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Radio Propagation Measurementsand Path Loss Formulas for Microcellular Systems

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요 약

본 논문에서는 현재까지 셀룰라 서비스와 PCS서비스를 위해 얻어진 전파전파 측정에 대한 전체적인 요약을 하였다. 이렇게 얻어진 협대역신호 기반의 측정치와 광대역 신호에 의한 이동통신 채널 측정에 대해 고찰을 한 후 미국 캘리포니아의 오클랜드시에서 얻어진 측정치를 이용하여 불규칙한 높이의 건물로 이뤄진 도시 환경에서 쓰일 수 있는 마이크로셀용 신호 감쇄 예측 공식을 만들고, 이를 균일한 높이의 건물로 이뤄진 환경에서 얻은 신호 감쇄 예측 공식과 비교하였다.

Keyword: Path loss formula, Microcell measurements, Macrocell measurements, Non-uniform height environment

ABSTRACT

In this paper, we will provide a comprehensive review of radio propagation measurements conducted to date for mobile radio systems at frequency bands used for cellular and personal communications services in microcellular systems. Path-loss results were measured by using narrowband signal and multipath propagations were characterized by wideband measurements. This paper includes unpublished empirical path loss formulas for Oakland city of non-uniform building heights, and presents a comparison with path loss formulas obtained from typical low-rise building environments in order to discuss street grid dependence on route-specific building profile. We will also compare some empirical models developed based on the measurements with a few well-established theoretical prediction models.

I. Overview

As the demand for cellular mobile services dramatically increases in the recent years, microcells have been deployed in dense areas and inside buildings to increase capacity and to provide indoor coverage. To cope with microcells deployments, measurements have been carried out for small cells with low base station antennas. When the base station antenna is about the same height or even below the surrounding buildings, the dependence of radio signals on street orientation and building heights becomes even more significant. Therefore microcellular measurements usually involve street configuration andbuilding structure in addition to terrain profile and morphology. The microcellular measurements were commonly conducted along line-of-sight (LOS) path and/or non-LOS routes. The measurement results for non-LOS routes can be used to study the complex diffraction mechanism associated with propagation over rooftops or around building corners.

Measurements reviewed in this paper are classified into two categories: path-loss measurements using typical narrowband CW signal and multipath characteristics measurements employing wideband pulse signal. Following the review of radio propagation measurements made to date, we will comp

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are path loss formulas from Oakland city of non-uniform building heights with those from areas of uniform building heights and discuss how the street grid dependence is changed due to specific building profile. Furthermore, a comparison of some empirical models developed based on the measurements with a few well-established theoretical models is presented.

II. Microcellular Measurements

As compared to the macrocellular measurements, the microcellular measurements exhibit more diversified propagation characteristics due to relativelylow base station antenna placed on rooftop or lamppost.

A. Path-loss measurements

It was found by Harley in short-range path-loss measurements made in Melbourne, Australia[1] that there is a turning (break) point associated with signal variation in LOS path. However, he did not specify how to calculate the break point distance. Due to the presence ofdirect path between base station and mobile station, path-loss for LOS path is typically less than that for non-LOS paths. Measurement results obtained by Whitteker[2] and Chia et al.[3] showed that there is a difference of about 20 dB between the path-loss measured along LOS path and that measured in the route just turning around the corner, which is significantly more severe than that observed by Black and Reudink[4] in the macrocellular environments. In some dense urban environments having buildings aligned along streets, the break point is found to be pushed forward beyond the theoretical location due to waveguide effects, as observed by Rustako et al. [5].

More comprehensive propagation measurements involving LOS path and a variety of non-LOS paths were conducted by Xia et al. in San Francisco Bay Area[6-7]. The measurements were made to characterize microcellular radio signal variation in the cellular and PCS frequency bands (900 and 1900 MHz). In the measurements, the base station antenna was placed at heights hb of 3.2 m, 8.7 m and 13.4 m while the mobile antenna height hr was fixed at 1.6 m. The propagation mechanism associated with LOS paths were discussed in details in [6] using the LOS measurement results obtained in various urban, suburban, and rural areas. The Sunset District and the Mission District of San Francisco, which have attached buildings of quasi-uniform height built on a rectangular street grid on flat terrain, were selected as typical low-rise environments for the measurements. Figure 1 shows the test routes used in the measurements with a transmitter located in the middle of a block in a street, which is part of a rectangular street grid.

