7.0 Indoor Radio Propagation

The performance of the wireless alarm system depends heavily on the characterstics of the indoor radio channel. Excessive path loss within the home can prevent units from communicating with one another. Thus, it is useful to attempt to predict path loss as a function of distance within the home.

The indoor mobile radio channel can be especially difficult to model because the channel varies significantly with the environment. The indoor radio channel depends heavily on factors which include building structure, layout of rooms, and the type of construction materials used. In order to understand the effects of these factors on electromagnetic wave propagation, it is necessary to recall the three basic mechanisms of electromagnetic wave propagation -- reflection, diffraction, and scattering [7].

Reflection occurs when a wave impacts an object having larger dimensions than the wavelength. During reflection, part of the wave may be transmitted into the object with which the wave has collided. The remainder of the wave may be reflected back into the medium through which the wave was originally traveling. In an indoor environment, objects such as walls and floors can cause reflection.

When the path between transmitter and receiver is obstructed by a surface with sharp irregularities, the transmitted waves undergo diffraction. Diffraction allows waves to bend around the obstacle even when there is no line-of-sight (LOS) path between the transmitter and receiver. Objects in an indoor environment which can cause diffraction include furniture and large appliances.

The third mechanism which contributes to electromagnetic wave propagation is scattering. Scattering occurs when the wave propagates through a medium in which there are a large number of objects with dimensions smaller than the wavelength. In an indoor environment, objects such as plants and small appliances can cause scattering.

The combined effects of reflection, diffraction, and scattering cause multipath. Multipath results when the transmitted signal arrives at the receiver by more than one path. The multipath signal components combine at the receiver to form a distorted version of the transmitted waveform. The multipath components can combine constructively or destructively depending on phase variations of the component signals. The destructive combination of the multipath components can result in a severely attenuated received signal.

One goal of this research project is to characterize how the indoor radio channel affects the performance of the wireless alarm system. In particular, we would like to determine the amount of attenuation that can be expected from walls, floors, and doors in a residential environment. Furthermore, we would like to be able to estimate the amount of path loss that can be expected for a given transmitter-receiver (T-R) separation within a home.

Since the properties of an indoor radio channel are particular to a given environment, researchers have focused their efforts on deriving large scale propagation models from empirical data measured within various building types. Sections 7.1.2-7.1.5 summarize some of the indoor radio propagation models that have been proposed for use in the home. The applicability of each of these models to the wireless alarm system is investigated in Sections 7.3.1-7.3.4. The results of this effort clearly demonstrate that a model geared specifically for the wireless alarm application is needed. The development of such a model is discussed in Section 7.4

7.1 Existing Indoor Propagation Models

7.1.1 Free Space Path Loss

Although the free space path loss model is not directly applicable to indoor propagation, it is included here because it is needed to compute the path loss at a close-in reference distance as required by the models discussed in Sections 7.1.2-7.1.4.

The free space model provides a measure of path loss as a function of T-R separation when the transmitter and receiver are within LOS range in a free space environment. The model is given by equation (7.1) which represents the path loss as a positive quantity in dB:

$$PL(d) = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right] \tag{7.1}$$

where G_t and G_r are the ratio gains of the transmitting and receiving antennas respectively, λ is the wavelength in meters, and d is the T-R separation in meters. When antennas are excluded, we assume that $G_t = G_r = 1$.

The free space path loss equation provides valid results only if the receiving antenna is in the far-field or Fraunhofer region of the transmitting antenna. The far-field is defined as the distance d_f given by equation (7.2).

$$d_f = \frac{2D^2}{\lambda} \tag{7.2}$$

where D is the largest linear dimension of the antenna. Additionally, for a receiver to be considered in the far-field of the transmitter, it must satisfy $d_f >> D$ and $d_f >> \lambda$.

7.1.2 Log-Distance Path Loss

The log-distance path loss model assumes that path loss varies exponentially with distance. The path loss in dB is given by equation (7.3).

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) \tag{7.3}$$

where n is the path loss exponent, d is the T-R separation in meters, and d_0 is the close-in reference distance in meters. $PL(d_0)$ is computed using the free space path loss equation discussed in Section 7.1.1. The value d_0 should be selected such that it is in the far-field of the transmitting antenna, but still small relative to any practical distance used in the mobile communication system.

The value of the path loss exponent n varies depending upon the environment. In free space, n is equal to 2. In practice, the value of n is estimated using empirical data.

7.1.3 Log-Normal Shadowing

One downfall of the log-distance path loss model is that it does not account for shadowing effects that can be caused by varying degrees of clutter between the transmitter and receiver. The log-normal shadowing model attempts to compensate for this.

The log-normal shadowing model predicts path loss as a function of T-R separation using equation (7.4).

$$PL(d) = \overline{PL}(d_0) + 10n\log\left(\frac{d}{d_0}\right) + X_\sigma \qquad (7.4)$$

where X_σ is a zero-mean Gaussian random variable with standard deviation σ. Both X_σ and σ are given in dB. The random variable X_σ attempts to compensate for random shadowing effects that can result from clutter. The values n and σ are determined from empirical data.

7.1.4 Addition of Attenuation Factors to Log-Distance Model

Several researchers have attempted to modify the log-distance model by including additional attenuation factors based upon measured data. One example is the attenuation factor model proposed by Seidel and Rappaport [8]. The attenuation factor model incorporates a special path loss exponent and a floor attenuation factor to provide an estimate of indoor path loss. The model is given in equation (7.5).

$$PL(dB) = PL(d_0) + 10n_{sf}\log\left(\frac{d}{d_0}\right) + FAF \qquad (7.5)$$

where n_{sf} is the path loss exponent for a same floor measurement and FAF is a floor attenuation factor based on the number of floors between transmitter and receiver. Both n_{sf} and FAF are estimated from empirical data.

A similar model was developed by Devasirvatham et al [9]. Devasirvatham's model includes an additional loss factor which increases exponentially with distance. The modified path loss equation is shown in equation (7.6).

$$PL(d) = PL(d_0) + 20\log\left(\frac{d}{d_0}\right) + \alpha d + FAF \qquad (7.6)$$

where α represents an attenuation factor in dB/m for a given channel.

A third model incorporates additional attenuation factors. This model was developed by Motley and Keenan [10] and is of the form shown in equation (7.7).

$$PL(d) = PL(d_0) + 10n\log(d) + kF \qquad (7.7)$$

where k is the number of floors between the transmitter and receiver and F is the individual floor loss factor.

The main difference between Motley and Keenan's model and that developed by Seidel and Rappaport is that Motley and Keenan provide an individual floor loss factor which is then multiplied by the number of floors separating transmitter and receiver. Seidel and Rappaport provide a table of floor attenuation factors which vary based upon the number of floors separating the transmitter and receiver.

7.1.5 An Additive Path Loss Model

An additional path loss model which has been investigated by researchers is an additive path loss model. In this model, individual losses caused by obstructions between transmitter and receiver are estimated and added together[11]. Researchers have developed tables of recorded average attenuation values for various obstructions including walls, floors, and doors. However, much of the recorded information is specific to only a few carrier frequencies. Furthermore, the resulting attenuations are not consistent among researchers.

7.2 Observed Performance of the Wireless Alarm System

In order to determine the applicability of the existing indoor propagation models to the wireless alarm system, we must know the maximum amount of path loss which the alarm system can tolerate. Furthermore, we should have an estimate of the maximum distance over which the alarms have successfully operated within some homes. Sections 7.2.1 and 7.2.2 discuss the methods used to determine these system parameters experimentally.

