The Post-Processing Resolution Required for Accurate RF Coverage Validation and Prediction

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Abstract -- **With the trend of cellular providers shifting to higher frequencies, there is an increasing migration to smaller cells that is further driven by the growing demand for wireless Internet service. This obviously calls for higher resolution Radio Frequency (RF) validation and prediction. Yet, to our knowledge, there has been no study as to what resolution is required for accurate RF modeling and prediction. Many of today's computer prediction tools can provide estimates of RF signal strength at arbitrary spatial resolution. However, the choice of this resolution is often left up to the discretion of the user. Even worse, sometimes the prediction resolution is hard-coded to be the same as that of the terrain data base. Choosing a resolution bin size that is too small is both computationally inefficient and unnecessarily wasteful of valuable memory resources. Choosing a resolution bin size that is too coarse introduces ubiquitous uncertainty about the quality of RF coverage. This paper investigates the spatial quantization noise requirements of RF prediction and RF coverage validation. It is found that the minimum resolution bin size required to mitigate spatial quantization noise effects is about one fortieth of the cell radius.**

I. INTRODUCTION

PERHAPS the best introduction to this topic is by way of a much more familiar example found in speech processing. Without companding, speech encoders require about 12 bits since the dynamic range of most speech is about 70 dB. For unsigned sample values, this yields 4096 (=2^{12}) different quantum levels. Thus, speech signals that are encoded with 12 bit A/D converters are imperceptibly degraded by quantization noise.

An extreme example of how quantization noise can affect an RF design is given in Figure 1. As shown in Figure 1(a), what we are asking in this paper is: "What is the quantization noise level of large scale Radio Frequency (RF) prediction and coverage validation?" Alternatively, we wish to know what spatial resolution is required before our estimates of RF coverage are imperceptibly degraded. Note that though there could be significant variation of the signal strength from one sample to another, we are only interested in the large scale path loss model and, hence, we present the following example.

Suppose the resolution bin size, Δx, is set equal to the diameter, $2R$, of the cell (In practice, one would never do this; this is only an example to demonstrate the effect). As illustrated in Figure 1(b), it is impossible to determine the full extent of RF coverage since model tuning requires more than one sample. In Figure 1(c) the bin size is reduced to be equal to the cell radius, R. As illustrated in Figure 1(d), making the bin size smaller improves the estimate of the extent of RF coverage by improving the accuracy of the tuned prediction model.

II. BACKGROUND

In reference [6] the requirements for accurately estimating the radius of a cell were characterized under the assumption of a

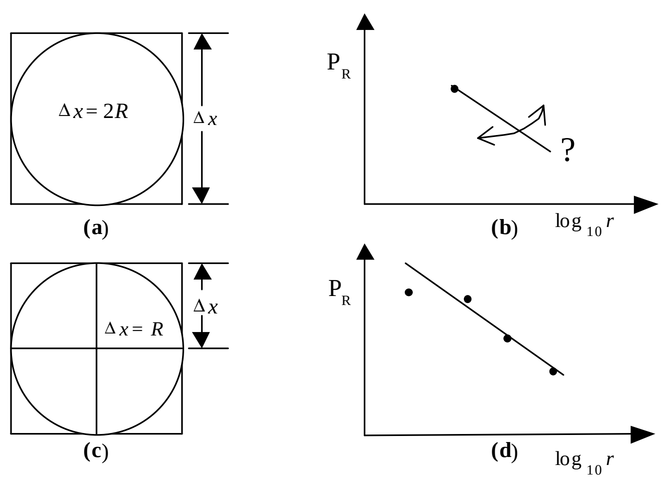

Figure 1. Extreme example of sampling resolution and quantization noise in RF design: (a) The sampling resolution, Δx, is equal to the diameter of the cell (one sample) **(b)** For this case, it is impossible to estimate path loss as a function of range since there is only one signal strength sample **(c)** The sampling resolution is reduced to equal the cell radius (four samples) **(d)** A slightly better estimate of path loss can be made since there are more (four) strength samples than for the first example.

linear path loss and uncorrelated lognormal shadowing (worst case shadowing). It was shown that the cell radius is a much better metric of RF coverage than estimating area reliability. For the past 25 years, area reliability has been considered the most important metric of RF coverage [2]. The cell radius that results from prediction model tuning is another common method of estimating RF coverage [1]. In reference [6] it was discovered that these two measures cannot be treated

