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Efficient Wireless Broadband Communications for Rural Australia

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***Abstract*—This paper discusses how internet services can be brought one step closer to the rural dispersed communities by improving wireless broadband communications in those areas. To accomplish this objective we describe the use of an innovative Multi-User-Single-Antenna for MIMO (MUSA-MIMO) technology using the spectrum currently allocated to analogue TV. MUSA-MIMO technology can be considered as a special case of MIMO technology, which is beneficial when provisioning reliable and high-speed communication channels. This paper describes channel modelling techniques to characterise the MUSA-MIMO system allowing an effective deployment of this technology. Particularly, it describes the development of a novel MUSA-MIMO channel model that takes into account temporal variations in the rural wireless environment. This can be considered as a novel approach tailor-maid to rural Australia for provisioning efficient wireless broadband communications.**

***Index Terms*—MIMO, MUSA-MIMO, Time-Varying Wireless Channel Modelling**

I. Introduction

Access to broadband services with desirable data rates is vital for the economic and social growth of rural Australia. In future, government services such as health, and education will be increasingly delivered through the internet [1]. Additionally, the internet will be widely used to conduct business and to deliver commercial services. As a result, the demand for internet infrastructure that supports high data rates is evermore increasing.

However, the availability of broadband internet to Australian rural areas is hindered due to many reasons. For instance, as stated in [2], 40-50 % of Australian houses in remote areas do not have internet access. Furthermore, 50-60% houses in very remote areas do not have access to the internet. Therefore, improving the broadband internet infrastructure in rural areas, which include large geographical areas, is vital to provide broadband internet services.

Due to the sparsely scattered population over a wide area, with only 2.7 people per square kilometre and large land mask, providing wireless broadband connectivity to Australia's rural and remote areas is a challenging task. For instance, the estimated cost to provide broadband services to internet dispersed Australian rural areas using fibre-to-the-premise (FTTP) infrastructure is 101 billion Australian dollars [1]. Similarly, third generation (3G), fourth generation (4G) and WiMAX technologies will introduce economic and technical (coverage and data rate) challenges when providing broadband services to rural areas [1].

Therefore, new paradigms and innovative telecommunication technologies need to be explored to overcome the challenges of providing faster, more reliable and more secure broadband internet services to internet dispersed rural areas. Analogue TV spectrum is proposed to use along with Multiple Input Multiple Output (MIMO) antenna technology, as a novel approach to provide broadband internet to those areas. Using high towers and low frequencies to transmit data would increase the coverage area, which will result in less transmission towers to cover a given area. Furthermore, according to the proposed access solution a single receiver at a rural house will be served by a transmitting antenna array mounted on a single tower. Many such rural houses will be served by a single base station. Therefore, more specifically, the proposed solution will implement a Multiple Users with Single Antenna for MIMO (MUSA-MIMO) system.

Characterization of the MIMO channel is vital, to optimize the performance and adequate planning of wireless communication systems in different scenarios (indoor and outdoor) and operating frequencies [3]. The characterization and modelling of MIMO channels, both experimentally and theoretically, has been a popular research topic in recent years. However, the effectiveness of MIMO communication technology depends on the availability of high quality channel state information (CSI) at the communicating nodes [4]. Usually, CSI is obtained by periodic transmission of known training data from which the receiver estimates the channel transfer matrix. When the channel state is highly varying, this training must be frequently repeated, using the available transmission bandwidth and therefore resulting in low effective channel capacities. These observations suggest that accurate MIMO performance prediction requires an accurate representation of channel temporal variations[4]. While the understanding of the time variant channel behaviour has to be obtained from experimental measurements or detailed electromagnetic simulations, such understanding only becomes useful when it is accommodated in the models that can be used in performance simulations of the radio system [4].

