Application Note | October 2001 | AN9895.1

Authors: Karen Halford and Mark Webster

## Introduction

When comparing wireless LAN PHY products, it is customary to define performance in terms of the delay spread that can be tolerated. However, as we show in this tech brief, delay spread is NOT an indicator of performance unless the parameter is well defined and is related to a known channel model. In other words, simply knowing "the delay spread" of a particular system is meaningless without knowing more about that parameter and the channel model that was assumed.

This tech brief shows how a channel model can be used to describe the distortion in real world scenarios. We then describe two popular channel models as they relate to the real world, and the typical delay spread parameters are defined and compared for these two models.

## Representing Distortion in an Indoor Wireless Environment

As shown in Figure 1, when a communication signal is transmitted through the air to a receiver, that signal will likely take several different paths before it reaches the receiver. Because the transmitter does not know precisely where the receiver is, it must transmit in several different directions. However, the direct path from the transmitter to the receiver is not the only signal that is received. Reflectors in the environment (filing cabinets, computers, etc.) reflect aberrant signals back to the receiver. All of these signal paths are combined at the receiver to produce a signal that is a distorted version of the transmitted signal.

Figure 2 demonstrates distortion produced by these multiple signal paths. Notice that the received signal has a different appearance from the transmitted signal. As shown at the bottom of the illustration, these distortions can be represented by a single channel model. This channel model is then used to simulate the distortions encountered in similar wireless environments.

