Prediction and Measurement of Multiuser MIMO-OFDM Channel in Rural Australia

Hajime Suzuki and David Robertson
CSIRO ICT Centre
PO Box 76, Epping NSW Australia
Email: {hajime.suzuki,d.robertson}@csiro.au

Nisal L. Ratnayake and Karla Ziri-Castro
Queensland University of Technology
Brisbane QLD Australia
Email: {nisal.ratnayake,karla.ziricastro}@qut.edu.au

***Abstract*—Commonwealth Scientific and Industrial Research Organisation (CSIRO) has recently conducted a technology demonstration of a novel fixed wireless broadband access system in rural Australia. The system is based on multi-user multiple-input multiple-output orthogonal frequency division multiplexing (MU-MIMO-OFDM). It demonstrated an uplink of six simultaneous users with distances ranging from 10 m to 8.5 km from a central tower, achieving 20 bits/s/Hz spectrum efficiency. This paper reports on the analysis of channel capacity and bit error probability simulation based on the measured MU-MIMO-OFDM channels obtained during the demonstration, and their comparison with the results based on channels simulated by a novel geometric optics based channel model suitable for MU-MIMO-OFDM in rural areas. Despite its simplicity, the model was found to predict channel capacity and bit error rate probability accurately for a typical MU-MIMO-OFDM deployment scenario.**

I. Introduction

Providing inexpensive high data rate internet access to the homes in rural and remote areas presents many challenges. User terminals (UTs) are scattered over large geographic areas (e.g. tens of residences per 100 km^2), and the cost of deploying a wired network is considered to be prohibitive. Alternatively, wireless technologies are expected to reduce the cost [1]. However, the frequencies suitable for fixed terrestrial wireless access (i.e. VHF and UHF bands) are typically in high demand for various services, and their availability may be limited. The system capacity of a wireless network can be increased by deploying more access points (APs) each covering a smaller geographic area and catering to a smaller number of UTs, but the cost of deploying such a network will increase. Hence, the spectrum efficiency of an AP needs to be improved by an order of magnitude in order to provide high data rate links, e.g. 12 Mbit/s and above, simultaneously to many users, e.g. 10 to 100 users, connected to an AP.

Commonwealth Scientific and Industrial Research Organisation (CSIRO) proposed the use of multi-user multiple-input multiple-output orthogonal frequency division multiplexing (MU-MIMO-OFDM) for increasing the spectrum efficiency of fixed wireless multiple access systems in rural areas [2]. With the proposed method, the AP is equipped with multiple antennas while UTs are each equipped with a single antenna. The use of a uniform circular array at the AP, a low-complexity zero-forcing (ZF) precoding based downlink and ZF receiver based uplink, a simple user grouping method to avoid ill-conditioned channels, and time and frequency synchronization among UTs provided by the use of global positioning system (GPS) receivers at the AP and UTs are proposed [2]. It has been shown by simulation that the spectrum efficiency of both the uplink and downlink can be improved linearly as a function of the number of antenna elements at the AP, without increasing the total transmitting power [2].

While the use of MU-MIMO has been incorporated in the latest wireless standards, such as Long Term Evolution Advanced (LTE-A) [3], very few implementation works have been so far reported in the literature. Up to only two user MU-MIMO in a realistic environment had been previously demonstrated [4]. In December 2010, CSIRO demonstrated six user MU-MIMO-OFDM uplink in an actual rural environment for the first time in the world [5], achieving 20 bits/s/Hz spectrum efficiency. This demonstrated the practicality of the proposed method.

The performance of MU-MIMO in rural area is known to heavily depend on the actual locations of the UTs [2]. For example, as shown later in this paper, the channel capacity is significantly reduced if two UTs are closely located. For the planning of practical deployment of a MU-MIMO-OFDM system, it is crucial to have a tool capable of predicting system performance accurately, e.g. in terms of channel capacity or required signal-to-noise ratio (SNR) for a target bit error probability. This paper proposes a novel MU-MIMO-OFDM channel model suitable for rural areas. The model takes into account the three dimensional relationship of the transmitting and receiving antennas as well as three dimensional antenna pattern. The model is validated by comparing the channel capacity and required SNR for a target bit error probability derived using measured and simulated MU-MIMO-OFDM channels.

This paper is organized as follows. The measurement system used for measuring the MU-MIMO-OFDM channels in an actual rural environment is described in Section II. Section III reviews the measurement sites. Three measurement scenarios are considered in this paper, as described in Section IV; a case with six users, a case with two users with a long range, and a case with two users located closely. Our new channel model is proposed in Section V. Section VI gives the comparison results, followed by the conclusions in Section VII.