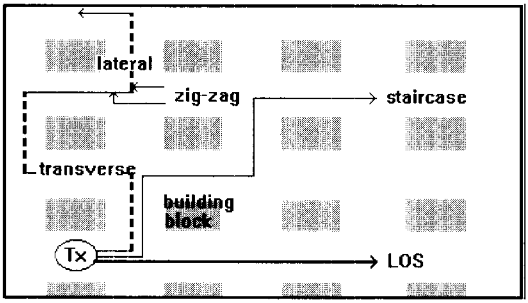


Figure 1 : Measurement test routes (adopted from [7])

Measurements were performed for radial distances up to 3 km. The zig-zag measurement results in [7] show that signal strength decreases10-20 dB as the mobile turned a corner from a perpendicular street into a parallel street. Therefore, the measurement results for the two different segments of the zig-zag path were treated as separate groups. On the parallel streets the propagation path is transverse to the rows of buildings. On the perpendicular streets the propagation path has a long lateral segment down the street. Signal strength on the staircase route showed continuous variation with distance traveled by the mobile, so that measurement results were treated as one group. Path-loss curves were then generated for the zig-zag and staircase groupings. These path-loss curves were later used by Har, Xia and Bertoni to establish empirical microcell models[8]. Difference in signal strength between parallel streets and perpendicular street s was also observed by Wagen in [9]. Measurements made along LOS streets and neighboring parallel streets in Dallas (US) are reported in [10]. Figure 2 shows a comparison of signal strengths obtained for the LOS path and the first parallel street. A constant gap of about 35 dB between LOS and parallel street measurements is shown in Figure 2 before the LOS break point.

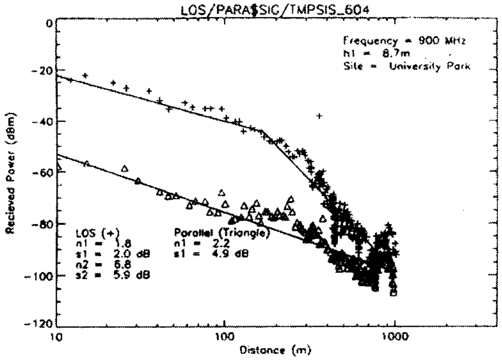


Figure 2: Received signal strength for LOS and parallel street measurements in University Park, Dallas (adopted from [10]).

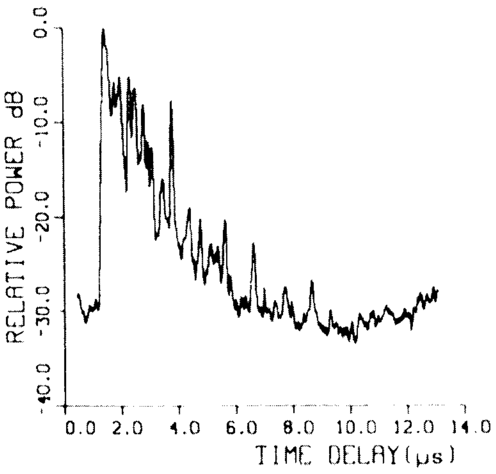
The gap becomes narrower after the break point distance at about 200 m and eventually vanishes at a distance of 1 km. Due to the anisotropic propagation characteristics as observed in the measurements, cell shape formed by radio signal contours in a dense building environments, as demonstrated in [8] and [11], is more closely approximated by a diamond rather than a regular hexagon.

Extensive radio propagation measurements in European cities were performed by many universities and institutions under the COST 231 program. Combined the COST 231 measurements with previously published theoretical model[12], COST 231-Walfisch-Ikegami model was developed for predicting radio signal propagation in different environments. The COST 231 measurement results were also used to validate the performance of other prediction models [13-15].