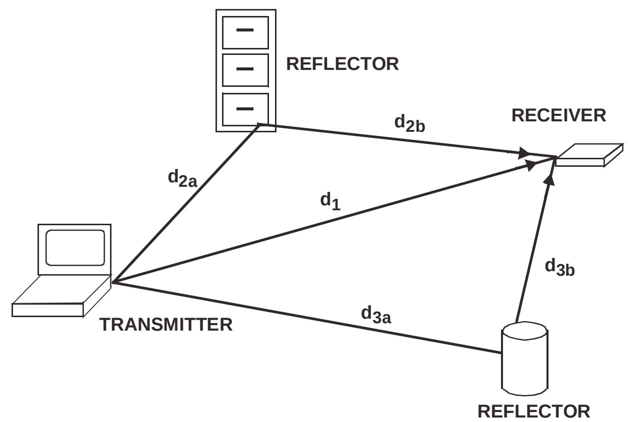



FIGURE 1. MULTIPATH ENCOUNTERED WHILE TRANSMITTING A SIGNAL THROUGH AN INDOOR WIRELESS ENVIRONMENT

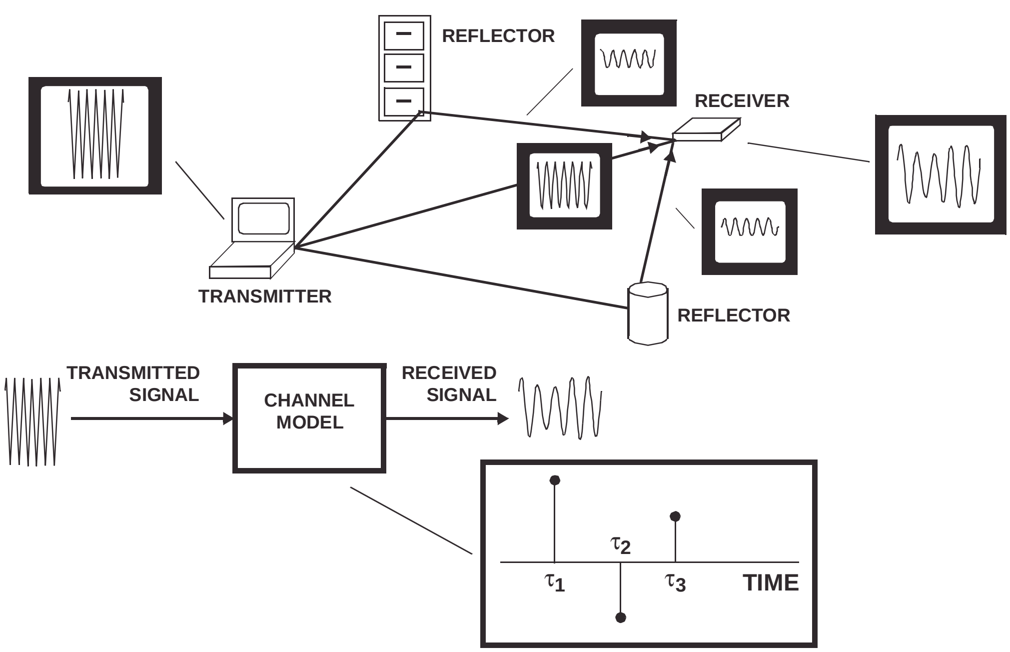



FIGURE 2. REPRESENTING DISTORTION IN AN INDOOR SYSTEM WITH A CHANNEL MODEL

In the simple example shown in Figure 1, the received signal can be modeled as 3 combined signals arriving at different times and with different amplitudes. The delay and amplitude of each path is largely a function of the length of the path; however, other factors such as the how much of the signal is absorbed by the reflector and movement of the reflector also impact the delay and amplitude of a given signal path.

## Channel Models for Indoor Wireless Communications

If we were to produce an exact channel model for a particular environment, we would need to know the attributes of every reflector in the environment at each moment in time. For instance, we would have to know the position of each reflector, how much of the signal was reflected back to the receiver, and whether or not the reflector was moving. Obviously, it is impossible to have this kind of information for a given environment at each point in time. Therefore, channel models have been developed that emulate the typical or average behavior of a channel. However, “typical” or “average” will vary widely depending on the environment of the channel. For instance, the reflectors encountered in a delivery warehouse will be very different from those encountered in a small conference room in an office building; the warehouse may contain a handful of reflectors that cause tremendous delays while the conference room may contain many reflectors that create small delays. Thus, when simulating a particular environment, it is important to choose an accurate channel model.

There are a plethora of channel models described in the literature; however, we describe two simple models that have become popular for indoor wireless environments. The first is a simple 2-ray model, and the second is a more complex exponential model.

### 2-Ray Model

The 2-ray channel model includes only two paths, a direct path and a reflected path with equal strength. The model is parameterized by the duration of the second delay, $\tau_d$. (In other words, the model can be completely characterized if $\tau_d$ is known.) Since the actual channel model can vary with time, the path delay profile is used to describe the average power of each path in the channel. The path delay profile for a 2-ray model is shown in Figure 3.

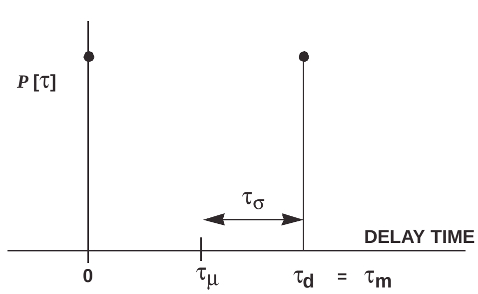



FIGURE 3. PATH DELAY PROFILE OF A 2-RAY CHANNEL MODEL

Three different path delay parameters are illustrated on the path delay profile in Figure 3: *mean excess delay*, $\tau_\mu$, *maximum excess delay*, $\tau_m$ and *RMS delay spread*, $\tau_\sigma$. The *mean excess delay* is simply the average delay of all the paths. The *maximum excess delay* is the last path delay with any “noticeable” amplitude. (A “noticeable” amplitude is typically 20dB below the peak amplitude.) The *RMS delay spread* is a measure of how “spread” the delays are about the mean. For the 2-ray model, the mean excess delay is:

,

$$\tau_\mu = \frac{1}{2}\tau_d$$

the maximum excess delay is:

$$\tau_m = \tau_d ,$$

and the RMS delay spread is:

$$\tau_\sigma = \frac{1}{2}\tau_d .$$

The 2-ray channel model is attractive because it is so simple; however, it is not a common scenario because the two paths have equal amplitude on average. Since the second path will suffer greater loss because the signal must travel further, the only way that this scenario will occur is when the first path passes through a barrier that absorbs some of the signal strength, as shown in Figure 4.

