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Deterministic Diffraction Loss Modelling for Novel Broadband Communication in Rural Environments

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***Abstract*—This paper presents a deterministic modelling approach to predict diffraction loss for an innovative Multi-User-Single-Antenna (MUSA) MIMO technology, proposed for rural Australian environments. In order to calculate diffraction loss, six receivers have been considered around an access point in a selected rural environment. Generated terrain profiles for six receivers are presented in this paper. Simulation results using classical diffraction models and diffraction theory are also presented by accounting the rural Australian terrain data. Results show that in an area of 900 m by 900 m surrounding the receivers, path loss due to diffraction can range between 5 dB and 35 dB. Diffraction loss maps can contribute to determine the optimal location for receivers of MUSA-MIMO systems in rural areas.**

***Index Terms* - Deterministic Modelling, Diffraction Loss, Digital Elevation Map**

I. Introduction

High-speed broadband internet access is widely recognised as a catalyst to social and economic development of the modern world. Particularly, in rural Australia, the provision of broadband services with the existing technologies, such as fibre-to-the-premise (FTTP), 3G, 4G and WiMAX, is an economic and technical challenge, as the rural population is sparsely scattered over an extensive geographical area with a low population density of 2.7 people / km^2 [1].

An innovative point-to-multi-point wireless broadband technology, termed as Multi-User Single-Antenna for Multiple-Input-Multiple-Output (MUSA-MIMO) technology, has been proposed as a feasible solution to provide high-speed broadband for rural environments [2]. Figure 1 illustrates MUSA-MIMO technology deployed in a rural area. The access point is equipped with multiple antenna array arranged in a uniform-circular architecture and each user around access point is equipped with a single antenna.

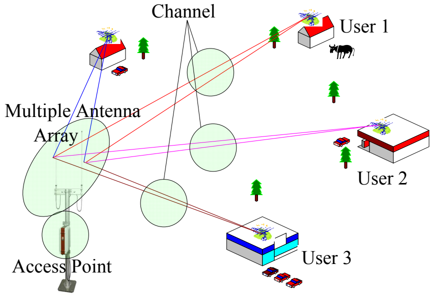


Figure 1. MUSA-MIMO technology deployed in a rural area

MUSA-MIMO technology utilises the analogue TV frequency spectrum, antenna beamforming techniques and high transmission towers. These properties enable the solution to be a long range fixed wireless access solution with predominant line-of-sight (LOS) paths. Moreover, when the LOS path from the transmitter (Tx) to the receiver (Rx) is obstructed by the terrain, propagation through diffraction can be prominent. Therefore, modelling and predicting diffraction loss for this solution is vital for the accurate planning and performance prediction for MUSA-MIMO technology in rural Australian environments. This paper describes the deterministic modelling techniques followed to determine the diffraction loss in a selected rural Australian environment. This research step is followed as an initial step in order to develop a comprehensive MUSA-MIMO channel model for rural Australia. Furthermore, it presents the simulation results obtained using these deterministic modelling techniques.

The paper is organised according to the following order. Next section provides an introduction to MIMO channel modelling techniques. Then, terrain profiles generation procedure and generated terrain profiles for the selected rural area are presented. The succeeding section presents the methods and results from diffraction loss calculations. Finally, the conclusion and future work are presented.

II. MIMO Channel Modelling Techniques

Multi-path propagation is a fundamental requirement for the proper functionality of MIMO systems. The performance of MIMO systems can vary from one environment to another and from time to time in the same environment [3], [4]. For instance, environments with multipath propagation, such as urban locations with high building densities, are able to provide less correlated signals at each antenna of the receiver array of a

MIMO system, therefore improving its performance. Accurate characterization and modelling of MIMO channels in different scenarios and environments (such as Urban, Rural, Indoor and Outdoor) is vital when integrating MIMO systems into real world applications. This fact highlights the importance of developing realistic channel models which can understand and mimic wireless channels and radio propagation concepts [5].

