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COMPOSITE MODELING OF UNDERGROUND WIRELESS MINE COMMUNICATION SYSTEMS

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Abstract: This work deals with the concept of a underground wireless communication systems modeling especially in mines and tunnels using existing terrestrial wireless models. The need for efficient underground communication systems has increased with increase in number of tunnels, metros, mines etc. Even though the basic principles of communication remain the same, the factors which are to be considered vary voraciously in case of underground. Unlike terrestrial environment, underground environment poses variety of challenges like humidity, wall penetration, bends, excess attenuation of signals, scattering over rough surfaces, multiple reflections etc. The model selected for the study in this case is COST231 model. This paper takes in to consideration some major losses which affect the signals in such environments to obtain the suitable correction factors pertaining to those losses. Then the conventional path loss equation is modified by adding the correction factors and a hybrid model is obtained from the existing terrestrial wireless communication models. This hybrid model holds good for most of the cases of underground communication, provided the conditions are satisfactory (ex. The operating frequency is around 900 MHz)
Keywords: Mine communication, composite modeling, Underground wireless communication COST231model.

I. INTRODUCTION

Underground wireless communication is currently a very active area for research. The number of underground networks, mines, tunnels etc has increased considerably over years leading to development of suitable communication systems inside them. We already have reached tremendous heights when it comes to communication on land i.e., terrestrial communication. There are lots of communication models, large number of antennas and efficient systems to minimize the signal losses to large extent. The question arises whether it is possible to achieve the same amount of development and efficiency in underground environments also. This paper aims to present the challenges faced in the underground wireless systems. It also provides a study of various factors which affect the underground

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signal propagation and finally a hybrid model is obtained using the terrestrial model equation with suitable assumptions and loss corrections. This model fairly approximates the underground condition and serves as a useful tool for modeling communication systems underground.

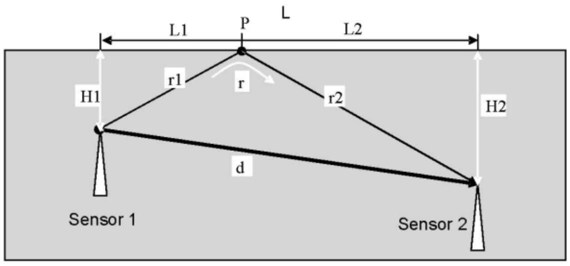


Figure 1. Typical underground transmission system

II. TERRESTRIAL WIRELESS MODELS

1. Okumura Model: One of most widely used models for signal prediction. Operational frequency range from 150MHz-1920MHz. But it can be extended up to 3000MHz. Distances range from 1km-100km and antenna height range from 30-1000m. Major demerit is its slow response to rapid changes in terrain. Formula for Okumura Model is expressed as follows:

$$L_m(dB) = L_F(d) + A_{mu}(f,d) - G(h_M) - G(h_B) - G_{AREA}$$

Where,

L_m = median path loss

$L_F(d)$ = free space propagation pathloss.

$A_{mu}(f,d)$ = median attenuation relative to free space

$G(h_B)$ = base station antenna height gain factor

$G(h_M)$ = mobile antenna height gain factor $G(h_B) = 20\log(h_B/200)$ $1000m > h_B > 30m$

$G(h_M) = 10\log(h_M/3)$ $h_M <= 3m$

$G(h_M) = 20\log(h_M/3)$ $10m > h_M > 3m$

G_{AREA}: gain due to environment type.

2. Hata Model: It is an empirical formulation of graphical path loss data provided by Okumura and is valid from 150MHz-1500MHz. Hata proposed empirical mathematical relationships to describe the graphical information given by Okumura. Hata's formulation is limited to certain ranges of input parameters and is applicable only over quasi-smooth terrain.

The mathematical expression and their ranges of applicability are as follows:

$L(dB) = 69.55 + 26.16f_c - 13.82\log h_{te} - a(h_{re})$

$+ (44.9-6.55\log h_{te})\log d$ CarrierFrequency:150MHz≤ f_c ≤1500MHz BS Antenna Height(h_{te}): 30m ≤ h_b ≤ 200m MS Antenna Height(h_{re}): 1m ≤ h_m ≤ 10m Transmission Distance(d):1km≤ d ≤ 20 km.