7.2.1 Determination of Maximum Tolerable Path Loss

The maximum tolerable path loss was measured by placing two units directly opposite one another on an indoor soccer field. Units were placed at a height of about 0.75 m. The units were moved further and further apart until they could no longer communicate with one another. The maximum distance over which the units could communicate was 64 m. Using this distance in the free space path loss equation, it was determined that the alarm units can tolerate a maximum path loss of 61 dB.

This theoretical measurement compares well with actual system specifications. Recall from Section 2.2 that the wireless alarm units have an EIRP of -41.1 ± 4 dBm and a receiver sensitivity of -105.5 dBm. This implies that the units can tolerate a maximum path loss given by equation (7.8).

$$-41.1 dBm \pm 4\, dBm - (-105.5 dBm) = 64.4 \pm 4\ dB \tag{7.8}$$

Any discrepancy between the measured maximum tolerable path loss and the specified tolerable path loss may be caused by tolerances within the design of the alarm units. Furthermore, the discrepancy may have resulted because the experimental measurement was done within a building as opposed to a pure free space environment.

For the remainder of the discussion, we will assume that the alarm units can tolerate a maximum path loss of 61 dB to allow for worst-case conditions.

7.2.2 Observed Maximum Allowable T-R Separation Within Two Homes

The alarm units were tested in two different homes to obtain an estimate of the maximum allowable separation between units. Although the test was limited to only two homes, the results provide a general understanding of the unit-to-unit operating range. This estimated range can then be compared with results obtained from existing indoor propagation models to determine the appropriateness of the models for this application..

The first home in which the units were tested was built in 1910. It is a 24'x50' two-story home with a basement. Two units were placed at various locations within the home and tested to see if they could communicate with one another. A vertical cross-sectional view of the home is shown in Figure 7.1. Figure 7.1 shows the home as if you are looking into it from the front.

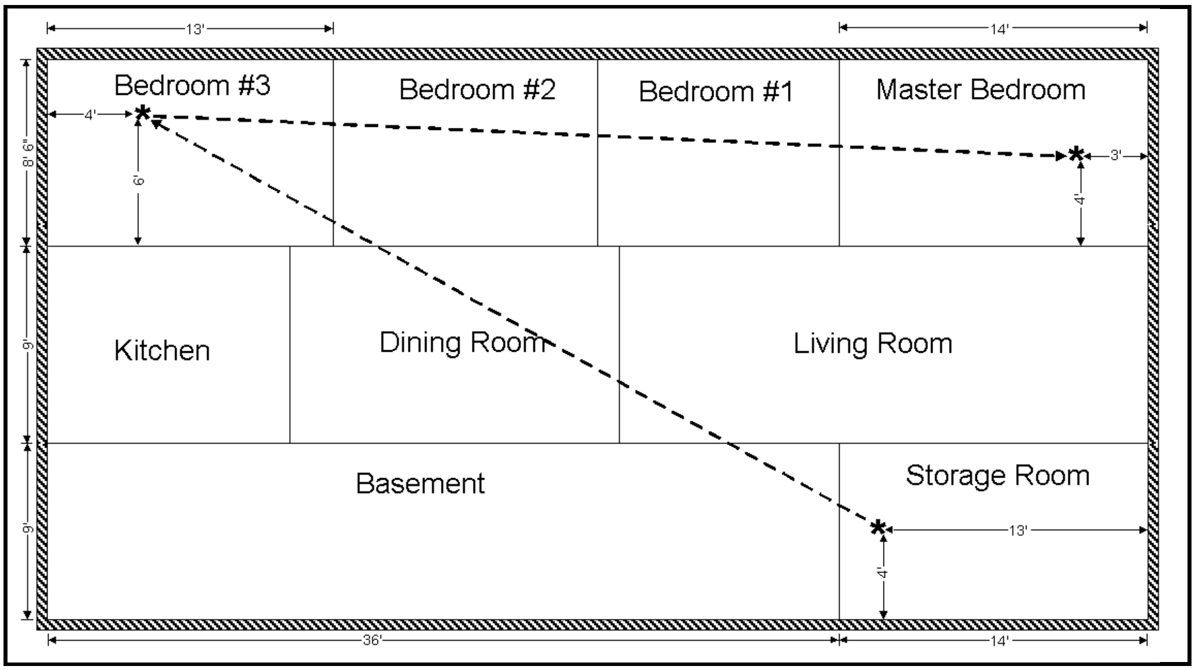

Figure 7.1: Vertical Cross-Section of First Home in Which Alarm Units Were Tested

In Figure 7.1, the asterisks represent the position of the alarm units. The figure shows that there were two failing unit-to-unit links in the home. Interestingly, the two link failures occurred in only one direction.

In the first failure, one alarm unit was placed on top of a bookcase in bedroom #3, while the other alarm unit was positioned on top of a radiator in the master bedroom. The link was successful in both directions when just the master bedroom door was open and when both bedroom doors were open. However, if either the master bedroom door or both bedroom doors were closed, the link from the master bedroom to bedroom #3 was unsuccessful. In this scenario, the additional attenuation provided by the doors was just enough to prevent the units from working correctly.

The second failure occurred when the unit in the master bedroom was moved to a shelf in the storage room in the basement. In this case, the link from the storage room to the master bedroom was successful, while the opposite link was not.

The three dimensional position of each unit within the first home is summarized in Table 7.1

Table 7.1: Three-Dimensional Positioning of Alarm Units Within Home #1

	Distance from leftmost side of home (ft)	Distance from bottom floor (ft)	Distance from front of home (ft)
Bedroom #3	4	24	5.5
Master Bedroom	47	22	5.5
Storage Room	37	4	4

The distance between the alarm unit in bedroom #3 to each of the other two alarm unit locations was calculated from the information in Table 7.1 These distances along with a summary of the obstructions between the alarm unit in bedroom #3 and the units in the other two locations are given in Table 7.2.

Table 7.2: Distance and Obstacles Between Unit in Bedroom #3 and the Other Two Unit Locations Within the First Home

	Distance to Alarm Unit in Bedroom #3	Obstructions in LOS Path to Alarm Unit in Bedroom #3
Alarm Unit in Master Bedroom	43.05’ ≈ 13.12 m	3 walls, 2 doors
Alarm Unit in Storage Room	38.62’ ≈ 11.77 m	3 walls, 2 floors

The second home in which the units were tested was built in 1992. It is a 28’x66’10” two-story home with a basement. A vertical cross-sectional view of the home is not included since floor plans of this home are included in Appendix C. Table 7.3 summarizes the distance and obstructions between locations in which unit-to-unit links failed.

Table 7.3: Distance and Obstacles Between Locations in Which Unit Links Failed Within the Second Home

Unit-to-Unit Distance	Obstructions in LOS Path Between Units	Direction of Link Failure
27’ ≈ 8.23 m	2 floors, 3 walls, HVAC unit	From second floor to basement
33’ ≈ 10.06 m	2 floors, 4 walls	From second floor to basement
51’ ≈ 15.54 m	2 floors, 3 walls	From basement to second floor

In both homes, there were successful bi-directional links over distances greater than some of those listed in Tables 7.2 and 7.3. Obstructions in addition to distance contribute significantly to path loss.

7.3 Application of Existing Indoor Models to the Wireless Alarm System

7.3.1 Log-Distance Path Loss

Researchers have applied the log-distance path loss model to many indoor environments on the basis of its simplicity. By analyzing empirical data, researchers adjust the value of the path loss exponent to match a given environment. There have been many published values for the path loss exponent. In a survey of existing indoor propagation models, one researcher indicates that the path loss exponent has been shown to vary anywhere from 1.5 to 6.0 depending upon the carrier frequency of the transmitted signal, the building type, and whether the transmitter and receiver are within LOS range [11].