Therefore, this paper describes the development of a novel MUSA-MIMO channel model that takes into account temporal variations in the rural wireless environment. Furthermore, it

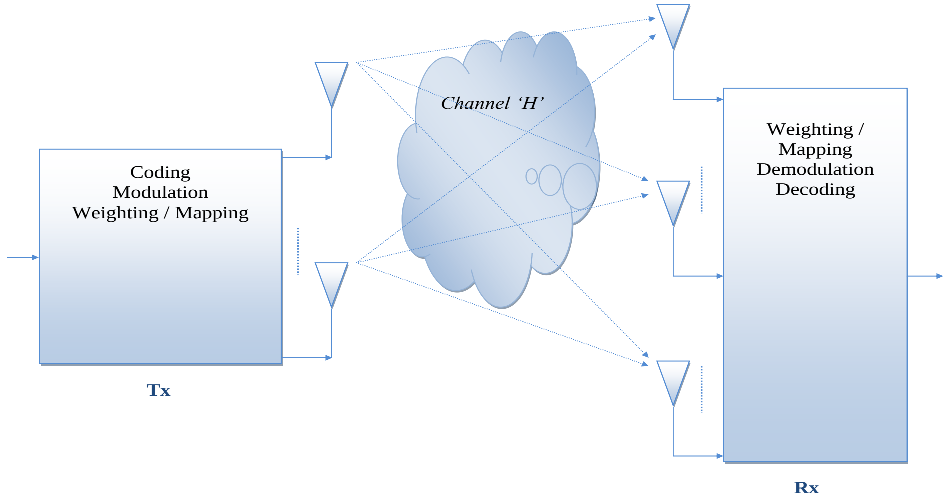

Figure 1. A MIMO Wireless Transmission System

will discuss the state-of-art channels models and reasons for time variations in rural environments. Path loss simulation results for 600 MHz in rural areas have also been presented in this paper.

The paper is organised according to the following order. Next section provides an introduction to MIMO technology. In Section III, MUSA-MIMO technology and its benefits for the provision of broadband services to rural areas are highlighted. Furthermore, Section III presents an analysis of the challenges in deploying MUSA-MIMO technology. Then, in Section IV, existing MIMO channel models are explored to identify the additional requirements which have to be incorporated in the present MIMO channel models. Section V presents novel MUSA-MIMO channel model development steps and path loss simulation results for 600 MHz in rural areas. Finally, the conclusion and future work are presented.

II. Introduction to MIMO Technology

The employment of multiple antennas at both transmitter and receiver in wireless systems is generally identified as MIMO technology. Due to its dominant performance intensifying potential such as high capacity, increased diversity and interference suppression, it has rapidly achieved recognition over the past decade [5]. The concept behind the MIMO is to improve the data rate (bits/sec) or the quality of service (bit-error-rate or BER) of the communication for each user by combining the signals on transmit (Tx) antennas and receive (Rx) antennas at two distinct ends [6]. If N antennas are used at both ends, MIMO can enhance spectrum efficiency by N-folds in a favourable radio environment. This advantage leads to a significant enhancement of the quality of service and capacity of the network. Figure 1 illustrates a MIMO wireless transmission system.

A. Benefits of MIMO Technology

The principal performance enhancing potentials such as high capacity, increased diversity and interference suppression of MIMO systems results from array gain, diversity gain, spatial multiplexing gain and interference reduction [7]. Each of these leverages is discussed to explore how MIMO technology can be used in a beneficial way to improve wireless communications in rural areas.

B. Array Gain

Array gain is the enhancement in average receive signal-to-noise ratio (SNR) that results from a coherent combining effect of wireless signals at a receiver. It is obtained through processing at the Tx and Rx. Depending on the number of Tx and Rx antennas, transmit and receive array gain require channel knowledge at the Tx and Rx, respectively. Though channel knowledge at the Rx is usually available, the CS at the Tx is more complex to maintain. The coverage and the range of a wireless network can be improved by the array gain, as it improves resistance to noise.