3. Cost-231 Model: Most future PCS systems are expected to operate in 1800-2000 MHz frequency band. Some studies have suggested that the pathloss experienced at 1845 MHz is approximately 10 dB larger than those experienced at 955

MHz, all other parameters being kept constant. The COST231-Hata model extends Hata's model for use in 1500-2000 MHz frequency range, where it is known to underestimate path loss. The model is expressed in terms of the following parameters:

Carrier Frequency f_c =1500-2000 MHz

BS Antenna Height h_b =30-200 m MS Antenna Height h_m =1-10 m Transmission Distance d =1-20 km

The path loss according to the COST231- Hata model is expressed as:

$L_p(db)=A+B\log_{10}(d)+C$

Where,

$A= 46.3 + 33.9 \log_{10}(f_c) -13.28 \log_{10}(h_b) - a(h_m)$.

$B=44.9 – 6.55 \log_{10}(h_b)$

C=0 for medium-city and suburban areas and 3 for metropolitan areas.

While both the Hata and COST231 are designed for use with base station antenna heights greater than 30 meters, they may be used with shorter antennas provided that surrounding buildings are well below this height. Lastly, the model should not be used for prediction with transmission distances below 1 km, as path losses become highly dependent on local topography below this range.

4. ITU Model for Indoor Attenuation: The ITU Indoor Propagation Model, also known as ITU Model for Indoor Attenuation estimates the path loss inside a room or a closed area inside a building delimited by walls of any form.

Frequency used: 900 MHz to 5.2 GHz

Floors: 1 to 3

The ITU indoor path loss model is formally expressed as:

$$L = 20\log f + N\log d + P_f(n) - 28$$

where,

L = the total path loss (dB).

f = Frequency of transmission (MHz). d = Distance (m).

N=The distance power loss coefficient. n=Number of floors

$P_f(n)$=The floor loss penetration factor.

5. Log-distance path loss model: The log- distance path loss model is a radio propagation model that predicts the path loss that a signal encounters inside a building or densely populated areas over distance.

Log-distance path loss model is formally expressed as:

$$PL = P_{Tx_{dBm}} - P_{Rx_{dBm}} = PL_0 + 10\gamma \log_{10} \frac{d}{d_0} + X_g,$$

Where,

PL is the total path loss measured in dB. P_{Tx} is the transmitted power in dBm.

P_{Rx} is the received power in dBm.

P_{L0}(dB) is the path loss at the reference distance d0 ie., the reference distance, usually 1 km (or 1 mile).

Xg is a normal (or Gaussian) random variable with zero mean, reflecting attenuation (in decibel) caused by fading. In case of no fading, this variable is 0.

III. EXPERIMENTAL PROCEDURE

a. Selection of suitable model for implementation:

We chose Cost231, Log distance Model and ITU model for our project. Measured values were collected. The distances of the points of measure A, D and C from the transmitting station are 1,15 and 30 metres respectively. Code was written in matlab to compare the values obtained from actual equation of each of the models with the curve obtained from measured values. For each of the models we obtained the Standard deviation of measured values from actual values and Mean error. The results are presented in table.1. The same procedure was repeated for BFSK and 0.3GMSK modulation schemes also.

Table 1. Measured pathloss values in dB for different modulation at different distances of transmission

	BPSK	**BFSK**	**0.3GMSK**
A (d=1m)	119.7185	119.7185	119.7185
D(d=14m)	137.4461	134.7918	132.5873
C(d=30m)	150.2984	147.9036	146.1967

Table 2. Tabulation of Standard Deviation (S.D) and Mean Error obtained by different models for different frequencies for BFSK Modulation.

