Comparison of Empirical Propagation Path Loss Models for Fixed Wireless Access Systems

V.S. Abhayawardhana*, I.J. Wassell†, D. Crosby‡, M.P. Sellars‡, M.G. Brown§
* BT Mobility Research Unit, Rigel House, Adastral Park, Ipswich IP5 3RE, UK.
viraj.abhayawardhana@bt.com
†LCE, Dept. of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK.
ijw24@eng.cam.ac.uk
‡Cambridge Broadband Ltd., Selwyn House, Cowley Rd., Cambridge CB4 OWZ, UK.
{dcrosby,msellars}@cambridgebroadband.com
§Cotares Ltd., 67, Narrow Lane, Histon, Cambridge CB4 9YP, UK.
mgbrown@cotares.com

Abstract— **Empirical propagation models have found favour in both research and industrial communities owing to their speed of execution and their limited reliance on detailed knowledge of the terrain. Although the study of empirical propagation models for mobile channels has been exhaustive, their applicability for FWA systems is yet to be properly validated. Among the contenders, the ECC-33 model [1], the Stanford University Interim (SUI) models [2] and the COST-231 Hata model [3] show the most promise. In this paper, a comprehensive set of propagation measurements taken at 3.5 GHz in Cambridge, UK is used to validate the applicability of the three models mentioned previously for rural, suburban and urban environments. The results show that in general the SUI and the COST-231 Hata model over-predict the path loss in all environments. The ECC-33 models shows the best results, especially in urban environments.**

I. Introduction

Propagation models are used extensively in network planning, particularly for conducting feasibility studies and during initial deployment. They are also very useful for performing interference studies as the deployment proceeds.

These models can be broadly categorised into three types; empirical, deterministic and stochastic. Empirical models are those based on observations and measurements alone. These models are mainly used to predict the path loss, but models that predict rain-fade and multipath have also been proposed [4]. The deterministic models make use of the laws governing electromagnetic wave propagation to determine the received signal power at a particular location. Deterministic models often require a complete 3-D map of the propagation environment. An example of a deterministic model is a ray-tracing model [5]. Stochastic models, on the other hand, model the environment as a series of random variables. These models are the least accurate but require the least information about the environment and use much less processing power to generate predictions.

Empirical models can be split into two subcategories namely, time dispersive and non-time dispersive [6]. The former type is designed to provide information relating to the time dispersive characteristics of the channel i.e., the multipath delay spread of the channel. An example of this type are the Stanford University Interim (SUI) channel models developed under the Institute of Electrical and Electronic Engineers (IEEE) 802.16 working group [2]. Examples of non-time-dispersive empirical models are ITU-R [7], Hata [8] and the COST-231 Hata model [3]. All these models predict mean path loss as a function of various parameters, for example distance, antenna heights etc. Although empirical propagation models for mobile systems have been comprehensively validated, their appropriateness for FWA systems has not been fully established. In this paper, the validity of various empirical models for the FWA scenario will be determined by comparing their predictions with measurements taken at 3.5 GHz in Cambridge, UK from September to December 2003.

II. Measurement Program

A commercial scale FWA network was established in Cambridge, UK in 2003 under the patronage of Ofcom, UK. The objectives were to fully understand the implementation and operational issues relevant to the deployment of a FWA network [9]. Propagation modeling was also addressed since this is fundamental to the planning of FWA networks. The trial network had five operational Base Station (BS) sites and approximately 65 subscribers with Customer Premises Equipment (CPE) installed at their locations. Four Access Points (APs), each having a horizontal antenna beamwidth of 90^0 were located at each BS site to achieve 360^0 coverage. The regions served by four of these BS sites were selected for measurement since they encompassed all typical environments and terrains. The first BS site was installed 14.6 m above ground level on the roof of the William Gates Building (WGB), which is to the West of the City Centre. This BS serves quite flat terrain with open fields, especially to the West and South and also regions with high foliage density. The second BS site was installed on top of the Addenbrooke's Hospital (ADD), some 36 m above ground level. The regions covered by this BS are typically suburban. The third BS was on the Lime Kiln Hill (LKH) which is to the Southeast of the City at 45 m above sea-level. This BS covers quite hilly areas and farmland. The fourth BS was on the roof of the

Anglia Polytechnic University (APU), situated in the heart of the City. It is some 16 m above ground level and serves an urban environment.