978-1-4673-0990-5/12/$31.00 ©2012 IEEE

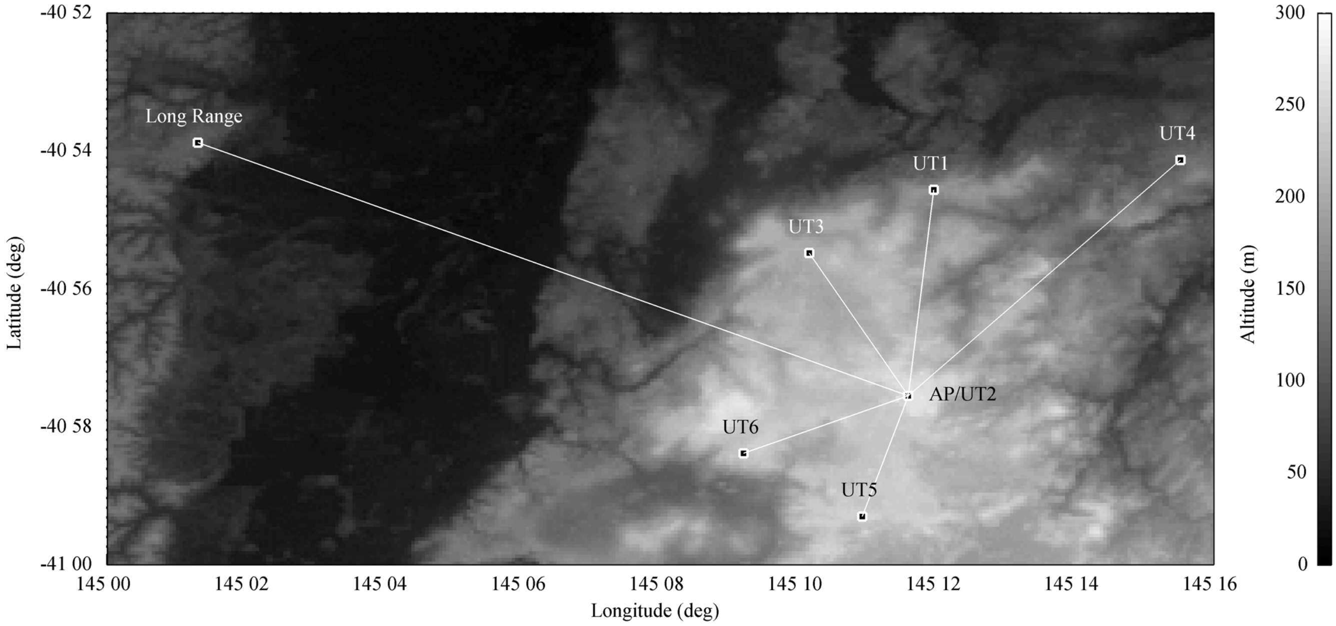

Fig. 1: Locations of AP and six UT sites.

II. Measurement System

MU-MIMO-OFDM Demonstrator [5] developed by the CSIRO ICT Centre was used for the channel measurement. The measurement system consisted of one AP unit and up to six UT units. The AP was equipped with a 12 element antenna array, with a vertically polarized folded dipole antenna as an element. The 12 antennas formed a uniform circular array in horizontal space with a radius of 40 cm (approximately one wavelength), but were displaced in vertical space in three levels, with a level separation of 40 cm, in order to remove antenna mutual coupling effects [5]. The AP antenna array was installed on a commercial broadcasting tower at the height of 71 m from the local ground. A three dimensional model and the photograph of the AP antenna array can be found in [5].

The UT was equipped with a 9 element directional Yagi antenna with a nominal gain of 11.5 dBd. The UT antenna was typically installed on a mast at the height of 9 m from the local ground. The main lobe of the UT antenna was pointed towards the AP site at each of the UT site.

The measurement system was operated at the center frequency of 641.5 MHz with 7 MHz channel bandwidth. We note that this band is typically utilized for television broadcasting. A scientific spectrum licence was acquired from the Australian Communications and Media Authority prior to the measurement for the operation in this band. The maximum rms UT transmitting power was 7.5 W from the power amplifier. The UT transmitting power was adjusted so that the received power at the AP from each of the UT was approximately the same. High performance 7 pole channel filters were used both at the AP and UT in order to limit the out-of-band transmission from the UT transmitter and to limit the effects of out-of-band interference at the AP receiver. (High power national and commercial analog television broadcasting transmitting antennas were co-located with the AP receiving antennas.)

