Site-Specific Engineering for Indoor Wireless Communications

Analysis of in-building communications must include the effects of floors, ceilings, walls and partitions and well as distance

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Now that Personal Communication Systems (PCS) are becoming a reality, wireless system designers are being presented with entirely new challenges as these networks move into and between buildings. Distances over which reliable communication must take place are rapidly decreasing, with corresponding drops in transmitter power, and the channel path is becoming much more cluttered with users and obstructions. Building layout, construction materials used, and interference from other signal sources all affect indoor PCS reliability.

Wireless carriers are being pressed hard by customers who want indoor wireless networks installed now, but (until recently) there have been virtually no comprehensive computer modeling tools for the indoor channel to assist in wireless network engineering and management. Finding and correcting "dead zones" in a building after system deployment can be frustrating and expensive!

RF propagation in the indoor environment is affected by reflection, diffraction, and scattering, but now the conditions are much more variable than in the "great outdoors." With the decreasing carrier wavelengths in PCS, factors such as the position of desks, whether doors are open or closed, and even the movement of people can have a marked affect on the signal energy at specific locations within the building. Unlike the design processes of old, simply saturating an area with RF at high power is no longer a viable option due to interference problems. Therefore, it's important to determine which of these propagation-influencing factors must be taken into account when designing an indoor wireless network.

Partition	Loss	Frequency
Metal wall	26 dB	815 MHz
Aluminum siding	20 dB	815 MHz
Concrete block wall	13 dB	815 MHz
Foil insulation	4 dB	815 MHz
Sheetrock (2 × 3/8 in. sheets)	2 dB	9.6 GHz
Dry plywood (3/4 in. sheet)	1 dB	9.6 GHz

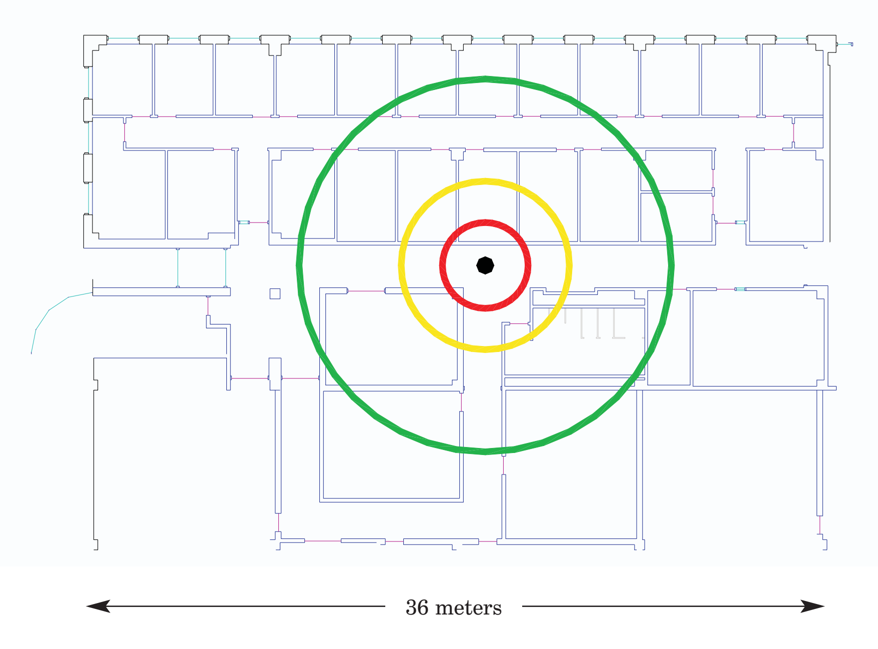
▲ **Table 1. Typical RF penetration losses for various building partitions.**

Propagation models can be used to estimate the received signal strength indication (RSSI) at a communications receiver when its location is known relative to the corresponding transmitter. These models vary widely in complexity and are often based upon empirical measurements for a specific communication application. To gain insight into how to analyze the performance of an indoor site-specific environment, we employ the site engineering and management software package called SitePlanner, available from Wireless Valley Communications, Inc. (http://www.wvcomm.com). SitePlanner offers a new way of modeling, measuring, and optimizing in-building communication systems.