The propagation measurements were taken using a van that had a pneumatically operated telescopic mast to which the antenna of a CPE was attached. At each measurement location measurements were taken starting from a CPE antenna height of either 10 m or 12 m down to a height of 5 m at intervals of 1m. A GPS unit was used to accurately establish the measurement location. All measurements were taken with the network using a channel bandwidth of 3.5 MHz and with the symbol rate set to 2.5 MHz. The CPE antenna beamwidth is 23^0 and both AP and CPE antennas are Right-Hand Circularly Polarised. The measurement locations were concentrated mainly within a region from 250 m to 2 km from the BS site and lay on concentric circles with radial increments of 250 m. In total over 550 measurements were taken at more than 300 locations. Each measurement consisted of 100 individual snapshots taken at an interval of 0.3 s of various parameters including received signal power. The calculated average received signal power was used to estimate the path loss corresponding to each measurement.

Path loss can be defined as the ratio of the transmitted to received power, usually expressed in decibels. The equation for the Least Square (LS) regression analysis shows the path loss at distance d in the form

$$PL(d) = PL(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) \quad (1)$$

where, d_0 is the reference point at 1 km and n is known as the path loss exponent. The path loss values, $PL(.)$ are expressed in decibels. Note that for Free Space Loss (FSL) the path loss exponent is equal to two. The path loss exponent is valuable since it shows the rate of increase of path loss with respect to distance. A value close to two would indicate that the path loss is very similar to FSL, and thus the environment could be categorised as one having less clutter and foliage.

In order to increase the statistical significance of the Least Squares (LS) regression analysis, results from sectors having similar environments have been combined. To this end, the South and West APs of WGB BS site are combined to give measurements typical of a rural environment and similarly, the North and East sectors of the ADD BS site are combined to give measurements typical of a suburban environment and all APs of the APU BS site are combined to give measurements typical of an urban environment.

III. Standard Empirical Models

The LS regression analysis results will be compared against some of the accepted empirical models available for the analysis of FWA coverage. Three models will be evaluated, namely the Stanford University Interim (SUI) model, the COST-231 Hata model and the ECC-33 model.

A. Stanford University Interim (SUI) Model

IEEE working group 802.16 is at the forefront of developing technical standards for FWA systems. After developing standards for frequency bands above 11 GHz, their attention was directed to bands below 11 GHz. The proposed standards for the frequency bands below 11 GHz contain the channel models developed by Stanford University, namely the SUI models. Note that these models are defined for the Multipoint Microwave Distribution System (MMDS) frequency band in the USA, which is from 2.5 GHz to 2.7 GHz. Their applicability to the 3.5 GHz frequency band that is in use in the UK has so far not been clearly established.

The SUI models are divided into three types of terrains[1], namely A, B and C. Type A is associated with maximum path loss and is appropriate for hilly terrain with moderate to heavy foliage densities. Type C is associated with minimum path loss and applies to flat terrain with light tree densities. Type B is characterised with either mostly flat terrains with moderate to heavy tree densities or hilly terrains with light tree densities. The basic path loss equation with correction factors is presented in [2], [10],

$$PL = A + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_f + X_h + s \quad \text{for } d > d_0 \quad (2)$$

where, d is the distance between the AP and the CPE antennas in metres, $d_0 = 100$ m and s is a lognormally distributed factor that is used to account for the shadow fading owing to trees and other clutter and has a value between 8.2 dB and 10.6 dB [2]. The other parameters are defined as,

$$A = 20 \log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \quad (3)$$

$$\gamma = a - bh_b + c/h_b \quad (4)$$

where, the parameter h_b is the base station height above ground in metres and should be between 10 m and 80 m. The constants used for a, b and c are given in Table I. The parameter γ in (4) is equal to the path loss exponent. For a given terrain type the path loss exponent is determined by h_b.