Several MIMO channel models [6], [7], [8] have been proposed in recent years. Almers et al. [5] survey on MIMO channel models classifies the existing MIMO channel models as physical and analytical models. The electromagnetic wave propagation between the location of the transmit array and the location of the receive array is the baseline for characterizing physical channel models [5]. On the other hand, analytical channel models characterize the impulse response of the channel mathematically, without considering the electromagnetic wave propagation, i.e. [9] and [10]. Analytical models study channel coefficients as random variables.

Physical propagation models are further classified as deterministic, geometry-based stochastic and non-geometrical stochastic [5]. A given physical propagation model is deterministic (eg. ray tracing), if it is possible to reproduce the actual wave propagation scenario (process) for a given environment. The relevant propagation process can be simulated from the computer programs through the use of building databases, which accurately represent the building or terrain features [11]. Deterministic models are more realistic and accurate, due to the representation of the environment specific geometry [5]. Therefore, the computer program has to run multiple times when characterizing different geometric environments. As the deterministic models are more realistic and accurate, a deterministic modelling technique is followed to model the rural wireless channels for MUSA-MIMO technology.

The following section discusses the procedure to generate terrain profiles for a selected rural environment.

III. Terrain Profiles Generation

Figure 2 illustrates the field trial site 1, where six receivers are positioned around the access point (AP), approximately in a 15 km radius. The paper focuses on modelling the downlink channels (from the access point to the users), and hence the users are referred as receivers and the access point as the transmitter. The transmitter and receiver antenna heights are 70m and 1.5m, respectively. This section discusses terrain profile generation for these six receivers around the field trial site 1.

A digital elevation map (DEM) is used to analyze the terrain profile between the access point and receivers. A DEM with better resolution improves the accuracy of the analysis [12]. Digital elevation maps are available in several resolutions such as 1 arc-second, 3 arc-seconds and 9 arc-seconds. For instance, adjacent data points (terrain heights) in 3 arc-seconds map are 90 m apart. The best available DEM for the rural area under investigation is 3 arc-seconds DEM obtained from the Shuttle Radar Topography Mission (SRTM3) version 2_1 elevation data [13].

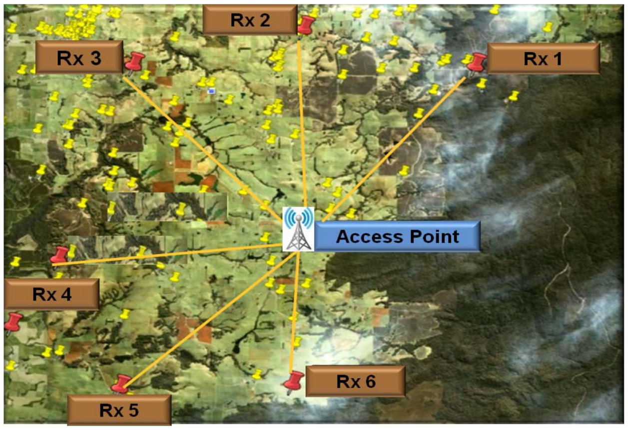


Figure 2. Receiver Positioning for the Field Trial Site 1

A Matlab program was developed to extract the terrain profiles for six receivers around the access point. Longitude and latitude (in decimal degrees) of the access point and receivers are taken as the input parameters under this task. These locations are used to determine the terrain profiles for each transmitter-receiver combination. The curvature of the earth is not taken into account in this model as the distances of interest are small. After generating terrain profiles, a terrain analysis algorithm determines LOS path availability and terrain obstructions.

For a given terrain profile, the terrain analysis algorithm determines the availability of a LOS path or diffraction edges. If a terrain obstruction does not block the first Fresnel zone ellipsoid, then the diffraction loss can be minimal [11]. Therefore, for a given transmitter-receiver profile, the terrain analysis algorithm determines the LOS path availability, if the first Fresnel zone is not obstructed by the terrain profile. The Fresnel zone radius r_n for the n^{th} Fresnel zone is given by [11]

$$r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \tag{1}$$

where, d_1 is the distance from the transmitter to the point where the Fresnel radius is calculated, d_2 is the distance from the Fresnel zone calculation point to the receiver and λ is the wavelength of the signal. Figure 3 illustrates first, second and third Fresnel zone for a given propagation path. The parameter n denotes the Fresnel zone number.