The channel measurement was performed in frequency domain at 1,705 consecutive OFDM sub-carriers with sub-carrier spacing of 8 MHz/2,048 = 3.90625 kHz. Code-division multiplexed channel training sequence suitable for MU-MIMO-OFDM operation in rural area [6] was sent from the UTs and the MU-MIMO-OFDM channel was estimated by decoding the received channel training sequence at the AP.

More detail of the measurement system is described in [5].

III. Measurement Sites

The MU-MIMO-OFDM uplink channel measurement was performed in December 2010 near Smithton, Tasmania. The location of the AP and UT sites are shown in Fig. 1. Six UT sites, UT1 to UT6, except UT2, were chosen near existing residential houses, representing a practical deployment of fixed wireless broadband services in rural areas. The location of UT2 was chosen to be close to that of the AP in order to verify the robustness of the system from near-far effects.

In addition to the six UT sites for six user MU-MIMO-OFDM channel measurement, one site with a longer range, herein referred as Long Range site, was selected, as shown in Fig. 1. The horizontal distances from the ground of the AP site to each of the UT sites range from 10 m to 16 km. The parameters of the measurement sites are summarized in Table I.

Since both the transmitter and the receiver were fixed and free of surrounding clutter, the channel response was observed to be stable for long duration (multiple of seconds). More detailed analysis on the characteristics of the temporal variation of the measured channel response and capacity is being prepared for a future publication.

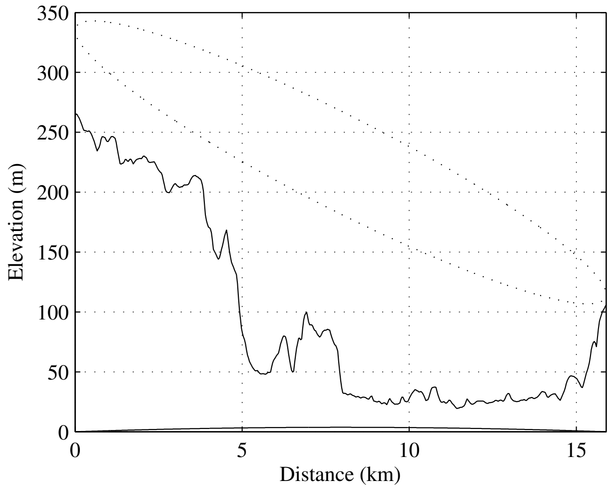

Fig. 2: Example terrain profile: AP to Long Range site.

Terrain profile analysis between the AP and each of the UT sites was conducted by using the digital elevation data (3 second resolution) obtained by the Shuttle Radar Topography Mission. An example terrain profile is shown in Fig. 2. The analysis showed that none of the selected sites have substantial obstruction of the first Fresnel zone by the terrain.

IV. Measurement Scenarios

Three channel measurement scenarios are considered in this paper as follows:

1) Six user MU-MIMO-OFDM uplink channel. This scenario represents a typical MU-MIMO-OFDM uplink channel aiming for a high spectral efficiency. This scenario is referred as Six User case.
2) Two user MU-MIMO-OFDM uplink with a long range. This scenario represents a case where one UT is at a long range (16 km) from the AP. UT1 and Long Range sites in Fig. 1 constituted this scenario. This scenario is referred as Long Range case.
3) Two user MU-MIMO-OFDM uplink with a small angle. This scenario represents a case where two UTs are located close in space. For this purpose, another UT antenna (not shown in Fig. 1) was installed 70 m west from the UT1 site, at the height of 6 m from the local ground. This scenario is referred as Small Angle case.

In all cases, all twelve AP receivers were used for the estimation of the channel capacity and the required SNR.

V. Proposed Channel Model

With an appropriate time and frequency synchronization, and assuming that proper cyclic extension of OFDM symbols provides the frequency domain flat fading channel, the uplink MU-MIMO-OFDM channel during one symbol time is described as

$$r_{l,n} = \sum_{m=1}^{N_{\text{UT}}} h_{l,m,n} x_{l,m} + n_{l,n}, \tag{1}$$

where $r_{l,n}$ and $x_{l,m}$ are the receive symbol at the nth AP receiver and the transmitted symbol from the mth UT transmitter, respectively. AWGN at the nth AP receiver is $n_{l,n}$. The subscript l indicates the channel at the lth OFDM sub-carrier. The channel is assumed to be stationary for the duration of many OFDM symbols. (An analysis of our channel measurement results showed that the channel was practically stationary for at least several hundreds milliseconds.)