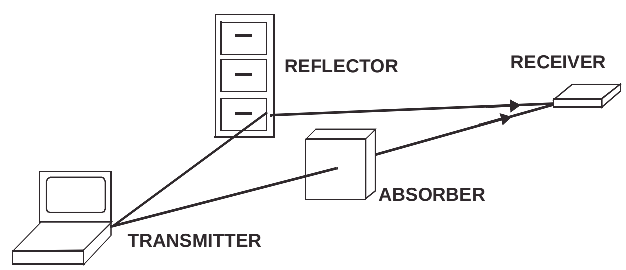



FIGURE 4. 2-RAY CHANNEL MODEL SCENARIO

### Exponential Model

An exponential channel model has a path delay profile that drops off exponentially. The channel model that is recommended in the IEEE 802.11 WLAN specification is an exponential channel model [1]. As shown in Figure 5, this model represents a real world scenario in which the positions of the reflectors generate paths that are longer and longer.

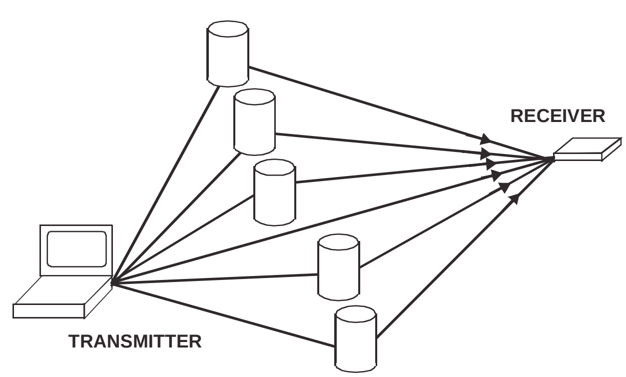



FIGURE 5. SCENARIO FOR EXPONENTIAL CHANNEL MODEL

As we can see from the scenario, this channel model is more realistic than the 2-ray model, and, although it tends to be a bit pessimistic, it is a reasonably accurate representation of many real world indoor wireless environments. As shown in Figure 6, the path delay profile for this model has the form: $P[\tau] = 1/\tau_d \exp(-\tau/\tau_d)$ where the parameter $\tau_d$ completely characterizes the path delay profile.

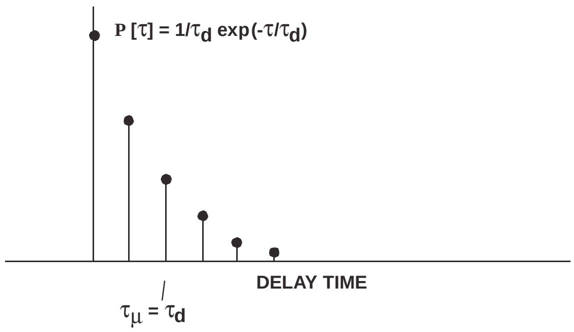



FIGURE 6. PATH DELAY PROFILE FOR AN EXPONENTIAL CHANNEL MODEL

For an exponential model, the *mean excess delay* is $\tau_\mu = \tau_d$, *RMS delay spread* is $\tau_\sigma = \tau_d$, and the *maximum excess delay*:

$$\tau_m = \frac{A \times \tau_d}{10 \times \log_{10}(e)},$$

where A is the amplitude of the smallest "noticeable" amplitude given in dB relative to the amplitude of the 0th delay (line of sight) path. For example, if the parameter $\tau_d = \tau_\mu = \tau_\sigma$ = 50ns, and the smallest noticeable amplitude is defined as 20dB below the amplitude of the 0th delay path, the maximum excess delay is 230ns. In other words, the delay must be 230ns before the average power of that path is 20dB below the direct path from transmitter to receiver.

Coincidentally, the mean excess delay spread is $\tau_\mu = \tau_d$, and the RMS delay spread is also $\tau_\sigma = \tau_d$. Thus, if the mean excess delay spread or the RMS delay spread is known, the path delay profile can be completely characterized.

### *Other Models*

We have described two popular channel models that are easily defined; however, as mentioned previously, there are many other channel models available. One interesting set of models is the JTC suite of models that was developed in 1994 by the Joint Standards Committee (JTC) as a "measuring stick" for wireless communications systems [8]. The JTC's indoor set of models encompasses three different indoor scenarios: residential, office and commercial areas. Each of these scenarios is represented by 3 different channel profiles. During a simulation, one of these channels is selected with some probability based on a parameter known as "path loss". Path loss is a function of path distance. Figure 7 shows the three channel profiles that are used in the "residential JTC model."

Notice in Channel C in Figure 7 that the largest path is not the most direct path. In this case, the signal that travels on a direct path is passing through some type of absorbent surface, and arrives at the receiver at a lower power than a signal that took a longer route.

