outer conductor of the coaxial cable. He used dyadic green's function to calculate the radiation field of the equivalent surface magnetic current densities. Using these methods, Wang calculated the coupling loss of the leaky coaxial cables with different periods, and the size and shapes of the slots. Feng et al. [4] started from the basic electromagnetic theory to analyze the radiating modes of leaky coaxial cable fields. They also studied straight and zigzag slots and provided a formula for the radiating field [4].

This paper presents the suggested model of the received signal at the underground mine, assuming the transmitted signal is Binary Phase Shift Keying (BPSK) considering slot separation that will cause a phase shift between the RF signals transmitted from adjacent slots. A mathematical expression is derived for the received RF signal and it is numerically evaluated.

In *section II* a statistical description of the wireless channel is provided, assuming small scale fading and large scale fading. In *section III* the mathematical expression of the received signal is given. *Section IV* Simulation. *section V* provides a brief conclusion and directions for future studies.

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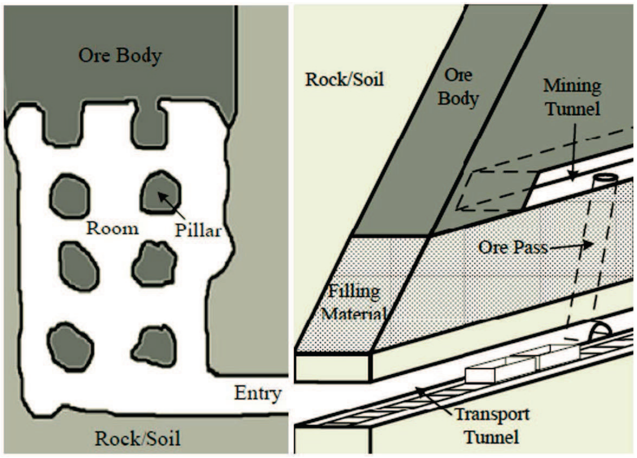

Fig. 1. Mine structure of different mining methods[6].

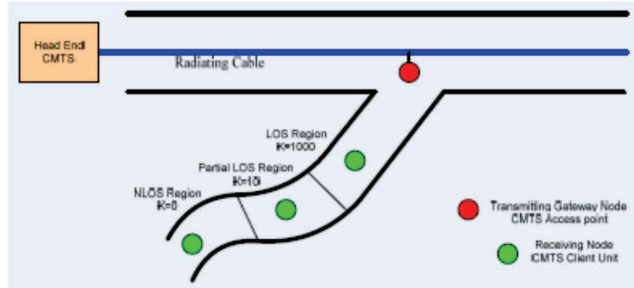

Fig. 2. Different portions of a mine with different strengths of line of sight components [6].

II. Statistical Description of the Underground Wireless Channel

To better understand the underground wireless channel, it is important that the received power is examined as a function of the distance. The received power can vary robustly by 100 dB or more. Also, variations occur on different spatial scales:

- On a very-short-distance scale, power fluctuates around a (restricted) mean value. These fluctuations happen on a scale that is analogous with one wavelength, and are therefore called small-scale fading. These fluctuations are due to the interference among the different Multi Paths Components (MPCs) which is very high in mines. Fluctuations in field strength can be defined only statistically; specifically by the (local) mean value of the power and the statistics of the fluctuations around this mean.
- Mean power, averaged over approximately 10 wavelengths, also shows fluctuations by itself. These fluctuations occur on a larger scale; normally a few hundred wavelengths. This phenomenon is fundamentally different from the interferences that cause small-scale fading. These variations can be seen most clearly when moving around the transmitter in different parts of the mine at approximately the same distance. Depending on the topology, the variation can be large. Although this *large-scale fading* is also described by a mean and the statistics of fluctuations around this mean in general [5], this description can only give vague results in underground environments. The mean value depends on the distance between the transmitter and the receiver is a vague sense. The reason for these variations is shadowing by large objects at some places while the tube-like tunnels can act like waveguides and very well allow the signal to propagate in some other areas which results in large variation is the path loss exponents that can vary all the way from 1 to 5 or 6. Due to this large fluctuation, the received signal strength (RSSI) based measurements are very inaccurate in mines.

A. Small-Scale Fading

Due to the large number of interacting objects, a deterministic description of the radio channel is not accurate. Ray tracing techniques are often used to predict the signal strength in mines and tunnels. A simple case is the two-path model. More general multi-path propagation models will yield better results. However, ray tracing is computationally intensive and results are very specific to the topography of the mine under consideration.

