Accuracy evaluation analysis for indoor measurement-based radio-wave-propagation predictions

A. Aragón-Zavala, B. Belloul, V. Nikolopoulos and S.R. Saunders

Abstract: An accuracy evaluation analysis of in-building path loss prediction models is presented, comparing the performance of measurement-based prediction against traditional indoor radio propagation models, such as Keenan–Motley, tuned with measurements. The analysis was conducted using extensive walk test data from various antennas at 1800 MHz collected in two types of buildings: an old Victorian manor-house built from brick and a modern purpose-built office building with open-plan construction. The measured data were split into two parts: a tuning set and an evaluation set, such that the data used to run the measurement-based prediction were excluded from the data used for the accuracy evaluation analysis. The results show a significant improvement in the prediction accuracy for the indoor measurement-based model over the tuned Keenan–Motley model.

1 Introduction

In-building systems are an essential component of most wireless systems. They provide the following benefits: improved coverage in the locations where hot spots of traffic occur, such as airports and shopping centres; focused capacity for these large public hot spots; flexible tariffs and wireless services for corporate offices and excellent control of interference and wideband channel dispersion for high-data-rate systems. Despite having a fixed building geometry, this control of interference is possible by selecting antenna locations appropriately, taking into account building partitions and openings, therefore coverage is maximised in the desired directions, and cell footprint can be shaped more accurately, hence reducing interference with adjacent cells.

Today, many technologies require the deployment of such systems, including second generation (2G) and third generation (3G) cellular, TETRA and wireless LAN (WLAN). WLAN systems in particular have been responsible for an explosive growth in the number of in-building systems in the last year, while 3G is already starting to stimulate new in-building systems to realise its highest data rate potential. For systems based on TETRA, in-building systems are helping to provide safe policing and management of public and private buildings.

To design these systems effectively and economically, system designers need processes and tools which can provide a high level of confidence in the designs. This paper explains the issues and gives indicators of approaches which we have found helpful in our extensive experience of in-building design, as well as presenting an accuracy evaluation of a novel technique, Measurement-based prediction (MbP) [1] applied to in-building scenarios relative to traditional indoor propagation models.

2 In-building technologies

There are many options for technologies to provide in-building coverage, including dedicated picocells, off-air repeaters, radiating cables, passive distribution systems and increasingly the use of active systems, often involving RF modulated onto optical fibres. All of these can be regarded as distributed antenna systems (DAS) of various sorts, as explained in [2]. DAS can provide excellent performance compared with single antennas or penetration into buildings from outside macrocells. Each radiating element (antenna or radiating cable) is located so as to bring the signals to the most important locations for coverage or capacity, as originally proposed in [3–5] for indoor use. The signal power is distributed among the various elements, and the coverage can then be provided without encountering excessive signal loss through the internal walls and floors of the building. As a result the radiated power is reduced, helping to keep the system within health and safety limits, as recommended in [6], and minimising the signal power that leaks out of the building.

Despite the increasing maturity and volume of in-building systems, no standard design approach has yet emerged. Typically, the location of antennas, the associated power and the structure of the distribution system are arrived at based on judgements made by an experienced RF engineer, subject to constraints on location and types of antennas and distribution equipment imposed by the building owner or manager.

While there is no substitute for experience, the absence of objective methods for evaluating and optimising the performance of the system tends to lead to overdesign, increasing the cost and reducing the overall take-up of in-building systems, to the detriment of the market. There is a lack of consistency of approach between designers, and the conflicting demands of in-building coverage and

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isolation from the external network mean that the stated design criteria are rarely met in full.

It is perhaps surprising that this situation persists; after all, in today's environment, outdoor systems are designed using sophisticated planning tools based on well-known propagation models [7], shown to give good results. Until now, however, the inadequacies of existing design approaches have been overcome by frequency planning, or simply by avoiding in-building systems wherever possible. A fresh approach is required, however, in order to cater for third generation (3G) cellular systems, wireless local area networks (WLAN) and high-performance private digital and second generation (2G) cellular systems.

3 Challenges for in-building planning tools

Planning tools for in-building systems are available, but are rarely used in practice. The main reason for this is that they simply do not operate with sufficient accuracy to justify the effort which must be expended on using them. The in-building environment is extremely complex, and is impacted by propagation mechanisms including reflection, rough surface scattering, diffraction and transmission through walls and furniture. Although these mechanisms can be successfully simulated using techniques such as ray-tracing [8–10], the required software usually requires large computational time, and is extremely sensitive to the internal building geometry and material properties. Even when a combination of empirical and ray-tracing methods is employed, as in [11], where the prediction accuracy is improved and the processing time is reduced, the time is still prohibitive for practical engineering designs. As a result, such tools have only really been found to be useful in an academic research context.