Model Parameter	Terrain A	Terrain B	Terrain C
a	4.6	4.0	3.6
b (m^{-1})	0.0075	0.0065	0.005
c (m)	12.6	17.1	20

TABLE I
Numerical values for the SUI model parameters

The correction factors for the operating frequency and for the CPE antenna height for the model are [2],

$$X_f = 6.0 \log_{10}\left(\frac{f}{2000}\right) \quad (5)$$

1. The word 'terrain' is used in the original definition of the model rather than 'environment'. Hence it is used interchangeably with 'environment' in this subsection. The word 'terrain' will be used when referring to the model and 'environment' elsewhere.

and,

$$X_h = -10.8 \log_{10}\left(\frac{h_r}{2000}\right) \quad \text{for Terrain types A and B}$$
$$= -20.0 \log_{10}\left(\frac{h_r}{2000}\right) \quad \text{for Terrain type C} \qquad (6)$$

where, f is the frequency in MHz and h_r is the CPE antenna height above ground in metres. The SUI model is used to predict the path loss in all three environments, namely rural suburban and urban.

B. COST-231 Hata Model

A model that is widely used for predicting path loss in mobile wireless system is the COST-231 Hata model [3]. It was devised as an extension to the Hata-Okumura model [8], [11]. The COST-231 Hata model is designed to be used in the frequency band from 500 MHz to 2000 MHz. It also contains corrections for urban, suburban and rural (flat) environments. Although its frequency range is outside that of the measurements, its simplicity and the availability of correction factors has seen it widely used for path loss prediction at this frequency band. The basic equation for path loss in dB is [3],

$$PL = 46.3 + 33.9 \log_{10}(f) - 13.82 \log_{10}(h_b) - ah_m + (44.9 - 6.55 \log_{10}(h_b)) \log_{10} d + c_m \qquad (7)$$

where, f is the frequency in MHz, d is the distance between AP and CPE antennas in km, and h_b is the AP antenna height above ground level in metres. The parameter c_m is defined as 0 dB for suburban or open environments and 3 dB for urban environments. The parameter ah_m is defined for urban environments as [6]

$$ah_m = 3.20(\log_{10}(11.75 h_r))^2 - 4.97, \text{ for } f > 400 \text{ MHz} \qquad (8)$$

and for suburban or rural (flat) environments,

$$ah_m = (1.1 \log_{10} f - 0.7) h_r - (1.56 \log_{10} f - 0.8) \qquad (9)$$

where, h_r is the CPE antenna height above ground level. Observation of (7) to (9) reveals that the path loss exponent of the predictions made by COST-231 Hata model is given by,

$$n_{COST} = (44.9 - 6.55 \log_{10}(h_b))/10 \,. \qquad (10)$$

To evaluate the applicability of the COST-231 model for the 3.5 GHz band, the model predictions are compared against measurements for three different environments namely, rural (flat), suburban and urban.

C. ECC-33 Path Loss Model

The original Okumura experimental data were gathered in the suburbs of Tokyo [11]. The authors refer to urban areas subdivided into 'large city' and 'medium city' categories. They also give correction factors for 'suburban' and 'open' areas. Since the characteristics of a highly built-up area such as Tokyo are quite different to those found in typical European suburban areas, use of the 'medium city' model is recommended for European cities [12], [13]. Although the Hata-Okumura model [8] is widely used for UHF bands its accuracy is questionable for higher frequencies. The COST-231 model extended its use up to 2 GHz but it was proposed for mobile systems having omni-directional CPE antennas sited less than 3 m above ground level. A different approach was taken in [1], which extrapolated the original measurements by Okumura and modified its assumptions so that it more closely represents a FWA system. The path loss model presented in [1], is referred to here as the ECC-33 model. The path loss is defined as,

$$PL = A_{fs} + A_{bm} - G_b - G_r \qquad (11)$$

where, A_{fs}, A_{bm}, G_b and G_r are the free space attenuation, the basic median path loss, the BS height gain factor and the terminal (CPE) height gain factor. They are individually defined as,

$$A_{fs} = 92.4 + 20 \log_{10}(d) + 20 \log_{10}(f) \qquad (12)$$

$$A_{bm} = 20.41 + 9.83 \log_{10}(d) + 7.894 \log_{10}(f) + 9.56[\log_{10}(f)]^2 \qquad (13)$$

$$G_b = \log_{10}(h_b/200)\{13.958 + 5.8[\log_{10}(d)]^2\} \qquad (14)$$

and for medium city environments,

$$G_r = [42.57 + 13.7 \log_{10}(f)][\log_{10}(h_r) - 0.585] \qquad (15)$$

where, f is the frequency in GHz, d is the distance between AP and CPE in km, h_b is the BS antenna height in metres and h_r is the CPE antenna height in metres. The medium city model is more appropriate for European cities whereas the large city environment should only be used for cities having tall buildings. It is interesting to note that the predictions produced by the ECC-33 model do not lie on straight lines when plotted against distance having a log scale. For the sake of completeness, the path loss gradient at 2km will be compared with the path loss predicted by other models. The predictions using the ECC-33 model with the medium city option are compared with the measurements taken in suburban and urban environments.