The channel coefficient $h_{l,m,n}$ describes the transformation between the digital to analog converter (DAC) at the mth UT transmitter and the analog to digital converter (ADC) at the nth AP receiver. This includes the effects of radio up-converter/down-converter, power amplifiers, and channel filters, in addition to the effects of the antenna and radio propagation between the antennas.

The above equation can be written in a vector-matrix form as

$$\mathbf{r}_l = \mathbf{H}_l \mathbf{x}_l + \mathbf{n}_l, \tag{2}$$

where the channel transfer matrix $\mathbf{H}_l$ is an $N_{\text{AP}} \times N_{\text{UT}}$ matrix whose mth row and nth column element is $h_{l,m,n}$. The channel is normalized so that $\text{var}[h_{l,m,n}] = 1$.

The proposed channel model takes into account the following factors:

- Three dimensional location of the antennas. This includes the precise geometry of the AP antenna array and the effect of the elevation of the terrain. The elevation as given in Table I was used in the derivation of the simulated channel. This allows realistic modeling of differences in channel phase.
- Three dimensional antenna patterns. The antenna pattern of a theoretical vertically polarized dipole antenna is used for each of the AP antennas. The modeling of this effect is particularly important for the propagation channel to UT2, which located at the ground of the AP tower. The antenna pattern of the UT antenna is simplified as a constant gain, given that, in the measurement, the main lobe of the UT Yagi antennas was pointed towards the AP antennas.
- Transmitting power of the UT. During the measurement, the transmitting power of the UT was adjusted so that the received power at AP from each of the UT was approximately the same. Additional 10 dB attenuator was used to limit the transmitting power of the UT2 which was located closest to the AP.
- Measured channel filter frequency response. The filter frequency response was measured inside the laboratory and applied to the simulated channel.

The complex channel coefficient at the lth OFDM sub-carrier between the mth UT transmitting antenna and the nth AP receiving antenna for the uplink, $g_{\text{U},l,n,m}$, is given by

$$g_{l,m,n} = \frac{P_m}{d_{m,n}} \mathbf{h}_{\text{UT},m} \cdot \mathbf{h}_{\text{AP},n} \exp\left(-j2\pi f_l \frac{d_{m,n}}{c}\right) \tag{3}$$

where P_m is a UT specific constant depending on the UT transmitting power setting, the line-of-sight path length be-

TABLE I: Parameters of measurement sites.

Site	Latitude	Longitude	Elevation	Antenna height	Distance	Heading
AP	−40°57'33"	145°11'35"	264 m	71 m	0 m	N/A
UT1	−40°54'34"	145°11'57"	169 m	9 m	5.5 km	5.6 deg
UT2	−40°57'33"	145°11'35"	264 m	1.5 m	10 m	143.6 deg
UT3	−40°55'29"	145°10'9"	205 m	9 m	4.3 km	332.7 deg
UT4	−40°54'8"	145°15'31"	125 m	6 m	8.5 km	40.7 deg
UT5	−40°59'18"	145°10'55"	242 m	9 m	3.3 km	195.7 deg
UT6	−40°58'23"	145°9'12"	235 m	9 m	3.6 km	245.5 deg
Long Range	−40°53'53"	145°1'19"	106 m	1.5 m	16.0 km	297.1 deg

tween mth UT antenna and nth AP antenna is $d_{m,n}$, the vector effective height [7] of the mth UT transmitting antenna and the nth AP receiving antenna for the line-of-sight path is $\mathbf{h}_{\text{UT},m}$ and $\mathbf{h}_{\text{AP},n}$, respectively, f_l is the carrier frequency at the lth OFDM sub-carrier, and c is the speed of light.

In [2], the ground reflected path was taken into account in modeling MU-MIMO channel in rural area. However, given the complication of estimating the exact ground reflected path over a realistic terrain and the finding that the contribution of ground reflected path to the MU-MIMO channel capacity in rural area was small in [2], we opt to exclude the effects of ground reflected path in this analysis.