Another approach to the creation of such tools is to neglect the more complicated propagation mechanisms and simply assume that signals always travel along a direct path from transmitter to receiver, suffering attenuation from any walls or floors encountered on the way. Examples of such models are the Keenan and Motley (K&M) [12], which includes both wall- and floor-loss factors, and the ITU-R 1238 model [13] which assumes only average behaviour of walls on the same floor. These models can give some useful indications of coverage for basic 'what-if' evaluations, but do not yield enough accuracy to deploy a low-cost system with sufficient confidence.

Both the sophisticated and simplified prediction approaches share a common basic difficulty: that of obtaining data representing the building with sufficient accuracy. There are two parts to this: digitising the building layout and then assigning electrical properties to all elements of the building.

In capturing the building layout, at least the locations and sizes of all the floors and walls in the building are required. Sometimes, these can be obtained from computer-assisted design (CAD) drawings of the building in question. However, obtaining these drawings in electronic form for use is often difficult, involving issues of copyright, which is typically owned by the architects of the building. Even if the files can be obtained, the drawing conventions used vary widely, requiring careful import filtering to separate the walls from other features of the drawing. More usually, only bitmap images or paper plots of the building are available, and the wall locations have to be digitised manually from these. This process is time-consuming and prone to errors.

Once the building plan has been digitised, it is necessary to assign material types and other properties to all of the walls. The range of materials used in buildings varies widely. The electrical properties also vary significantly, even with superficially similar materials [14]. For example, the density of concrete varies over a wide range depending on the structure, from lightweight concrete composite floors in steel framed structures to dense concrete floors and walls in concrete framed structures. These variations have a profound impact on the losses at radio frequencies [15]. Similarly, the presence and spacing of reinforcing bars within concrete can cause very rapidly frequency-varying loss factors.

The end result of these uncertainties, and others, is that the planning tools currently available have been too hard to use, insufficiently accurate, and have extended the design time beyond acceptable limits.

4 The role for measurements

During the design and deployment of most in-building systems, it is common practice to conduct RF site surveys to confirm the coverage available from particular antenna locations, and to provide assurances to both the client and the end customer that the coverage meets their requirements. A typical example is shown in Fig. 1. Such surveys, if conducted carefully with properly calibrated equipment, provide an accurate guide to coverage. However, interpreting the results is rather subjective, with the coverage level depending on the locations surveyed. Nevertheless, good quality surveys contain all of the information on the complex propagation mechanisms taking place in the building, with the materials of the building implicitly represented via the signal strength variations recorded. If this information could be extracted from the measurements and processed appropriately, it could be used to analyse and optimise any proposed design to ensure it meets the requirements set down by the client at the outset.

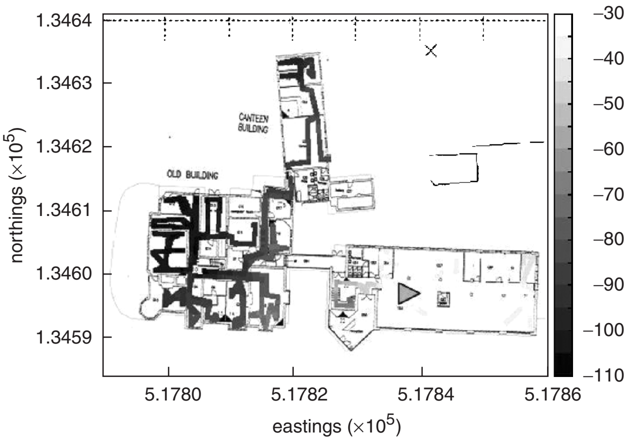

Fig. 1 *Typical indoor RF site survey*
The level in the greyscale bar indicates the signal strength in dBm recorded from the highlighted transmit antenna

5 Measurement-based prediction (MbP)

In seeking a way to improve our confidence in our in-building designs, we investigated the potential of a process which we had developed previously for application to macrocellular systems. This process, known as MbP [1], creates an optimum combination of measurements and simple models to predict complete system coverage performance. Predictions are made over the whole area of interest, even though the measurements are only limited in extent, with each measurement point influencing every prediction point to varying extents. We found that we could apply a modified version of the MbP process to the in-building environment, yielding very accurate predictions.

The overall MbP scheme is illustrated in Fig. 2. The process is described in the following subsection.