Therefore, one should take refuge in stochastic description methods. The stochastic description is essential for the whole field of wireless communication. Depending on the location of the mine a line of sight component may or may not be present (see Fig. 2). It is well known that the Rayleigh distribution will govern the area where there will be no line of sight component and Rice distribution dominates otherwise. The Rice factor K_r ratio of the power in the line of sight component to the power in the disperse component varies a lot in underground environment. There are often areas where neither the Rice nor the Rayleigh distribution is applicable. The value of K_r has to be often found by experimental means [6].

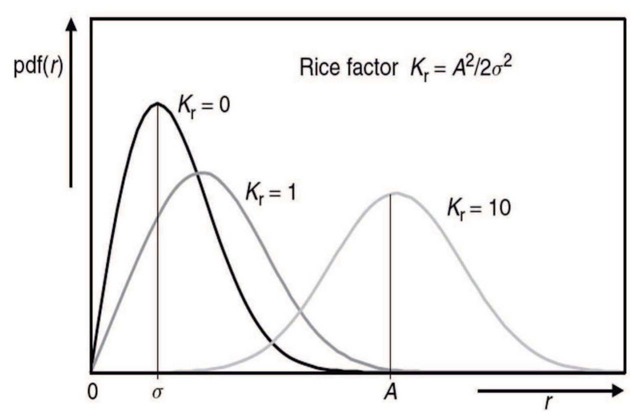

Fig. 3. Rice distribution for three different values of K_r (i.e., the ratio between the power of the LOS component and the diffuse components). Often in mines neither the Rice nor the Rayleigh distribution is applicable [5].

III. Derivation of the Received Signal

Leaky feeders can be considered as distributed antennae. They are predominantly used to provide radio propagation signals in train tunnels and underground mines. They have recently been considered as an alternative for conventional antennae for indoor micro-cells as well. Leaky feeders are constructed from coaxial cable where the outer shield has a series of holes with different shapes and different distances among them. The coaxial cable is usually about hundreds of metres long and can be fixed through a building or a tunnel offering radio radiation in a way that would require many individual omni-directional antennae.

Fabrication costs of leaky feeders are relatively low, and if deployed intelligently, leaky feeders can reduce network infrastructure costs. The propagation model presented considers the path between a leaky feeder and a single omni-directional antenna as a receiver without taking into account the thorough geometry of the tunnel upon the radiation from each slot of the leaky feeder. The model is constrained to two dimensions, only the relative signal strength is considered and reciprocity is assumed.

The leaky feeder has randomly distributed transversal slots. The feeder's linear axial attenuation assumed to be K at a certain frequency f GHz, with the relative phase velocity of β. The model uses a ray-tracing technique based on Devasirvatham's model for indoor path loss [7]. Each transverse leaky feeder slot is approximated by the radiation profile of a dipole antenna. The leaky feeder was modeled as a group of radiating dipoles lying on the y = 0 axis of a two dimensional plane, with the input at X = 0 and N slots at coordinates (D(n), 0) for n = 1,2, ... , N, as shown in Fig. 4.

To derive the impulse response of the channel, we assume the input signal at X=0 is an impulse with amplitude A and phase φ, it can be written as $P = Ae^{j\varphi}$ that propagates along the leaky feeder from $x = 0$ at a velocity of $c\beta$ m/s, where c is the speed of light in free space. The impulse will take $t_1(n) = \frac{D(n)}{c\beta}$ seconds to travel to slot n. The attenuated and phase-rotated impulse at this point is described in (1), where λ is the free space wavelength [8].The attenuated signal at the nth slot is S(n) and is given by,

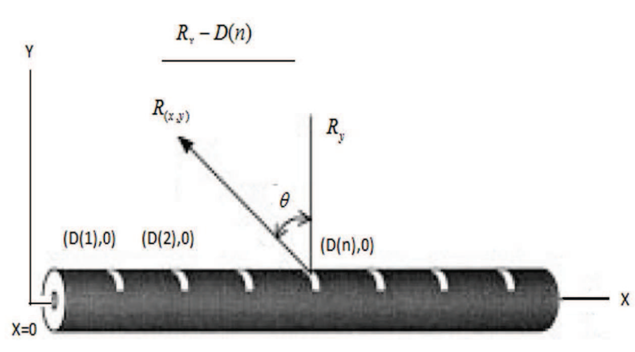

Fig. 4. The Leaky Feeder Model.

$$S(n) = 10^{\frac{-D(n)k}{20}} A e^{j\left(\varphi + \frac{2\pi\beta D(n)}{\lambda}\right)}. \tag{1}$$