The JTC model is typically easier to implement in hardware than the exponential channel model and harder to implement than the 2-ray model. This model is less challenging than the exponential model but more sophisticated than the 2-ray model. An advantage of the JTC model is that it was agreed upon in a standards committee as an acceptable model for wireless indoor communications and is therefore appropriate as a way to compare various systems' performance.

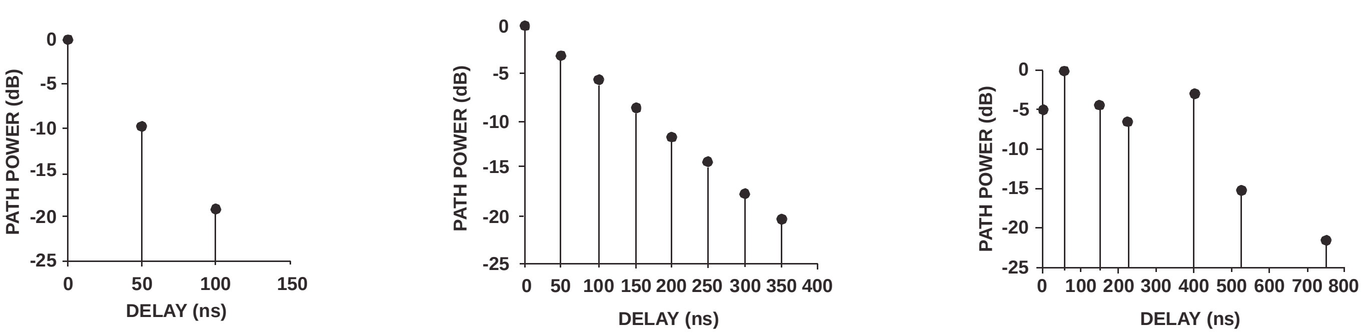



FIGURE 7. CHANNEL PROFILES FOR THE 3 DIFFERENT CHANNELS THAT COMPOSE THE "RESIDENTIAL" JTC MODEL

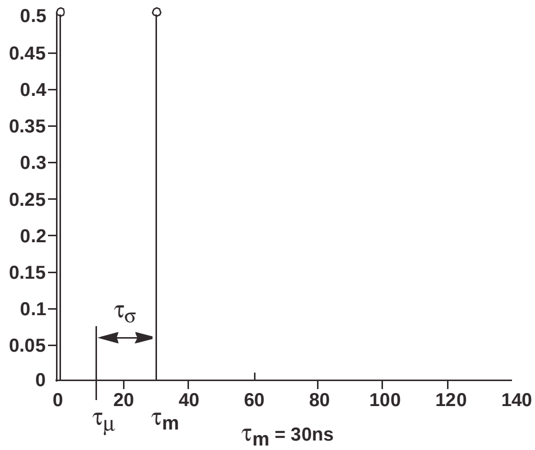



FIGURE 8A. 30ns MAXIMUM EXCESS DELAY

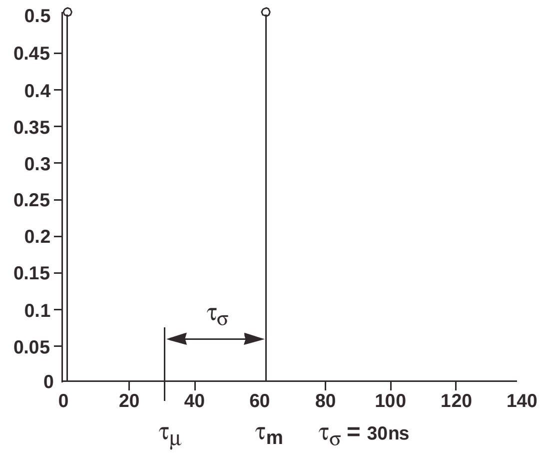



FIGURE 8B. 30ns RMS DELAY SPREAD

FIGURE 8. TWO-RAY CHANNEL MODELS WITH “DELAY SPREAD” OF 30ns

## Performance Evaluation Based on Delay Spread

As we have shown, it is critical to have some information about the channel model or path delay profile before drawing conclusions based on delay spread parameters. The term “delay spread” is ambiguous unless it is defined (e.g., *RMS delay spread, mean excess delay*, etc.) Also, vastly different channel models (which will produce very different performance results) can still have identical delay spread parameters. In this section we demonstrate how this confusion can cause one to draw incorrect conclusions about a particular receiver’s performance.

