

# ESTIMATION OF CELL AREA COVERAGE AND CELL-SITE DIVERSITY GAIN UNDER RAINY CONDITIONS IN 30 GHz FIXED WIRELESS CELLULAR SYSTEMS USING RADAR MEASUREMENTS

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## ABSTRACT

Cell area coverage and cell-site diversity in mm-wave fixed cellular systems were studied by simulating radio paths and cells on radar images. Coverage was computed by considering the joint impact of rain attenuation and lognormal shadowing loss. A prediction model was developed for diversity gain as a function of angular separation between the serving hubs, which might be at different distances from the subscriber terminal.

## INTRODUCTION

This paper briefly reviews studies on the impact of rain attenuation on mm-wave fixed cellular networks, which have been reported in detail in [1]–[4]. Cell area coverage in 30 GHz fixed cellular radio systems with circular cells was studied by simulating radio cells on radar images to consider the spatio-temporal variations of rain attenuation. Coverage, expressed relative to the nominal, circular area of the cell, is defined as the fractional area within which any subscriber terminal receives the signal transmitted from the hub at a level above the minimum acceptable received power. Diversity gain when two hubs are available to serve a subscriber terminal in a selection combining mode was examined by simulating convergent links. The results were used to develop a model for diversity gain prediction and specify criteria for subscriber locations that potentially benefit from the cell-site diversity.

## RADAR MEASUREMENTS

The cellular systems studies were preceded by an evaluation of the power-law expression that relates either the radar reflectivity factor  $Z$  ( $\text{mm}^6/\text{m}^3$ ) or rainfall rate  $R$  ( $\text{mm}/\text{h}$ ) to the specific attenuation  $Y$  ( $\text{dB}/\text{km}$ ) of rain, for later use in computing rain attenuation estimates from the radar data. The power-law coefficients were derived from raindrop size distribution measurements made in Montreal and Toronto using JWD (Joss-Waldvogel Disdrometer) and POSS (Precipitation Occurrence Sensor System) measurement equipment. The  $Y$ - $R$  coefficients so obtained were found to differ slightly from those recommended by the ITU-R in [5]. However, those for frequencies in the 20–30 GHz range were the most similar to the ITU-R coefficients. The differences are believed to be the results of differences in the method of DSD measurement and parameter derivation. More details of this study can be found in [1].

In the following simulations using radar data, a radar measurement  $Z$  at any point (pixel) on a radar image was converted into an estimate of  $Y$  using the derived  $Y$ - $Z$  coefficients for vertical polarised waves at 30 GHz,  $Y = 1.74 \times 10^{-3} Z^{0.776}$ . Radar data used in this work were recorded during measurements of radar reflectivity factors over an area of 45-

km radius around Montreal. A total of 138,939 radar images with a  $1^\circ \times 150$  m resolution were recorded between October 1998 and October 2000, with a sampling period of five minutes. Two circular regions in the radar coverage area that were free from the effects of ground clutter and the melting layer were selected for the simulated cell sites. Rain attenuation  $A$  (dB) on a simulated radio link was computed by integrating the estimates of the specific attenuation  $Y$  (dB/km) along the link. To evaluate area coverage of a circularly shaped radio cell, radial links were simulated around the cell centre, with  $1^\circ$  azimuth intervals. Rain attenuation for each link was then computed and the area coverage determined for a maximum allowable attenuation using the method described in the following section.

## CELL AREA COVERAGE

A method for assessing cell area coverage by simulating radio cells on radar images was first reported in [6], [7]. The evaluations in the cited papers, however, assumed line-of-sight (LOS) conditions for all subscribers in the nominal area of the cell. This might be considered unrealistic, especially in areas with obstacles such as buildings or trees.