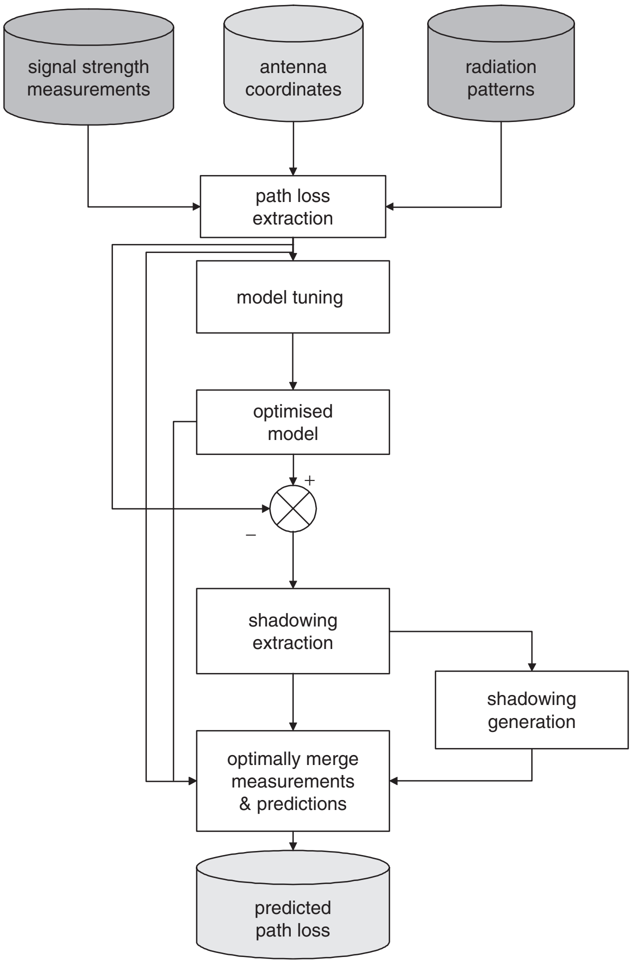

Fig. 2 *Measurement-based prediction (MbP) methodology*

5.1 Signal strength measurements

In the first phase of the MbP scheme, measured data, which include accurate measurement locations and signal strength levels, are carefully calibrated and filtered. These measurements are carried out with the use of an RF receiver, an external omnidirectional antenna, proprietary data collection software installed in a handheld device and some sort of navigation and positioning system. For outdoor measurements, this equipment is fitted in a test vehicle, and a global positioning system (GPS) receiver is used for determining the receiver's location. However, for indoor scenarios, GPS data are not available and positioning can be obtained either with the use of mobile robots, as suggested in [16] for special measurement campaigns requiring position accuracy with high route repeatability, or with a method known as 'way-points', often employed for practical indoor propagation measurements, and is the one we used here. In the latter, a digital representation (bitmap) of parts of the building is available. The user then chooses manually on the bitmap his current position, and starts data collection for a period of time, in which he walks a certain distance until he stops and updates his position again. The collection software then interpolates all the samples that were collected over this period of time and spreads them in different ways, which may vary depending on the software tool manufacturer. This process is repeated for each location in the building for which the user changes direction of movement, until all the data have been collected.

The aforementioned signal strength measurements should be filtered prior to using them in MbP. Filtering removes samples that are either beyond the noise floor of the receiver or clipped due to very strong field strength at short distances from a strong transmitter antenna to the receiver.

5.2 Path loss extraction

Site information such as antenna coordinates and radiation patterns is required for path loss extraction. These parameters along with the signal strength measurements are processed to yield measurements of path loss against location. This loss is made up of two components. The first is a distance-dependent r component, resulting from the bulk characteristics of the propagation medium, known as median path loss L_{50} and is given by

$$L_{50} = k_1 + 10n\log r + k_2 r \quad (1)$$

For path loss extraction, the effects of antenna radiation pattern are removed. For this, manufacturer's radiation patterns are used, often provided in two planes (azimuth and elevation). However, as three-dimensional (3-D) patterns are required for prediction work, a method to estimate these 3-D patterns having only two available planes has been investigated and implemented [17].

Constants k_1 and k_2 in equation (1) are tuned using the signal strength measurements described in Section 5.1, to obtain an optimised model, which often represents a best-fit model for the collected data. The path loss exponent n is determined from this tuning process.

The second component for the path loss depends on the characteristics of the nearby propagation environment (local clutter). Subtracting the distance-dependent part of equation (1) from the total loss L yields the latter component, known as shadowing or slow fading L_s, and this is given by

$$L_s = L - L_{50} \quad (2)$$

First- (mean, standard deviation, probability density function) and second-order (autocorrelation and cross-correlation) statistics of the shadowing are then analysed to yield representative parameters of the test area.

5.3 Optimal merge of measurements and predictions

The derived shadowing parameters are used to generate a set of shadowing predictions for the whole area of interest, mapped onto each prediction point. The result is added to the distance-dependent path loss predictions produced by the propagation model for the area. The outcome has then very similar characteristics to measurements which would have been produced not only at the measurement route but over the whole prediction area, as is demonstrated in this paper, without the need for detailed building geometry, as with ray-tracing algorithms.

The benefits of MbP have been exploited for various technologies, and have been especially significant in the design of UMTS indoor systems to control and manage interference effectively, as described in [18, 19].

6 Comparison of accuracy with different modelling approaches

To compare the accuracy of different modelling approaches, we have conducted extensive measurements at 1800 MHz in a Victorian-style building. The building is in two parts: a Victorian manor-house, built from brick, with thick external walls, some solid internal walls and some light chipboard-type walls (Fig. 3*a*). Adjoining this, and connected via a footbridge, is a 1970s purpose-built office building with open-plan construction (Fig. 3*b*). Both portions of the building are on two storeys.