IV. Comparison with Measurements

The measurements taken within the combined West and South APs of the WGB BS site are taken as a typical of a rural environment. Only the measurements taken with CPE antenna heights of 10 m and 6 m are considered for ease of presentation. The LS regression curves along with the underlying measurements are shown in Figure 1. The LS curves closely follow FSL, owing to the flat terrain in the region and the use of directional antennas. Figure 1 also shows the predictions made using two models, namely the SUI and the COST-231 Hata models with an AP antenna height, $h_b = 15$ m. Note that the ECC-33 model is not applicable to rural environments. Terrain type 'C' for the SUI model and 'flat' environment for the COST-231 Hata model are used in the presented comparisons since they are the most appropriate. The corresponding error statistics in terms of the mean prediction error, μ_e and the Standard Deviation (SD) of the prediction error, σ_e are shown in Table II. By definition,

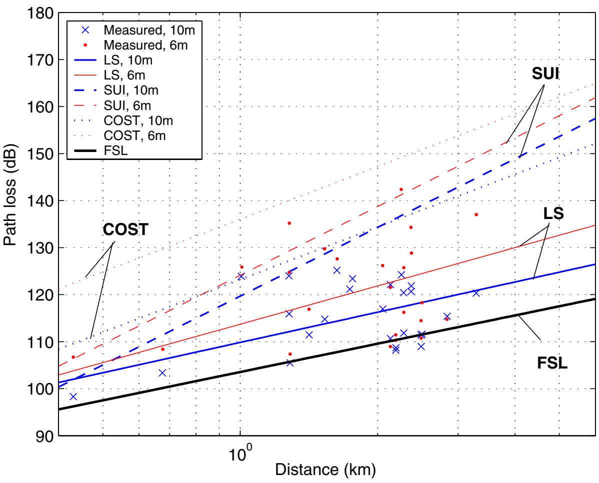

Fig. 1. Comparison of empirical models with measurements from a typical rural environment

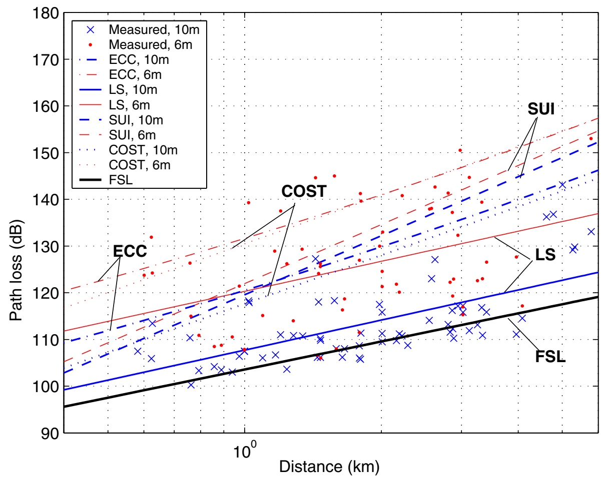

Fig. 2. Comparison of empirical models with measurements from a typical suburban environment

CPE	**LS (dB)**	**SUI (dB)**		**COST (dB)**	
(m)	σ_e	μ_e	σ_e	μ_e	σ_e
10	6.7	14.8	10.6	16.3	8.2
6	10.0	14.2	12.0	24.1	10.5

TABLE II

ERROR STATISTICS OF MODEL PREDICTIONS COMPARED WITH LS REGRESSION ANALYSIS FOR A RURAL ENVIRONMENT

CPE	**LS(dB)**	**SUI (dB)**		**COST (dB)**		**ECC (dB)**	
(m)	σ_e	μ_e	σ_e	μ_e	σ_e	μ_e	σ_e
10	6.5	16.9	8.8	13.1	7.5	15.4	6.9
6	11.1	6.1	12.4	13.0	11.7	13.6	11.4