Partition losses

Indoor signal propagation is affected not only by distance-dependent losses, but also by losses associated with the various partitions which form the internal and external building structure. Some typical partition losses that were measured in office buildings are given in Table 1.

Table 2 shows how a signal is attenuated



▲ **Figure 1. Signal contours from a distance-dependent analysis that accounts for distance and obstructions through selection of the path loss exponent. An isotropic antena is located near the ceiling of this floor.**

when it penetrates from floor to floor. As expected, there is significant attenuation from one floor to another, but the amount of per-floor loss actually decreases for multiple floor penetration. This could be the result of reflection from nearby buildings, RF ducting within the building being analyzed, or both. After about four floors of separation between transmitter and receiver, very little additional path loss is experienced. As a result, accurate RF signal models cannot assume that floor-to-floor attenuation is a linear function of the number of floors.

Number of Floors	Total Loss	Frequency
Through 1 floor	13 dB	914 MHz
Through 2 floors	19 dB	914 MHz
Through 3 floors	24 dB	914 MHz
Through 4 floors	27 dB	914 MHz

▲ **Table 2. Typical floor-to-floor RF penetration losses.**

Business	n	Frequency
Retail store	2.2	914 MHz
Office, moveable walls	2.4	900 MHz
Office, fixed walls	3.0	1.5 GHz
Metalworking factory, line of sight	1.6	1.3 GHz

▲ **Table 3. Path loss exponents for different types of office environments.**

Armed with these propagation measurements, we now examine ways in which they can be used to assess the performance of an indoor wireless communication system.

Path loss models based on distance

Perhaps the simplest propagation model is called the d^n model, where RSSI is determined by the distance between transmitter and receiver for a given path loss exponent. This can be expressed mathematically as:

$$PL = PL(d_0) + 10n\log(d/d_0) \qquad (1)$$

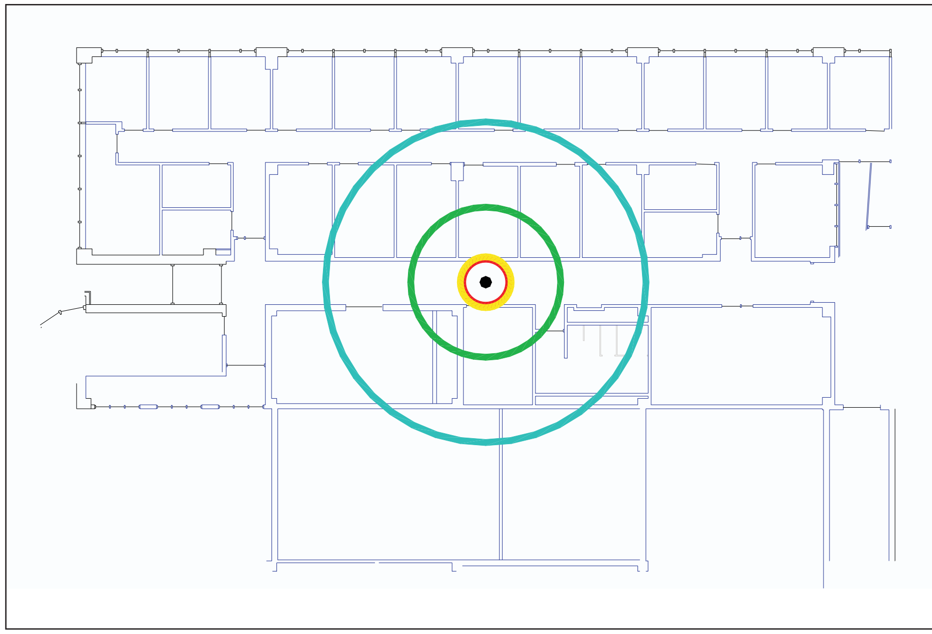
where path loss PL values are given in dB. Distance d_0 is a known free-space reference distance from the transmit antenna (usually 1 meter in indoor situations), n is the path loss exponent (which, of course, becomes a multiplier when using logarithmic dB figures), and d is the distance being measured. Free space has a path loss exponent of 2, so RSSI decreases by 6 dB each time transmitter-receiver separation is doubled (–6 dB per octave).