Fig. 3 *Cellular Design Services Headquarters Building, 'Graylands'*
a Old building
b New building

The antennas used for the measurements are from Mat-Jaybeam [20], dual-band GSM directional indoor antennas of the type known as 'sharksfin'. The maximum gain at boresight direction is 4.7 dBi at 1800 MHz, a horizontal beamwidth of 140° and a vertical beamwidth of 70°. These antennas are often used in applications where coverage is to be maximised in a specific direction, especially on corridors or corners, and are normally mounted on walls.

One of the characteristics of MbP is that the results can be applied when antenna types are changed, e.g. omnidirectional antennas are used to conduct the MbP measurements and, once propagation predictions are available, other omni-antennas or even directional ones can be used with excellent results [21]. This capability is extended even further when antenna tilt, orientation and location can also be modified, which effectively speeds the indoor design process with a minimum of measured antenna locations.

The perimeters of the external walls of the building in consideration are shown in Fig. 4. The x and y axes indicate true UK grid co-ordinates, which has special relevance because absolute building representation may be required, particularly when outdoor-to-indoor penetration measurements are merged with indoor predictions. Axis marks are at 10 m intervals. For our investigation, we selected three antenna locations; A and B on the first and ground floors of the old building, respectively, and C on the ground floor of the new building.

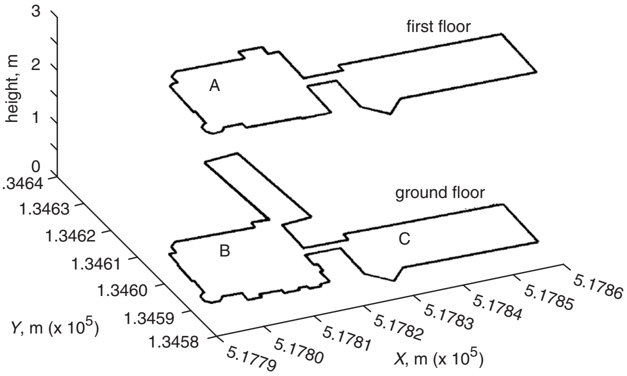

Fig. 4 *Exterior wall perimeters for Graylands, the building under investigation*

This investigation was conducted by subdividing the measurement data set into two separate sets: a tuning set which was exclusively used for driving the measurement-based prediction process and an evaluation set which was used to evaluate the accuracy of the predictions at those measured locations. The tuning set was chosen to be representative of the extent of walk testing which is reasonable to perform in a practical situation, while the evaluation set was extensive, covering large areas of both the old and new buildings.

We compared the MbP process with an implementation of the Keenan and Motley model (K&M), as defined in [12]. To give the K&M model the best possible opportunity for success, we tuned the wall n_w and floor n_f factors using all the available data, to establish a fair comparison between the two models. In practice, to determine path loss, users of the K&M model would have to guess the wall and floor factors based on their experience and assessment of the likely material properties, along with knowledge of the number of trespassed walls a_w and floors a_f

$$L_{50} = L_1 + 20 \log r + n_w a_w + n_f a_f \tag{3}$$

Figure 5 shows a linear regression approach to estimate the average wall loss factor to be used in the model, neglecting floor losses, because measurements and predictions were conducted on the same floor. The excess loss L_{ex} in dB is defined as

$$L_{ex} = L_i - L_{FSL} \tag{4}$$

L_i is the path loss at point i, in dB, as given by the measurements, and L_{FSL} represents the free-space loss from the antenna location to the point, which is dependent only of distance. By performing this operation, only the excess losses, which are assumed to be due to local clutter and wall losses, are plotted against the number of trespassed walls. A calibration factor is added to the equation to account for

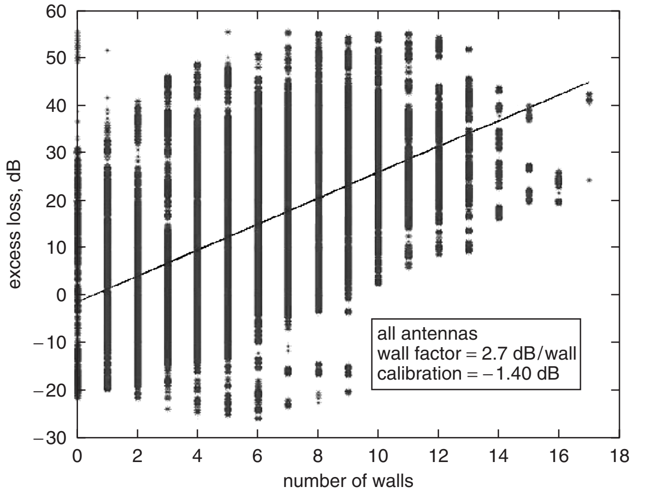

Fig. 5 *Wall and calibration factors for accuracy evaluation of K&M*

errors during the measurements due to inaccurate calibration, which appears as any additional losses to free-space loss at 1 m from the transmitter, and denoted as L_1 in equation (3).