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separately and that cell radius estimation is a much more critical step in the RF validation process. It was shown that area reliability and cell radius are an equation pair which jointly describe the reliability of cellular coverage. It is impossible to measure an area reliability without specifying a cell radius. Alternatively, it is impossible to measure a cell radius without also specifying an area(/edge) reliability. The results of this analysis showed that it takes 50 times as many independent signal strength samples to estimate the cell radius as it does to estimate the area reliability. Thus, estimating the cell radius is the limiting factor in determining the reliability of RF coverage. It was recommended that radio survey analyses select cell radius estimation as the preferred method of the coverage validation.

Although the following discussion is primarily concerned with omni cell networks, the conclusions are easily extended to include sectored cells. The signal strength measurements are inverse filtered and averaged to remove the anisotropic weighting introduced by the horizontal antenna pattern since we seek to characterize the propagation effects of the environment (terrain and clutter), not of the antenna [3].

It has long been known that the equal power contours of real cells can be highly irregular due to terrain and clutter shadowing effects. The focus on predicting these irregularities has been so extreme that there is now an overwhelmingly popular belief that there is little or no value in considering a real world cell as a regular shape (e.g., circular, hexagonal, etc.), except perhaps only at the highest level of initial network design. The following quote supports this point [7]:

> *"Some otherwise perfectly intelligent people are convinced that… the more irregular the contour, the more accurately it describes the limits of coverage. Therefore my admonition:* ***Never draw circular contours****"*

The prevailing wisdom is that more information is always better, and this seems to be regardless of whether the information is correct or even necessary. In this view, the network engineer is like a stone mason mortising together irregular shaped cells to build a contiguous wall of RF coverage.

However, unlike the mason who gets to search through dozens of stones to find the shape that fits, the network designer is constrained to accept whatever irregular cell shape that the adjacent propagation environment dictates. Because of this, it is nearly impossible to exploit the irregularities of individual cell boundaries in a network design.

The goal of the network engineer is to determine the ***average*** extent of reliable coverage and the position of the next base station in the network. We contend that this decision must be viewed as an inherently lowpass process, having little or nothing to do with the high (spatial) frequency irregularities of cell boundaries. We argue that the majority of the degradations from these irregularities must be absorbed by

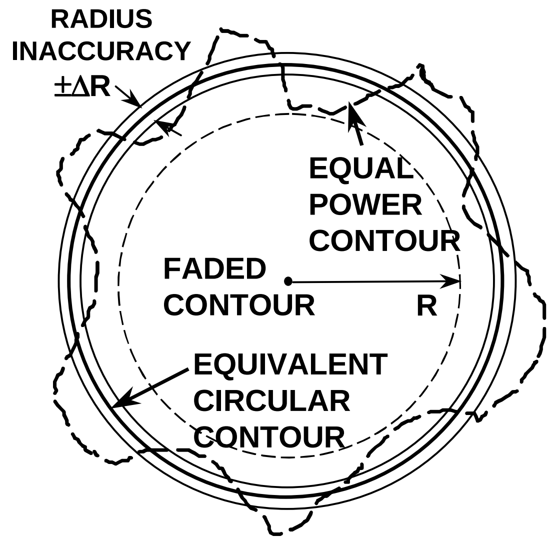

Figure 2. Effective radius of a cell. The measurement approach computes the best circular approximation to the equal power contour. The effective radius, R, of the cell is measured and the accuracy quantified in terms of a radius inaccuracy ring, $\pm\Delta R$. The average signal strength on the circular contour is equal to the signal strength of the equal power contour. The radius (faded contour, dashed circle) is computed by subtracting the fade margin from the radius of 50% cell edge reliability.

the fade margin in the design as shown in Figure 2 (see the faded circular contour).

For all of the above reasons, we have proposed estimating the "effective radius" of a cell as an alternative to the current coverage validation approaches [4][5]. The proposed method estimates the best circular boundary that matches the cell edge at the desired area reliability, as illustrated in Figure 2. It should be emphasized that this approach does not in any way require that the true cell edge be circular. Rather, even the most irregular cell edge can be fitted with a circle such that the average power along the circumference is equal to the power of the true cell edge. This circle encloses the area over which the RF signal meets or exceeds the desired area reliability (e.g., over 90% of the area, the signal power is above -90 dBm). It is the radius of this fitted circle that is estimated. Thus, this radius can be considered the "effective radius" of the cell and is well defined for any cell, circular or otherwise.