f in MHz	**Cost 231 Model**		**ITU Propagation model**		**Log-Distance Path loss model**	
	S.D	**Mean Error**	**S.D**	**Mean Error**	**S.D**	**Mean Error**
100	9.8	-14	9.33	-70.6	13.63	-88
500	9.8	9.5	9.33	-56.65	13.63	-74.
900	9.8	18.3	9.33	-51.5	13.63	-68.9
940	**9.8**	**18.9**	9.33	**-51.17**	13.63	**-68.54**
1000	9.8	19.9	9.33	-50.63	13.63	-68
1500	9.8	25.9	9.33	-47.11	13.63	-64.48
2000	9.8	30.2	9.33	-44.61	13.63	-62

From table 1 we can see that in case of cost231 model and ITU model the standard deviation is almost the same. Hence Cost 231 model more suitably matches the given measured values compared to ITU model and Log Distance Path loss model. Hence for BPSK, BFSK and0.3GMSK modulation we chose Cost231 model for our further proceedings and calculations.

b. Different losses considered and their corresponding correction factors (for BPSK):

1. Bending loss: It is the loss encountered due to the bending of signals along the bends in tunnel walls or any other tilted obstacles. It can be formulated as:

$$L_{\text{tilt}} = \frac{4.343\pi^2\theta^2 z}{\lambda}$$

Where,

θ= tilt in the walls in radians.

z= distance of tilt from transmitter.

λ= wavelength of the signal used.

Bending loss increases linearly with the increase in frequency.

2. Diffraction loss: We deal with knife edge diffraction here. Estimating the signal attenuation caused by diffraction of radio waves over steep/pointed obstacles is essential in predicting the field strength in a given underground environment.

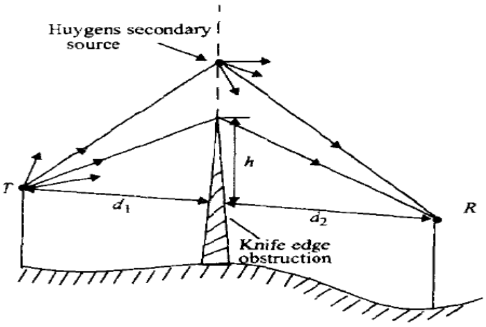


Figure 3. Illustration of knife edge diffraction geometry

The Diffraction loss can be formulated as:

$$G_d(dB) = 20\log\left(\frac{0.225}{v}\right)$$

Where, v= Fresnel Kirchhoff diffraction parameter (=2.5)

3. Scattering loss: It occurs due to the scattering of the signals over rough surfaces wherein the surface roughness becomes comparable with wave length. It can be given in dB by following equation:

$$L_{\text{roughness}} = 4.343\pi^2 h^2 \lambda \left(\frac{1}{d_1^4} + \frac{1}{d_2^4}\right) z$$

4. Penetration loss: Penetration loss occurs in the form of partition losses and obstacle transmission losses when the signal /radio waves transmit through a medium or obstacle of a particular permittivity and permeability. It can be formulated as:

$$PL(dB) = \alpha d + FAF(dB) + \sum PAF(dB)$$

α = attenuation constant for channel in dB/m., FAF = floor attenuation factor, PAF = Partition attenuation factor. For obtaining these the above parameters we assumed bricks, concrete and wooden walls and partitions.

5. Low frequency interference loss: This loss occurs due to the presence of the power cables or any other Electromagnetic devices near the antenna system. It poses interference issues resultingin signal degradation and loss. We assumed a power line of 345Kv, 60 m away from the wireless system. The loss can be formulated as:

$$LFI = [4.8x10^{-5}f^{2} – (0.094f+2)]dB$$

f is the frequency of operation ie., 940MHz.

6. Antenna Height correction Factor: At the effective height of 200m, no correction gain is required (0dB). Base station antennas above 200m introduce positive gain in the pathloss models and antennas lower than 200m have negative gain factor. Since Cost231 model has the antenna height correction already embedded in the equation as $a(h_r)$ there is no need to consider it again.

Steps followed for obtaining the correction factors:

 Code was written for obtaining different
values of losses at different frequencies and distances within specified range. (we have chosen matlab because of the convenience of plotting tools).