There are a number of ways in which site-specific information can be added to improve the accuracy of the distance dependent model while retaining its simplicity (and computational speed). For example, adjusting the value of the path loss exponent n could be used to account for office clutter. Table 3 shows some typical values for n that have been measured in buildings used for different business purposes. Interestingly, RF ducting in some of the buildings can result in values of n that are less than the free-space value of 2, especially in line-of-sight (LOS) situations.

Figure 1 shows a CAD drawing of the first floor of an office building in which an 870 MHz transmitted signal at -–10 dBm is fed into an isotropic (omnidirectional in azimuth and elevation with unity gain) antenna. The path loss exponent n is set to 3.0 to account for clutter in the form of permanent walls. Three constant-RSSI contours were drawn using the d^n propagation model in SitePlanner. The outermost contour is at –70 dBm and the other two are at 10 dBm intervals. Notice that this particular model produces concentric contours and no irregularities occur as the signal passes through various building partitions.

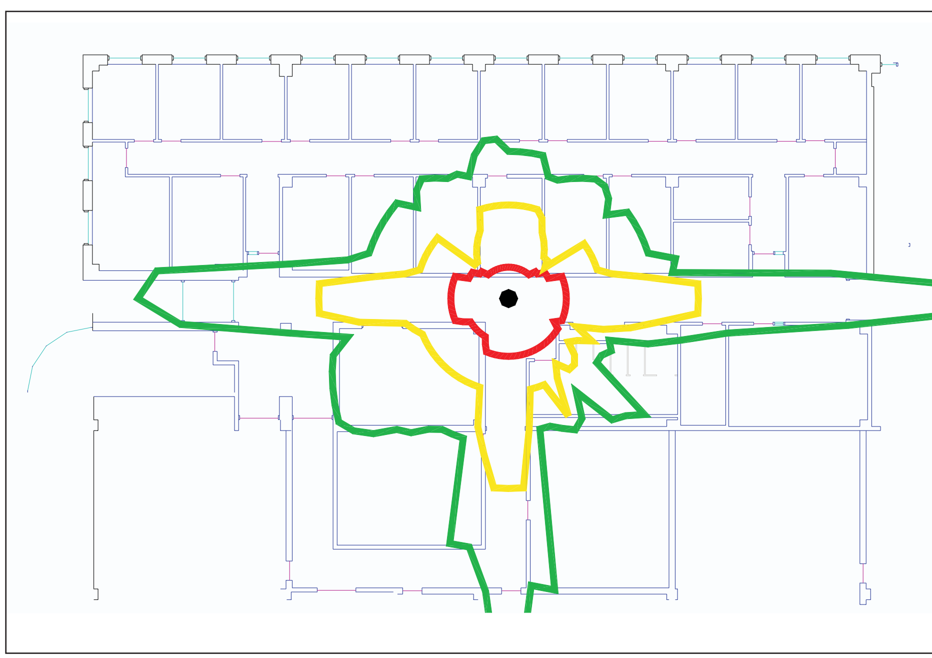
Accuracy of this method can sometimes be improved by allowing the path loss exponent to change to a new value at discrete distances from the transmitting antenna. For example, if the antenna is located in the center of a large room, then n might be set to 2 for locations within the room and to higher values for RSSI calculations elsewhere in the building, especially for floors other than that where the transmitter is located. The signal contours thus generated are still concentric but their spacing will be different than that obtained using a constant n.

Figure 2 provides an example of using a different path loss exponent to model RSSI in the same building as that shown in Figure 1. In this case, the receiver is now located on the second floor of the building with the transmitter still on the first floor. The path loss exponent n is set to 4.2 to account for greater signal attenuation through the floor. RSSI contours are plotted at –80, –70, –60, and –50 dBm.