In 1983 S.E. Alexander, a researcher from British Telecom, published the results of 900 MHz measurements within three different homes [12]. Alexander reported a different path loss exponent for each home. The path loss exponents obtained were 1.4, 4.0, and 2.2. Figure 7.2 depicts the path loss that can be anticipated for various T-R separations using the log-distance path loss model coupled with Alexander's path loss exponents.

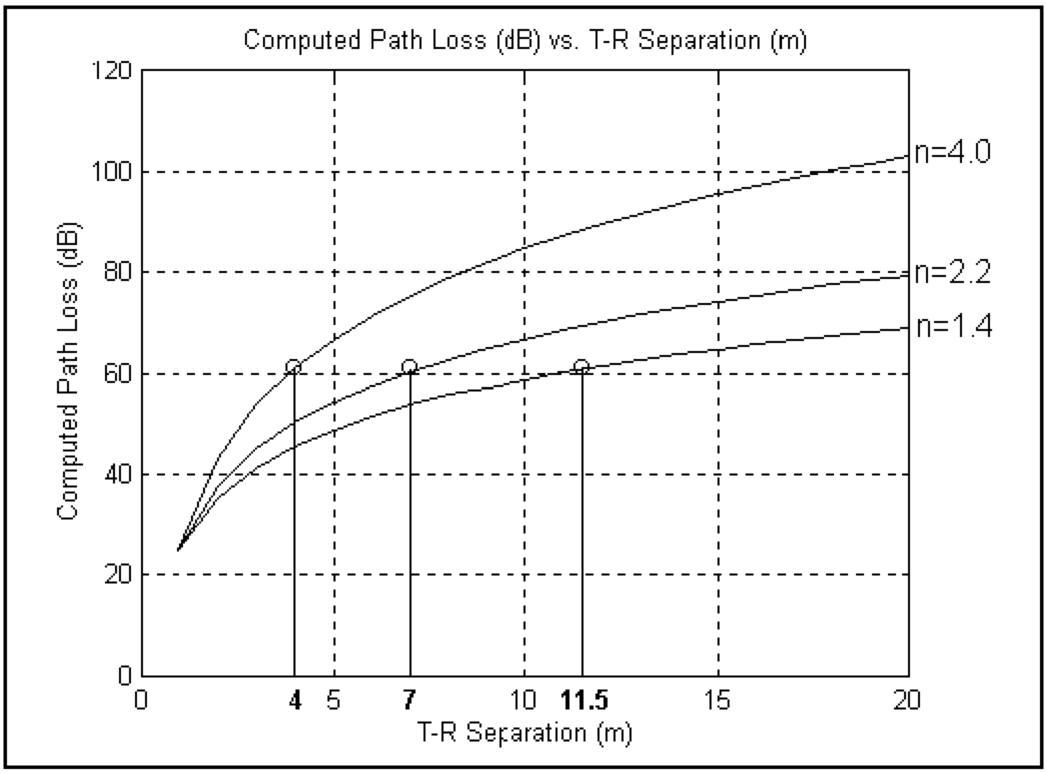

Figure 7.2: Path Loss vs. Distance as Computed from Log-Distance Path Loss Model

In Figure 7.2, the distances in boldfaced type represent the average T-R separations at which the path loss is 61 dB, the maximum path loss which the wireless alarm system can tolerate. The figure demonstrates that these T-R separations vary for different values of the path loss exponent.

It is apparent from Figure 7.2 that the variations in the path loss exponent produce significant differences in computed path loss. Alexander's work indicates that the path loss exponent obtained from 900 MHz measurements differs among homes. If the log-distance model were applied to the wireless alarm system, it would be necessary to conduct measurements in each home so that an appropriate path loss exponent could be determined. This effort is simply not practical and makes the log-distance path loss model inappropriate for the wireless alarm system.

Furthermore, it is believed that Alexander's measurements were conducted in European homes. European homes are typically constructed from much different materials than those used in American homes. Since the wireless alarm system targets an American market, Alexander's results may have limited relevance to this application.

A final drawback of the log-distance path loss model is that it does not account for obstacles separating transmitter and receiver. In Section 7.2.2, it was shown that obstacles are an important consideration in predicting path loss within homes. For example, recall from Section 7.2.2 that in the second home, a unit-to-unit link failed at a distance of 8.23 m. However, within the same home, unit-to-unit links as distant as 11.3 m were successful. This discrepancy indicates the need to incorporate attenuation factors for obstructions between units.

7.3.2 Log-Normal Shadowing

The log-normal shadowing technique is similar to the log-distance model, but includes the addition of a random variable X_σ to account for shadowing effects. In 1994, Anderson, Rappaport, and Yoshida reported that 900 MHz measurements within a home indicate that the log-normal shadowing model matches empirical data reasonably well for values of $n = 3.0$ and $\sigma = 7.0$ [13]. The path loss which results when these values are used in the log-normal shadowing path loss equation is summarized in Figure 7.3.

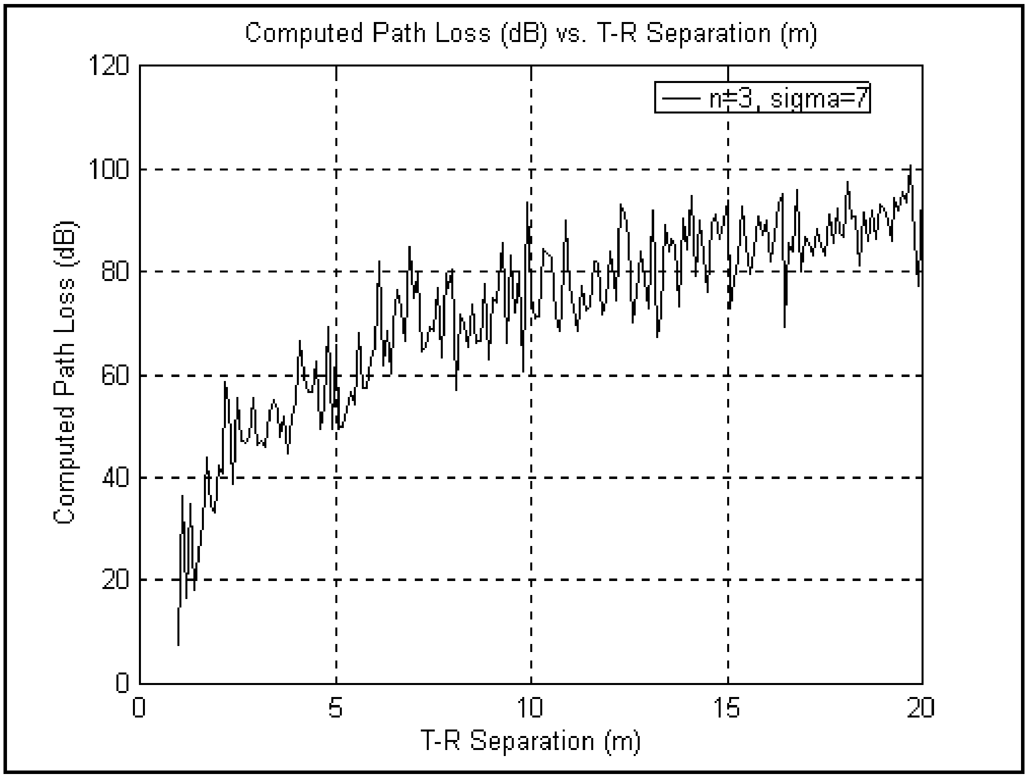

Figure 7.3: Path Loss vs. Distance as Computed from Log-Normal Path Loss Model

The log-normal path loss model appears to be an improvement over the log-distance model as it considers to a limited extent the attenuation from obstacles separating transmitter and receiver. One drawback of the log-normal path loss model is that reported values for n and σ are limited, particularly within a home environment. It may be worthwhile to consider the log-normal model for the wireless alarm system, provided that values of n and σ can be derived from empirical measurements.