Antenna radiation pattern information was added to the predicted K&M path loss to produce signal strength values which could be directly compared with those generated by MbP.

As an example, for antenna B a total of 2709 measurement samples were used for the MbP tuning out of a total of 5911, a tuning set to evaluation set ratio of 46%/54%. The full measurement data set for antenna B is shown in Fig. 6. All measurement data were averaged to remove fast fading and to yield an accurate estimate of the local mean signal strength before being applied to either model. Transmit power was 33 dBm and the peak antenna gain is 4.7 dBi.

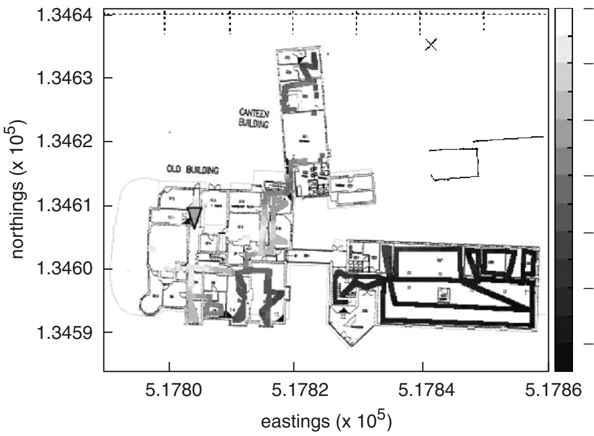

Fig. 6 *Extent of measurement walk for antenna B*
Local mean signal strength is shown in dBm

Predicted coverage on the ground floor using the tuned K&M model and MbP for antenna B is shown in Fig. 7. K&M produces results which are obviously from an approximate model; the boundaries between walls cause sharp discontinuities in the signal and the influence of these discontinuities extends over very long distances (the ‘rays’ seen in the new building area). The predicted signal strength using the MbP process, by contrast, exhibits the dynamic range and complexity of signals observed in practical measurements, because it is informed by the signal characteristics in the tuning set and uses these to produce an accurate prediction in other locations.

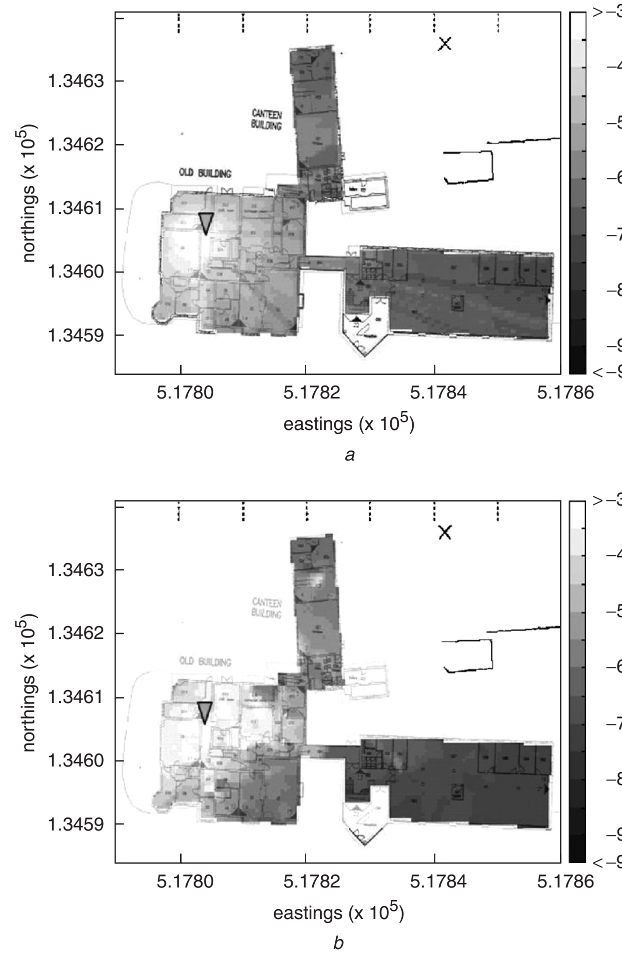

Fig. 7 *Coverage from antenna B predicted by K&M and by MbP on the ground floor*

For a quantitative comparison of the accuracy see Table 1, which shows the statistics of the difference between measurements and predictions for both models. The standard deviation, which indicates the typical deviations between the measurements and models, is reduced from over 8 dB with K&M to only 2 dB for MbP, which is a very high-confidence outcome. Similarly, the correlation coefficient is 99.6% for MbP, indicating its ability to track the detail of signal variations. The K&M model correlation coefficient of 92.2% is also high, showing that the tuning of this model was performed correctly. Combining the prediction results from all three antennas yields the statistics shown in Table 2.