The accuracy of the cell radius estimate is quantified in terms of a radius inaccuracy ring, $\pm\Delta R$, also shown in Figure 2, where the dimension of ΔR is expressed in units of distance. The width of this ring depends mostly on the number of signal strength samples in the regression, and also upon the amount of lognormal fading in the cell.
Provided the error of the cell radius estimate, δ_R, is less than 50%, it can be approximated with a simple empirical expression [6]

$$\delta_R = \frac{\Delta R}{R} \approx \frac{3.821\sigma + 4.619}{N} \qquad (1)$$

where

δ_R is the relative error of the cell radius estimate (%)

ΔR is the absolute error of the cell radius estimate (meters)

R is the cell radius (meters)

σ is the standard deviation of the lognormal shadowing (dB)

N is the number of independent signal strength samples.

Here δ_R is chosen according to the following two-sided 95% confidence interval

$$P\left(1-\delta_R \le \frac{\hat{R}}{R} \le 1+\delta_R\right) = 95\% \qquad (2)$$

where $\hat{R}$ is the estimate of the cell radius (meters).

The dependence of the accuracy of coverage estimation, δ_R, on the standard deviation of the lognormal shadowing, σ ,of the terrain and clutter is clear in equation (1). However, the effect of terrain is greatly reduced if a large number of independent signal strength measurements, N, are taken. For example, if N=5000 samples and $6 \le \sigma \le 10$, the simulations in reference [6] showed that δ_R was between 2% and 3%. There is little value in increasing the number of independent samples much beyond 5000 since this provides less than a 3% improvement in the cell radius estimate. At this point there is almost no relationship between the resolution required to describe the terrain and the resolution required for accurate coverage estimation. Thus, the dynamic range requirements of RF prediction and coverage validation are similar to that of the speech processing in that they require about 12 bits since $5000 \approx 2^{12.3}$.

III. UNIFORM SPATIAL SAMPLING APPROACH

We recommend that all the signal strength measurements be averaged in distance with a window that is at least 40λ in length [3].

From the previous section, 5000 independent signal strength samples are all that is needed to accurately characterize the path loss within a cell. An important question is: "How should these samples be distributed within the cell?" Since we are trying to estimate the cell radius, samples at the cell edge are more useful than samples under the base station. Hence, we choose the arbitrary but reasonable sampling strategy illustrated in Figure 3.

We wish to sample a region equal to the area of the cell. However, the measurements within half of the cell radius of the base station are excluded (i.e., the inner 25% of the cell area). For typical wireless designs, less than 1% of the outages are contained within this area, so this data contributes very little to the cell radius estimate. An additional 25% of the cell area is sampled beyond the cell radius. Thus, the total sampled area is still πR^2.

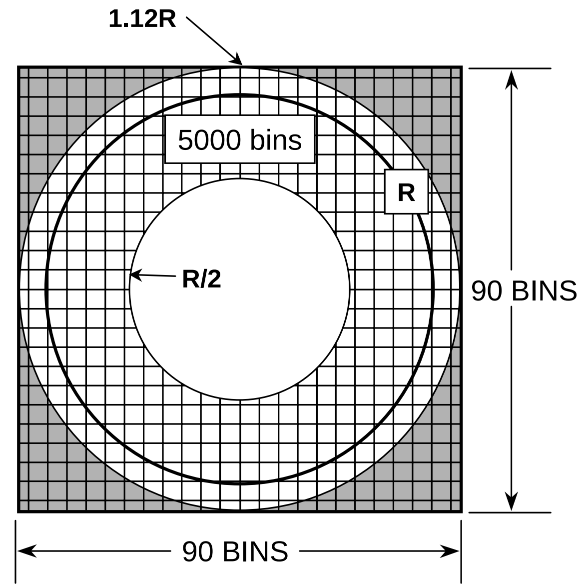

Figure 3. Uniform spatial sampling approach for estimating RF coverage. The inner 25% of the cell area is excluded and an additional 25% of the area is sampled beyond the cell radius. The annulus is enclosed by a bounding square of 90 bins and subdivided into 5000 bins of equal size.