C. Diversity Gain

The fading effect in wireless channels can be lessened by diversity techniques that rely on the transmission of the signal over multiple (ideally independent) fading paths in time, frequency or space. The diversity ensures that the receiver receives multiple copies of the same transmitted signal. If these copies are affected by independent fading conditions, the probability of fading all the copies at the same time decreases [7]. Therefore, the diversity helps to improve the quality of a wireless system. The most common diversity technique is spatial (or antenna) diversity [8] in MIMO systems, whereby multiple antennas are spatially separated and the receiver selects the best signal at a given time.

D. Spatial Multiplexing Gain

Spatial multiplexing gain is the linear increase in capacity offered by MIMO channels without additional power or bandwidth [9]. It is a transmission algorithm which is only possible

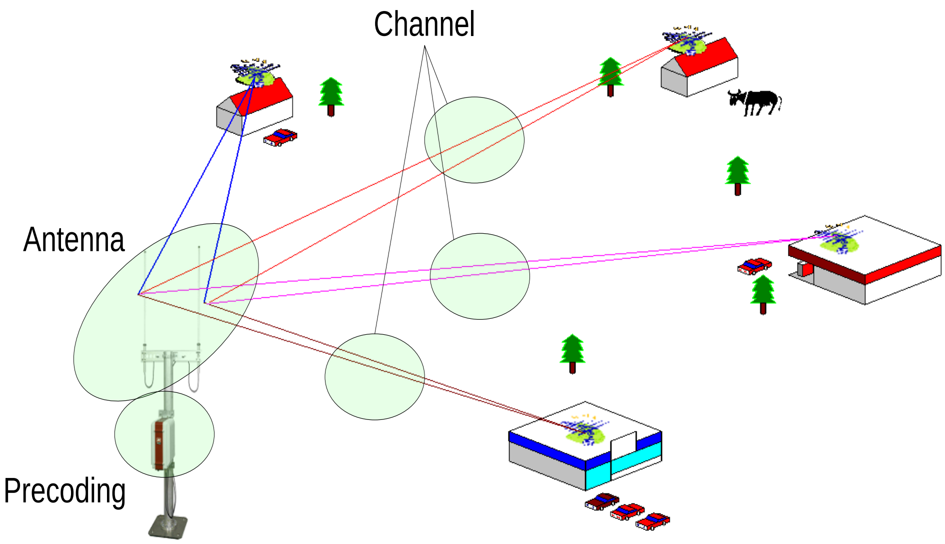

Figure 2. Typical Multi-user MIMO Scenario with distributed users in a rural area

in MIMO systems. This is comprehended by transmitting multiple, independent data streams from the individual antennas within the bandwidth operation. The receiver can split the different data streams under suitable channel conditions such as rich scattering, yielding a linear increase in capacity in the wireless network.

E. Interference Reduction or Avoidance

Co-channel interference results from frequency reuse in wireless channels. With the aid of multiple antennas, the separation between preferred signal and co-channel signals can be used to reduce interference. Although interference reduction requires knowledge of the channel of the desired signal, precise knowledge of the channel of the interferer may not be essential. Furthermore, the interference reduction can be executed at the Tx, by decreasing interference energy sent to the co-channel users, while transmitting the signal to the desired user. The multi-cell capacity can be enhanced by interference reduction as it allows for aggressive frequency reuse.

As explained in this section, due to dominant performance intensifying potentials of the MIMO wireless communication system, such as high capacity, increased diversity and interference suppression, a reliable and high speed information transmission can be achieved when a MIMO system is deployed.

III. MUSA-MIMO TECHNOLOGY

Multi-User-Single-Antenna for MIMO (MUSA-MIMO) technology has been proposed as a novel and practical solution to provide cheaper and faster internet services to rural Australia in a spectrally efficient and cost effective manner. Faster wireless broadband services will be provided by employing multiple antennas at the base station to serve users equipped with a single antenna receiver. System will be capable of serving multiple users sparsely distributed in a given area using the same frequency and bandwidth. This approach facilitates the allocation of a wider bandwidth for each user, thus giving them access to faster data rates. Efficient usage of the radio spectrum and a simple user terminal with a single antenna lead to cheaper services. The concept of MUSA-MIMO together with spectrally efficient orthogonal frequency division multiplexing (OFDM) will be used as the physical layer technology.