7.3.3 Addition of Attenuation Factors to Log-Distance Model

Several researchers have modified the log-distance model by including additional loss factors. Recall from Section 7.1.4 that Seidel and Rappaport's variation requires a same floor path loss exponent and a floor attenuation factor.

One researcher's 900 MHz measurements within a home indicate that a same floor path loss exponent of *3.0* provides a good fit with measured data [13]. Seidel and Rappaport developed two sets of floor attenuation factors [8]. Each set was derived from measurements in a different office building. In the following analysis, we use the set of floor attenuation factors which produces the least amount of path loss, as it is anticipated that the path loss within a home is less than that encountered in a multi-story office building because of differences in construction materials. This set of floor attenuation factors is given in Table 7.4.

Table 7.4: Floor Attenuation Factors

Number of Floors between Transmitter and Receiver	FAF (dB)
0	0
1	12.9
2	18.7
3	24.4
4	27.0

Using these floor attenuation factors along with $n_{sf}=3.0$ in Seidel and Rappaport's model, we obtain an estimate of path loss as a function of T-R separation. The results are shown in Figure 7.4

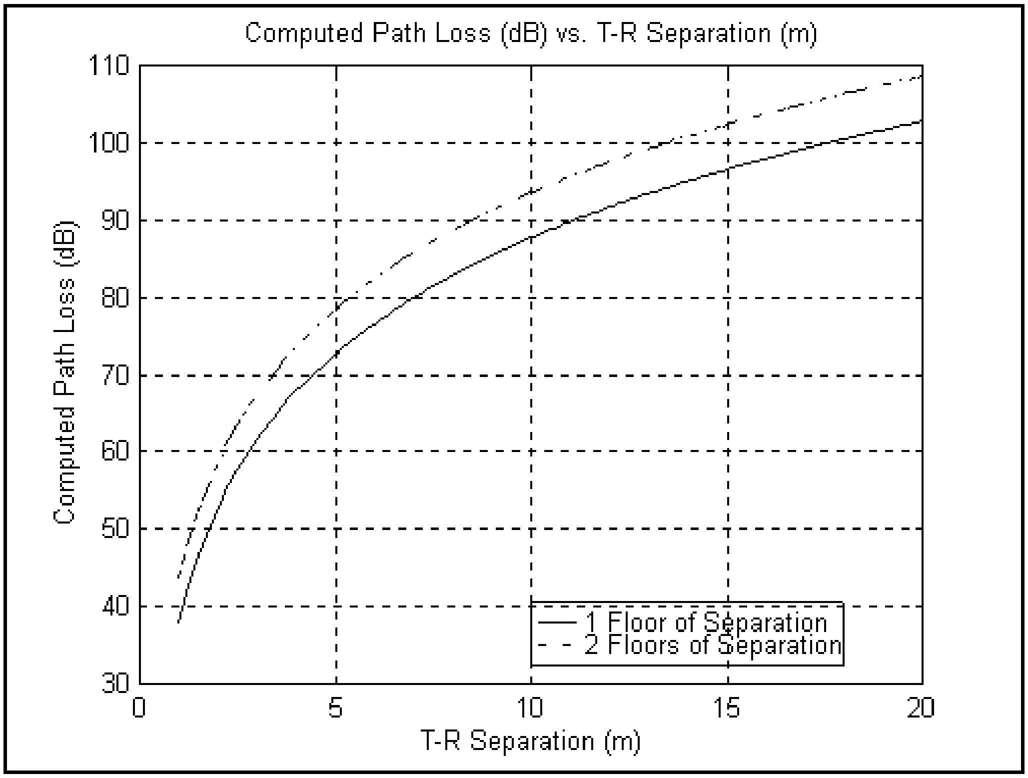

Figure 7.4: Path Loss vs. Distance as Computed from Attenuation Factor Path Loss Model

Figure 7.4 demonstrates that Seidel and Rappaport's model combined with this particular set of parameters predicts much larger path losses than those observed in the testing discussed in Section 7.2.2. This model may provide more promising results if the parameters were adjusted for the wireless alarm application. It may be worthwhile to develop an appropriate same floor path loss exponent and a set of floor attenuation factors from empirical measurements within some homes.

Recall from Section 7.1.4 that Devasirvatham's model is similar to Seidel and Rappaport's model with the inclusion of an additional path loss constant. It is possible that Devasirvatham's model may be applicable to the wireless alarm system, provided that appropriate values for the path loss exponent, floor attenuation factor, and additional path loss constant are derived from empirical measurements within some homes.

Motley and Keenan's model, also discussed in Section 7.1.4, was developed from measurements taken in a multi-story office building. However, two researchers, Owen and Pudney, applied the model to measurements taken within a home [14]. Owen and Pudney concluded that floors within a home do not contribute significantly to path loss because they are typically made of wood and plasterboard. As a result, Owen and Pudney applied the model to the home without the use of the floor loss factor. Without the addition of the floor loss factor, Motley and Keenan's model essentially reduces to the log-distance path loss model. The conclusion drawn by Owen and Pudney implies that within homes, a wall loss factor may be more appropriate than a floor loss factor. It appears worthwhile to consider applying a modified model to homes, incorporating a wall loss factor in place of a floor loss factor.

7.3.4 Additive Path Loss Model

The additive path loss model provides the potential to model specific homes with little effort, as path losses due to obstacles between transmitter and receiver are simply added together. One serious drawback of the additive path loss model is the limited availability of measured data, particularly within a home environment. Much of the existing data is based upon measurements within offices and factories.

Furthermore, existing data is grossly inconsistent among researchers. As one author states, "path loss experienced by signals passing through concrete walls has been reported at 7 dB, 8.5 to 10 dB, 13 dB, and 27 dB by different investigators" [11].

The additive path loss model may be applicable to the wireless alarm system. However, its use first mandates that attenuation data be compiled from measurements within homes.

7.4 Development of an Indoor Propagation Model for the Wireless Alarm System

The discussion in Section 7.3 indicates that none of the surveyed indoor propagation models can be directly applied to the wireless alarm system without first adjusting model parameters. In fact, none of the propagation models discussed in Section 7.3 are the result of measurements at carrier frequencies within the band in which the wireless alarm system operates. Much of the existing indoor propagation literature summarizes measurements at frequencies ranging from 900 MHz up to 60 GHz. The wireless alarm system, however, operates at 418 MHz. An indoor propagation study at 418 MHz will not only provide insight as to whether existing models can be applied to the wireless alarm system, but will also help to fill a gap in existing indoor propagation literature.

7.4.1 Indoor Measurement Procedure

To characterize the amount of path loss that can be expected within a residential environment, narrowband (CW) signal strength measurements were conducted in three homes. The measurements have provided insight about the relationship between path loss and T-R separation and have resulted in an estimate of the attenuation that can be expected from walls, floors, and doors within homes. The equipment used to conduct the indoor measurements is shown in Figure 7.5.