The assumption of lognormal shadowing in the coverage analysis of cellular systems involves modelling the local mean of received power as being lognormally distributed around a mean that itself decreases with distance in a power-law fashion with exponent  $\alpha$ , and as having standard deviation  $\sigma$  in dB that varies with the type of environment [8]. For mm-wave frequencies around 30 GHz, the closeness of the lognormal model to field measurements of path loss has been reported ([9], [10]). The reported path loss exponents varied in the range of 4–5, and the standard deviation ranged from 13 to 17 dB. Following the analytical method in [8], the point coverage in the presence of rain and lognormal shadowing at a given time at a particular distance  $r$  and azimuth  $\theta$  relative to the hub can be computed by adding the rain attenuation to the mean path loss, as given by:

$$\Pr[P(r, \theta) > P_{Th}] = \frac{1}{2} - \frac{1}{2} \operatorname{erf} \left( \frac{-M + 10\alpha \log_{10}(r/L) + A_{rain}(r, \theta, t)}{\sigma\sqrt{2}} \right) \quad (1)$$

where  $M = P - P_{Th}$  is the power margin at the cell perimeter,  $P$  the mean power at the cell perimeter ( $r=L$ ) that depends on the transmit power and the gains of the antennas,  $P_{Th}$  the minimum acceptable received power for a specified fractional coverage of locations at the cell perimeter and  $A_{rain}(r, \theta, t)$  rain attenuation on link  $(r, \theta)$  at observation time  $t$ . The probability notation on the left-hand side reflects the spatial variation of shadowing. The margin at the cell rim is defined with respect to the clear-sky mean path loss with an exponent of  $\alpha$ . Fig. 1(a) describes pictorially the computation of point coverage at  $(r, \theta)$  under precipitation. The cell area coverage  $C(P_{Th})$  for a threshold  $P_{Th}$  is:

$$C(P_{Th}) = \frac{1}{\pi L^2} \int_0^{2\pi} \int_0^L \Pr[P(r) > P_{Th}] r dr d\theta \quad (2)$$

In the simulation, the nominal area of each of the two cells studied was divided into bins, for each of which point coverage was obtained using (1), and the area coverage computed using a discrete form of (2). An examination of individual effects of variations in  $\alpha$ ,  $\sigma$ ,  $L$  and  $M$  is reported in [3], [4]. Typical CDFs (cumulative distribution functions) of coverage obtained from the simulations are shown in Fig. 1(b) for  $\alpha = 4$ ,  $L = 2$  km,  $M = 10$  dB and various values for  $\sigma$ . In the figure, coverage values that are less than 100% in the upper range of probability are due only to the shadowing effects. The CDFs for different standard deviations converge in the lower range of probability. This is caused by heavy rain events that can result in outages throughout a large portion of a cell area, regardless of shadowing conditions. Statistical results such as these, derived from the analysis of radar measurements, could serve as the basis for developing a coverage statistics prediction model for the region in which the radar measurements were made, as exemplified in [4] for the Montreal area.

## CELL-SITE DIVERSITY

It is considered that cell-site diversity could be advantageous in situations where rain attenuation can degrade cell coverage. This was first studied in connection with mm waves as reported in [11] using radar data for links of equal lengths. In our study, scenarios for links of equal or different lengths with selection combining were evaluated. It was assumed that both links are either under LOS conditions or blocked with equal, small shadowing loss. For different link lengths  $L_2 \geq L_1$ , the difference in path loss is accounted for by assuming free-space propagation.

