Reception Reliability in Three-Dimensional Personal Communications Systems

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ABSTRACT

In tomorrow's wireless communications systems it is envisaged that users will be able to roam freely throughout a building while transferring information via a range of electronic technologies. To achieve this objective, knowledge of the indoor propagation environment is required. In this paper the effects that floors and walls have on system performance and efficiency are investigated. Comparisons of system performance are made using outage probability and a measure of spectral efficiency. It is shown that floors and walls can obstruct the propagation path of the indoor channel sufficiently to enable efficient system design.

I. INTRODUCTION

With the proliferation of wireless technologies it is envisaged that cellular type communications systems will be incorporated within buildings to provide reliable service to high capacity areas [1]. Users will be scattered throughout a three-dimensional environment as shown in Fig. 1 and system planners will need to understand the effects of frequency reuse in three dimensions.

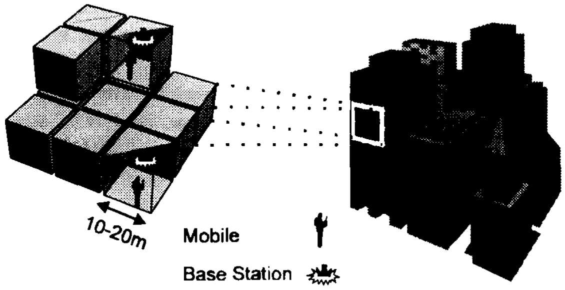

Fig. 1. A built-up area with base stations located in three dimensions to provide a ubiquitous communications service.

As cellular systems mature, the amount of communications traffic increases. To accommodate this increase, natural cellular evolution is towards reduced cell sizes. However even *microcells* with diameters of only 100 metres may not be able to meet the capacity demands found in buildings. This is because even a small street-based microcell could encompass several multi-storey buildings containing thousands of potential subscribers.

Ubiquitous service within buildings could be provided by deploying low power "base stations" throughout the indoor environment. These base stations would probably have transmitter powers of a few mW and coverage ranges of around 20 metres.

If base stations are to be deployed throughout buildings, then it is essential to understand the effects of the indoor propagation environment. This paper presents results of ongoing research in which these effects are investigated. In particular the effect of cochannel interference (CCI) resulting from other users within a building is determined.

The fundamental objective in designing an indoor communications system is no different from that for other cellular type systems, namely the provision of an efficient and reliable communications service. However definitions of *efficiency* and *reliability* are not definitive nor universally standard. Suitable measures of efficiency and reliability are also discussed in this paper.

II. THE INDOOR ENVIRONMENT

Indoor propagation environments appear to have some unique properties that are different from those of conventional outdoor cellular environments. However, multipath propagation is still a key characteristic of the indoor channel and various models can be used to describe the received signal strength statistics. Rayleigh fading is a useful model of signal variability where no dominant multipath component exists [2]. The Rician distribution appears to be a good model where a dominant component and a number of weaker multipath components are present [2]. Other distributions that have also been empirically verified for modelling the indoor channel are the log-normal, Suzuki, Weibull and Nakagami distributions [2]. These probability density functions usually have a mean power about which the variability occurs. Prediction of this mean power is of major interest in both indoor and outdoor cellular systems.

0-7803-1927-3/94/$4.00

The prediction of mean power indoors is different from that for outdoor environments, for which numerous authors have modelled mean power at a receiver, $\overline{P}_r$, as a function of the transmitter-receiver (Tx-Rx) separation, *d*, namely, $\overline{P}_r \propto d^{-\gamma}$. The propagation constant, γ, represents the slope of the path loss on a dB scale.

Various models have been developed for predicting mean power in indoor channels [2,3]. Eq. (1) shows the mean power prediction model used in this paper. A free space path loss is associated with the Tx-Rx separation, *d*, and wall and floor attenuation factors (WAF, FAF) are included [4].

$$\overline{P}_r(dB) \propto -20\log(d) - FAF - WAF \qquad (1)$$

The use of Eq. (1) is illustrated in Fig. 2, in which the plan view of a floor in a building is shown. The layout of the walls has been simplified to a regular grid pattern.

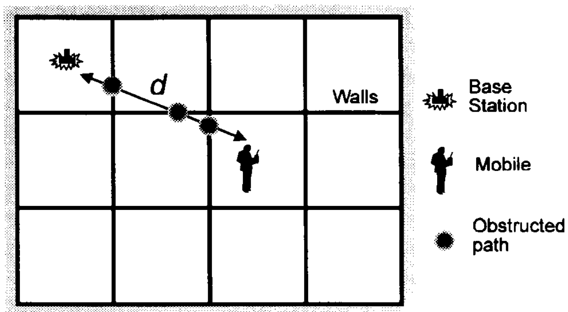

Fig. 2. Plan view of the floor in a building showing the assumed propagation path. This propagation path is used to estimate the mean power.