▲ **Figure 2. Signal contours from a distance-dependent analysis that accounts for distance and obstructions through selection of the path loss exponent. An isotropic antenna is located near the ceiling of the floor below.**

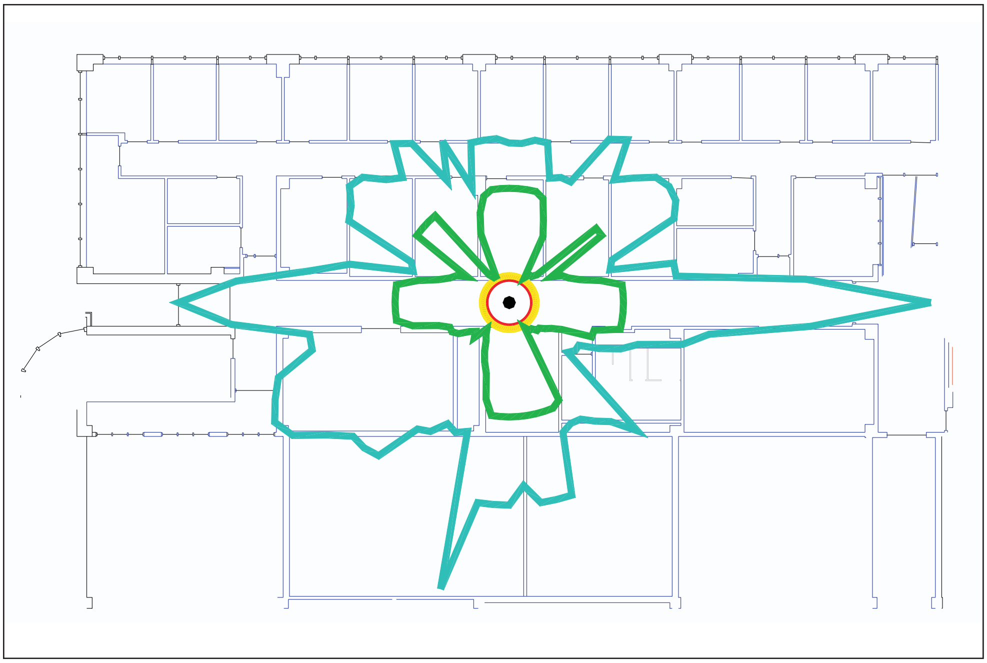
Although simple to compute, many designers are uneasy with a strict distance-dependent analysis method because it doesn't directly show losses from actual partitions within the building. As a result, areas of poor RF penetration may not be adequately identified prior to network deployment. Although careful selection of n will ensure accurate average RSSI values, signal strength standard deviations can be greater than 10 dB when using the distance dependent model alone. In other words, about one-third of the locations in this building will have measured RSSI that is more than 10 dB in error from the predicted values. For example, we know from Table 1 that RSSI readings on either side of a concrete block wall will differ by about 13 dB, even though a strict distance dependent analysis won't show this. Instead, the distance dependent model may underestimate RSSI on the transmitter side of the wall and overestimate RSSI on the side of the wall away from the transmitter.



▲ **Figure 3. Signal contours from a path loss analysis that accounts for distance using free space loss, and obstructions using their assigned attenuation factor. An isotropic antenna is located near the ceiling of this floor.**

Incorporating partition losses into propagation models

In order to account for specific partition losses, including losses from floor to floor, the location of each partition and its attenuation factor must be placed into the engineering model that is used for wireless net-



▲ **Figure 4. Signal contours from a path loss analysis that accounts for distance using free space path loss and obstructions using their assigned attenuation factors. An isotropic antenna is located near the ceiling of the floor below.**

work performance analysis. Once this is done (e.g., through a CAD drawing in SitePlanner), then equation (1) can be modified to give a better estimate of total path loss PL as:

$$PL = PL(d_0) + 10n\log(d/d_0) + \sum[(P_i)(AF_i)] + FAF \quad (2)$$

where the signal passes through P_i partitions of class i with attenuation AF_i. For multiple floor analysis the appropriate floor attenuation factor FAF from Table 2 is also used. Since partition losses are now being accounted for directly, the path loss exponent n is often set to its free space value of 2.

Although SitePlanner allows for the entry of up to eight different partition classes, there is seldom a need to specify that many. Research by the Mobile and Portable Radio Research Group (MPRG) at Virginia Tech has shown that very accurate results can be obtained by dividing building partitions into only three or four classes; e.g., outside walls, metal walls such as elevators, interior fixed walls, and interior moveable walls. Doors and windows could be assigned the same attenuation factors as interior moveable walls. This simplifies the database and allows a floorplan drawing to be done quickly.