Finally, the normalization is performed to obtain

$$h_{l,m,n} = \frac{g_{l,m,n}}{\sqrt{\text{var}[g_{l,m,n}]}}. \tag{4}$$

When the MIMO channel is completely known by the receiver but is unknown to the transmitter, the Shannon capacity of the MIMO channel at the lth OFDM subcarrier is given by [8]

$$C_l = \sum_{m=1}^{N_{\text{UT}}} \log_2 \left(1 + \frac{\rho}{N_{\text{UT}}} \lambda_{m,l}\right), \tag{5}$$

where ρ is the average SNR per receiver over MIMO subchannels and OFDM subcarriers, and $\lambda_{m,l}$ is the mth eigen value of $\mathbf{H}_l^H \mathbf{H}_l$. We note that the channel capacity defined in this paper is a sum of N_{UT} users and is an average over different OFDM sub-carriers.

VI. Results

A. Channel Capacity

The channel capacity was calculated using measured and simulated channel according to (5) for the three scenarios described in Section IV, and was averaged over OFDM sub-carriers. An example SNR value of $\rho = 25$ dB was used. The results are shown in Table II.

Despite its simplicity, the proposed channel model predicted the channel capacity based on the measured channel well for the Six User case, within 0.1 b/s/Hz. Since this is only a single case, a further verification is recommended with different UT locations and different terrain, but the result is considered to be promising.

The channel capacity based on the simulated channel for the Long Range case was somewhat (approx 14%) smaller than that based on the measured channel, although it can still be considered to be practically useful. However, the proposed model significantly under-predicted the channel capacity for the Small Angle case. It is considered that the existence of any additional radio propagation paths due to horizontal multipath (e.g. by hills) and scattering (e.g. by trees nearby UT antennas) would increase the measured channel capacity in Small Angle case, and hence the fact that we did not take those effects into account in the proposed channel model may have caused the observed under-prediction. The effects are considered to be significant only when the line-of-sight paths cannot support a higher capacity.

TABLE II: Comparison of measured and simulated MU-MIMO-OFDM channel capacity. $\rho = 25$ dB.

Scenario	Measured	Simulated
Six User	51.6 b/s/Hz	51.5 b/s/Hz
Long Range	23.9 b/s/Hz	20.6 b/s/Hz
Small Angle	18.6 b/s/Hz	12.2 b/s/Hz

B. Bit Error Probability

Monte Carlo simulation was performed by using measured and simulated MU-MIMO-OFDM channels for the three scenarios described in Section IV in order to estimate the required SNR to achieve coded bit error probability of 10^{-5}. Channel training was performed by using code division multiplexed [6] 16 OFDM symbols in order to reduce the effects of channel estimation errors in the simulation. 1,680, out of the total of 1,705, sub-carriers were used as data sub-carriers. The data sub-carriers were modulated by 64QAM. Rate $3/4$ industry standard convolutional coding with the constraint length of 7 was used for forward error correction. Frequency domain interleaver, similar to that specified in [9], was used. Simple zero-forcing linear receiver [2] was used for uplink data detection with a soft Viterbi decoder.

Fig. 3 shows an example bit error probability versus SNR curves based on the measured and simulated channels. The results for the Six User case show that the model predicts required SNR very well. The prediction results are considered to be useful in predicting the measured results for the Six User case.

The results for Long Range case are vary favorable, with less than 0.5 dB differences between the measurement and prediction. However, the proposed model over-predicted the required SNR for the Small Angle case by a significant margin

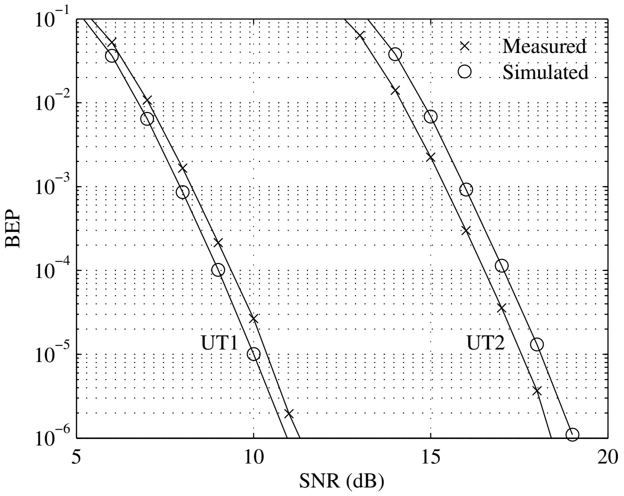

Fig. 3: Example bit error probability: AP to Long Range site.

TABLE III: Required SNR to achieve bit error probability of 10^{-5}, 64QAM rate 3/4, based on measured and simulated MU-MIMO-OFDM channels.