As discussed in Section II, MIMO technology uses multiple antenna elements for transmitter and receiver array. However, it is recognised that equipping the user terminal with many antennas in a small user device would be technically very challenging and probably also not cost effective.

In MUSA-MIMO technology, only the access point (the base station) is equipped with multiple antennas. In this point-to-multipoint topology, the multiple users are each equipped with a single antenna. They can collectively be considered as one end of a MIMO link. Such system is known as multi-user MIMO [5], [10] and is illustrated in Figure 2. For the downlink, such a system has the potential to combine the high throughput achievable with MIMO processing with the benefits of space division multiple access. This allows the transmission of multiple spatially multiplexed data streams in the downlink to multiple users, resulting in very high data rates.

A. Benefits Achieved from MUSA-MIMO Technology

MUSA-MIMO technology is a superior solution to provide broadband communications in rural settings, since it provides:

- **Lower power requirements and cost reduction**: Optimizing transmission toward the wanted user (transmit beamforming gain) achieves lower power consumption and amplifier costs. The use of simple receivers with a single antenna also limits the cost of the user's receiver equipment.
- **Improved link quality/reliability** due to antenna diversity gain at the base station.

- **Interference Avoidance**: Analogue TV frequency band is used to deploy MUSA-MIMO system in rural areas. Using lower carrier frequencies and high transmission towers will increase the coverage area. Therefore, in terms of coverage, a wireless regional area network (WRAN) [11], [12] will be deployed with the MUSA-MIMO system. Reusing the frequency in WRAN cells may cause co-channel interference for the users. This effect can be significant for low carrier frequencies, since they exhibit less decrement in field strength as moving away from the transmitter (due to low pathloss effects) compared to higher frequencies. Precise control of the transmitted power and exploitation of the knowledge of properties of the received signal allows for interference reduction and increased numbers of users sharing the same available resources or reuse of these resources by users served by the same base station. Furthermore, implementation of OFDM will reduce the interference effects of the wideband channel. In addition, antenna polarization discrimination can be exploited to cope the interference effects among the WRAN cells [11].
- **Increased range or coverage** due to the beamforming gain at the base station.

Therefore, MUSA-MIMO technology can effectively be used to improve wireless broadband access in rural areas, especially when the users are distributed in a large geographical area. Furthermore, this will be a cheaper option to the end users, since only a single antenna is used, while achieving a high data rate to the end users.

B. EMC Challenges

Electromagnetic Interference (EMI) to radio and TV reception may result due to positioning receivers in a hostile environment or in an area where the available signal is inadequate. As stated in [13] most common cause of EMI to radio and TV originate from the arcing and corona occurring on high voltage power lines. This interference is strongest in areas close to power lines and remote from the broadcast transmitter or where the reception of radio and TV is poor. Since, the analogue TV frequency band is used to deploy MUSA-MIMO system, receiver can be more than 20 kms away from the transmitter (WRAN cell) and receiver signal can be affected from EMI. Moreover, many service providers are operating in the UHF/VHF frequency bands and the electromagnetic environment found around transmitting stations is considerably harsher than that normally encountered, because of the high field strengths, and equipment immunity [14].

Therefore, electromagnetic disturbance limits of the broadcasting system equipment have to be considered when deploying MUSA-MIMO system. Currently, electromagnetic disturbance limits of the mobile multimedia broadcasting system equipment are not proposed as a worldwide standard [15]. However, adhering to the Australian EMC standard (AS/NZS CISPR) [16] is vital in order to reach the desired performance and to cope with the electromagnetic interference when deploying the MUSA-MIMO system. Furthermore, additional protection measures can be taken in to the consideration such as shielding and filtering, to ensure satisfactory operation of equipment.

