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# Optimization of Parameters for Minimum Path Loss in Underground Tunnels using CSP

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***Abstract*— Communication in underground tunnels is one of the most important and challenging areas for engineering fraternity with multiplicity of constraints. Various factors such as frequency, tunnel size, cross-section shape and curvature, material used for construction, antenna position and polarization, all influence the path loss. With the availability of large number of factors which influences the path loss, the task of finding the optimal solution becomes complex. Constraint Satisfaction Programming has the potential of tackling wide range of search problems easily. The task of optimizing the path loss in tunnels can be modeled in CSP as that of searching the optimal set of parameters affecting the path loss.***

***Index Terms*— CSP; Path Loss; Propagation Model; Wireless Communication.**

## I. INTRODUCTION

Wireless communication networks are expected to provide seamless connectivity in all types of environments and in all locations. For this accurate and efficient characterization of wireless channel is very important. The physical channel properties depend upon a wide number of parameters. While designing networks the effect of each parameters needs to be analyzed and best combination should be chosen so that the best performance is obtained.

Constraint satisfaction programming (CSP) is a very powerful tool which can solve multi-variable complex problems effectively and easily. Such problems, which have multiple variables to be assigned values from a range after satisfying constraints can be modeled as search problems in CSP if only solution is to be found out or as search and optimization problem if the result needs to be optimized also.

Basically, CSP is composed of finite set of variables, each of which is associated with a set of domain and set of constraints that restricts the value that a variable can take. The constraint satisfaction problem deals with assignment of values from its domain to the variables in such a way that no constraint is violated [2]. The constraint satisfaction algorithm can be viewed as an iterative procedure that repeatedly assigns domain values to the variables [1].

In this paper the problem of finding the path loss in underground tunnels has been modeled as a constraint satisfaction problem, which is a branch of constraint programming and is probably used for solving most of the industrial problems involving constraints, and has been solved by chronological backtracking and after solving the problem the result was optimized using branch and bound algorithm used for optimization of CSP.

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### *Modeling the Propagation Channel:*

Models used for characterization of tunnel environment for wireless propagation can be categorized depending upon the method they use for calculating various parameters such as path loss or received power and includes models based on geometric optical theory, waveguide theory, multimode theory, empirical models and full wave model. The GO model and the full wave model are limited to numerical results and can create great computational burdens. The waveguide model provides analytical results but is only applicable for the far region in empty tunnels. The multimode model gives analytical results for both the near region and far region in empty tunnels [16, 17].

The four slope channel model is an empirical model and has been used to characterize long tunnels. This model divides the tunnel in four regions. Each region has its specific path loss formula. In the first region near to the transmitter the path loss follows free space path loss. In the next region the path loss has constant slope. This slope is determined by the path loss coefficient in this region, it depends on the size of the tunnel and the operating frequency. The third region starts from where the far region of the waveguide model starts. In this region only the fundamental mode exist and the path loss follows the attenuation rate of this fundamental mode. Waveguide effect vanishes after certain distance and the path loss again follows the free space attenuation curve. This is the fourth region and these four regions are divided by three break points [13].

In this paper the CSP is used for predicting the path loss in predicting the path loss and break point locations in the four slope path loss model using chronological backtracking algorithm, which is a basic algorithm of CSP. After predicting the path loss at different set of parameters such as frequency (f), transmitter height (ht), receiver height (hr), tunnel cross-section (x), polarization (p) and dielectric constant (rp) of the tunnel we find the optimal set at which path loss is minimum. Branch and bound algorithm is used to optimize the constraint satisfaction problem.

## II. METHODOLOGY OF CSP

The two algorithms of CSP, chronological backtracking and branch and bound were used for to solve and optimize wireless propagation in tunnels.

### *Chronological Back-tracking Algorithm*

The basic operation of chronological backtracking algorithm in CSP context is to find the solution tuples. This algorithm took one variable at a time, and considers one value for it at a time, making sure that the newly picked variable does not violate the constraints specified. If any of the constraints are violated then it backtracks and assigns another value to the variable and again checks whether it satisfies all constraints or not.


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If the constraints are satisfied then the next variable in the list is picked and a value from the range of variables is assigned to it and the same procedure is repeated as was done for earlier variable. The assignment of values to the variables is known as labeling. The task of finding a solution is reduced to that of labeling all the variables using CSP. If all the variables are labeled, then the problem is solved [3].