The signal variations of the two approaches can be better compared in Fig. 8. It is clear that the MbP process is able to thick the measurements closer than the K&M model, as suggested by the first-order statistics shown in Tables 1 and 2. Although K&M succeeds in tracking the major signal variations, it fails to capture any of the detail in the way that the MbP process does. This results from some of the more complex propagation mechanisms and the fine structure of windows, furniture and other objects of which it has no knowledge, and which would be impractical to digitise and include in any prediction. MbP has access to all of this information implicitly via the measurements. In particular, closer to the antenna location, i.e. the first 500 samples, the K&M model lacks details from that of surrounding objects, hence underestimating path loss, as shadowing variations cannot be accounted for accurately

Table 1: First-order statistics of the prediction error between MbP and the K&M predictions for antenna B

MbP model			K&M model		
Mean error, dB	Standard deviation, dB	Correlation coefficient, %	Mean error, dB	Standard deviation, dB	Correlation coefficient, %
−1.63	1.96	99.6	−2.30	8.43	92.2

Table 2: Prediction error statistics of the combined evaluation datasets from antennas A, B and C

MbP model			K&M model		
Mean error, dB	Standard deviation, dB	Correlation coefficient, %	Mean error, dB	Standard deviation, dB	Correlation coefficient, %
−1.96	3.61	98.7	−2.03	7.42	94.7

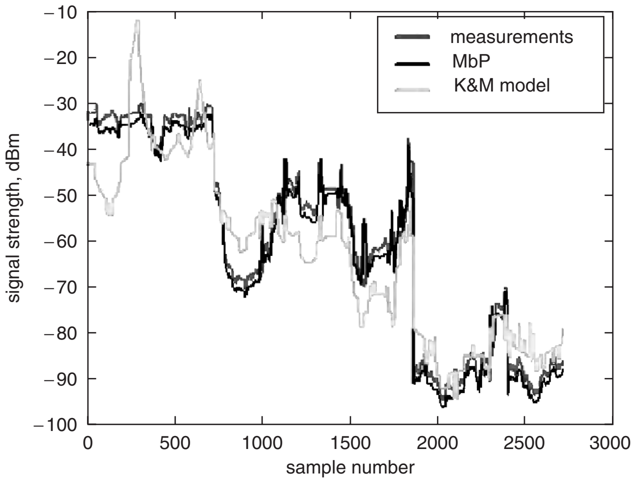

Fig. 8 *Comparison of signal strength measurements and predictions from MbP and K&M*

enough to trace measurements. This effect is diminished as distance between transmit antenna and receiver is increased, as the effect of walls, which are accounted for by K&M, supersedes these slow fading variations. Nevertheless a consistent difference, which is less than that for the first samples, exists between K&M and measurements, as clearly observed in Fig. 8.

The improvements from MbP depend on the specific measurements and locations, but they are consistently significant. Having used the process over a very wide range of environments and frequencies, we have found that the standard deviation of the prediction error is reliably less than 5 dB, which compares extremely favourably with the levels achieved using other prediction techniques, which more usually produce errors of 8–10 dB, even if the building material characteristics are very carefully entered and optimised.

7 Hit-rate analysis

The first-order statistics reported in Tables 1 and 2 give only a global perspective of the accuracy of the predictions, but are not always sufficient. To complement first-order statistics, hit rates were estimated [22] for evaluating the performance of both propagation models compared with measurements. Hit rates are more sensitive to changes in model accuracy than the standard deviation, and correlate more closely with the expected performance of the models in predicting system coverage in particular areas, because they include a measure of the model's spatial correlation with measurements.

Hit-rate metrics are obtained by assessing both predicted and measured values, at each point along a route, against a field strength or path loss threshold. If the measured path loss is less than or equal to a given path loss threshold, then, at those particular points along the route, 'coverage' is achieved for the experimental result. Otherwise, 'outage' is achieved. The same test is applied to the set of predicted path loss data. When both measured and predicted values agree, either as 'coverage' or 'outage', a 'hit' is declared; otherwise a 'fail' occurs. The cumulative density function for these 'hits' is computed as a percentage, and hence sufficient coverage is achieved if this percentage supersedes that of a minimum requirement, specified by operators: in practice, these requirements vary from 90% to 98%, depending on the specific application, environment and frequency band.

For this experiment, different signal strength thresholds were tested for this hit-rate analysis, obtaining the results shown in Fig. 9 for the three antennas under consideration. A threshold of −85 dBm is often selected for practical applications, for which 'acceptable' coverage is assumed. It is evident that the performance of MbP consistently exceeds that of K&M, especially for antennas A and B, from 5% to 10% improvement. This has a significant impact in a much better definition of handover areas, especially when this handover is performed with external macrocells; i.e. it is essential for operators that handover occurs in well-delimited areas between outdoor and indoor cells, as normally mobile users need to hand over to indoor cells just as they enter a building, and, hence, accurate handover boundaries need to be delimited. This avoids excessive handover operations and capacity is not stolen from the indoor cell.