TABLE III

ERROR STATISTICS OF MODEL PREDICTIONS COMPARED WITH LS REGRESSION ANALYSIS FOR A SUBURBAN ENVIRONMENT

the LS regression analysis has a zero mean error. Note that the prediction errors are calculated as the difference between predictions and measurements. Hence a significant positive mean value, as shown in Table II indicates that the two models in general over-predict the actual path loss for FWA systems in rural environments. Table V compares the path loss exponents obtained through LS regression analysis and those predicted by the different models. It clearly shows that the both the SUI and the COST-231 Hata models predict a higher path loss exponent than does the LS regression for rural environments. Consequently the path loss predictions made by these models are gross overestimates, particularly in excess of 5 km.

The regions covered by the combined North and East APs of the ADD BS site are assumed to be typically suburban. The measurement results and the LS regression curves are shown in Figure 2. It also shows the predictions made by all three models, namely the SUI model with terrain type 'B', the COST-231 Hata model for a 'suburban' environment and the ECC-33 model with the 'medium city' environment. The AP antenna height, h_b is assumed to be 38 m. The error statistics are shown in Table III. All three models generally over-predict path loss but the ECC-33 model and the COST-231 Hata models give the lowest errors. In particular, as shown in Table V, the SUI model shows the highest difference in the path loss exponent compared with that from the LS regression analysis for suburban environments. Both of the other models also predict a higher exponent, but note for the ECC-33 model, the gradient of the path loss at 2km has been presented.

The measurements taken in all AP sectors of the APU BS site are used to compare the predictions of the three models for urban environments. The AP antenna height, h_b is assumed to be 17 m. The results are shown in Figure 3. Note that the SUI model does not specifically have a classification for urban environments, but terrain type 'B' is considered the most appropriate. The assumptions for 'urban' and 'medium city' are used for the COST-231 Hata model and the ECC-33 model, respectively. The error statistics are shown in Table IV. The SUI model shows the lowest mean prediction errors for a CPE antenna height of 10 m but under-predicts the path loss at 6 m. Again this model, as shown in Table V overestimates the path loss exponent compared with that of the LS regression analysis. Note that the LS regression analysis shows a reduction in path loss exponent with a reduction of the CPE antenna height from 10 m to 6 m.. This is attributed to the 'ducting effect', where the RF energy is channelled through the streets in an urban environment. The COST-231 Hata model grossly over-predicts the path loss at 10 m, however the predictions at 6 m are much better. The path loss exponents show a better agreement with the LS results than do those of the SUI model. The best performance is given by the ECC-33 model, particularly at a CPE antenna height of 6 m. The SD of of prediction error, σ_e for the ECC-33 model is comparable with that obtained by the LS regression analysis.

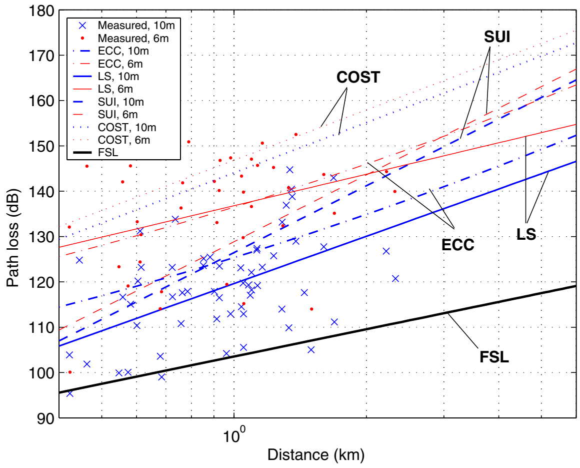

Fig. 3. Comparison of empirical models with measurements from a typical urban environment

CPE (m)	LS(dB)	SUI (dB)		COST (dB)		ECC (dB)	
	σ_e	μ_e	σ_e	μ_e	σ_e	μ_e	σ_e
10	9.6	4.2	10.1	24.2	9.7	6.4	9.8
6	11.7	-12.3	13.3	8.4	12.1	-0.7	11.8