### *Branch and Bound Algorithm*

Branch and Bound is a general search algorithm and makes use of knowledge of the *f* value in finding the optimal solution. A constraint satisfaction optimization problem (CSOP) is defined as CSP, together with an optimization function *f* which maps every solution tuple to a numerical value. So constraint satisfaction optimization problem is written as (Z, D, C, *f* ), where (Z, D, C) represent CSP with a set of variables (Z), domain (D), constraints (C) and *f* is the optimization function. A bound is nothing but a global variable which is defined according to the minimization or maximization problem, it depends on the case that either you want minimized or maximized value of the function you are solving [3]. The branch and bound algorithm is used to find particular set of frequency, transmitter height, receiver height, tunnel size and dielectric constant of the tunnel walls at which path loss is minimum. The branch and bound algorithm is used for finding the minimum value based upon certain bounds. The calculated values of path loss obtained after labeling all the variables are taken as *f* values. In this algorithm whenever a branching is done the minimum bound is compared with the *f* value. If the bound is lower than the *f* value then we conclude that the final value obtained in this branch is not less than the already obtained value. So, because the branch which is being presently evaluated does not give us the new minimum bound we leave it and go for another branch and again check the value obtained with the minimum bound available. If the new value is less than the bound, we replace the bound with new value and go further.

### *CSP Formulation*

A CSP is a tuple (Z, D, C)
where Z is a set of n variables {Z1, Z2, Z3……..Zn).
D is a set of n domains {D1, D2, D3…n}, Di being a finite domain of candidate values associated with the variable Zi.
C is set of K constraints {C1, C2, C3……..Ck} restricting the values assumed by variables.

The solution set consists of all the possible assignment of values to variables, so that all the constraints are satisfied simultaneously. In the present case the variables are {frequency, tunnel size , transmitter height, receiver height, polarization, dielectric constant}.

Domains of variables are:
Frequency {860-1900MHz};
Tunnel Size {b: 5m-8m, a: 9m-12m};
Where a is tunnel width and b is tunnel height in meters.
Transmitter Height {(b/2) to (b-.20b)m};
Receiver Height {(b/2) to (b-.20b)m};
Polarization {horizontal, vertical};
Dielectric constant {relative permittivity: 4-12, conductivity: 0.01-0.25} etc.

These are the values foe generally used construction material.

Constraint is path loss.

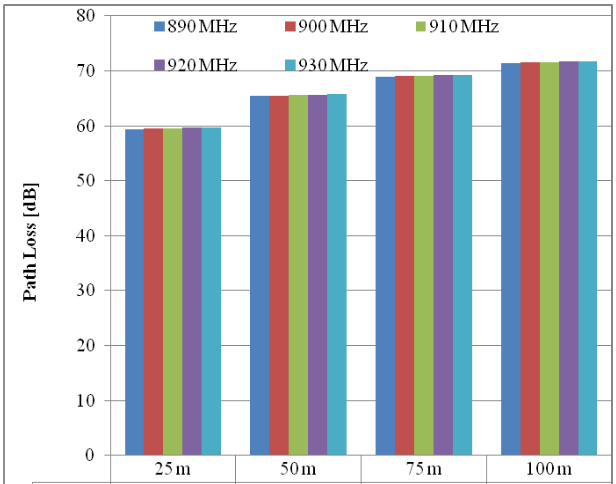
## III. RESULTS AND DISCUSSION

The four-slope channel model was implemented with the constraint satisfaction programming. The results obtained are explained below.

### *Near Region:*

In the near region free space propagation takes place, so the path loss is given by

$L[dB] = 20log_{10}\left[\left(\frac{\lambda}{4\pi}\right)\frac{1}{D}\right]$ here d is distance in meters and $\lambda$ is wavelength in meters.




| | 25m | 50m | 75m | 100m |
|---|---|---|---|---|
| 890MHz | 59.38660031 | 65.40720022 | 68.9290254 | 71.42780013 |
| 900MHz | 59.48365036 | 65.50425028 | 69.02607546 | 71.52485019 |
| 910MHz | 59.57962802 | 65.60022793 | 69.12205311 | 71.62082785 |
| 920MHz | 59.67455672 | 65.69515663 | 69.21698181 | 71.71575655 |
| 930MHz | 59.76845914 | 65.78905906 | 69.31088424 | 71.80965897 |

Figure 1: Path Loss variation with Distance and Frequency in Near Region

The distance before first break point is characterized by high attenuation rate and wide ranging fluctuations. The effect of frequency and distance in near region is shown in figure 1. From figure it is clear that frequency has less impact on path loss in near region whereas the effect of distance is significant. So the distance up to which near region extends should be less. In near region the tunnel size and antenna heights have no effect on path loss.

### *First Break Point:*

The location of first break point is given by

$$D_0 = \frac{4h_r h_t}{\lambda}$$

Where $h_r$ and $h_t$ are the heights of receiver and transmitting antenna respectively.