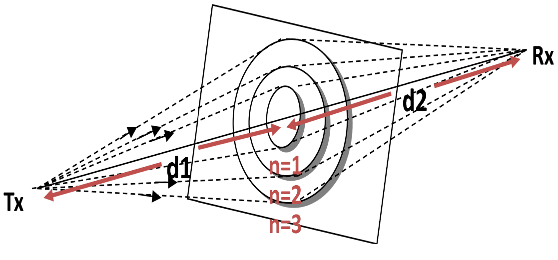


Figure 3. Fresnel zones and related parameters

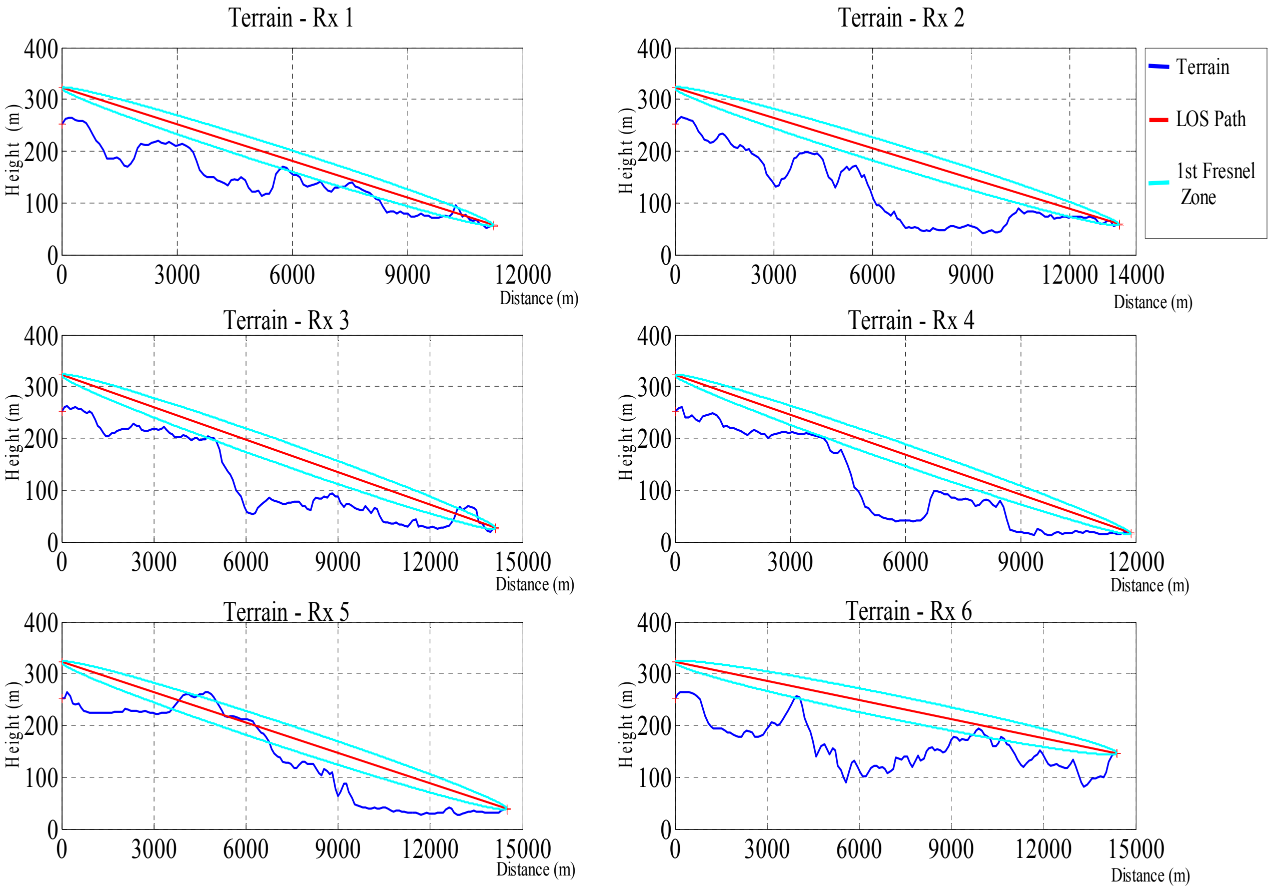


Figure 4. Terrain Profile and first Fresnel zone for six receivers

Figure 4 presents generated terrain profiles and first Fresnel zones for six receivers around the access point for the field trial site 1. These figures show that most of the transmitter-receiver LOS paths are obstructed by the terrain. This observation suggests that the accurate modelling of diffraction loss is vital for accurate performance prediction of MUSA-MIMO technology in rural areas. Therefore, the following section presents diffraction loss prediction calculations and simulation results for six receiver positions.

IV. Diffraction Loss Predictions

Diffraction is a well known wave propagation mechanism, which may occur over different hills in the rural environments, over buildings in microcells, or around corners in the indoor environment [14]. Diffraction occurs when there is a partial blocking of a portion of the wave front by a surface with irregular edges [15]. This gives rise to bending of waves around the obstacle, even when a line-of-sight path does not exist between the transmitter and the receiver.

Terrain obstructions are determined by the terrain analysis algorithm to determine the diffraction loss. If the first Fresnel zone is obstructed by the terrain, the algorithm detects those terrain heights as terrain obstructions. After detecting terrain obstructions, the diffraction losses due to terrain obstructions are calculated. Under this task terrain obstructions were approximated as knife edges. The extension of the single-edge diffraction theory to multiple obstacles is a mathematically complex problem [16]. However, several multiple knife-edge diffraction methods such as, Bullington's equivalent knife-edge [17], Epstein-Peterson [18], Japanese [19] and Deygout [16] exist in the literature.