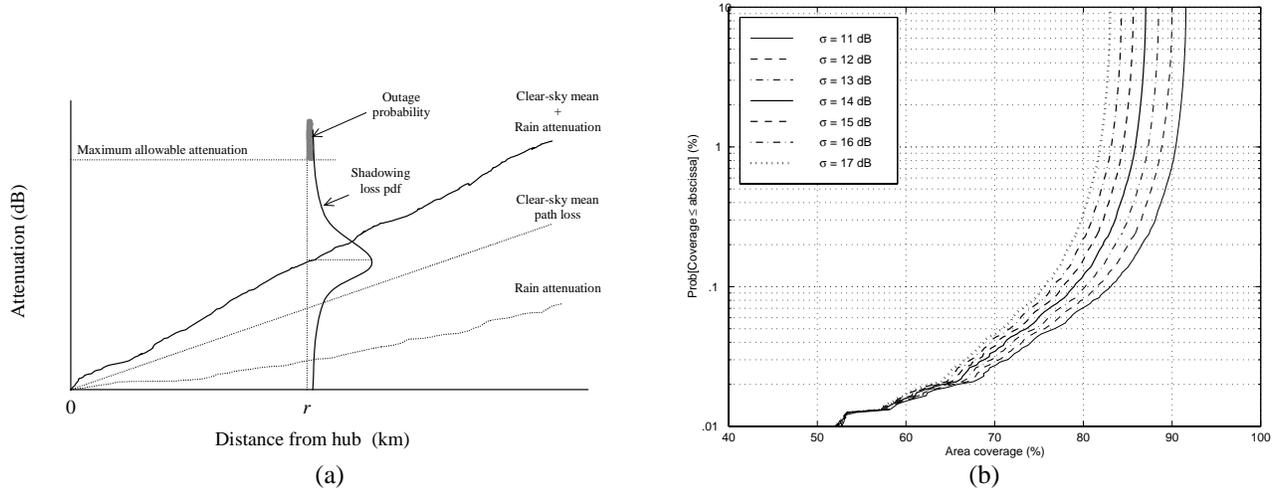


Fig. 1 (a) Computation of distance-dependent outage probability with lognormal shadowing and rain attenuation. (b) CDFs of coverage for  $\alpha = 4$ ,  $L = 2$  km and  $M = 10$  dB and various values for  $\sigma$ .

Hence, for this simulation, the single-link attenuations  $A_1$  and  $A_2$  were obtained as:

$$\begin{aligned} A_1 &= A_{1,\text{rain}} \\ A_2 &= A_{2,\text{rain}} + 20 \log_{10}(L_2/L_1), \quad L_2 \geq L_1 \end{aligned} \quad (3)$$

The attenuation  $A_d$  for the diversity system is the least of the two. Diversity gain was computed with respect to the statistics of attenuation  $A_1$  on the shorter link, referred to herein as the reference link. The CDFs acquired (not shown) indicate that: (1) diversity gain would be useful during rare events of heavy rain, (2) larger angular separation between the links gives higher gain, but the improvement is nonlinear, with only marginal gain when the separation angle increases beyond  $90^\circ$ , and (3) diversity gain diminishes when one link is longer than the other. When diversity gain for a given combination of lengths was averaged over various azimuth orientations of the reference link, it was found that on average the gain varies symmetrically around  $180^\circ$ . A typical result is shown in Fig. 2(a) constructed using data for two 2-km links at 0.1% probability on CDFs for rain attenuation. It also shows the range of  $\pm s$ , where  $s$  is the standard deviation of gain, and a curve in the form of  $G_{180^\circ} \sin^k(\theta/2)$ , with parameters  $G_{180^\circ}$  and  $k$  obtained by nonlinear curve fitting, which approximates well the average curve. Considering these, a model having the general form

$$G(\theta, p) = G_{180^\circ}(p) \sin^{k(p)}(\theta/2), \quad 0^\circ < \theta < 360^\circ \quad (4)$$

was proposed in [2] for cell-site diversity gain, where  $G(\theta, p)$  is the diversity gain obtained for angular separation  $\theta$  at fading time percentage  $p\%$ , with parameters  $G_{180^\circ}(p)$  and  $k(p)$  varying for different combinations of link lengths. This model was fit through non-linear regression to values calculated from simulations with the reference link azimuth ranging from  $0^\circ$  to  $330^\circ$  with  $30^\circ$  spacing. Values of  $G_{180^\circ}$  and  $k$  for various combinations of link lengths and percentages of time are presented in [2]. It was found that generally, arrangements of two links with equal length ( $L_1 = L_2$ ) produce  $k$  approximately 0.5, whereas two links of unequal lengths ( $L_1 < L_2$ ) yield  $k$  around one. It was also found that  $L_1/L_2 \geq 0.75$  is necessary to prevent the difference in path loss from dominating over the advantage of diversity, at least for links with lengths between 1 km and 4 km. The link length should be at least 2 km in order for  $G_{180^\circ}$  to become significant (2 dB for a reliability of 99.9%).