Effects of terrain variation on propagation in small urban cells are studied by Lampard and Vu-Dinh in [16]. Also, signal strength attenuation due to trees is estimated in [17-19]. Measurements made in a few specific environments such as tunnels or railways are reported in [20-24].

B. Multipath characteristics measurements

Microcellular propagation measurements reveal multipath characteristics significantly different from that observed in macrocellular measurements. Microcellular propagation measurements reveal multipath characteristics significantly different from that observed in macrocellular measurements. It was found by Bultitude and Bedal[25] in their multipath measurements at 910 MHz that the rms delay spread value of a microcell channel is only one quarter of that measured in a macrocell channel results[26]. In Figure 3, power delay profiles of macrocell channel and microcell channel are plotted. The rms delay spread is computed by using significant multipath components with power over a threshold of -25 dB with respect to the peak. Unlike the macrocellular measurement results, microcellular measurement results often demonstrates clear relationship between path-loss and rms delay spread. In their measurements made at 1.9 GHz in a suburban area of St. Louis (US), Devasirvatham et al.[27] observed that rms delay spread doubled, statistically, for every 19 dB increment of path loss over a distance range less than 600 m.



(a)

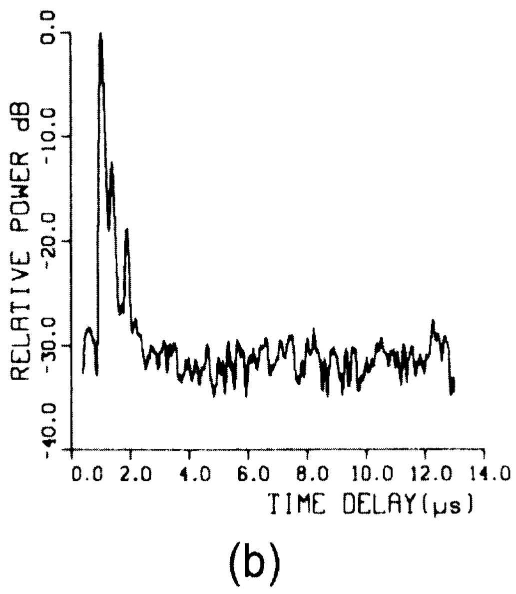


Figure 3 : Power delay profiles of (a) macrocell channel (adopted from [26]) and (b) microcell channel (adopted from [25]).

The measurements were conducted by employing a base station antenna at heights about the roof top level of two story houses and a mobile station at heights of 2~3 m. Similar relation between rms delay spread and path loss is shown in the microcell measurement results[28] for low base station antennas ranging from 3 to 13 m. An upper bound of rms delay spread as a function of path-loss is obtained in [28] by using the measurement results. It is expressed as **sd = exp[0.065*PL]**, where sd is the rms delay spread in nanoseconds and PL is the path loss in dB. With secured line-of-sight between transmitter and receiver located on tops of buildings, multipath measurements were made by Bartolom[29] at 1.9 GHz in an urban area of Madrid (Spain), which shows a rms delay spreadof 59.1, 54.9, 65.5 ns for antenna separation of 50, 150, 300 m, respectively. Mostly for smart antenna applications, angles of arrival for different multipaths were extensively measured in recent years. Some of the measurement results are published in [30-32].

Ⅲ. Path loss formulas

A. Comparison of path loss formulas

Empirical microcell models have been established based on some of the aforementioned microcellular measurements. Here we compare two of these empirical microcell models, i.e., the COST 231-Walfisch-Ikegami model[15] and the Har-Xia-Bertoni model[8] with two theoretical path-loss prediction models, the Walfisch-Bertoni model[33] and the Xia-Bertoni model[34]. The comparison is made for low-rise environments with relative base station antenna height Δh in a range of -5 m $< \Delta h <$ 5 m. The relative base station antenna height is measured over the average rooftop level of surrounding buildings. In Figure 4, we plot the path-loss, excluding the loss due to diffraction at the last rooftop adjacent to the receiver at street level, predicted by these models at a distance of 1 *km* for frequencies of 900 MHz and 1.9 GHz.