Bullington's equivalent knife-edge method proposes to calculate diffraction loss by replacing the real terrain obstacles with a single equivalent knife-edge at the point of intersection of the horizon ray from each of the transmitter and receiver terminals [17]. Bullington method produces an optimistic estimate of field strength at the receiving point [16]. Moreover, if Bullington method is used, important obstacles can be ignored. Epstein-Peterson method computes the attenuation for each obstacle and sums them to obtain the overall loss. This method determines the attenuation due to a given diffraction edge, by joining the peaks of preceding and following diffraction edges. Comparing with the Millington's rigorous solution, it has revealed that Epstein-Peterson method predicts large errors when two obstacles are closely spaced [16]. Millingtion [20] proposed a correction factor for the Epstein-Peterson method.

The technique proposed by the Japanese method is similar in the concept to the Epstein-Peterson method. The Japanese method considers the effective source as the projection of the horizon ray through that point on to the plane of one of the terminals.

Deygout method is known as the ‘main-edge’ method because the first step of this method is to calculate Fresnel-Kirchoff diffraction parameter (v-parameter) for each edge alone, as if all other edges are absent [16]. The edge having the largest v-value is termed as the main edge and its loss is calculated using the complex-Fresnel integral. Diffraction loss due to other terrain obstructions are found with respect to a line joining the main edge to the transmitter and receiver. For a path with many obstructions, the total loss is calculated as the sum of the individual losses for the obstacles in the order of decreasing v-value [16]. In practice, the total loss is calculated as the sum of three components only, the main edge and the subsidiary main edges on either side.

Among these methods, the Deygout method shows good agreement with the rigorous theory [16]. The accuracy of this model is highest when there is a dominant obstacle. Also, correction factors are introduced for two comparable obstructions [16]. Therefore, Deygout method is used to calculate diffraction loss under this study. After employing Deygout method, v-parameter and the complex Fresnel integral are calculated for the main edge and the subsidiary main edges on either side.