Let the resolution bins be square and of size ΔxXΔx. The minimum resolution bin size, Δx, can now be easily calculated since $$\frac{\pi R^2}{\Delta x^2} \approx 5000$$

which yields $$\Delta x \approx R/40 \qquad (3)$$

As shown in reference [3], Δx must also be greater than about forty wavelengths of the carrier frequency.

Table 1 shows the bin sizes that are required for several typical cell radii. To reduce the effects of spatial quantization, the resolution bin must be reduced in proportion to any reduction in the cell radius.

Cell radius R (m)	1000	2000	3000	4000	6000	8000
Bin Size Δx (m)	25	50	75	100	150	200

Table 1. The minimum bin sizes required to virtually eliminate quantization noise effects for several cell radii.

Thus, equation (3) demonstrates that to avoid spatial quantization errors in RF coverage validation and prediction, the resolution bin size must be at least one fortieth of the cell radius. There is no need to make the bin size any smaller.

Note, for example, that 100 meter resolution is insufficient for cell radii less than 4 km (most urban cells). For urban and dense urban designs, coverage predictions (and model tuning) with

100 meter resolution will be unsatisfactorily corrupted with quantization error.

IV. QUANTIZATION NOISE IN TERMS OF CELL RADIUS UNCERTAINTY

In this section the quantization noise level is represented in terms of an equivalent error in the cell radius estimate. We begin by assuming that if all 5000 bins in Figure 3 are driven, then 100% of the cell area has been sampled (i.e., we will ignore any reduction in error below 3%). Likewise, 50 bins corresponds to 1% of the cell area and 500 bins corresponds to 10%. Let p be the percentage (decimal, $0.02 < p \le 1$) of the cell that has been driven. Then from equation (1) and (3), it is easy to show that provided $\delta_R < 50\%$, the error of the cell radius estimate is given by

$$\delta_R \approx \begin{cases} \dfrac{3.821\sigma + 4.619}{p(5000)\left(R/(40\Delta x)\right)^2} & \text{for } R < 40\Delta x \\ \dfrac{3.821\sigma + 4.619}{p(5000)} & \text{for } R \ge 40\Delta x \end{cases} \tag{4}$$

The above equations can be used to define the quantization noise level and are plotted in Figure 4 for p=0.10 and σ=8 dB. The meaning of the curves in this figure is easily understood by tracing one curve. Observe from equation (4) that $\delta_R(p,\sigma) \approx 7\%$, provided the resolution bin size is sufficiently small (i.e., $R \ge 40\Delta x$). For Δx=100m, this is true provided $R \ge 4\,\text{km}$. However, note that as the cell radius is decreased below 4 km, the cell radius error increases rapidly. This increase is solely due to quantization error. For example, if R=2 km and Δx=100m, then $\delta_R(p,\sigma) \approx 28\%$. In other words, the quantization noise accounts for an additional 21% (=28-7) error in the cell radius estimate.

Let $K(p,\sigma)$ be the component of the cell radius error that is solely due to drive testing only p% of the cell area, where

$$K(p,\sigma) = \frac{3.821\sigma + 4.619}{p(5000)} \tag{5}$$

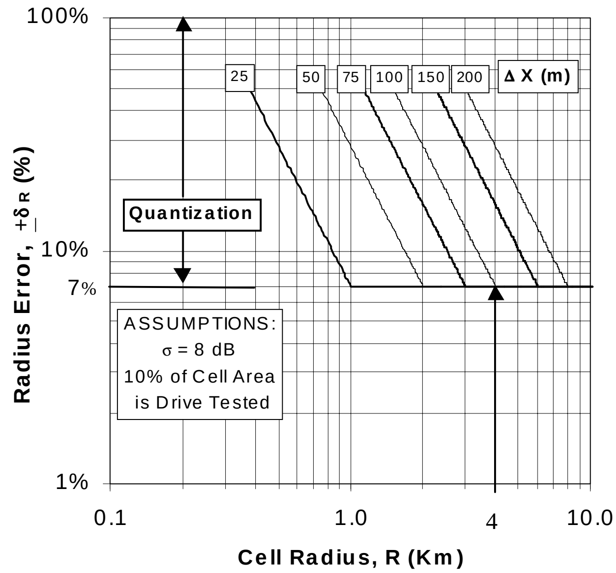

Figure 4. Quantization noise effects of various bin sizes. The effect of bin size (the parameter associated with each curve) in terms of the error of the cell radius estimate (ordinate) as a function of cell radius (abscissa).