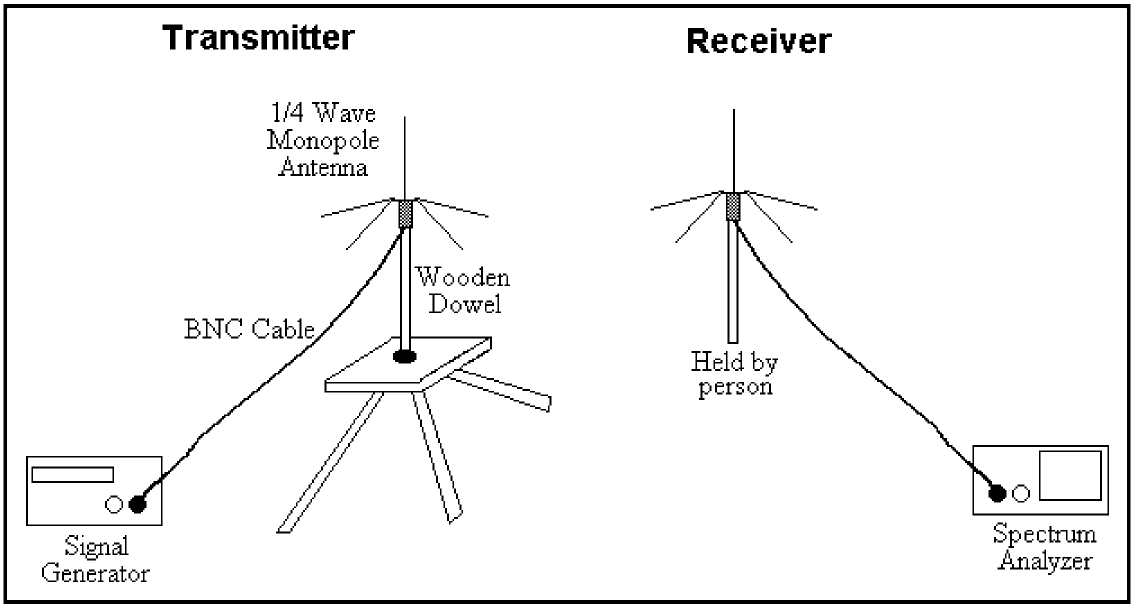

Figure 7.5: Test Equipment Used for Indoor Measurements

A 10 dBm CW signal was transmitted using a Hewlett-Packard 8648C signal generator connected to a ¼ wave monopole antenna. The transmitting antenna was attached to a wooden dowel. The dowel was attached to a tripod so that the antenna could remain fixed at ceiling height. This antenna height emulates the position at which the wireless alarm units are typically installed.

Received signal strength was measured using an identical ¼ wave monopole antenna connected to a Hewlett-Packard 8594E Spectrum Analyzer. This antenna was also attached to a wooden dowel so that it could be vertically positioned at ceiling height.

The transmitter was fixed at a central location within each home, where one would expect a wireless alarm unit to be installed. The receiver was moved to the middle of every room on each floor of the homes. At each location, five received signal strength measurements were recorded at spatial intervals of $\lambda/8$. The five measurements were averaged together to provide an estimate of the received signal strength within the middle of each room. The path loss at each receiver location was determined using equation (7.9).

$$PL = P_{tx} - L_{tx\,cable} - L_{rx\,cable} - P_r \tag{7.9}$$

where P_{tx} is the power of the transmitter, $L_{tx\,cable}$ is the transmitter BNC cable loss, $L_{rx\,cable}$ is the receiver BNC cable loss, and P_r is the received signal power. The losses from the transmitter and receiver cables were measured as 1.72 dB and 1.38 dB, respectively.

7.4.2 Indoor Measurement Results
7.4.2.1 House #1

The first home in which measurements were taken is a split-level home. The transmitter remained fixed at a central location on the upper level, while the receiver was placed at fifteen different locations throughout the home. The locations of the transmitter and receiver are shown in the floor plans included in Appendix B.

In the floor plans of Appendix B, the fixed transmitter location is denoted by *Tx* enclosed within a square. The receiver locations in both figures are numbered. The direction in which the receiver was moved to obtain measurements at increments of $\lambda/8$ is shown with arrows at each receiver location.

For each receiver location, the T-R separation was computed. Also, the average received signal strength, path loss, and obstructions blocking a LOS path between transmitter and receiver were recorded. Table 7.5 summarizes the resulting data.

Table 7.5: Measurement Results from House #1

Receiver Location	T-R Separation (m)	Avg. Received Signal Strength (dBm)	Path Loss (dBm)	Obstructions Between Transmitter and Receiver
1	1.83	-25.34	32.24	None
2	5.94	-38.84	45.74	1 wall, 1 closet
3	6.38	-28.98	35.88	2 walls
4	7.06	-45.18	52.08	2 walls
5	3.45	-39.10, door open -44.76, door closed	46.00 51.66	1 wall corner
6	2.31	-21.28, door open -21.42, door closed	28.18 28.32	1 wall
7	4.44	-38.56, door open -38.20, door closed	45.46 45.10	2 walls
8	2.90	-25.60, door open -25.64, door closed	32.50 32.54	1 wall, 1 closet
9	4.85	-38.64, door open -38.54, door closed	45.54 45.44	2 walls, 1 closet
10	5.13	-40.40	47.30	1 floor, 2 walls
11	2.79	-40.06, door open -40.20, door closed	46.96 47.10	1 floor, 2 walls
12	6.91	-49.08, door open -49.24, door closed	55.98 56.14	1 floor, 2 walls, 2 closets
13	3.94	-47.06, door open -46.72, door closed	53.96 53.62	1 floor
14	3.86	-44.36, door open -45.54, door closed	51.26 52.44	1 floor, 1 wall
15	6.73	-47.66	54.56	1 floor, 3 walls

Path loss as a function of T-R separation in House #1 is plotted and shown in Figure 7.6.