Table 1: Effect of Tx Height and Frequency (Same Band) on Break Point 1

| | Frequency (MHz) | | | | |
|---|---|---|---|---|---|
| Height (m) | 900 | 901 | 902 | 903 | 904 |
| 1.7 | 40.8 | 40.84 | 40.89 | 40.93 | 41.02 |
| 2.5 | 60 | 60.06 | 60.13 | 60.2 | 60.33 |
| 3.5 | 84 | 84.09 | 84.18 | 84.28 | 84.46 |
| 5 | 120 | 120.13 | 120.26 | 120.4 | 120.66 |

It can be seen from the table that with increase in frequency of operation and increase in the height of antenna break point increases.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The increase in the distance at which break point is located has the effect of increasing the path loss, because after the break point the slope of the path loss curve decreases. From the table it is clear that the break point distance increase much more with change in height than with change in operating frequency. In the table 1 and Table 2 the effect of frequencies from different GSM bands on break point is also shown

### *Mid Region*

In the mid region path loss is given by

$$L[dB] = L_0[dB] - \alpha(D - D_0)$$

Where $L_0$ is path loss at first break point, $\alpha$ is path loss coefficient whose value depends on frequency and tunnel size, D is the distance and $D_0$ is the first break point location. Table 3 gives the typical values of $\alpha$ for different frequencies of operation and tunnel size.

Table 2: Effect of Tunnel Size and Frequency on Path Loss Coefficient

| **Frequency (MHz)** | **Path Loss Coefficient (dB/km)** | |
|---|---|---|
| | **10m x 7m** | **12m x 8m** |
| **900** | 42 | 28 |
| **950** | 37.5 | 24 |
| **1800** | 28.5 | 20 |

With increase in both frequency and tunnel size, path loss coefficient decreases. Change in tunnel dimension has predominating effect on the values of path loss coefficient, it is because the attenuation rate of different modes is inversely proportional to the cube of tunnel dimension and directly proportional to the square of wavelength.

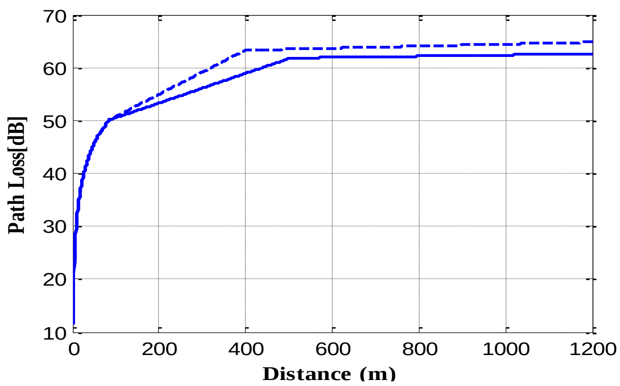


Figure 2: Path Loss Curve for Different Tunnel Sizes

Figure 2 shows the path loss for two tunnels with different l cross sections. The solid line is for cross section of 12m x 8m and the dotted line for 10m x 7m, with antennas placed in center of the tunnel

2. Effect of Transmitter Height: With increase in transmitter the fluctuations and the attenuation rate of path loss in near region increases. When transmitting antenna is placed at near to the tunnel walls, the first break point location moves farther. This has the effect of increasing the path loss because the free space path loss is followed for much longer distance. Its effect is shown in Figure 3.

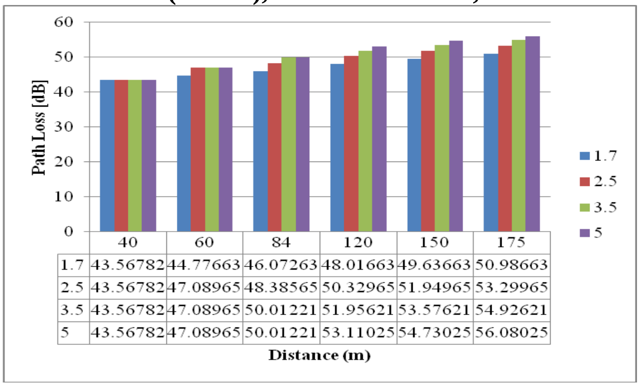


Figure 3: Path Loss vs Distance for different Tx heights

### *Second Break Point*

This is the boundary between the mid region and far region where all the higher order modes have been attenuated and the total received power being mostly because of fundamental mode. Both, the frequency and tunnel size effects the location of break point and the effect is depicted in figure 4.