C. MUSA-MIMO Deployment Challenges

The design and implementation of MUSA-MIMO still faces significant challenges, such as designing optimum antenna arrays for the access point, pre-coding schemes suitable for MUSA-MIMO downlinks, and efficient and accurate methods for obtaining channel state information (CSI) at the transmitter.

Accurate CSI is not only useful in achieving higher SNR at a desired receiver, but also eliminates interference caused by the network on the desired co-channel users in MU-MIMO systems [5]. In order to obtain the CSI, feedback of the receiver can be considered at the transmitter end. However, the challenge in MU-MIMO is that the receiving antennas associated with different users at each end of the MIMO link are typically unable to coordinate with each other. Therefore, obtaining CSI at the transmitter can be a very challenging and costly problem for multi-user channels [5]. Thus, a novel approach will be followed to overcome the problem of CSI at the transmitter in deploying the MUSA-MIMO technology. The approach will be discussed in the following paragraphs.

Empirical work has already shown that varying weather conditions such as wind in the vicinity of the wireless channel have a pronounced effect on the received signal [17]. Therefore, effects due to temporal variations such as those caused by varying weather conditions need to be considered in wireless channel modelling. Furthermore, for accurate performance predictions and adequate planning of wireless communications systems in rural areas, the channel models need to mimic and reflect the real world propagations scenarios and temporal variations such as varying weather conditions.

If the MUSA-MIMO channel is modelled accurately for the time varying weather conditions, the transmitter array can adjust its properties to improve the spectral efficiency and the quality of the transmitted signal, provided the accurate knowledge of weather conditions is fed to the transmitter. The knowledge about accurate weather conditions can be obtained from a reliable weather monitoring station. Therefore, to deploy this novel approach, it is important to investigate whether the existing MIMO channel models support the requirements of the proposed MUSA-MIMO technology. Therefore, following section will focus on the MIMO channel models.

IV. A SURVEY ON TIME VARYING WIRELESS CHANNELS

Significant research work [18], [19], [20], [21] has been carried out to examine how wireless channels behave under different weather conditions. Experiments have been conducted in different carrier frequencies including UHF and VHF frequency bands, since frequency itself decides the amount of attenuation introduced when exposed to diverse weather conditions. Furthermore, literature highlights a high correlation between vegetation and different weather conditions when considering the temporal variations in outdoor wireless channels [18]. Rain and wind found to be the major contributors in weather which introduce temporal variations in outdoor wireless channels. However, only few studies [17] have been found in current literature, to investigate the effect of varying weather conditions in outdoor wireless channels in rural Australian environment.

Hashim and Stavrou [21] examined the scattering effects due to vegetation in different wind conditions. The objective of the study was to investigate the influence of vegetation movement on the shadowed LOS signal under different wind conditions. Measurements are taken in the controlled and outdoor environments. In the outdoor scenario, 900 and 1800 MHz carrier frequencies has been used. The experiment was conducted when the transmitter and receiver in static conditions. Hence, the shadowing/slow-fading component was assumed to be constant and the fast fading component was extracted by normalizing the received signal values to its mean. The authors analysed the variation in received signal in windy conditions, compared to no wind condition for shadowed LOS signals due to a line of trees. Then, the fading amplitude distribution constructed from measured data is compared and found to be Rician distributed. Further analysis on the Rician k-factor distribution in different wind speeds has shown that, k-factor decays exponentially with the wind speed. Authors modelled the relationship for Rician k-factor and wind speed (v) as [21],

$$k \cong F_c k_0 e^{\alpha v}$$

where, v = Wind speed in m/s, F_c = Configuration factor (F_c = 1 for a single-tree configuration),K_0 = 18.19 (A constant) and α = -0.75 (A constant).