The error of the cell radius estimate can be expressed as

$$\delta_R = \delta_Q + K(p,\sigma) \tag{6}$$

where δ_Q is the component due to quantization noise.

For the example given in Figure 4, $K(p,\sigma) \approx$ 7%, p=10% and $\sigma = 8$ dB.

Provided $\delta_R < 0.5$, the quantization noise component can be written as

$$\delta_Q \approx \begin{cases} K(p,\sigma)\left[\left(\dfrac{40\Delta x}{R}\right)^2 - 1\right] & \text{for } R < 40\Delta x \\ 0 & \text{for } R \ge 40\Delta x \end{cases} \tag{7}$$

where δ_Q can be interpreted as a percentage increase in cell radius error that is due to quantization noise.

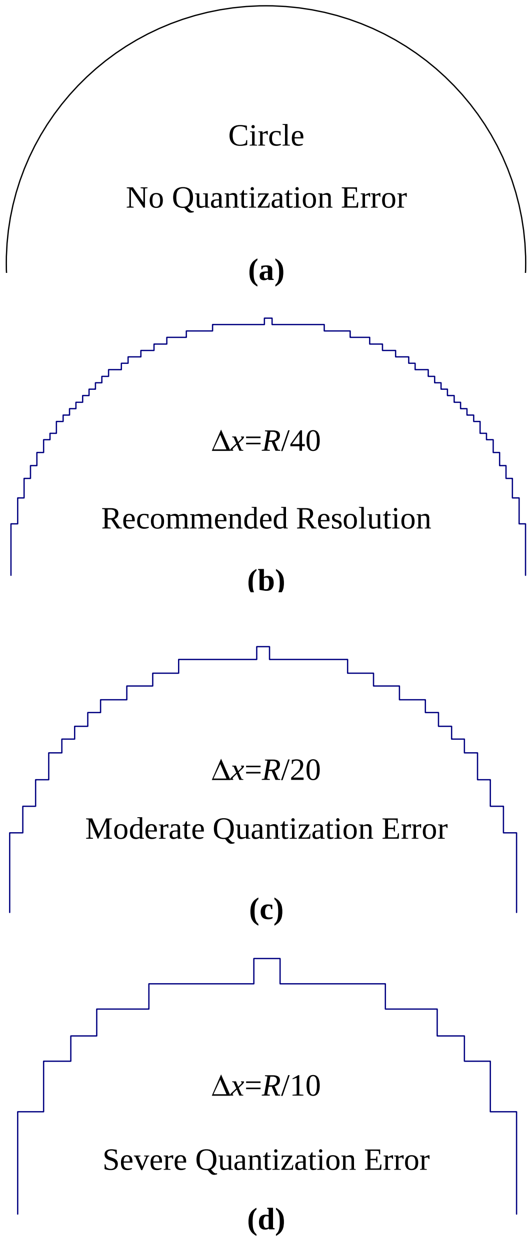

Figure 5. Quantization along the perimeter of a circle for several bin sizes, Δx. (a) No quantization noise, continuous case; **(b)** quantization noise for the recommended sampling resolution ($\Delta x = R/40$); **(c)** moderate quantization error ($\Delta x = R/20$); **(d)** severe quantization error ($\Delta x = R/10$). The accuracy of RF coverage prediction for the resolutions in **(c)** and **(d)** is limited by quantization error.

Thus, if $R < 40\Delta x$, the quantization noise is the product of two independent components. The first term, $K(p,\sigma)$, describes the completeness of the drive test sampling process. The second term describes the effect of changing the post processing resolution. The latter term grows inversely with the square of the radius and directly with the square of the resolution bin size. This term demonstrates the ubiquitous degradation due to coarse binning. Notice that if the post processing resolution is too coarse, no amount of additional drive testing will improve the cell radius estimate.

Figure 5 shows the perimeter of a circle quantized at three different resolutions. Figure 5(a) is the original circle. In Figure 5(b) the circle is quantized at the recommended resolution ($\Delta x = R/40$). There is little improvement in the accuracy of coverage prediction and validation at higher resolutions. However, the accuracy of RF prediction and validation for both of the cases in Figure 5(c) and Figure 5(d) will be significantly limited by quantization noise.