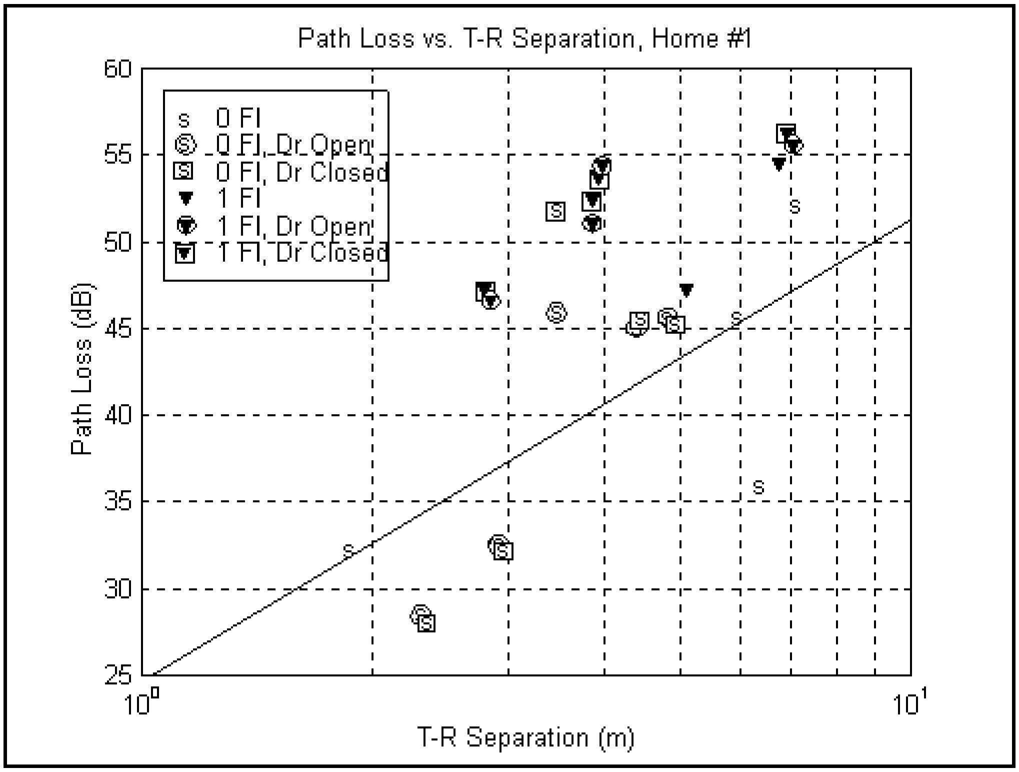

Figure 7.6: Measured Path Loss in House #1

Several trends can be observed in the data shown in Figure 7.6. For example, Figure 7.6 shows that measurements through one floor experience greater path loss than same floor measurements at similar T-R separations. Furthermore, the difference between same floor path loss and path loss through one floor decreases as T-R separation increases. Also, opening and closing doors does not have a significant effect on path loss. In fact, in some cases, the path loss with an open door was slightly greater than that observed with a closed door.

Figure 7.6 shows that a constant can be added to the same floor path loss to estimate path loss through one floor for a given T-R separation. Thus, it seems appropriate to model the same floor path loss with the log-distance path loss model. Path loss through one floor can then be modeled by the addition of a floor attenuation factor.

Recall that the log distance path loss model represents path loss as a linear function of distance. Thus, we can model the same floor path loss by fitting a straight line to the same floor path loss measurements. From the log-distance path loss model, this line is of the form shown in equation (7.10).

$$PL(d) = PL(d_0) + 10n\log\left(\frac{d}{d_0}\right) \qquad (7.10)$$

For our model, we assume that d_0 is 1m, as it must be larger than the Fraunhofer distance but smaller than any practical T-R separation in the system. Using the free-space path loss equation given in Section 7.1.1, we find that the path loss at d_0 is 24.87 dB.

Using the path loss at d_0 along with the same floor path loss measurements, we can find a straight line which provides a minimum mean square error fit to the measured data. The mean square error is given in equation (7.11).

$$J(n) = \sum_{i=1}^{k} (p_i - \hat{p}_i)^2 \tag{7.11}$$

where p_i is the measured received power at a distance d_i and $\hat{p}_i$ is the estimated received power using the log-distance path loss model. Setting the derivative of the mean square error to zero, and solving for n yields a path loss exponent of 2.63. Thus, for this home, the same floor path loss is given by equation (7.12).

$$PL(d) = 24.87 + 10(2.63)\log(d) \tag{7.12}$$

This same floor path loss estimate is depicted by the line in Figure 7.6. In order to complete the model, we must introduce a floor loss factor.

The floor loss factor is the increase in path loss relative to the same floor path loss when the transmitter and receiver are separated by one or more floors at a given T-R separation. Using the measurements from House #1, we can estimate an appropriate floor loss factor.

Figure 7.6 shows that there are three clusters of measurements through one floor that exhibit a path loss greater than the same floor path loss at the same T-R separation. These clusters occur at T-R separations of 2.8 m, 4 m, and 7 m. At each of these T-R separations, we can estimate the same floor path loss using the log-distance path loss model with a path loss exponent of 2.63. The empirical data in Table 7.5 gives the observed path loss given one floor of separation at these distances. To estimate a floor attenuation factor, we can take the difference between the average observed path loss through one floor and the estimated same floor path loss. This approach yields the data in Table 7.6.

Table 7.6: Estimated Floor Loss Factor Analysis, House #1

d (m)	**Same Floor Path Loss, PL_{SF} (dB)**	**Avg. Path Loss Through 1 Floor, PL_{1F} (dB)**	**PL_{1F} - PL_{SF}**
2.8	36.63	48.0	11.37
4	40.70	53.0	12.30
7	47.1	56.0	8.90

This limited information indicates that a floor loss factor of about 12 dB is appropriate over small T-R separations. As the T-R separation increases, the floor loss factor decreases. Although no further conclusions can be drawn at this point, it is anticipated that the measurements obtained from the other two homes will provide more insight into the floor loss factor.

7.4.2.2 House #2

The second home in which measurements were taken is a two-story colonial home with a finished basement. The transmitter remained fixed at a central location on the main level, while the receiver was placed at sixteen different locations throughout the home. The locations of the transmitter and receiver are shown in the floor plans in Appendix C.

Table 7.7 summarizes the T-R separation, average received signal strength, path loss, and obstructions blocking a LOS path between the transmitter and receiver for each of the receiver locations shown in Appendix C.

Table 7.7: Measurement Results from House #2

Receiver Location	T-R Separation (m)	Avg. Received Signal Strength (dBm)	Path Loss (dBm)	Obstructions Between Transmitter and Receiver
1	4.93	-41.52	48.42	1 wall, 1 closet
2	3.07	-34.92	41.82	1 wall corner
3	3.99	-39.38	46.28	2 walls
4	6.36	-47.12, door open -47.80, door closed	54.02 54.70	3 walls
5	9.68	-50.78, door open -50.14, door closed	57.68 57.04	3 walls
6	4.57	-40.54	47.44	1 wall, 1 closet
7	4.75	-37.20, door open -37.04, door closed	44.10 43.94	1 floor, 2 walls
8	4.55	-43.12, door open -42.84, door closed	50.02 49.74	1 floor, 2 walls
9	3.16	-42.02, door open -42.54, door closed	48.92 49.44	1 floor
10	4.36	-45.22, door open -44.72, door closed	52.12 51.62	1 floor, 2 walls
11	6.45	-46.68, door open -48.46, door closed	53.58 55.36	1 floor, 2 walls, 1 closet
12	5.72	-37.36, door open -37.18, door closed	44.26 44.08	1 floor, 1 wall
13	5.08	-46.40	53.30	1 floor, 1 wall
14	4.89	-38.56	45.46	1 floor, 1 wall
15	4.57	-34.70	41.60	1floor, 2 walls
16	4.29	-38.40, door open -39.16, door closed	45.30 46.06	1 floor, 2 walls

Path loss as a function of T-R separation in House #2 is plotted and shown in Figure 7.7.