In Fig. 2 the base station is located at the centre of a room and the mobile is several rooms away. The path loss in this case is estimated by calculating the distance separating the Tx and Rx, *d*, and then adding attenuation for each wall (or floor) between the Tx and Rx. It is appreciated that this propagation model is somewhat simplistic since only one dominant path is considered in the estimation of mean power and no electromagnetic phenomena such as diffraction or reflection, are taken into account. However the model is useful for estimating the general effects of walls and floors on system performance.

III. EFFICIENCY AND QUALITY

A useful way to compare different system arrangements is to estimate the spectral efficiencies of each system. A simple but useful measure for spectral efficiency is the number of channels available per cell, namely "radio capacity" [5]. The measure *channels/cell* implicitly accounts for the cluster size and consequently the reuse distance and interference protection ratio - all of which are fundamental considerations in the design of a cellular system [6].

It is important to realise that efficiency must be considered in association with the quality of reception since simultaneously maximising quality and efficiency is usually not possible. It is misleading to quote a particular value of spectral efficiency without indicating the associated quality. In this paper, *quality* refers to *reception reliability* i.e. the percentage of time that reliable communications are maintained. Reception reliability is the complement of *outage probability.*

Since indoor systems are likely to include a large number of cochannel interferers located in three dimensions, an "interference only" outage probability expression is considered. As a consequence, the possibility of the desired signal fading below the receiver's minimum reception threshold is ignored.

The outage probability expression used in this paper applies when the desired signal and cochannel interfering signals suffer Rayleigh fading only. This is known as a Rayleigh/Rayleigh model and the outage probability, P_{out}, is given by [7,8],

$$P_{out} = 1 - \prod_{i=1}^{I}\left(\frac{\Lambda_i}{\alpha + \Lambda_i}\right), \qquad (2)$$

where α is the interference protection ratio dependent on the modulation scheme, Λ_i is the *i*th carrier to interference ratio and I is the number of active cochannel interferers. Other fading models (e.g. [9]) have been considered by the authors but are not presented here.

The results presented in this paper have been calculated for an interference protection ratio, α, of 8dB. Such a value would be appropriate for a digital modulation scheme.

IV. SYSTEM CONFIGURATION

The inter-relationships between the indoor propagation environment, reception reliability and spectral efficiency are somewhat complex. Some authors have shown how outage probability varies as a function of spectral efficiency [10]. However, this is usually performed in a uniformly varying propagation environment.

By incorporating the effects of walls and floors the analysis becomes more complex since the prediction of mean power is no longer a function of distance alone. So as not to unduly complicate the analysis and obscure the important trends in system performance, the reception quality is kept constant in the following analyses and the effect that walls and floors have on spectral efficiency is investigated. In this paper *adequate quality of reception* is defined to mean that a receiver must maintain a reception reliability that exceeds 95%, i.e. the carrier to combined interference ratio is greater than the interference protection ratio (α) 95% of the time. In association with this definition, the "quality" is deemed acceptable if throughout a room (essentially a cell) all locations have reception reliability greater than 95%.

To calculate the channels/cell ratio (efficiency) for a particular system, knowledge of the allocated bandwidth is required. The exact frequency allocation that a building might require to operate an effective service is difficult to estimate but in this paper a bandwidth of 2MHz is assumed for a full duplex system. Each (digital) channel is assumed to have an effective spacing of 25kHz. Consequently 40 unique channel pairs are available in the 2MHz of spectrum space.

V. BUILDING LAYOUT

If the effects of walls and floors on spectral efficiency are to be investigated, a mathematical model of a building is required. The building model adopted in this paper assumes room dimensions of 10x10m located on each floor as shown in Fig. 3. Floors are assumed to be spaced 5m apart and rooms are stacked directly on top of each other. The overall dimensions of the building are not specified as they do not affect the results in this analysis.

Each 10x10m room is assumed to be a cell with its own base station positioned centrally on the ceiling. Base station antenna patterns are assumed to be omni-directional in the x-y plane but radiate from the ceiling to the floor in the z-axis.

If a fixed channel assignment strategy is used then each cell could be surrounded by up to eight closest cochannel cells on the same floor, as shown in Fig. 3. When only a single floor is being considered only these eight dominant interferers are included in the estimation of reception reliability.

VI. EFFECTS OF WALLS AND FLOORS

Walls in buildings vary considerably in their construction which influences their effect on the propagation of electromagnetic energy. The attenuation introduced by walls is of major interest and the literature reports values from 1.4dB for cloth covered partitions to 7dB for 8-in. concrete blocks [2].