8 Conclusion

The MbP technique was compared with a traditional model in a challenging in-building environment. Both methods benefited from the use of site-specific measurements. It was shown that the prediction accuracy, expressed in terms of the mean, standard deviation and hit rate was significantly better with MbP. These improvements have been verified in a wide range of other environments and yield in-building systems, which provide a high-level of confidence in the coverage provided and reduce the cost of the infrastructure to meet a given requirement. This cost reduction comes as a result of the minimisation of antennas to be used, if accurate

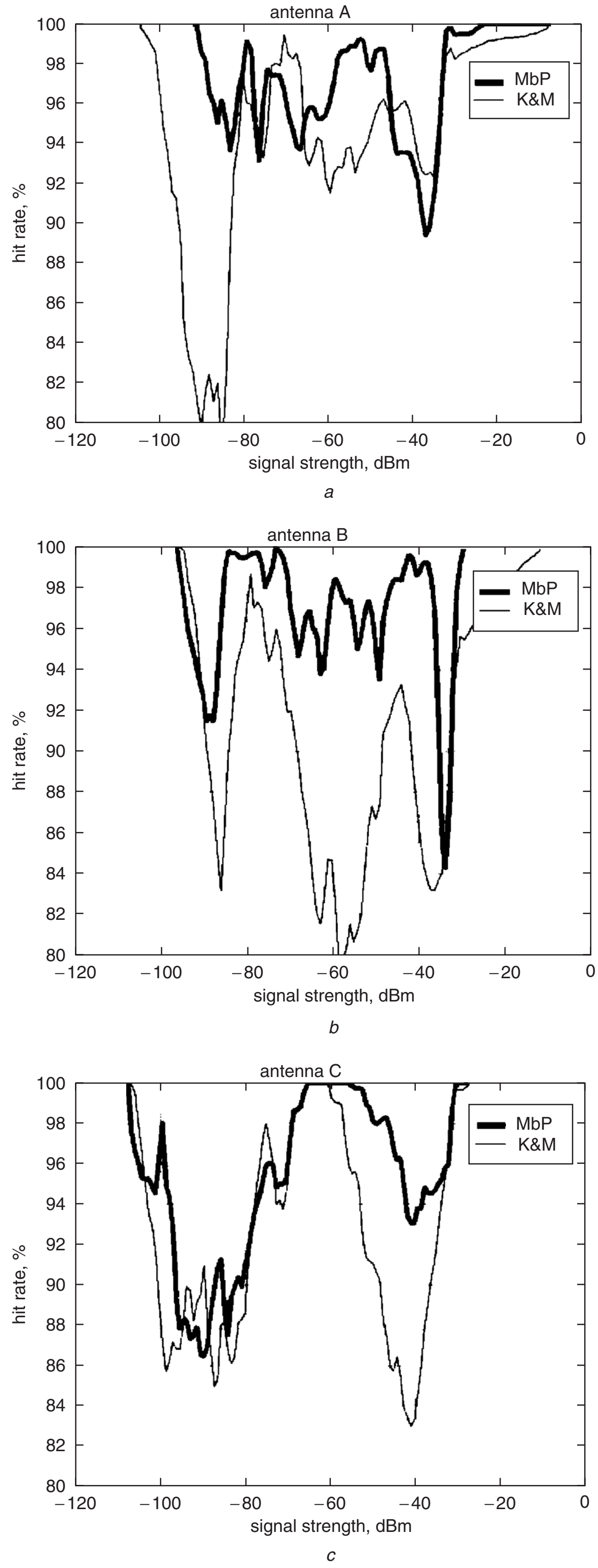

Fig. 9 *Hit-rate results for the accuracy evaluation analysis*

predictions are performed [23, 24], which has an impact in the reduction of other equipment associated with these number of antennas; e.g. passive (splitters, cables etc.) and/or active devices (hubs, repeaters etc.). As a result, radio planners benefit from higher confidence predictions, allowing them to plan the indoor network with minimum fading margins, thus minimising cost, leakage and potential interference to external cells.

In addition, QoS for cellular systems is also benefited from accurate predictions, because a better control of interference can be achieved and the cell footprint can be controlled more accurately, avoiding unnecessary hand-overs and minimising leakage. This benefit of path loss prediction can be applied to any system relying on accurate cell footprint definition, such as DAS or multiple-input multiple-output (MIMO) systems.