 In each case specific loss was varied keeping other losses constant(evaluated at
940 MHz)

 Curve fitting of the values obtained was done with respect to log of frequency and distance.

 It was compared with the measured valuescurve and the deviation was obtained.

 Polynomial corresponding to the deviation was calculated using curve fitting which is the correction factor is pertaining to that loss.

 All the correction factors so obtained were subtracted from the cost231 model and finally hybrid correction factor to be added was obtained owing to the deviation of the measured plot and the corrected cost 231 plot.

 The final hybrid cost231 model fits the measured values given and thus can be used in underground conditions at ease.

 The procedure was implemented for 3modulation formats BPSK, BFSK and 0.3GMSK.

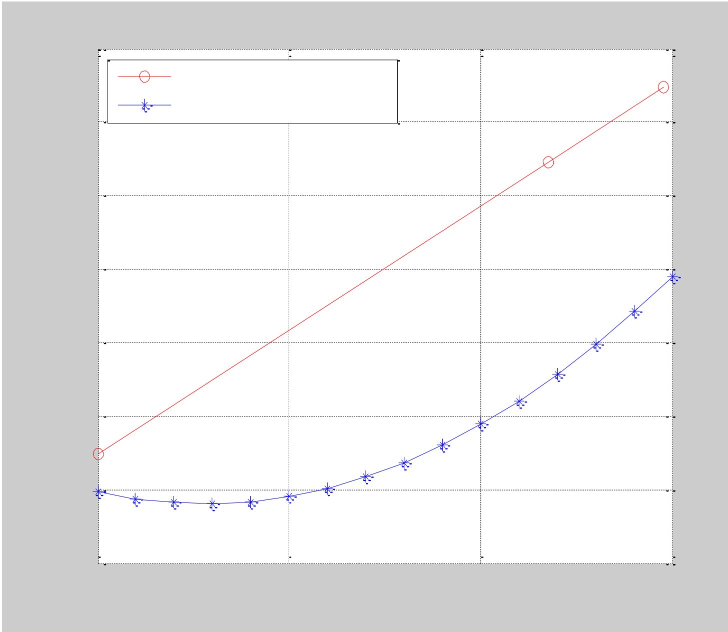


Figure 2. Deviation of actual cost231 model from measured values for BPSK scheme

IV. CORRECTION FACTORS

All the correction factors we obtained are with respect to frequency. They can even be modelled with respect to distance.