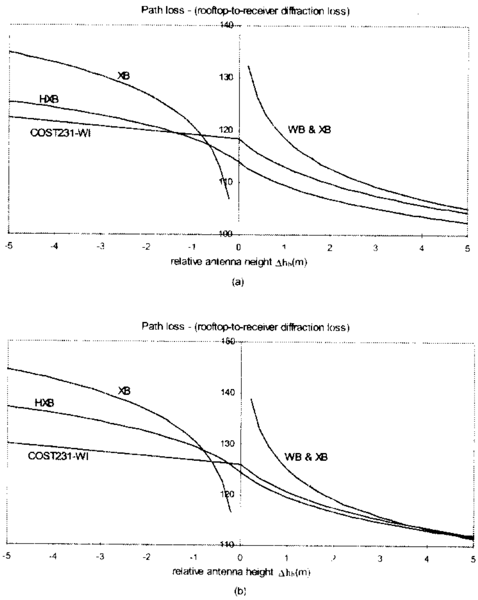


Figure 4: Comparison of path loss values excluding rooftop-to-receiver diffraction loss according to four path loss models for (a) 0.9 GHz and (b) 1.9 GHz. Relevant parameters are antenna separation R_k=1 *km*, average building height h_{BD}=8 *m*, average spacing of building row

d=50 *m*, distance between base station antenna and first building row r_H=50 *m* (only for XB model).

It seems that the theoretical models, Walfisch-Bertoni model and Xia-Beroni model, are slightly more pessimistic as compared to the empiricalmodels, COST231-Walfisch-Ikegami model and Har-Xia-Bertoni model. The singularity of Walfisch-Bertoni model and Xia-Bertoni model at Δh=0 m, i.e. base station antenna height is at the rooftop level, results from the unbounded value of multiple diffraction loss at rooftops.

In the foregoing discussion, prediction models were obtained for suburban/urban areas where the building height is relatively uniform. These formulas can be used for the environments where the dominant contribution of the received signal is given by the propagation over the surrounding rooftops. However, some urban environments consists of the buildings of non-uniform heights, in which different propagation characteristics are observed. As an example, downtown Oakland is composed of low to high buildings and shows somewhat different range dependence for each route. For this particular environment, we will attempt to derive site-specific formula and compare with the other formulas obtained from low-rise environments of relatively uniform building heights.

B. Path loss formulas for non-uniform building height area

In [8], the empirical path loss formulas for low-rise environments of quasi-unifrom building heights, such as Sunset and Mission districts where the formulas were obtained, are given by

Staircase route:

$$PL(R_k)=[137.61+35.16\log f_G]+[12.48+4.16\log f_G]\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)+[39.46-4.13\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)]\log R_k \qquad (1)$$

Transverse route:

$$PL(R_k)=[139.01+42.59\log f_G]+[14.97+4.99\log f_G]\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)+[40.67-4.57\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)]\log R_k \qquad (2)$$

Lateral route:

$$PL(R_k)=[127.39+31.63\log f_G]+[13.05+4.35\log f_G]\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)+[29.18-6.70\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)]\log R_K \qquad (3)$$

where

$$\mathrm{sgn}(x)=\begin{cases}+1 & x>0\\ -1 & otherwise\end{cases}$$

and $\Delta h=h_b-h_{BD}$ (h_b = antenna height measured from ground level, h_{BD}= average building height measured from ground level), f_G=frequency in GHz, R_k=antenna separation in *km*.

As is shown by eq.(1)-(3) first constant of each formula correspnds to path loss at 1 *km* for 1 GHz with Δh=0 *m*. Based on the first constants, lateral route show very different values of path loss. This disparity between lateral route and staircase or transverse route is also observed in other areas of relatively uniform building heights. It was pointed in [8] that large segment length on ray path between the nearest rooftop from a receiver and the receiver can be regarded as the principal cause for the small path loss related with lateral route.