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10 References

1 Saunders, S.R., and Belloul, B.: 'Making wireless networks deliver', *Ingenia, R. Acad. Eng.*, 2002, **12**, pp. 36–40
2 Aragon-Zavala, A.: 'In-building cellular radio system design and optimisation using measurements'. PhD dissertation, Department of Electrical Engineering, University of Surrey, Guildford, UK, 2003, pp. 23–27
3 Saleh, A.A.M., Rustako, A.J., and Roman, R.S.: 'Distributed antennas for indoor radio communications', *IEEE Trans. Commun.*, 1987, **35**, (12), pp. 1245–1251
4 Kerpez, K.J.: 'A radio access system with distributed antennas', *IEEE Trans. Veh. Technol.*, 1996, **45**, (2), pp. 265–275
5 Chow, P., Karim, A., Fung, V., and Dietrich, C.: 'Performance advantages of distributed antennas in indoor wireless communication systems'. IEEE 44th Veh. Technol. Conf., VTC'94, Stockholm, Sweden, June 1994, pp. 1522–1526
6 'Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz)', International Commission on Non-Ionising Radiation Protection (ICNIRP), *Health Phys.*, 1998, **74**, (4), pp. 494–522
7 Saunders, S.R.: 'Antennas and propagation for wireless communication systems' (J. Wiley & Sons, Chichester, 1999), pp. 151–179
8 Catedra, M.F., Perez, J., De Adana, F.S., and Gutierrez, O.: 'Efficient ray-tracing techniques for three-dimensional analysis of propagation in mobile communications: applications to picocell and microcell scenarios', *IEEE Antennas Propag. Mag.*, 1998, **40**, (2), pp. 15–28
9 Klepal, M., Pechac, P., and Mazanek, M.: 'New fast approach to wideband propagation prediction in picocells'. 11th Int. Conf. Antennas Propag., ICAP'01, Manchester, UK, April 2001, pp. 216–219
10 Tarng, J.H., Chang, W.R., and Hsu, B.J.: 'Three-dimensional modelling of 900 MHz and 2.44 GHz radio propagation in corridors', *IEEE Trans. Veh. Technol.*, 1997, **46**, (2), pp. 519–526
11 Wolfle, G., Hoppe, R., and Landstorfer, F.M.: 'A fast and enhanced ray optical propagation model for indoor and urban scenarios, based on an intelligent pre-processing of the database'. 10th IEEE Int. Symp. Personal, Indoor and Mobile Radio Commun., PIMRC'99, Osaka, Japan, Sept. 1999, pp. F5–3
12 Keenan, J.M., and Motley, A.J.: 'Radio coverage in buildings', *B. Telecom Technol. J.*, 1991, **8**, (1), pp. 19–24
13 'ITU-R Recommendation P.1238: Propagation data and prediction models for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz' International Telecommunication Union, Geneva, Switzerland, 1997
14 Stavrou, S., and Saunders, S.R.: 'Review of constitutive parameters of building materials'. 12th Int. Conf. Antennas Propag., ICAP'03, Exeter, UK, April 2003, pp. 211–215
15 Stavrou, S., and Saunders, S.R.: 'Factors influencing outdoor to indoor radio wave propagation'. 12th Int. Conf. Antennas Propag., ICAP'03, Exeter, UK, April 2003, pp. 581–585
16 Aragon-Zavala, A., and Saunders, S.R.: 'Autonomous positioning system for indoor propagation measurements'. 48th Vehicular Technology Conference, VTC'99, Amsterdam, The Netherlandss, Sept. 1999, pp. 785–789
17 Aragon-Zavala, A., and Koulinas, K.: 'Antenna radiation pattern estimation in 3-D for indoor environments'. 15th Int. Conf. Electron. Commun. Comput., CONIELECOMP'05, Puebla, Mexico, Feb. 2005, pp. 26–31
18 Aragon-Zavala, A., and Saunders, S.R.: 'Measurement-based optimisation of in-building coverage for UMTS'. 3rd Int. Conf. 3G Mobile Tech., 3G2002, London, UK, May 2002, pp. 221–224
19 Gatzoulis, L., Aragon-Zavala, A., Povey, G., and Saunders, S.R.: 'Performance analysis of in-building FDD deployment using measured data'. 4th Int. Conf. on 3G Mobile Tech., 3G2003, London, UK, June 2003, pp. 167–172
20 MAT-JAYBEAM.: URL: http://www.matjaybeam.com

21 Aragon-Zavala, A., and Saunders, S.R.: 'Three-sector antenna prediction based on omnidirectional antenna measurements'. Millenium Conf. Antennas Propag., AP 2000, Davos, Switzerland, April 2000, pp. 221–224

22 Owadally, A.S., Montiel, E., and Saunders, S.R.: 'A comparison of the accuracy of propagation models using hit rate analysis'. 49th Veh. Technol. Conf., VTC'01, Atlantic City, USA, Sept. 2001, pp. 1979–1983

23 Datta, S., Aragon-Zavala, A., and Saunders, S.R.: 'Automatic optimisation for UMTS indoor coverage using distributed antenna systems'. 4th Int. Conf. on 3G Mobile Tech., 3G 2003, London, UK, June 2003, pp. 42–47

24 Aragon-Zavala, A., and Saunders, S.R.: 'Coverage optimisation based on power control and antenna location in a distributed antenna system'. 1st Int. Conf. Electr. Electron. Eng., ICEE-CIE 2004, Acapulco, Mexico, Sept. 2004, pp. 84–89