The set of criteria that was recommended for use in determining if a subscriber station might benefit from cell-site diversity includes: (i) the two hubs must involve links with approximately equal clear-sky attenuation, (ii) the distance ratio between the closer hub, at least 2 km from the subscriber, and the farther should not be less than 0.75, and (iii) the angular separation between the hubs should be as close as possible to  $180^\circ$ , but a separation as small as  $108^\circ$  is acceptable if a slight reduction in diversity gain from  $G_{180^\circ}$  is acceptable. When these criteria were applied in a cellular scenario consisting of 4-sectored rectangular cells with 4 corner hubs and a 20% reduction in diversity gain was considered acceptable, 32% of the service area concentrated near the borders of adjacent cells was found to benefit from cell-site diversity, as shown in Fig. 2(b).

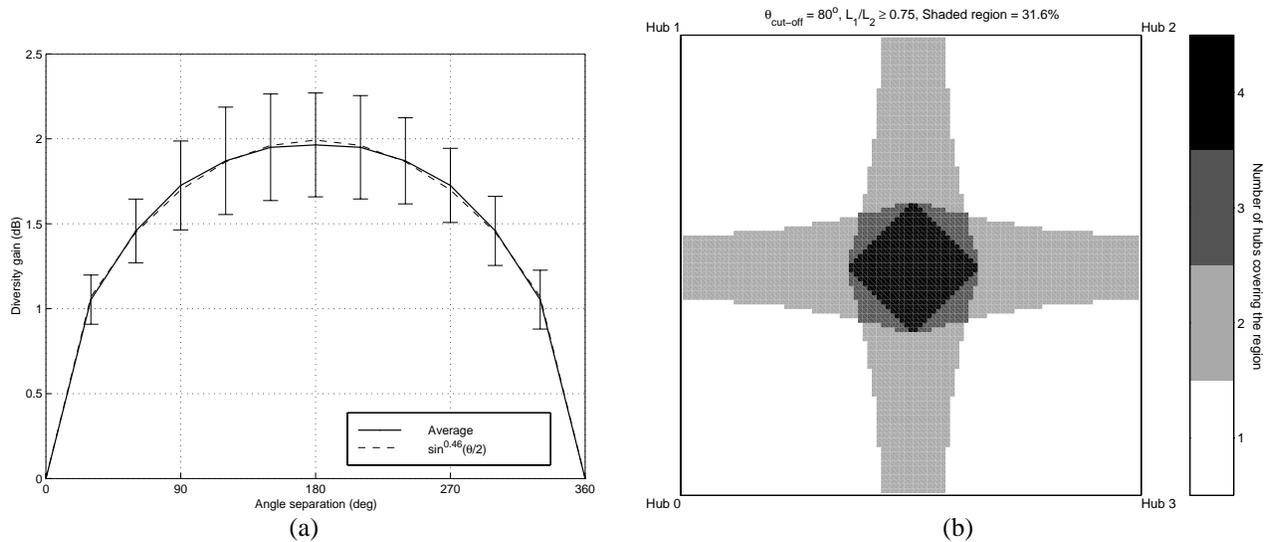


Fig. 2 (a) Average diversity gain from simulation results for two 2-km links at 99.9% reliability. (b) Areas that can benefit from cell-site diversity predicted by the model when a 20% reduction in diversity gain is acceptable.

## CONCLUSIONS

A study of cell coverage and cell-site diversity in 30 GHz cellular systems using radar data has been described. For the coverage analysis, the emphasis of the contribution is on the consideration of lognormal shadowing loss, in addition to the impact of rain attenuation. The diversity study results in a prediction model that well approximates the azimuthally averaged diversity gain and accounts for combinations of links with different lengths. Cell-site diversity was found to be most beneficial for subscribers near the border between two cells.

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