Hashim et al. [21] suggests to conduct further studies on wind effect for different vegetation environments, different seasons, threshold speeds for different signal variation levels as well as the signal behaviour of other frequencies in the presence of wind effect. While the understanding of the time variant channel behaviour due to the effects such as varying weather conditions has to be obtained from experimental measurements, such understanding only becomes useful when those effects are accommodated in the models that can be used for real world channel performance prediction. Hence, the following subsection will be focusing on the time varying MIMO channel models.

A. Time Varying MIMO Channel Models

The performance of MIMO systems can vary from one environment to another and from time to time in the same environment [17], [22]. Therefore, 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. Many MIMO channel models [22], [23], [24] have been proposed in recent years. Almers et al. [25] 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 [25]. On the other hand analytical channel models characterize the impulse response of the channel mathematically, without considering the electromagnetic wave propagation. Furthermore, Almers et al. showed the key features that are not included in most of the present physical and analytical models. These features include the time variations and polarization effects.

Wallace and Jensen conducted a significant research work [4], [26], [27] on time variant effects on outdoor environments. They assumed that temporal variations occur mainly because of receiver movement [27]. Therefore, time variation matrices are interpreted in terms of distance which can easily convert to time, having a receiver motion velocity. Measurements taken from four different environments confirm a strong correlation between angular spread of mulitipath and channel time variability.

Wallace et al. [4], [26] developed modelling strategies to accommodate the time-varying behaviour of MIMO channels. They extended the multivariate complex normal (MVCN) [4], [26] distribution and physical time-variant clustering (TVC) model [4], [26] to incorporate time variant effects. The TVC model is based the double-directional channel concept and incoherent cluster modelling strategy [4]. Therefore, it treats the multipath components as the clusters of arrivals and departures, and estimates only the cluster parameters. The time index (n) is included in this model to accommodate time varying effects.

Suzuki et al. [17] investigated the effect of wind speed on wireless broadband channels in urban and suburban environments. According to their previous investigation, a strong correlation between signal variation and local wind speed is observed in an outdoor-to-indoor link (suburban area) at 2.4 GHz. Furthermore, their measurement results have shown that in both indoor and outdoor environments, temporal variation of received signal level often followed Ricean distribution. An increment in the signal variation during the day (08.00 am-08.00 pm) was also experienced. Suzuki et al. argue that very few attempts have been made to characterise the time variation effects of wireless broadband channels, especially the longer distance channels in the indoor-to-outdoor environment.

As shown in this Section, it is important to incorporate these time varying effects due to varying weather conditions in the present MIMO channel models in order to predict the accurate CSI. Furthermore, as it is the first time Multiple Users with Single Antenna for MIMO (MUSA-MIMO) technology of this kind is developed, there are no other existing channel models that suit such technology and associate time varying weather conditions that define the wireless channel in the rural environment. Therefore, following Section will discuss the initial development plan to develop the novel MUSA-MIMO channel model.

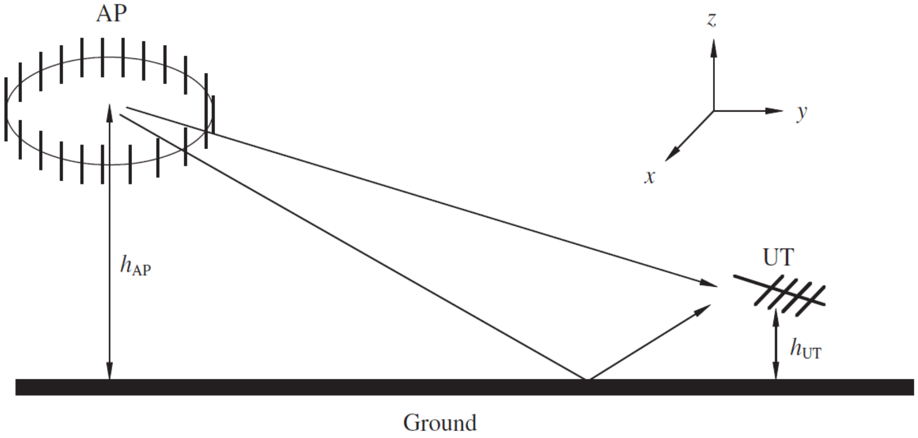

Figure 3. Example of a one tier circular transmitter array [28]