The v-parameter and the complex-Fresnel integral $F(v)$ are given by [16]

$$v = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \tag{2}$$

$$F(v) = \frac{(1 + j)}{2}\int_{v}^{\infty} e^{\frac{-j\pi t^2}{2}} dt \tag{3}$$

where d_1 and d_2 denote the distance from the access point to diffraction edge and the diffraction edge to the receiver (along the LOS path), respectively. The parameter h represents the height of the obstacle and the wavelength is represented by λ. Parameters d_1, d_2 and h are shown in the Figure 5.

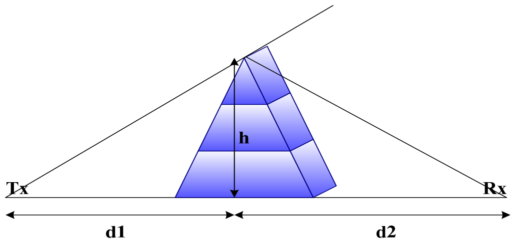


Figure 5. Parameters related to diffraction calculations

After calculating the complex-Fresnel integral from diffraction theory, gain of the diffracted signal (compared to the LOS signal) can be calculated as

$$G(v) = 20 * log|F(v)| \tag{4}$$

where G(v) is the gain of the diffracted signal for a given v-parameter.

A. Analysis

Figure 6 illustrates the diffraction loss prediction for 900 m x 900 m area around all six receivers. A unit distance in the grid corresponds to 90 m distance. This grid provides significant information to determine the position of the receivers to minimise diffraction loss in rural environments. Calculated diffraction loss for six receivers around the access point is shown in Table I.

Receiver Number	**Diffraction Loss / dB**
1	**14.64**
2	**9.75**
3	**26.32**
4	**11.66**
5	**15.44**
6	**7.02**

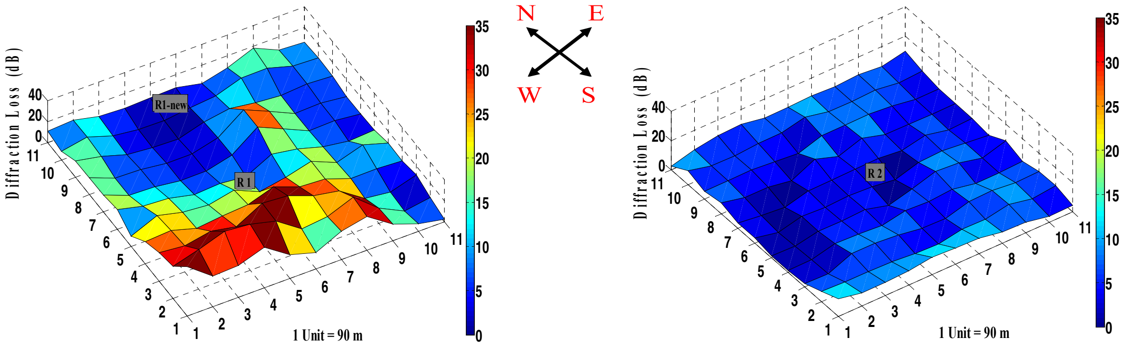
Table I
Predicted Diffraction loss for the receivers showed in Figure 2

According to Table I, receivers 1, 3 and 5 experience higher diffraction losses compared to receivers 2, 4 and 6. These results exhibit a correlation between the terrain obstructions and the diffraction loss experienced by each receiver. According to the Figure 3, the first Fresnel zone of receivers 1,3 and 5 are fully obstructed. Therefore, these receivers experience higher diffraction loss. On the other hand the first Fresnel zone of receivers 2, 4 and 6 are partially obstructed. Therefore, these receivers experience low diffraction loss compared to receivers 1, 3 and 5.

From Figure 6, it can be noted that relocating receiver 1 a few hundred meters (approx. 400 m, R1-new) north will reduce the diffraction loss by approximately 15 dB. Also, predicted diffraction losses around receiver 3 show that by relocating it approximately 500 m (R3-new) north west, path loss due to diffraction could be reduced by 20 dB. Therefore, the diffraction modeling technique presented in this paper significantly contributes to determine the optimal location for MUSA-MIMO receivers in rural environments.