TABLE IV

ERROR STATISTICS OF MODEL PREDICTIONS COMPARED WITH LS REGRESSION ANALYSIS FOR A URBAN ENVIRONMENT

V. CONCLUSION

Measurements taken in Cambridge, UK were compared against predictions made by three empirical propagation models. The SUI model showed quite large mean path loss prediction errors, generally over-predicting the path loss. Future research could also be directed towards optimising the parameters to accommodate urban environments. The COST-231 Hata model, in general overestimated the path loss, especially at greater antenna heights. This is perhaps to be expected owing to the mobile scenario for which this model is most appropriate. Clearly as the CPE antenna height is raised, the less applicable this model is likely to become. Both models show some scope to be optimised for the 3.5 GHz band. The ECC-33 model shows the closest agreement with the measurement results. It is highly recommended for urban environments and should be applicable for most lightly built-up European cities. However, the model does not provide any correction factors for suburban or rural environments.

Model	Rural		Suburban		Urban	
	10m	6m	10m	6m	10m	6m
LS	2.13	2.70	2.13	2.13	3.46	2.30
SUI	4.85	4.85	4.20	4.20	4.89	4.89
COST	3.71	3.71	3.45	3.45	3.68	3.68
ECC	-	-	3.24	3.24	3.37	3.37

TABLE V

PATH LOSS EXPONENTS OF DIFFERENT MODELS

Although the SUI model proposes different sets of parameters for three types of environments, the categories are not specified in a particularly systematic manner and do not explicitly include urban and suburban environments.

It should be noted that the suburban and urban measurements were taken in the Winter of 2003 and so the foliage density was quite low. However, except for the North AP of the ADD sector, propagation is not limited by foliage in the areas considered representative of suburban and urban environments. The rural measurements were taken in early Autumn of 2003 and so most trees were still in full leaf. Consequently, the measurements presented here can be considered to be representative of worst case conditions in rural and urban environments and typical conditions in suburban environment.

ACKNOWLEDGMENTS

This paper is based on results from a project funded by Ofcom, UK (Ofcom Ref: AY4463). The authors wish to thank Ofcom for their funding and support.

REFERENCES

[1] Electronic Communication Committee (ECC) within the European Conference of Postal and Telecommunications Administration (CEPT), "The analysis of the coexistence of FWA cells in the 3.4 - 3.8 GHz band," tech. rep., ECC Report 33, May 2003.

[2] V. Erceg, K. V. S. Hari, *et al.*, "Channel models for fixed wireless applications," tech. rep., IEEE 802.16 Broadband Wireless Access Working Group, January 2001.

[3] COST Action 231, "Digital mobile radio towards future generation systems, final report," tech. rep., European Communities, EUR 18957, 1999.

[4] R. K. Crane, "Prediction of attenuation by rain," *IEEE Transactions on Communications*, vol. COM-28, pp. 1727–1732, September 1980.

[5] G. E. Athanasiadou, A. R. Nix, and J. P. McGeehan, "A microcellular ray-tracing propagation model and evaluation of its narrowband and wideband predictions," *IEEE Journal on Selected Areas in Communications, Wireless Communications series*, vol. 18, pp. 322–335, March 2000.

[6] H. R. Anderson, *Fixed Broadband Wireless System Design*. John Wiley & Co., 2003.

[7] Recommendation ITU-R P.1546, "Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz," tech. rep., International Telecommunication Union, 2001.

[8] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE Transactions on Vehicular Technology*, vol. vol. VT-29, pp. 317–325, September 1981.

[9] Cotares Ltd., Cambridge Broadband Ltd. and Cambridge University, "A study on efficient dimensioning of broadband wireless access networks," tech. rep., Ofcom, UK, 2003. *See Ofcom website*.

[10] V. Erceg, L. J. Greenstein, *et al.*, "An empirically based path loss model for wireless channels in suburban environments," *IEEE Journal on Selected Areas of Communications*, vol. 17, pp. 1205–1211, July 1999.

[11] Y. Okumura, "Field strength and it's variability in VHF and UHF land-mobile radio-services," *Review of the Electrical Communications Laboratory*, vol. 16, September-October 1968.

[12] S. R. Saunders, *Antennas and Propagation for Wireless Communication Systems*. John Wiley & Sons Ltd, 1999.

[13] J. D. Parsons, *The Mobile Radio Propagation Channel, Second Edition*. John Wiley & Sons Ltd., 2000.