In Figure 8A, we show a 2-ray channel model with a *maximum excess delay* of 30ns and a second 2-ray channel model with an *RMS delay* of 30ns in Figure 8B. Notice that the second path of the channel with an *RMS delay* of 30ns takes twice as long to arrive as the other model. In fact, the *maximum excess delay* of the channel on the right is actually 60ns!

Simulations show that the channel model on the right is much more harsh than the one on the left even though they can both claim a “30ns delay spread.” This concept is demonstrated in Table 1 for an actual RAKE receiver for the 802.11 11Mbps CCK waveform. In this table, both rows show performance of a 2-ray channel model with a “100ns delay spread.” However, notice that the packet error rate is 0% if that the delay spread is simulated as *maximum excess delay*, and it is 10% if the delay spread is simulated as *RMS delay*. This shows that an identical receiver will yield very different performance depending on the definition of the delay spread parameter.

TABLE 1. PACKET ERROR RATE COMPARISON OF A 2-RAY CHANNEL MODEL WITH DELAY SPREADS OF 100ns

| RMS DELAY (ns) | MAXIMUM EXCESS DELAY (ns) | % PACKET ERROR |
|---|---|---|
| 50 | 100 | 0.0 |
| 100 | 200 | 10.0 |

NOTE: The top row has a maximum excess delay of 100ns, and the bottom row has an RMS delay of 100ns.

We have shown specific examples of two popular types of channel models: the 2-ray model and the exponential model. Using these two models, we can demonstrate the confusion that can occur when a delay spread parameter is given, but no channel model is indicated. In Figure 9, we show these two models with equivalent *mean excess delays*, $\tau_\mu$, and *RMS delay spreads*, $\tau_\sigma$; however, notice the huge difference between these two models. Not only does the exponential model contain many more paths, but we also find that the exponential model has more than twice the *maximum excess delay* of the 2-ray model! Therefore, it is very important to define the channel model associated with a particular delay parameter.

Figure 10 demonstrates the performance of a 2-ray and exponential channel model for different RMS delay spreads. The left plot shows the performance of a RAKE receiver with an equalizer, and the right plot shows the performance of a RAKE receiver without an equalizer. The details of the simulation are shown below the plots. These plots show that the exponential channel model is more challenging than the 2-ray model. In particular, an identical RAKE receiver without equalizer performs dramatically differently at 100ns RMS delay spread for the two channel models: the 2-ray model has a packet error rate of 0.0% while the exponential model has a packet error rate of 24%. The exact same receiver yields vastly different results depending on the channel model.