The effect of processing the drive test of a typical cell at different resolutions is shown in Figure 6. The cell radius is R=4 km and the roads cover about 8.5% of the total area of the cell. Figure 6(a) shows the roads at full resolution (no quantization). In Figure 6(b) the drive route is quantized at the recommended resolution ($\Delta x = R/40$). There is little improvement in the accuracy of coverage prediction and validation at resolutions higher than $R/40$. However, the accuracy of RF prediction and validation for both of the cases in Figure 6(c) and Figure 6(d) will be significantly limited by quantization noise. Many RF prediction tools provide floating-point estimates of signal strength. This level of accuracy is clearly unnecessary for the post-processing resolutions shown in Figure 6(c) and Figure 6(d).

V. DISCUSSION

The high data rates of 3G wireless networks, such as UMTS, require RF links that are significantly more reliable than the first and second generation voice-centric networks. One of the most important steps in ensuring this reliability is selecting the proper drive test resolution. We have shown that this resolution should be no coarser than one fortieth of the cell radius.

We have approximated the quantization noise due to coarse binning as a degradation in the estimate of the cell radius. Our main focus has been on how to avoid the quantization, rather than model it exactly.

Many complex adaptive interference control schemes have been proposed to reduce cochannel interference in cellular systems. We contend that precision design of static RF coverage is the most practical first step in improving the quality of service in today's wireless networks.

Numerous RF prediction planning tools are available that generate signal strength estimates at almost arbitrary resolution. However, even perfectly tuned prediction models are only correct in a "statistical" sense. That is, although these tools and models will predict the signal strength at a given position, if one actually drives to that position and makes measurements, they will most likely get a different value.

The measured value should be within the confidence interval of the statistical test (e.g., standard deviation of about ± 8 dB). Moreover, the accuracy of such tools is not necessarily improved by simply purchasing higher resolution terrain and clutter databases.