The following formula (2) is used to find the propagation distance from the nth slot to the receiver's antenna at point $R_{x,y}$, for n=1, 2,, N

$$R(n) = \sqrt{(R_x - D(n))^2 + R_y^2}. \tag{2}$$

Assuming free space, the time needs for the signal to travel from the slot to the antenna at $R_{x,y}$ is given by (3)

$$t_2(n) = \frac{R(n)}{c}. \tag{3}$$

If we consider each slot as an independent dipole, it can be then the radiation pattern of each slot relates the transmitted power in a given direction, to the cosine of the angle (θ) between the direction of propagation and a perpendicular line to the cable. It can be seen that the received impulse at the antenna is given by (4), where M(R(n)) is the amplitude path loss from slot n to the receiver antenna at position $R_{x,y}$.

$$W(n) = S(n)Cos(\theta)M\left(R(n)e^{\frac{jR(n)}{C\lambda}}\right) \tag{4}$$

where, M(R(n)) is a Devasirvatham's model and given by equation (6)[7].

$$M(R(n)) = \left(r10^{\left(\frac{0.7r}{20}+1.925\right)}\right)^{-1}. \tag{5}$$

Fig. 5 shows the path loss according to of Devasirvatham's model which is more accurate than the Rice or the Rayleigh models in the mine environments.

Since the input signal is an impulse, the impulse response of the channel will be the output h(t).

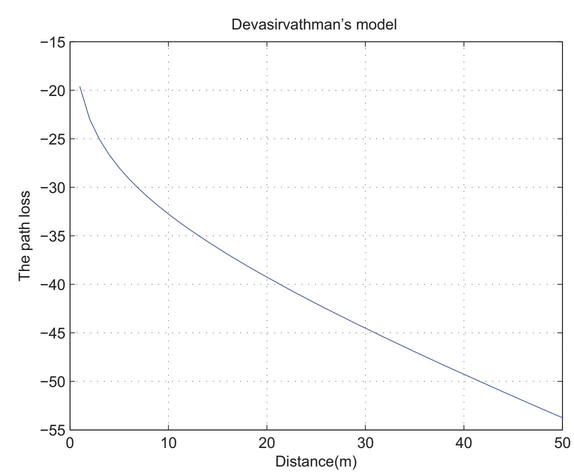

Fig. 5. Devasirvatham's Path Loss model.

TABLE I
THE PARAMETERS VALUES USED IN SIMULATION

Parameters	Value
Frequency f	300MHz
β	0.88
Axial attenuation of the LF k	0.15 dB/m
BPSK amplitude E_p	10 V
Receiver coordinates	(15,5)
The direction angle	30 degree

$$h(t) = \begin{cases} \sum_{n=1}^{N} W(n) & t = t_1(n) + t_2 \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

If we assume the input signal of the leaky feeder to be a BPSK with a form of

$$m(t)E_p cos(\omega_c t + (1-q)\pi). \tag{7}$$

where q=1,2, then the signal at the nth slot will be,

$$W(t) = E_p cos(\omega_c t + (1-q)\pi + kD(n)). \tag{8}$$

In this case the signal at the receiver y(t) will be,

$$y(t) = W(t) * h(t). \tag{9}$$

where * means the convolution operation. Hence,

$$y(t) = \sum_{n=1}^{N}(E_p cos(\omega_c t + (1-q)\pi + kD(n)) * \\ (S(n)cos(\theta)M(R(n))e^{\frac{jR(n)}{c\lambda}}). \tag{10}$$

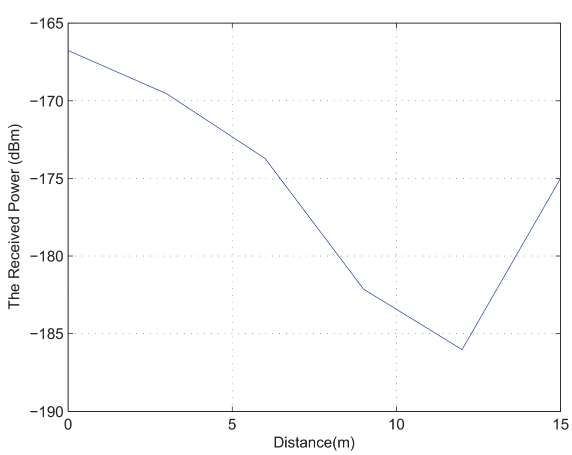

Fig. 6. Simulated BPSK signal response between the leaky feeder at y = 0 and a receiver at (15, 5).

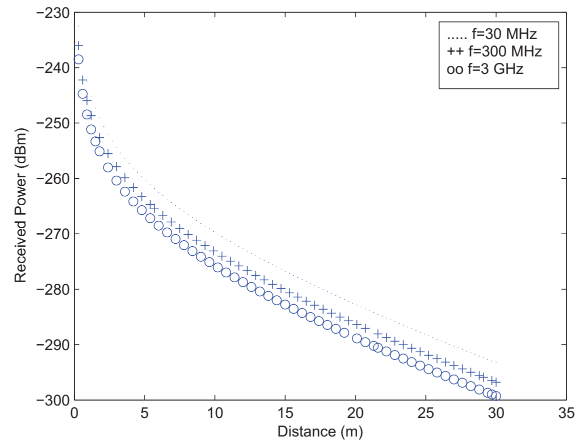

Fig. 7. The Received Power variation with the Carrier Frequency.