V. MUSA-MIMO Channel Development Steps and Simulation Results For Pathloss Predictions In Rural Areas

Pathloss simulations have been conducted as an initial step to develop the novel channel model. The distance from the transmitter to the receiver is taken as 20 km and the carrier frequency selected for the simulations was 600 MHz. Hata model (for Rural environments) [29], IEEE 802.16 Type A and C models [30] have been implemented as benchmark models. The transmitter and receiver heights are 70m and 2m, respectively. Twelve antennas are used in the transmitter array. The transmitter array is separated to three tiers with $\frac{\lambda}{2}$ height levels and each tier of circular array carries four antennas which are apart form $\frac{\lambda}{2}$ in arch length. A one tier circular transmitter array with several antennas shown in Figure 3. Simulations were performed for three antenna height levels, since they are arranged in three tiers. However, the distance between each antenna element ($\frac{\lambda}{2}$ in arch length) in the same tier can be considered as negligible when considering the 20 km distance between the transmitter and receiver. Therefore, only a single pathloss simulation was conducted for each antenna level. Simulation results for a single tier circular antenna array are shown in Figure 4.

When comparing these three models for a 20 km distance, Hata model predicts high received power compared to IEEE 802.16 models. Furthermore, IEEE 802.16 Type C model predicts high received power compared to IEEE 802.16 Type A model. That observation is expected since IEEE 802.16 Type A model is developed for hilly terrain with moderate-to-heavy tree densities whereas IEEE 802.16 Type C model is developed for flat terrain with light tree densities [30]. However, pathloss models provide a general idea about how much power is received for a given distance (with or without terrain variations). A ray tracing simulation will also be performed to analyse time varying effects for a given environment.

Then, channel measurements will be conducted for MUSA-MIMO system in different weather conditions. As the second step, a detailed statistical study is performed to examine the additional attenuation and temporal variations induced by the varying weather conditions as performed in reference [18]. As we have discussed in Section IV rain and wind have been identified as the main contributors for time variations in rural environments (Environments with vegetation). Therefore, measurements will be conducted under three rain intensities (RIs) and wind speeds (WS). The threshold values for RIs and WS are taken from the research work done by Meng et al. [18]. Three RIs are introduced as slight rain (RI < 2mm/h), moderate rain (2 mm/h < RI < 10 mm/h) and heavy rain (RI > 10 mm/h). Similarly, wind is classified by the wind speed (WS) as light wind (WS < 20 km/h), windy (20 km/h < WS < 40 km/h) and strong wind (WS > 40 km/h). As the final step, the variations obtained in different scenarios mentioned above will be incorporated to the current MIMO channel representation as a time varying component. Therefore, MU-MIMO system equation for the signal received by the k^{th} user can be extended as,

$$y_k = H_k.x_k + W_{k,t} + n_k \tag{1}$$

Where H_k, x_k and y_k is the propagation channel for k^{th} user, transmitted signal and received signal by the k^{th} user, respectively. $W_{k,t}$ represents the time varying component for user K, in time t. Furthermore, n_k represents AWGN noise component experienced by the k^{th} user.