1. Bending loss correction:

$C1_{bfsk} = 55.8(\log_{10} f)^2 - 315.37\log_{10}(f) + 453.5$

$C1_{gmsk} = 55.8(\log_{10} f)^2 - 315.37\log_{10}(f) + 456.2$

2. Diffraction loss correction:

$C2_{bfsk} = -24.36\log_{10}(f) + 81.727$

$C2_{gmsk} = -24.36\log_{10}(f) + 84.427$

3. Scattering loss correction:

$C3_{bfsk} = -35\log_{10}(f) + 113.248$

$C3_{gmsk} = -35\log_{10}(f) + 115.948$

4. Penetration loss correction:

$C4_{bfsk} = -49\log_{10}(f) + 150$

$C4_{gmsk} = -49\log_{10}(f) + 160$

5. Low frequency interference correction:

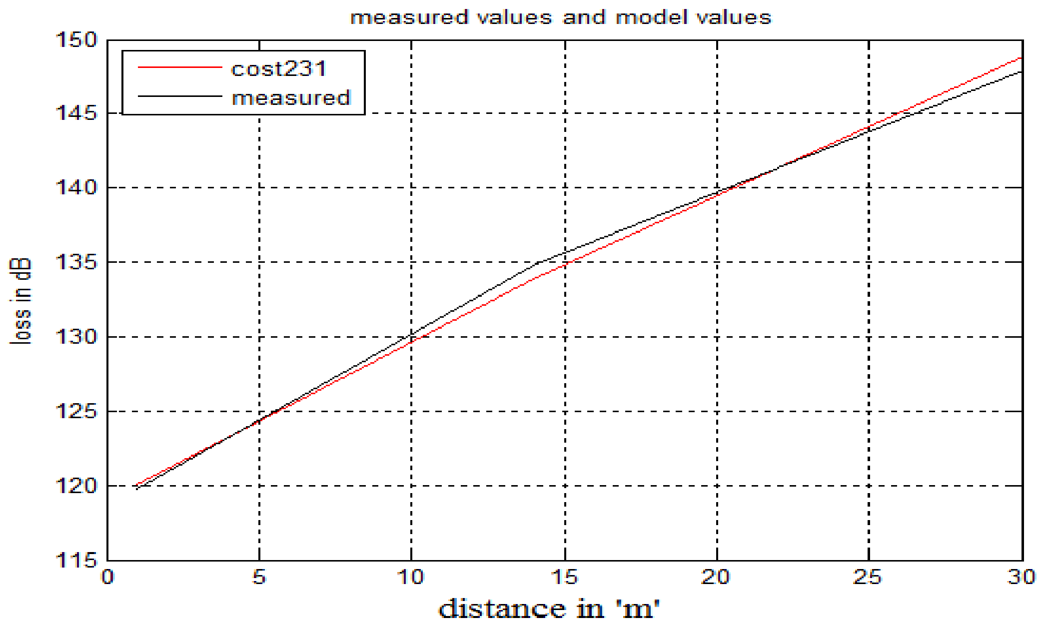
$C5_{bfsk} = -190(\log_{10}f)^2 + 1100\log_{10}(f) - 1600$

$C5_{gmsk} = -186(\log_{10}f)^2 + 1080\log_{10}(f) - 1554.2$

6. Hybrid Correction Factor added :

$Chy_{bfsk} = -134.2(\log_{10}f)^2 + 676\log_{10}(f) - 801.5$

$Chy_{gmsk} = -130.2(\log_{10}f)^2 + 656.3\log_{10}(f) - 737.6$



Plot of cost 231 model with added correction factors of all losses

We have considered about five loss parameters but there are many known and unknown factors in the underground environment that affect the signals which also need to be considered while designing a system. However our model perfectly matches the measured values which were obtained at a mine few years ago. Hence it can be used as a reference model while designing an underground system. The model becomes more accurate when we consider other parameters like pressure, humidity and other effects.

There are certain factors like penetration loss, diffraction etc. which also varies with distance. In such cases we can obtain the correction factors in terms of distance. Since we had all our programming done with respect to varying frequency we have limited the correction factors with respect to frequency.

The same procedure was repeated for 0.3GMSK and BPSK modulation schemes also and the plots were obtained including the hybrid model.

V. FUTURE ENHANCEMENTS

Even though we have considered the major losses that play dominant role in signal degradation there are many more parameters which play there role. Considering all these parameters makes the design more efficient and adaptable to all kinds of underground environments. Some of the important Parameters are listed below:

Burial depth: As the burial depth increases, there is no reflected signal from the surface between underground and above ground. The signal strength decreases as the burial depth increases. The trend is more significant for wet sand.

Antenna orientation: In wireless communication, the antenna is an important component affecting the received signal strength. In wireless underground sensor networks, the orientation of the antenna angle also affects the signal strength at the receivers.

Geo-Parameters: The received signal strength is affected by the engineering properties of the soil such as particle size, mineralogy, compaction, water content, saturation, salinity, and physical properties of the environment such as temperature, which characterize the electric conductivity and permittivity of the soils.

VI. CONCLUSION

The paper provides effective understanding of the underground wireless signal propagation. Based on the existing terrestrial wireless models, we have developed a hybrid corrected model to suit the given underground system. Most of the important parameters and losses which cause major effects in underground signal propagation are studied and the factors are added to compensate for the effects caused by the losses. The hybrid model obtained is expected to hold good for general underground environments at operating frequency range of 900 to 1000MHz, transmission distance of about 30 metres and transmitter and receiver antenna heights of 50m and 1m respectively. Future enhancements can be made to this model to obtain a much efficient model considering the entire parameters specific to the given environments like tunnels, mines etc.

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