The average building height of Oakland city was computed using a report which contained the number of stories of each building in this area. Antenna height used for measurements at 876 MHz, 1937 MHz were 3.2 *m*, 8.7 *m* and 13.4 *m*. Most buildings are lower than 5-story height while a few higher buildings are mixed in. Average building height was calculated as 12 *m*, the height between those of 3 and 4 stories. The average height of intervening buildings varied with each drive route. For transverse and lateral routes, most propagation paths are thought to be over the rooftops. In the staircase route, high-rise buildings located in the middle of the route cause the signal propagating over the rooftops to go around the building corners and subsequently produce large diffraction loss. However, for the whole area, we belie ve that propagation over the rooftop is the dominant process for most paths.

Since h_{BD} is 12 m, Δh= -8.8 m, -3.3 m and 1.4 m for the three base station antenna heights used. The non-LOS path loss formulas fit to the routes shown in Figure 1, by using the intercepts at 1 km and slope indexes, are found to be:

Staircase Route:

$$PL(R_k)=[140.14+32.13\log f_G]+[7.38+2.46\log f_G]\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)+[45.01-5.20\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)]\log R_k \tag{4}$$

Transverse Route

$$PL(R_k)=[128.23+39.97\log f_G]+[6.33+2.21\log f_G]\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)+[30.38-2.31\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)]\log R_k \tag{5}$$

Lateral Route

$$PL(R_k)=[126.68+42.13\log f_G]+[5.01+1.67\log f_G]\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)+[33.67-2.81\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)]\log R_k \tag{6}$$

Since the path loss values for the transverse and lateral routes are close to each other, the path loss on these two routes can be predicted by a combined zig-zag route formula given by

Zig-zag route

$$PL(R_k)=[127.46+41.05\log f_G]+[5.67+1.94\log f_G]\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)+[32.02-2.56\,\mathrm{sgn}(\Delta h)\log(1+|\Delta h|)]\log R_k \tag{7}$$

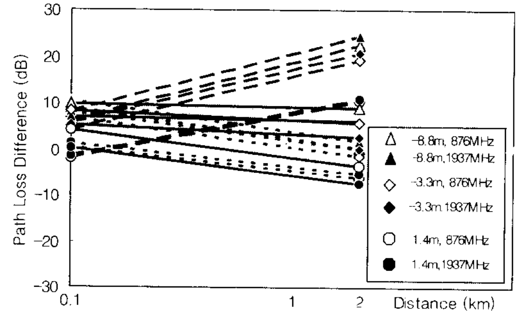
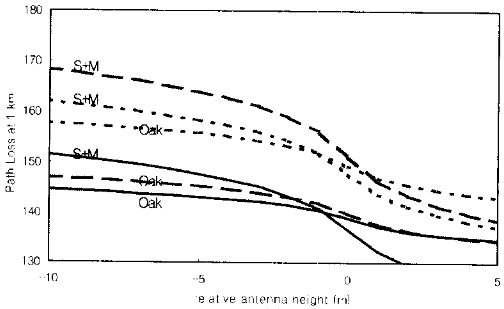


Figure 5: Path loss difference between the path loss formulas of eq.(1)-(3) and staircase (dotted lines), transverse (dashed lines) and lateral (solid lines) routes measurements obtained in downtown Oakland. Path loss of the transverse route is overestimated by the formula in eq. (2).

Figure 5 shows the prediction errors with three different antenna heights and two different frequencies when the individual formulas in eq.(1)-(3) are used for each route. Due to the scattering by tall buildings on staircase routes, the path loss on transverse route is overestimated by eq.(2). Except for the case of the transverse route, the formulas estimate the values of the path loss for the various routes with reasonable accuracy. The formulas fit to this environment are shown as the continuous curves in Figure 6. For a pictorial comparison, variation of intercepts and slope indexes based on eq.(1)-(3) is also illustrated in Figure 6.