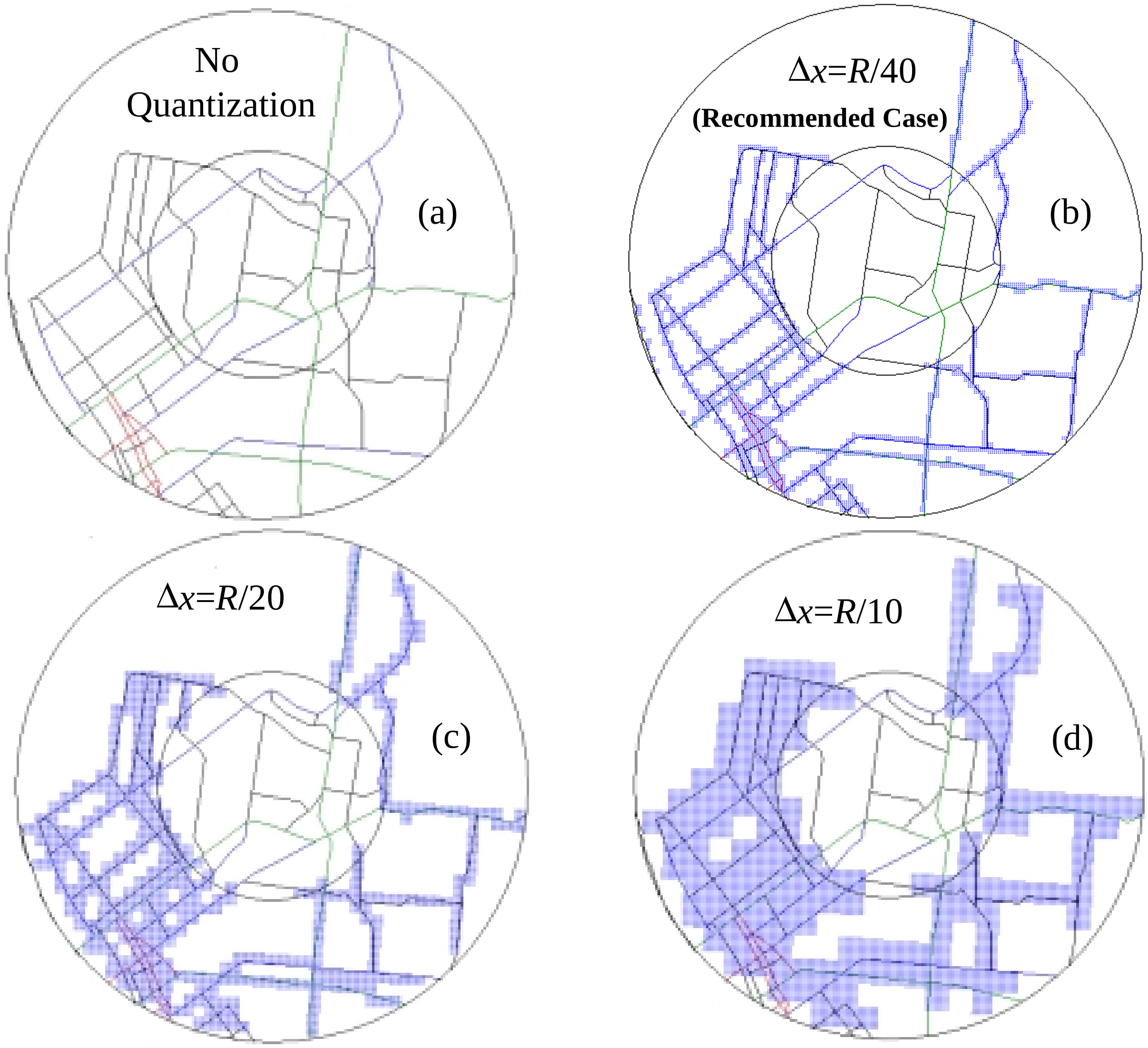

Figure 6. Drive test routes sampled at different post-processing resolutions (a) continuous case; **(b)** the recommended post-processing sampling resolution ($\Delta x = R/40$); **(c)** moderate post-processing quantization error ($\Delta x = R/20$); **(d)** severe post-processing quantization error ($\Delta x = R/10$). The accuracy of RF coverage validation and prediction for the resolutions in **(c)** and **(d)** is greatly limited by quantization.

In current wireless networks it is the root mean square (RMS) value, σ, of the terrain and clutter shadowing that is important, not the knowledge of the exact positions of the outages. This value (σ) determines the fade margin and the reliability of service. This is because knowing the exact location of the outages obviously still does not mean they can be easily eliminated. With current antenna technology, the RF engineer has limited options in servicing areas of poor coverage. He is often forced to compromise to static adjustments of the power transmitted over a wide coverage area (entire cell or sector). The exact position of individual outages will become more important when the base stations can actively track mobile users and adaptively focus more or less energy in their direction.

Thus, RF coverage estimation for accurate wireless network design is not synonymous with, and does not require "pico-resolution." The benefits of high resolution must always be evaluated in terms of the additional system benefit and actual improvement in design accuracy. This is especially true since each factor of two increase in resolution increases the memory and processing requirements by about a factor of four. We have chosen the concepts of "effective cell radius" and spatial quantization noise to help determine the point of diminishing return in the resolution required for accurate RF coverage estimation.

Typically the RF signal strength variation at cellular frequencies within a bin of resolution size R/40 is less than 4 dB, which is small compared to the standard deviation of the lognormal shadowing which is typically 8 dB. Thus the RMS error introduced by this variation has little effect on the path loss mode, the cell radius and the area reliability estimate.

VI. CONCLUSIONS

The quantization noise requirements of RF prediction and coverage validation were analyzed based on the assumption of uncorrelated lognormal shadowing (worst case shadowing). The quantization error was represented as an equivalent error in the cell radius estimate. The minimum required quantization resolution is approximately $\Delta x = R/40$, where R is the cell radius. For coverage validation, this resolution can be interpreted as the point at which spatial sampling makes best use of the cellular drive test. Effectively, this is the point at which no drive test information is lost, no computer memory is wasted and no unnecessary prediction computations are executed. It should also be emphasized that the quantization resolution requirement for accurate prediction and validation is almost completely independent of the resolution of the terrain (and building) data base, and these resolutions should only rarely be equal. The results of this analysis indicate that the resolution requirements for accurate RF prediction and validation should primarily be determined by the size of the cell radius (which in turn determines the acceptable level of spatial quantization noise), rather than by the terrain or building data base resolutions.

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