VI. Conclusion and Future Work

In this paper we have shown that accounting time-varying effects due to varying weather conditions in MIMO channel modelling is vital for accurate performance prediction in rural environments. Moreover, a survey on time varying wireless channels and channel models are presented in this paper. From our survey it can be concluded that more research is needed to include time varying effects in the present MIMO channel models, especially for effects due to varying weather conditions in outdoor environments. Pathloss simulation results are

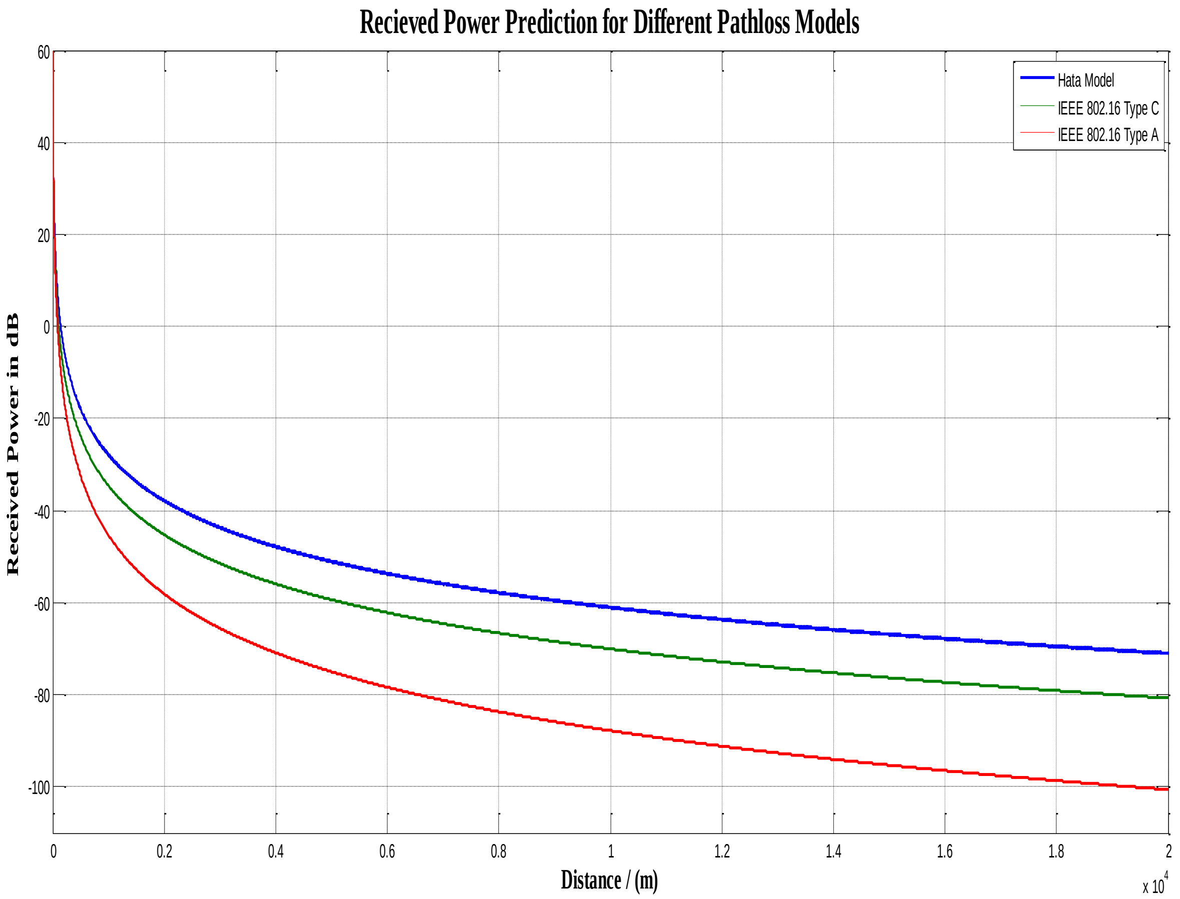

Figure 4. Pathloss simulations for 20 km rural area

also presented for outdoor rural environments. Finally, novel MUSA-MIMO channel development steps are illustrated.

As future work, the authors will develop the novel MUSA-MIMO channel model for rural Australian environment and channel tracking and prediction algorithms to enable efficient wireless broadband communications for rural Australia.

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