	Measured	Simulated	Difference
Six User UT1	19.2 dB	19.4 dB	0.2 dB
Six User UT2	17.3 dB	17.9 dB	0.5 dB
Six User UT3	25.2 dB	24.3 dB	−0.8 dB
Six User UT4	23.1 dB	23.9 dB	0.6 dB
Six User UT5	24.0 dB	24.0 dB	0.0 dB
Six User UT6	19.4 dB	18.1 dB	−1.3 dB
Long Range UT1	10.5 dB	10.1 dB	−0.4 dB
Long Range UT2	17.7 dB	17.8 dB	0.1 dB
Small Angle UT1	22.5 dB	35.0 dB	12.5 dB
Small Angle UT2	38.0 dB	49.8 dB	11.8 dB

(over 10 dB), to the point it is considered to be not practically useful. This corresponds to the under-prediction of channel capacity by the proposed method for Small Angle case as discussed above, and the further development of the channel model is called for in order to accurately predict the channel capacity and the required SNR in those scenarios.

VII. Conclusions

This paper presents a novel geometric optics based channel model suitable for fixed wireless access using MU-MIMO-OFDM in rural areas. As the proposed model was shown to predict actual measured channel capacity and required SNR in a typical case accurately, the model is considered to be useful for general deployment planning. However, as the proposed model failed to predict the available channel capacity when two UTs are closely located, a further development of the model by incorporating other propagation paths, such as horizontal multipath and local scattering, is recommended. Also, the current model only considers clear line-of-sight path cases. A further development taking into account the diffraction [10] is needed in order to extend the applicability of the model.

Acknowledgment

The authors wish to thank Alex Grancea, Arivoli, Boyd Murray, Carl Holmesby, David Humphrey, David Moreland, Frank Ceccato, Ivan Kekic, Jayasri Joseph, John Matthew, Joseph Pathikulangara, Juan Tello, Keith Bengston, Kevin Anderson, Les Komarek, Nipun Bhaskar, Rob Shaw, Rod Kendall, Steve Barker, and Steve Broadhurst for the development of the MU-MIMO-OFDM Demonstrator. We also thank Brad Lee, Daniel Hugo, Greg Timms, and John McCulloch for supporting the field measurement. Support from Broadcast Australia and Circular Head Council is greatly acknowledged. Valuable comments from the anonymous reviewers to improve this paper and our future works are very much appreciated. This work was supported by the Science and Industry Endowment Fund.

References

[1] S. M. Mishra, J. Hwang, D. Fillipini, T. Du, R. Moazzami, and L. Subramanian, “Economic analysis of networking technologies for rural developing regions,” *1st Workshop on Internet and Network Economics*, May 2005.

[2] H. Suzuki, D. Hayman, J. Pathikulangara, I. B. Collings, and Z. Chen, “Highly spectrum-efficient fixed wireless multiple access,” *International Application*, vol. PCT/AU2009/101022, August 2009.

[3] A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe, and T. Thomas, “LTE-advanced: Next-generation wireless broadband technology,” *IEEE Wireless Communications*, vol. 17, no. 3, June 2010.

[4] Nortel, “Nortel technology demo - Long term evolution wireless access,” available online, 2007.

[5] H. Suzuki, N. Svenson, and D. Robertson, “CSIRO Ngara wireless broadband access field trial, Smithton, Tasmania - technical results,” available online, February 2011.

[6] H. Suzuki, J. Pathikulangara, and D. Humphrey, “Solving user-symbol specific phase offset problem for multiuser MIMO-OFDM fixed uplink,” *Accepted at the IEEE Asia Pacific Microwave Conference, 2011*, December 2011.

[7] Y. T. Lo and S. W. Lee, *Antenna Handbook Volume II*. Van Nostrand Reinhold, 1993.

[8] J. H. Winters, “On the capacity of radio communication systems with diversity in a Rayleigh fading environment,” *IEEE Journal on Selected Areas in Communications*, vol. SAC-5, no. 5, pp. 871–878, June 1987.

[9] L. S. Committee, *IEEE Standard for Local and metropolitan area networks, Part 16: Air Interface for Broadband Wireless Access Systems*, 2009.

[10] N. L. Ratnayake, K. Ziri-Castro, H. Suzuki, and D. Jayalath, “Deterministic diffraction loss modelling for novel broadband communication in rural environments,” *Australian Communications Theory Workshop*, February 2011.