It is seen in Figure 6(a) that street grid dependence observed in Sunset and Mission districts no longer holds in downtown Oakland, as observed from close path loss intercept values of transverse route and lateral route. Also it is noted that antenna height dependence in downtown Oakland is reduced, since the range of path loss variation with 10 m < Δh < 5 m is smaller than that ofSunset and Mission districts. This also suggests that variation of path loss due to diffraction process around building edges to a receiver on staircase route and variation of power contribution due to scattering to receivers on transverse and lateral routes are less sensitive to antenna height as compared to that based on over-the rooftop propagation.



(a)

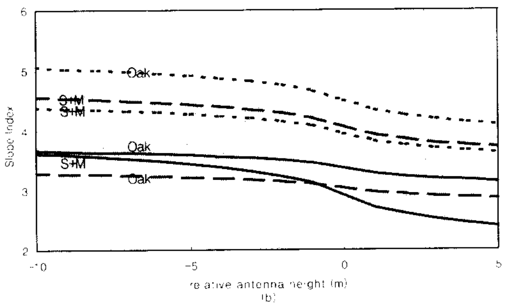


Figure 6: (a) Intercepts, (b) slope indexes and their fit lines of 1937MHz for staircase (dotted lines), transverse (dashed lines) and lateral (solid lines) routes. Fit lines associated with symbol "S+M" correspond to those of Sunset and Mission districts while symbol "Oak" indicates fit lines for downtown Oakland measurements.

For a receiver on non-LOS routes, each path to a receiver crosses rooftops that are typically represented by the edges ofabsorbing half screens oriented perpendicular to the direction of ray path and located at the middle of the buildings[8]. Due to the insensitivity to irregularities in the building spacing along the ray path, path loss for base station antenna heights near to the rooftops can be obtained with average building spacing[34]. It was shown in [8] that path loss varies as 20 log(M), where M is the number of intervening buildings, so that path loss is not strongly dependent on number of buildings when M is large. Moreover, distance between a receiver and the last rooftop on ray path of transverse route is close to that associated with staircase route. Therefore, for a given distance, individual path loss components, free space loss, multiple screen forward diffraction loss and diffraction loss at the last rooftop should show identical or close values with both routes.

Suppose the tall buildings are located at the same distances from the base station and are mixed in on transverse route instead of staircase route. Diffraction at building edges and scattering by building surfaces will affect the path loss of receivers on staircase route, as observed with transverse routes when they are on staircase route. Influence of these buildings on received signal level in dB scale associated with lateral route might be less significant due to higher received signal level. The boosted signal level on staircase route may result in diminished path loss difference denoted in dB scale, depending on the level of contribution from scattered and/or diffracted signals, between staircase route and lateral route while diffraction loss because of the buildings causes large path loss of receivers on transverse route. This argument can be extended further with arbitrarily located and more uniformly distributed tall buildings on non-LOS routes. Tall buildings on staircase route will affect path loss associated with transverse route whereas those on transverse route will have an influence on that corresponding to staircase route, suchthat it is expected street grid dependence of path loss in non-uniform building heights is getting more deviated with a few and more uniformly distributed tall buildings from that observed in areas of quasi-uniform building heights.

Ⅳ. Conclusions

In this paper, a comprehensive review of outdoor microcell measurements, path loss formulas derived for low-rise areas of non-uniform building heights and a discussion on street grid dependnece with a few tall buildings existing in non-LOS routes were presented. We have attempted to establish empirical path loss formulas for downtown Oakland. The areas pertinent to the scope of this paper are where over-the-rooftop propagation is the dominant process, which naturally precludes the application for high-rise urban core with low base station antenna. It is expected that transverse route formula obtained from downtown Oakland can be used in other areas of non-uniform building heights when a few tall buildings are located on staircase route. Similar path loss decrease associated with staircase route might be observed when a few tall buildings are located on transverse route instead of staircase route. In general, street grid dependence, which was clearly observed with low-ri se areas of relatively uniform building heights, is expected to be significantly reduced with a few tall buildings located on a particular or various type of non-LOS routes.

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