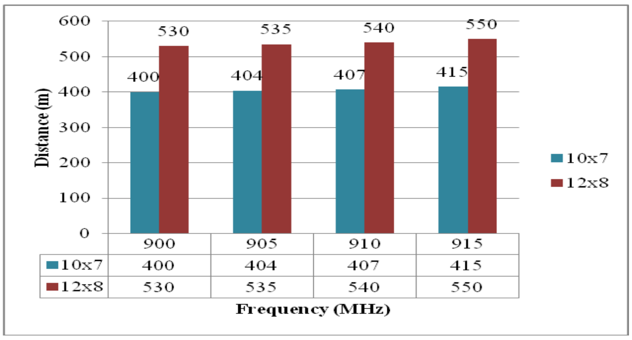


Figure 4: Break Point vs Frequency and Tunnel size

### *Path Loss in Far Region*

Where all the higher order modes in tunnel are attenuated far region starts. In this region path loss curve slopes equals that of fundamental mode and is given by:

$$L[dB] = L_1[dB] + 4.343\lambda^2\left(\frac{Re\{\varepsilon_r/\sqrt{\varepsilon_r - 1}\}}{a^3} + \frac{Re\{1/\sqrt{\varepsilon_r - 1}\}}{b^3}\right)(D - D_1)$$

The slope of the path loss in far region varies with frequency and tunnel dimensions. Typical values of slopes are given in next figure. As the dimensions of the tunnel increases the slope of the path loss curve also decreases, because with increasing dimensions the attenuation rate of modes decreases. Similar affect can be observed for frequency.

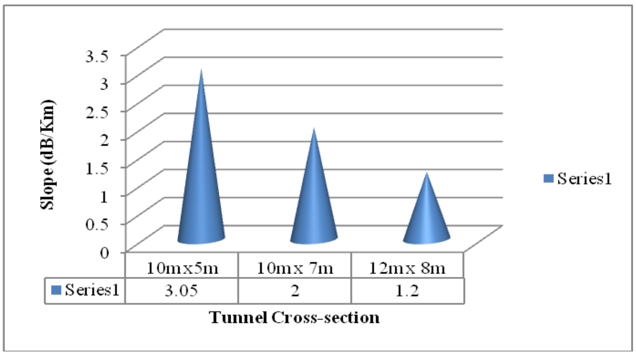


Figure 5: Path Loss Slope vs Cross-section


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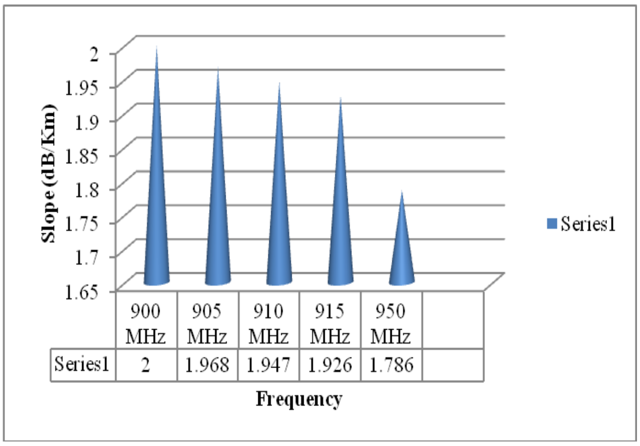


Figure 6: Path Loss Slope vs Frequency

It can be seen from the figure the effect of change in tunnel cross-section is more prominent than change in frequency.

### *Effect of Polarization*

The signal excited from a horizontal polarized antenna attenuates much slower than that excited from a vertical polarized one. It is consistent with the previous discussion about the relationship between the tunnel size and antenna polarization. Hence, it can be pointed out that: in wide but low tunnel, the horizontal polarized antenna is more appropriate while for narrow but high tunnel, the vertical polarized antenna is more suitable.

### *Electrical Parameters*

The electrical parameters consist of permittivity $\varepsilon$ and conductivity $\sigma$. The temperature, humidity and pressure have little influence on the air permittivity but may affect the conductivity more. However, the effect of different conductivity of tunnel air may be negligible, because it is very small compared to the permittivity. Therefore, the electrical parameters of tunnel air can be considered the same as those of atmosphere air. Tunnel walls electrical parameters can be looked up in, where the permittivity of tunnel materials are in the range of 5-10 and the conductivity is on the order of $10^2$ *s/m* at the UHF frequency band. In this value range, the received power curves with different wall electrical parameters are very close to each other. Hence it can be concluded that the electrical parameters of tunnel walls do not considerably influence the signal propagation inside the tunnel.

## VI. CONCLUSION

The path loss results in tunnels were obtained using constraint satisfaction programming on four-slope channel model. Analysis of various factors affecting the path loss was done and then branch and bound algorithm was used for optimizing the path loss in tunnels, which provided the optimized value of path loss for different set of parameters.

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