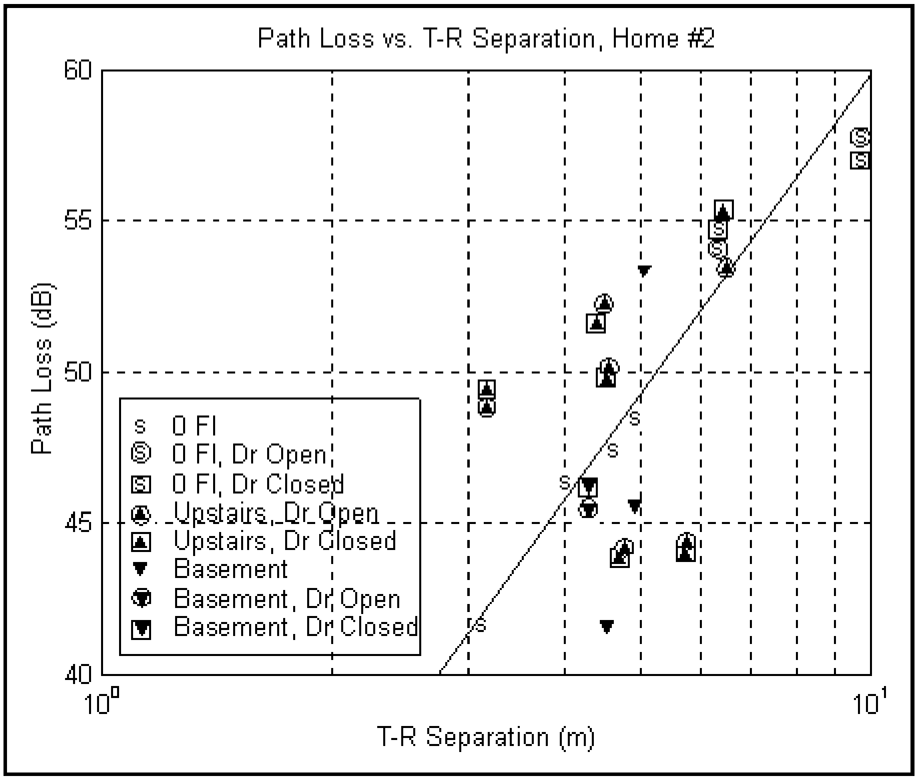

Figure 7.7: Measured Path Loss in House #2

The same floor path loss data in Figure 7.7 is fairly linear. In fact, the minimum mean square error (MMSE) estimate, depicted by the straight line in the figure, closely matches the same floor measurements. The path loss exponent which produces the MMSE fit is 3.508. Thus, the same floor path loss in this home can be estimated by equation (7.13).

$$PL(d) = 24.87 + 10(3.51)\log(d) \qquad (7.13)$$

As was observed in House #1, it appears that opening and closing doors within the home does not significantly impact path loss.

One interesting phenomenon shown in Figure 7.7 is that for some T-R separations, the same floor path loss is greater than that which results when the transmitter and receiver are on separate floors. One possible explanation for this is that there may be hidden obstructions between transmitter and receiver. For example, there may be wires and metal pipes that are hidden within walls and ceilings. These types of obstructions can significantly attenuate an RF signal and have not been investigated.

Several of the different floor measurements in Figure 7.7 do exhibit greater attenuation than the same floor measurements. Again, it seems appropriate that we should attempt to add a floor loss factor to the log-distance attenuation model. The technique used for House #1 is repeated here. The results are shown in Table 7.8.

Table 7.8: Estimated Floor Loss Factor Analysis, House #2

d (m)	Same Floor Path Loss, PL_{SF} (dB)	Avg. Path Loss Through 1 Floor, PL_{1F} (dB)	PL_{1F} - PL_{SF}
3.2	42.60	49.0	6.4
4.4	47.50	51.0	3.5
6.5	53.40	54.5	1.1

Table 7.8 indicates that for this home, a floor loss factor of about 6.4 dB is appropriate at small distances. The floor loss factor decreases rapidly with T-R separation. The floor loss factor for this home is much smaller than that which was observed in Home #1. The floor loss factor for this home is small because the path loss exponent for this home is large relative to that estimated for Home #1.

7.4.2.3 House #3

The third home is a bi-level home with a basement. The transmitter was placed on the main level, while the receiver was moved through twelve different locations throughout the home. The locations of the transmitter and receiver are shown in the floor plans in Appendix D.

Table 7.9 provides a summary of the measurement results for this home.

Table 7.9: Measurement Results from House #3

Receiver Location	T-R Separation (m)	Avg. Received Signal Strength (dBm)	Path Loss (dBm)	Obstructions Between Transmitter and Receiver
1	1.83	-25.90	32.80	None
2	3.67	-28.90, door open -30, door closed	35.80 36.90	1 wall
3	2.46	-24.76, door open -23.92, door closed	31.66 30.82	1 wall
4	3.36	-28.34, door open -29.30, door closed	35.24 36.20	1 wall
5	4.33	-42.68	49.58	2 walls
6	10.02	-49.36	56.26	2 walls
7	2.44	-41.34	48.24	1 floor
8	3.81	-43.42	50.32	1 floor, 1 wall
9	6.73	-36.04	42.94	2 floors, 2 walls
10	6.73	-42.78	49.68	2 floors, 2 walls
11	10.60	-49.48	56.38	2 floors, 2 walls
12	10.60	-55.76	62.66	2 floors, 2 walls

Path loss as a function of T-R separation in House #3 is plotted and shown in Figure 7.8

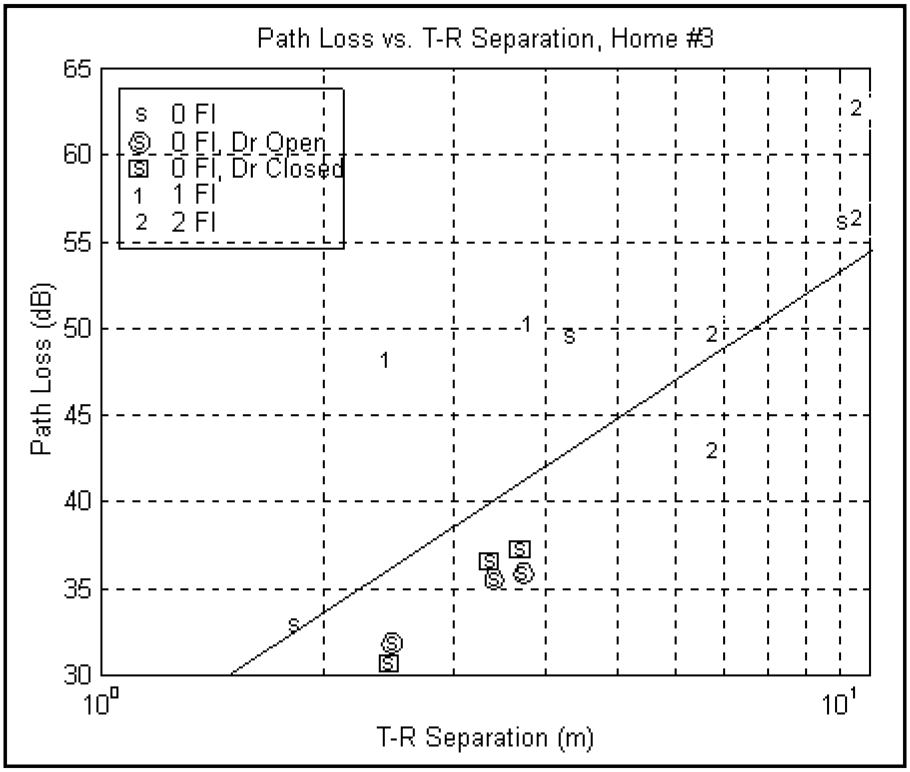

Figure 7.8: Measured Path Loss in House #3

Again, the log-distance path loss model has been fitted to the same floor path loss measurements. The resulting minimum mean square error (MMSE) estimate is shown by the straight line in Figure 7.8. The path loss exponent which produces the MMSE fit is 2.86. Thus, the same floor path loss in this home can be estimated by equation (7.14).

$$PL(d) = 24.87 + 10(2.86)\log(d) \qquad (7.14)$$

As was true with results from the first two homes, the measurements in House #3 indicate that opening and closing doors within a home does not significantly affect path loss.