If walls did not provide any attenuation and path loss was determined by a free space relationship alone, results show that to provide adequate quality in a 10x10m room, the closest eight cochannel interferers would need to be placed at least 150 metres away from the desired base station. This equates to a reuse distance (normalised to the cell radius) of 30 and a cluster size of over 200 cells, leaving less than one channel available per room. (Of course a building would have to be enormous to have a cochannel cell 150m away on the same floor but in reality cochannel interferers in nearby buildings might cause similar interference). This example illustrates that an unobstructed (free space) environment would yield a highly inefficient system i.e. a low number of channels per cell. Obstructions in the indoor environment improve efficiency drastically, as evidenced in the following examples.

Now assume that the walls in a building have an associated attenuation called the wall attenuation factor (WAF). Similarly, floors have an associated floor attenuation factor (FAF). The protection ratio (α) is assumed to be 8dB and the WAF is 6dB/wall. The eight dominant cochannel interferers are located 20m from the desired base station as shown in Fig. 3. This corresponds to a reuse distance (normalised to the cell radius) of 20/5 = 4 and a cluster size also of 4. Therefore the 40 available channels could be allocated to the four cells in each cluster, thus yielding an efficiency of 40/4 = 10 channels/cell. However, note that in calculating this efficiency, the reception quality has not been considered.

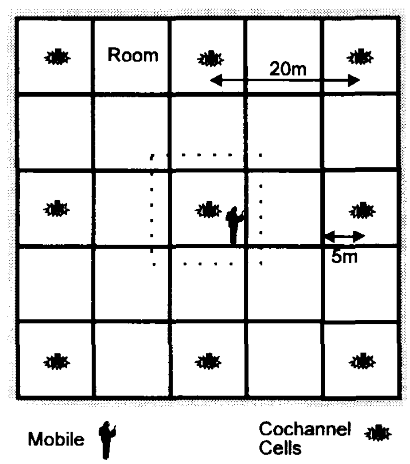

Fig 3 One possible arrangement of cochannel cells on a floor in a building. Each room is a cell with a radius of 5m. The reuse distance in this example is 20m.

Contours of common reception reliability can be used to provide a visual representation of the variation in quality throughout a room. Fig. 4 is a detailed contour plot of the room shown by the dotted region in Fig. 3 and shows the reception reliability contours throughout the room when the eight closest cochannel interferers in Fig. 3 are all active. The walls bounding the room are visible at ±5m in the x and y directions and the base station is located at the centre of the room {0,0}.

Fig. 4 shows that inside the 10x10 metre room, areas exist where reception reliability is less than 95%. Consequently, this system arrangement does not meet the defined quality criterion. Thus if each wall has 6dB attenuation, then a reuse distance of 20m is insufficient to provide adequate reception reliability. Improved quality throughout the room would result if either the cochannel cells were further apart or if the attenuation factor of each wall was greater.

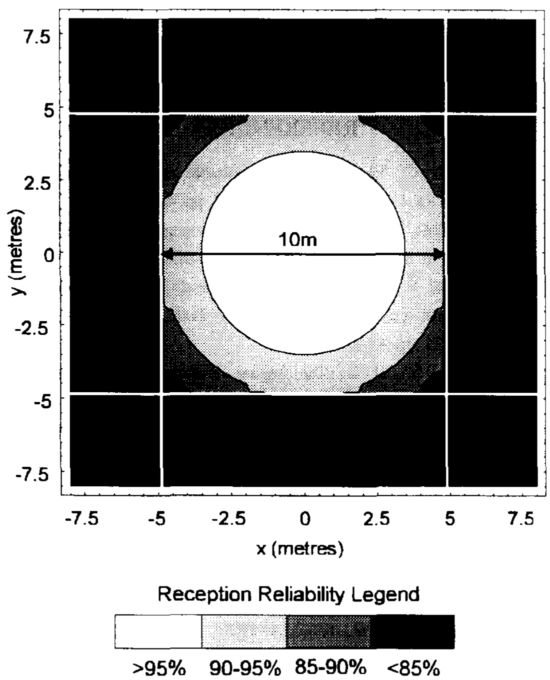

Fig 4 Reception reliability contours for a 10x10 metre room. Walls are shown as white for visual purposes only. Wall attenuation is 6dB/wall.

Fig. 5 shows the reception reliability contours for the same situation as Fig. 4 except that the wall attenuation is now assumed to be 8dB/wall. In this case it can be seen that the contours follow the shape of the room and that only the corners of the room have reception reliabilities less than 95%. Hence even with a WAF of 8dB/wall the 95% reception reliability standard is still not satisfied completely. In fact the WAF needs to be increased to 9dB/wall before the entire room has reception quality greater than 95%.