Figure 3 once again shows the first floor of our building, but equation (2) was used in SitePlanner to develop constant RSSI contours. Outside walls (black partitions) are assigned a 10 dB loss, inside permanent walls (blue partitions) have a 3 dB loss, and windows and doors are assigned a 2 dB loss each. The path loss exponent n was set to 2. These contours are now irregularly shaped to depict increased signal penetration into relatively unobstructed areas such as hallways and higher signal attenuation in areas of greater clutter. By comparing Figure 3 with Figure 1, it is evident that using only a distance dependent model will underestimate the signal strength within the hallways. On the other hand, the outside rooms at the top of the drawing have several partitions between them and the transmitter, so the distance dependent model will yield optimistic signal strength results in these areas. Using equation (2) instead of equation (1) improves RSSI standard deviations from about 10 dB to 4 dB.

Generating point-to-point path loss figures when the transmitter and receiver are located on different floors is similar to the same-floor analysis, but now partitions affecting the received signal will be located on both floors, and the floor itself will provide additional attenuation. Figure 4 plots the –80 through –50 dBm RSSI values using equation (2) in SitePlanner for a receiver located on the second floor of the building. As before, the transmitter and its isotropic antenna are on the first floor.

The ability to draw RSSI or carrier-to-noise (C/N) contours on a CAD drawing of an indoor floorplan produces a number of advantages to assist wireless site planning engineers. Adequate signal penetration within the area of interest can easily be checked by setting the outermost contour to the minimum usable RSSI or C/N values. Portions of the building outside the last contour will have poor service from the wireless node being analyzed. Directional antennas can be incorporated into the model and their position and orientation changed until the area of interest is adequately covered. Finally, carrier-to-interference (C/I) analysis can be carried out, and C/I contours drawn, to determine if other indoor wireless networks or outdoor macrocells are creating excessive interference.

Site-specific signal measurements

As the number of variables in our communication system performance model increases, there is an increased chance that significant errors will creep into the results.

How can we be sure, for example, that the partition and floor attenuation factors used in the model are correct? For regions between partitions, is the path loss exponent accurate? To discover these answers, signal measurements must be taken inside the building in which the wireless system will be deployed.

Actual attenuation factors can be determined by placing a transmitter and receiver on opposite sides of the partition and taking signal strength measurements. However, this method is prone to uncertainties leading to wide statistical variations, and can be difficult to accomplish in areas that have limited access.

Researchers have determined that the method for finding the most accurate attenuation factors and path loss exponent values is to place a test transmitter at the proposed location of the actual network transmitter, and then use a roaming receiver to check RSSI, C/I, or other measurements throughout the indoor service area. Next, these measurements are used to check the validity of the simulations. Several dozen measurements are usually required for this method to be valid. Without some kind of an automated data collection process, however, acquiring in-building measurement data can be far more time consuming than it is in the macrocellular world where automated equipment has been in use for several years.

SitePlanner reduces the tedium associated with this process in two ways. First, a test receiver can be tied directly to the CAD drawing of the building through a pen-based palmtop computer and a data link (Figure 5). User input consists of marking directly on the CAD drawing displayed on the palmtop each location at which a signal measurement is taken. The measurements are kept in a file linked to these locations. Next, an optimization program is run that adjusts the path loss exponent and various partition and floor attenuation factors to minimize the error between the measured data and the predictions. Of course, accuracy improves as a function of the number of signal measurements taken, as well as their locations within the building.

▲ **Figure 5. A pen-based computer and test receiver are used to inoput actual signal measurement data into SitePlanner.**

Once this process is complete, the designer can be assured of reasonably accurate results from simulation runs, provided that the transmitter location is not changed.

Other uses for site-specific models

As mentioned previously, site-specific building information can be used to check carrier-to-interference ratios (C/I) of other signals penetrating from outside. Indeed, C/I, not thermal noise, is often the limiting factor in the performance of wireless communication systems.