In general, Figure 7.8 shows that separating the transmitter and receiver by one or more floors results in an increase in path loss. Thus, it seems appropriate to add a floor loss factor to the log-distance path loss model. Furthermore, as was concluded from the measurements in House #1, at large T-R separations, the effect of floors on path loss is reduced. This result is intuitively correct because as the T-R separation increases, there is no longer a LOS path between transmitter and receiver. Thus, the observed path loss is no longer primarily caused by the floor of separation. Instead, multipath contributes significantly to the path loss.

A floor loss factor can be developed for this home in a manner similar to that for homes 1 and 2. The resulting floor loss analysis is shown in Table 7.10.

Table 7.10: Estimated Floor Loss Factor Analysis, House #3

d (m)	Same Floor Path Loss, PL_{SF} (dB)	Avg. Path Loss Through 1 Floor, PL_{1F} (dB)	PL_{1F} - PL_{SF}
2.5	36.25	48.0	11.75
3.8	41.45	50.0	8.55
10.6	54.19	60.0	5.81

The floor loss factor table does not include values for separations of more than one floor. Researchers have shown that in general, the largest amount of attenuation from floors is contributed by the first floor of separation [8]. Furthermore, as the number of floors between transmitter and receiver increases, the distance also increases. As we have already discussed, attenuation from floors decreases with an increase in T-R separation. Thus, evidence suggests that a single floor loss factor is adequate in residential environments.

Table 7.10 indicates that a floor loss factor of about 12 dB is appropriate at small distances and decreases for large distances. The floor loss factor required for this home is similar to that required for House #1. This makes intuitive sense, as the estimated path loss exponents for both homes are similar.

7.5 Summary of Indoor Propagation Measurements

Several conclusions can be drawn from the indoor propagation study. The most obvious is that indoor propagation within homes appears to be site-specific. The data collected in this study shows that there does not appear to be a “one model fits all” solution.

In spite of this, some useful information can be drawn from the study. Results of these measurements can provide a worst-case path loss model within homes. This information can guide the installation procedure for the wireless alarm system. Data collected in this study indicate that the model should be based on the log-distance path loss model with the addition of a distance-dependent floor loss factor. The use of a wall loss factor was investigated during the study, but a consistent relationship between wall separation, distance, and path loss could not be found from the data. Furthermore, doors within the home do not contribute significantly to path loss.

Based upon the data discussed in Sections 7.4.2.1-7.4.2.3, a path loss model of the format in equation (7.15) is appropriate.

$$PL(d)=\begin{cases} PL(d_0)+10n_{sf}\log\left(\frac{d}{d_0}\right)+FLF_1, d \le d_1 \\ PL(d_0)+10n_{sf}\log\left(\frac{d}{d_0}\right)+FLF_2, d_1 < d \le d_2 \\ . \\ . \\ PL(d_0)+10n_{sf}\log\left(\frac{d}{d_0}\right)+FLF_n, d_2 < d \le d_n \end{cases} \tag{7.15}$$

where n_{sf} is a same floor path loss exponent, and FLF_1 ,FLF_2 , and FLF_n are distance-dependent floor loss factors.

Each of the three homes studied here exhibits a different same floor path loss exponent. The same floor path loss exponent obtained for each home is 2.63, 3.51, and 2.86. Likewise, each home exhibits different distance-dependent floor loss factors.

In order to obtain a worst-case large scale path loss model, we will assume that the same floor path loss exponent is the largest of those obtained in the three homes. That is, the same floor path loss exponent is 3.51. It was shown that the home which exhibited the largest same floor path loss exponent also exhibited the smallest distance-dependent floor loss factors. Thus, to produce a viable model, we will not simply select the largest floor loss factors of the three homes. Instead, we will assume that the floor loss factors are identical to those observed in the home with the largest same floor path loss exponent. Thus, we have the floor loss factors shown in equation (7.16).

$$FLF(d)=\begin{cases} 6dB,\ d \le 4m \\ 4dB,\ 4m < d \le 7m \\ 1dB, d > 7m \end{cases} \tag{7.16}$$

The proposed worst-case large scale path loss model is given in equation (7.17).

$$PL(d)=PL(d_0)+10(3.51)\log\left(\frac{d}{d_0}\right)+FLF(d) \tag{7.17}$$

The worst-case large scale path loss model is plotted in Figure7.9.

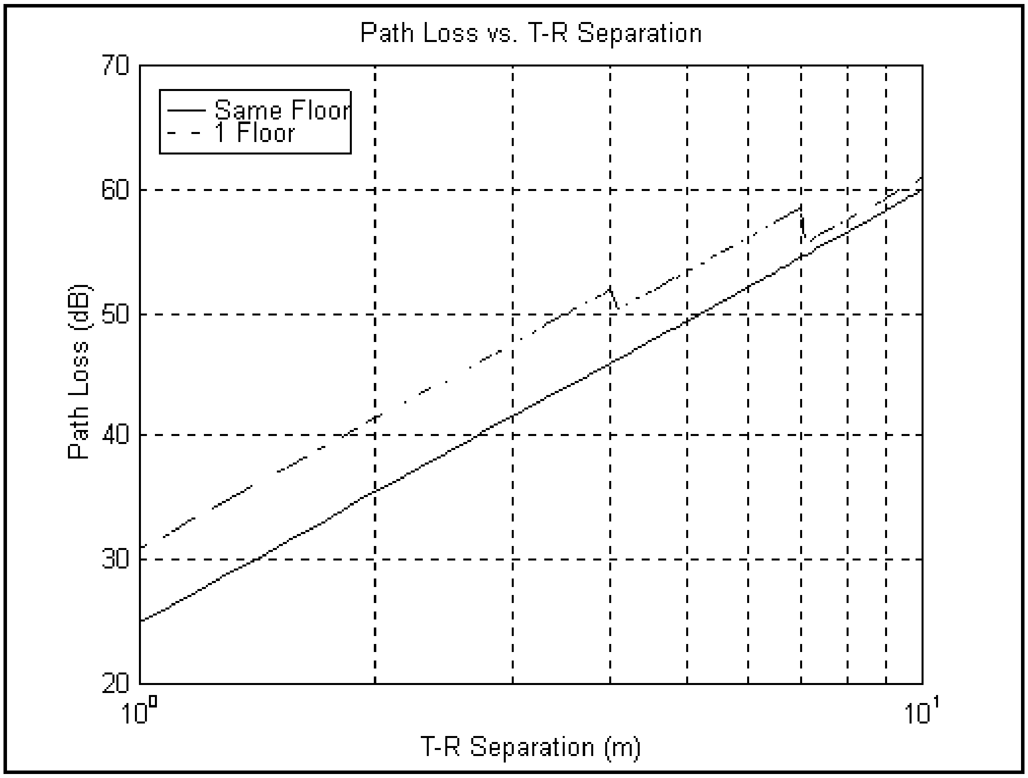

Figure 7.9: Worst-Case Large Scale Path Loss Model

The proposed worst-case large scale path loss modeled has been compared with the data measured in each home. Comparison results show that 83.9% of the same floor path loss measurements within the three homes are less than or equal to the path loss predicted by the worst case model. Likewise, 81.8% of the different floor measurements within the home are within the path losses predicted by this model. Thus, we can assume there is about an 82% probability that the path loss at a given T-R separation will be less than or equal to the path loss predicted by this worst-case model.

This indoor propagation study clearly indicates a need for a better understanding of indoor wave propagation within homes. Thus far, researchers have not found a large scale path loss model which closely matches measurements within homes. This may be an indication that new parameters need to be introduced into the path loss model, such as construction materials and layout of the home.