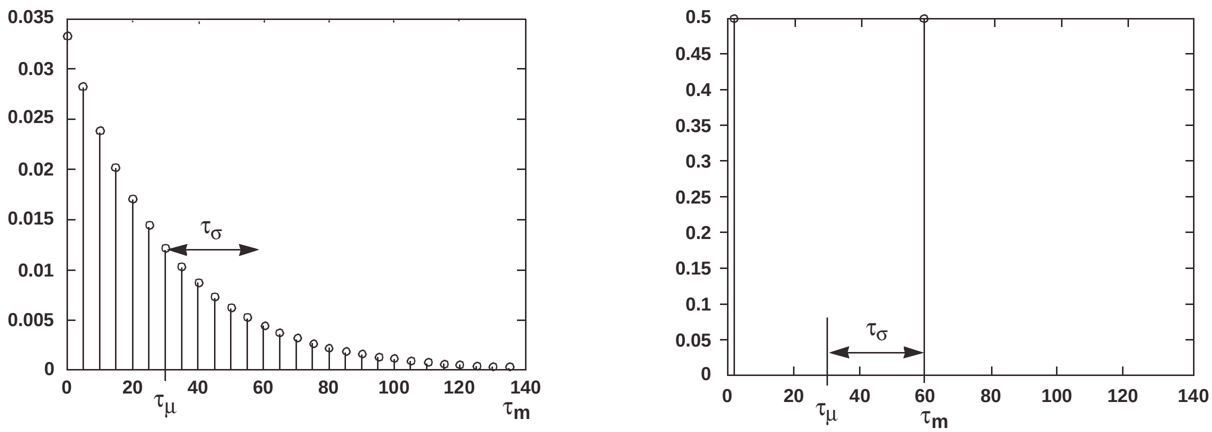
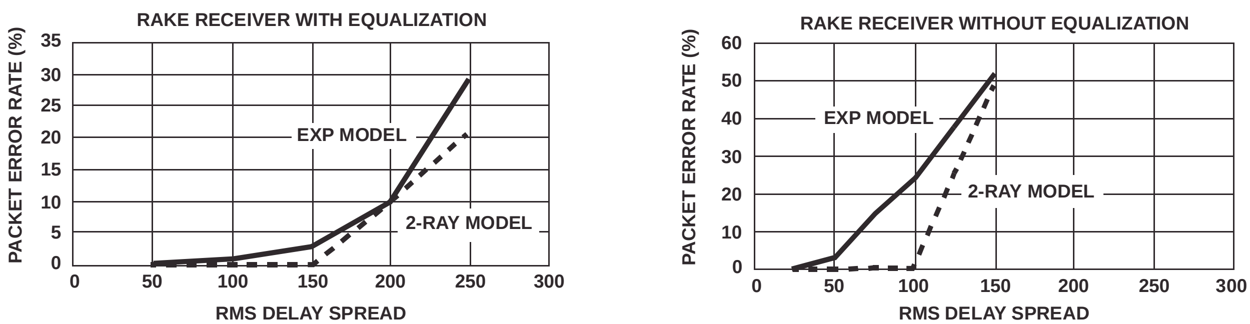



FIGURE 9. DELAY PROFILE FOR AN EXPONENTIAL PROFILE (LEFT) AND A 2 -RAY MODEL (RIGHT) WITH THE SAME RMS DELAY SPREAD. THE OTHER DELAY SPREAD PARAMETERS ARE INDICATED ON THE PLOTS.




SIMULATION PARAMETERS

| Signal Type: CCK 11Mbps | SNR: 20dB | IMPAIRMENTS: Channel Sample Rate: |
|---|---|---|
| Packets: 1000 | ADC/DAC | 8 Samples/Chip |
| Packet Size: 1024 bytes | Frequency Offset | Matched-Filter Sample Rate: |
| | Analog Chip Distortion | 2 Samples/Chip |

FIGURE 10. PERFORMANCE OF A RECEIVER WITH AND EQUALIZER AND WITHOUT AN EQUALIZER USING A 2-RAY MODEL AND AN EXPONENTIAL MODEL FOR VARYING RMS DELAY SPREADS.

Table 2 enumerates the major differences between the 2-ray model and the exponential model.

TABLE 2. COMPARISON OF 2-RAY CHANNEL MODEL TO EXPONENTIAL CHANNEL MODEL

| | 2-RAY MODEL | EXPONENTIAL MODEL |
|---|---|---|
| Maximum Excess Delay | $\tau_m = \tau_d$ | $\tau_m = \frac{A \times \tau_d}{10 \times \log_{10}(e)}$ |
| Mean Excess Delay | $\tau_\mu = \frac{1}{2}\tau_d$ | $\tau_\mu = \tau_d$ |
| RMS Delay Spread | $\tau_\sigma = \frac{1}{2}\tau_d$ | $\tau_\sigma = \tau_d$ |
| Complexity | Very Low | Low to Medium |

In conclusion, we have shown that the performance of a system can only be predicted based on a “delay spread” parameter if the channel model is known and the delay spread parameter is defined. We gave specific examples where performance results for identical receivers were drastically different depending on the channel model and the delay spread parameter. At Intersil, it is common practice to use an exponential model or the JTC model when testing for delay spread, and results are typically reported in terms of RMS delay spread.

## RMS Delay Spread Measurements

Table 3 is an overview of delay spread measurements from the literature. The “mean RMS delay spread” is the average of a set of RMS delay spread measurements. The “median RMS delay spread” is the median value in a set of RMS delay spread measurements (meaning half of the measurements were larger and half were smaller than this value.) The “maximum RMS delay spread” is the maximum RMS delay spread that was recorded in the set of measured RMS delay spreads. The table is broken into three main sections: a benign environment, a moderate environment, and a difficult environment.