Suppose that a wireless local area network (WLAN) shares the same channel set with an outside macrocell. How will WLAN performance be affected? The analysis can be done in SitePlanner as follows:

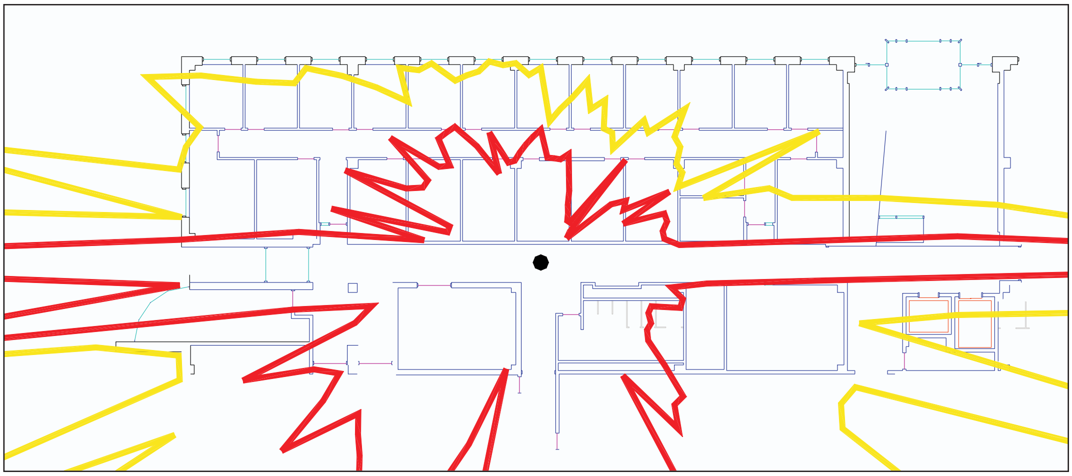
- Place a "virtual" macrocell outside the exterior wall on the same side of the building on which the actual macrocell is located;
- Use equation (1) with proper the path loss exponent to calculate a new (lower) power for the virtual macrocell so it produces the same RF field within the building's interior, or measure the in-building signal with a test receiver;
- Run a C/I analysis throughout the area of interest to check WLAN performance.

The results of such an analysis are shown in Figure 6. The WLAN node is in the same location as before, but now a virtual macrocell has been placed about 5 meters outside the north wall of the building. The virtual macrocell is transmitting at –10 dBm into a vertically polarized dipole antenna on the same frequency of 870 MHz as the WLAN node. Two C/I contours are shown; the innermost is at 30 dB and the outermost is at 0 dB. It is quite apparent from the plots that the rooms bounded by the north outside wall of the building have unacceptably low C/I for reliable service, so the indoor WLAN node should be assigned a different frequency set than that used by the macrocell.

Other cell-based designs can be analyzed as well. Site-specific modeling is perhaps the only reasonable way to test a picocellular indoor wireless network for correct operation prior to actual deployment. Proper placement of cells to guarantee adequate coverage without interference problems or areas of poor coverage is difficult at best. Site-specific models allow tremendous flexibility in base station and antenna placement, along with identification of handoff regions, to greatly increase the chance that the actual system will operate properly after deployment. These models cost far less to construct and analyze than performing in-building trial and error runs during the deployment phase.

Conclusion

Site-specific modeling of indoor communication systems can reduce deployment costs and time by allowing computer analysis of several different configurations tailored to the specific building of interest. With proper selection of the path loss exponent, a distance dependent model can give reasonably good average signal strength values with very fast computation times. Much greater accuracy can be achieved by incorporating actual partition attenuation factors from walls, floors, and other clutter into the model and coupling those with a path loss exponent that is approximately that of free space. Accuracy can be improved still further by taking actual signal measurements and using these to optimize partition attenuation factors and the path loss exponent to minimize the error between the calculated and measured values. Deployment headaches are minimized once an accurate simulation shows that the wireless communication system will perform adequately.



▲ **Figure 6. Carrier-to-interference (C/I) test using a virtual macrocell placd outside the building. The contours are 30 dB (red) and 0 dB (yellow), showing unacceptable WLAN performance in part of the building.**

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