By expanding and simplifying the convolution the final form of the signal will be,

$$y(t) = \sum_{n=1}^{N}(\frac{E_p}{\omega_c} sin(\omega_c t + (1-q)\pi + kD(n)) \\ (S(n)cos(\theta)M(R(n))e^{\frac{jR(n)}{c\lambda}}). \tag{11}$$

IV. SIMULATION

Equation (11) represents the suggested model of the received signal while the input signal was a BPSK. A simulation has been performed using the values shown in Table 1.

Fig. 6 shows the numerical values of the BPSK signal using equation (11). This graph shows the relatively *near field area* (short distance). A fading like behavior can be seen, although we did not consider multi-path effects. This is due to the phase difference in the RF signals emanating from different slots. Depending on the signal frequency and slot separation the signal may cancel out each other showing a fluctuation of

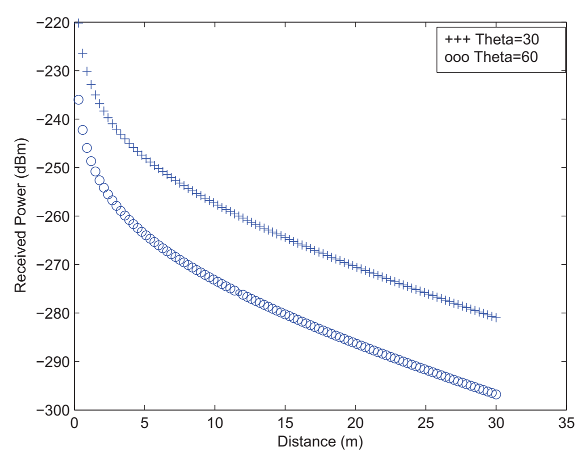

Fig. 8. The Received Power variation with the direction angle.

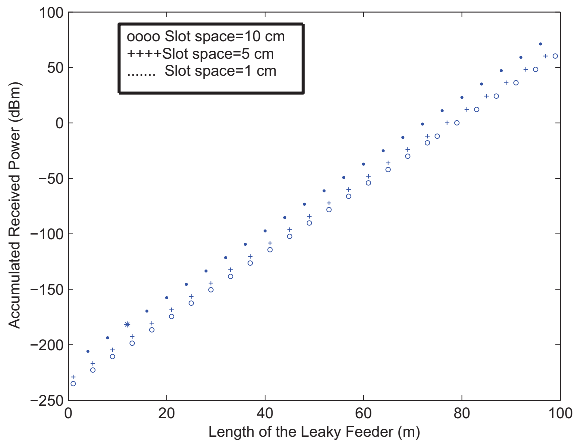

Fig. 9. The accumulated power at the receiver at (50, 5) produces by all slots for different slots space in the Leaky Feeder.

up to 20 dB in a short distance. This behavior needs further investigation.

Fig. 7 shows the received power at relatively long distance. We see that in this far-field area, the signal follows the Devasirvatham's model but with some deviation due to multiple slots. We can see that the attenuation is higher for high frequency signal.

Fig. 8 shows the received power variation with the angle in the far field area. Note the angle θ is measured from the perpendicular axis to the leaky feeder cable (Fig. 4). Therefore, as the receiver moves away from this axis, the signal strength decreases which indicates the directional property.

Fig. 9 shows the accumulated power from all slots of the LF at a certain receiver in the far field area. Different curves referred to different slot spacing. It can be observed that the received power nonlinearly decreases with the slot spacing because fewer slots, means lower radiated energy. However, this can make the cable to support longer tunnels because more energy will flow through. Therefore, the slot spacing shall be carefully designed to provide a balance between the amount of energy to be radiated and the required feeder length. Note that the slot separation will also affect the near field cancelation (fading) effect [9].

V. Conclusion and Future works

In this work, we radiation from a leaky feeder is studied considering the phase difference of the RF signal emanating from each slot. Our preliminary results show, there will be fading like effects in the near field. Far field energy decreases with the radio frequency, angle and slot separation. Further investigation is required to find optimum slot spacing for a given radio frequency and tunnel topography. Furthermore, the slot spacing can be done in a way that the correlation among the RF signals emanating from the slots in the vicinity is a minimum. In this case, leaky feeder can be modeled as a multi array antennae and appropriate coding can be applied to treat the entire system as a well-established MIMO (or MISO with a single antenna receiver) system.

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