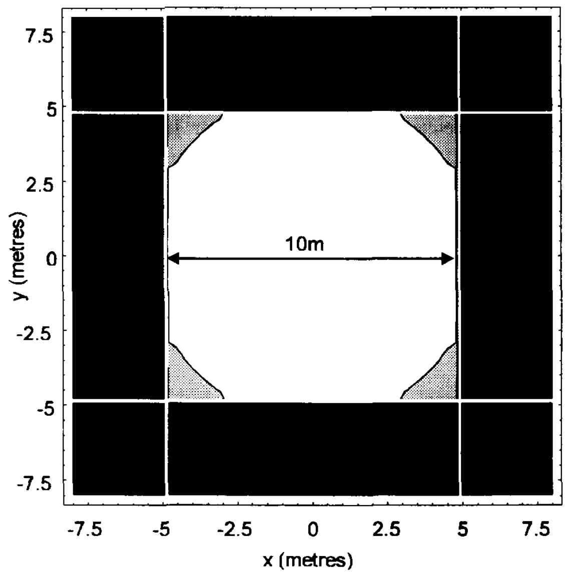

Fig. 5 Reception reliability contours for 10x10m room. Wall attenuation is 8dB/wall.

The effect of wall attenuation on spectral efficiency is shown in Table 1. In all the cases listed in Table 1 the 95% reception reliability requirement is satisfied. Theoretically if the WAF was 23dB then a cluster size of one would be possible, i.e. all 40 channels could be reused in adjacent rooms.

WAF (dB)	Cluster	Reuse (metres)	Efficiency (channels/cell)
23	1	10	40
12	2	14	20
9	4	20	10
8	5	22.3	8
6	8	28	5
5	9	30	4.4
4	10	31.6	4
0	225	150	<<1

Table 1 Variation in spectral efficiency as a function of wall attenuation. Reception reliability is greater than 95% in a 10x10 metre room for all listed values of wall attenuation.

The section of Table 1 of most practical significance is that pertaining to WAFs of 4-6dB as these values are closest to published wall attenuation figures. WAFs of 4-

6dB yield cluster sizes of around 8-10 and efficiencies of 4-5 channels/cell.

Floors in buildings obstruct propagation paths thus limiting the coverage range of a base station. Typical floor attenuation factors (FAF) range from 10dB to 30dB depending on construction [2]. The optimum vertical frequency reuse distance is of major interest to system planners and is strongly dependent on the FAF.

To investigate the effect of vertical frequency reuse, a system has been modelled where base stations are arranged so as to provide adequate reception reliability on a given floor in a building. This floor is called the *reference floor.* Specifically, a cluster size of 8 and wall attenuation of 6dB/wall (as shown in Table 1) are assumed.

The entire arrangement of base stations was repeated on each floor. Estimation of the cochannel interference (inter-floor interference) between the reference floor and the floor immediately above was investigated. The FAF was empirically adjusted so that the inter-floor interference from the cochannel cells on the floor above was negligible to the (reference) floor below.

Results show that if an identical frequency reuse pattern is repeated on adjacent floors, then for a cluster size of 8, a FAF of 21dB is required to ensure that the inter-floor interference is negligible. This value of FAF falls in the middle of the range of reported values (10-30dB). This implies that some buildings could tolerate identical frequency reuse on adjacent floors and other buildings could not.

Also considered was the case where the cochannel cells on adjacent floors were not located exactly above and below each other. Instead the frequency reuse patterns on each floor were assumed to be offset from each other. This effectively increases the three-dimensional frequency reuse distance. For this arrangement, the required FAF is only 8dB which is less than any reported value of FAF.

If the cochannel cells are not offset and the actual FAF of a building is less than 21dB then a greater vertical frequency reuse distance would be required to achieve acceptable quality. This would result in a concomitant increase in the cluster size and a degradation in the spectral efficiency.

VII. CONCLUSIONS

Highly obstructed paths between cochannel (indoor) cells are advantageous in yielding high efficiency systems. Offsetting of frequency reuse patterns between adjacent floors introduces greater path loss for interfering signals and requires no extra base stations to implement but simply the proper allocation of channels.

The threshold levels of FAF required to limit inter-floor interference depend on the cluster size and wall attenuation that occur on a particular floor. For every building, it would seem that there is a critical value of FAF above which the effects of vertical frequency reuse can be ignored and channel assignment on each floor can be considered independently of that on other floors.

It is readily acknowledged that corridors, stairwells and windows will cause the results in this paper to be optimistic, however the results provide insight into the likely performance of a three-dimensional system with typical wall and floor attenuation factors.

VIII. ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of *Telecom Corporation of New Zealand Ltd.*

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