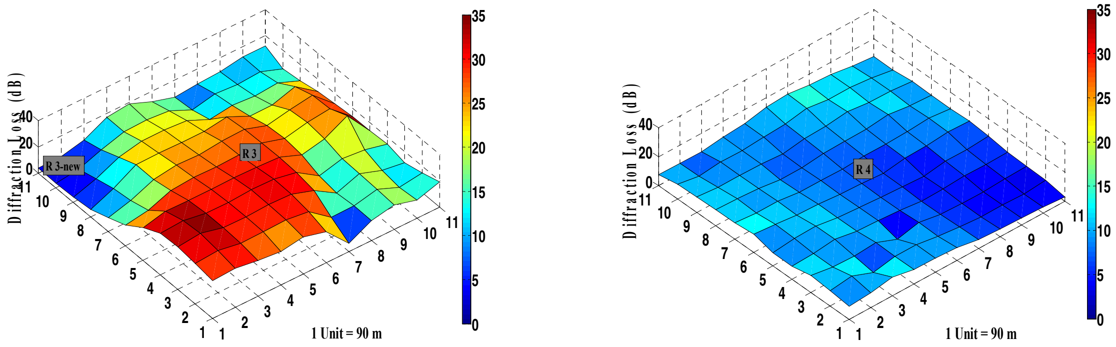
V. Conclusions

This paper discusses a deterministic modelling approach to predict diffraction loss for proposed MUSA-MIMO technology in a selected rural Australian environment. A digital elevation map with 3 arc-seconds (90m) resolution was used in this analysis. In order to predict diffraction loss, Deygout method and diffraction theory have been implemented. Simulation results for the diffraction loss have been presented in this paper. Results show that the predicted diffraction loss for the six receiver locations ranges between 7 dB to 26 dB.



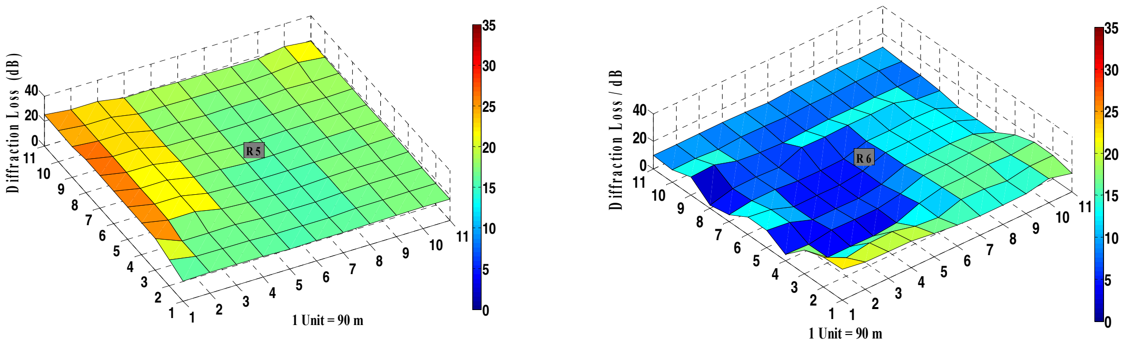
I. Diffraction prediction around receiver 1

II. Diffraction prediction around receiver 2



III. Diffraction prediction around receiver 3

IV. Diffraction prediction around receiver 4



V. Diffraction prediction around receiver 5

VI. Diffraction prediction around receiver 6

Figure 6. Diffraction loss prediction for 900m x 900m area around six receivers

Diffraction loss maps showed that by relocating some of the receivers within an area of 900m by 900m diffraction losses can be reduced by up to 20 dB. This modeling technique can significantly contribute to minimize diffraction loss at the receivers of MUSA-MIMO systems deployed in rural environments. In future, the authors will conduct channel measurements to compare these results with the experimental data and to develop a comprehensive outdoor channel model for rural Australia.

VI. Acknoledgemets

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