We can see from this table that even a single room in an office building has nontrivial delay spread. In other words, even over a short range with a line of sight path between the transmitter and receiver such as a conference room, there is still distortion due to reflected paths. Therefore, performance can be improved by eliminating this distortion.

The moderate environments have much more significant RMS delay spreads. These environments will require a system that compensates for delay spreads of 50ns to 100ns. Although, the moderate environment in this table does not explicitly include multi-family dwellings such as condominiums or apartment buildings, these environments will fall in this category.

The table also illustrates how systems placed in larger indoor areas such as shopping centers and laboratories can have significant delay spreads. This is particularly true when there is no line of sight (LOS) path from the transmitter to the receiver. A communication system placed in this environment must be able to handle delay spreads of 100ns at the desired data rate, or it will only work intermittently.

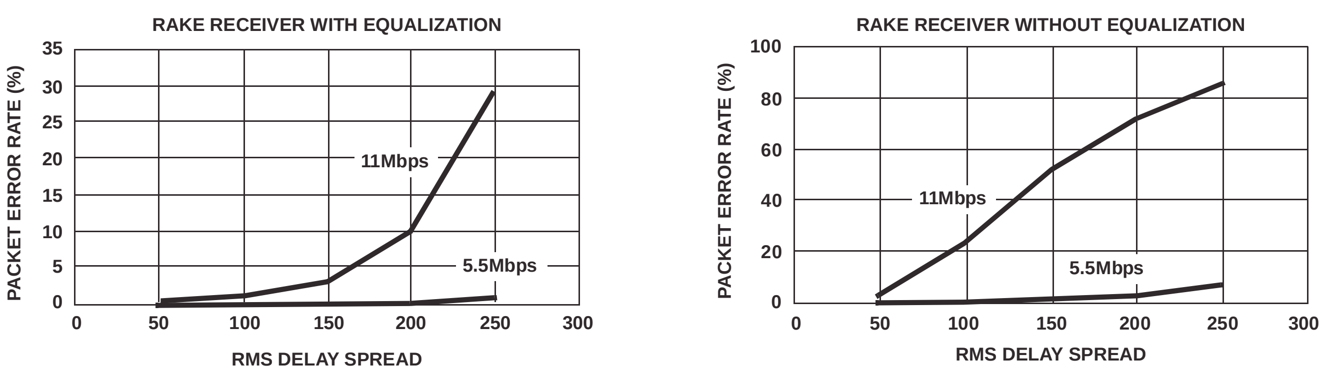
Figure 11 compares the performance two receivers for 11Mbps and 5.5Mbps (802.11 CCK waveform) for an exponential channel model. In the left plot, an equalizer was included. In the right plot, there was no equalizer. These plots combined with the results from the table above show that the 5.5Mbps system can tolerate even a difficult environment. The 11Mbps receiver with an equalizer will also perform very well even in difficult environments.

**TABLE 3. RMS DELAY SPREADS MEASUREMENTS FROM REAL ENVIRONMENTS**

| | MEAN RMS DELAY SPREAD | MEDIAN RMS DELAY SPREAD | MAXIMUM RMS DELAY SPREAD | LOCATION/CONDITION | REFERENCE |
|---|---|---|---|---|---|
| Benign Environment | (Note 1) | 25 | 30 | Office Building; Single Room | [2] (Note 2) |
| Moderate Environment | (Note 1) | 30 | 75 | Cafeteria | [4] (Note 2) |
| | 42 | (Note 1) | 65 | Eng. Building LOS | [6] |
| | 23 | (Note 1) | 74 | Retail Store LOS | [6] |
| | (Note 1) | 40 | 150 | Office Building | [3] |
| | 56 | (Note 1) | 75 | Eng. Building Lightly Obstructed | [6] |
| Difficult Environment | 70 | (Note 1) | 85 | Eng. Building Heavily Obstructed | [6] |
| | 74 | (Note 1) | 97 | Retail Store Lightly Cluttered | [6] |
| | 84 | (Note 1) | 100 | Retail Store Heavily Cluttered | [6] |
| | (Note 1) | 105 | 170 | Shopping Center | [4] (Note 2) |
| | (Note 1) | 106 | 270 | Laboratory | [5] (Note 2) |

NOTES:

1. Information Not Available.
2. Taken from reference [7].




**SIMULATION PARAMETERS**

| | | |
|---|---|---|
| | | IMPAIRMENTS: |
| Signal Type: CCK 11Mbps | SNR: 20dB | Channel Sample Rate: |
| Packets: 1000 | ADC/DAC | 8 Samples/Chip |
| Packet Size: 1024 bytes | Frequency Offset | Matched-Filter Sample Rate: |
| | Analog Chip Distortion | 2 Samples/Chip |

**FIGURE 11. PERFORMANCE A RECEIVER WITH AN EQUALIZER AND WITHOUT AN EQUALIZER FOR 2 DIFFERENT DATA RATES OVER VARIOUS RMS DELAY SPREADS FOR AN EXPONENTIAL CHANNEL MODEL.**

## Conclusion

We have shown that receiver performance based on “delay spread” means nothing unless the term “delay spread” is both defined and accompanied by a channel model. It is easy to misinterpret performance results based on a “delay spread parameter” unless that parameter is understood.

Two popular channel models used to simulate multipath environments are the 2-ray model and the exponential model. The 2-ray model is the simplest, but the exponential model is more realistic. We defined several delay spread parameters for each of these models and compared their performance for some specific waveforms and receivers.

Finally, we showed results from real world delay spread measurements. We concluded that even a typical, benign environment will contain some delay spread. Moderate environments such as office buildings and multi-family dwellings have RMS delay spreads that are in the range of 50ns - 100ns. Finally, difficult environments such as retail stores and factories can have RMS delay spreads in excess of 100ns. Using this information combined with simulation results on the 802.11 CCK waveform, we concluded that a receiver with an equalizer can handle even the most difficult environments at a data rate of 11Mbps. A RAKE receiver without an equalizer can handle these harsh environments at a rate of 5.5Mbps.

## JTC ‘94 Indoor Channel Model

**INDOOR RESIDENTIAL A** RMS Delay Spread = 18ns

| TAP | DELAY (ns) | DELAY n (n*1/88M) | AVG POWER (dB) | AVG. POWER (FRAC.) | VOLTAGE GAIN |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 |
| 2 | 50 | 4 | -9.4 | 0.114815362 | 0.338844156 |
| 3 | 100 | 9 | -18.9 | 0.012882496 | 0.113501082 |

**INDOOR RESIDENTIAL B** RMS Delay Spread = 70ns

| TAP | DELAY (ns) | DELAY n (n*1/88M) | AVG. POWER (dB) | AVG. POWER (frac.) | VOLTAGE GAIN |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 |
| 2 | 50 | 4 | -2.9 | 0.512861384 | 0.71614341 |
| 3 | 100 | 9 | -5.8 | 0.263026799 | 0.512861384 |
| 4 | 150 | 13 | -8.7 | 0.134896288 | 0.3672823 |
| 5 | 200 | 18 | -11.6 | 0.069183097 | 0.263026799 |
| 6 | 250 | 22 | -14.5 | 0.035481339 | 0.188364909 |
| 7 | 300 | 26 | -17.4 | 0.018197009 | 0.134896288 |
| 8 | 350 | 31 | -20.3 | 0.009332543 | 0.096605088 |

**INDOOR RESIDENTIAL C** RMS Delay Spread = 150ns

| Tap | Delay (ns) | Delay n (n*1/88M) | Avg Power (dB) | Avg. Power (frac.) | Voltage Gain |
|---|---|---|---|---|---|
| 1 | 0 | 0 | -4.6 | 0.34673685 | 0.588843655 |
| 2 | 50 | 4 | 0 | 1 | 1 |
| 3 | 150 | 13 | -4.3 | 0.371535229 | 0.609536897 |
| 4 | 225 | 20 | -6.5 | 0.223872114 | 0.473151259 |
| 5 | 400 | 35 | -3 | 0.501187234 | 0.707945784 |
| 6 | 525 | 46 | -15.2 | 0.030199517 | 0.173780083 |
| 7 | 750 | 66 | -21.7 | 0.00676083 | 0.082224265 |

**INDOOR OFFICE A** RMS Delay Spread = 35 ns

| Tap | Delay (ns) | Delay n (n*1/88M) | Avg Power (dB) | Avg. Power (frac.) | Voltage Gain |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 |
| 2 | 50 | 4 | -3.6 | 0.436515832 | 0.660693448 |
| 3 | 100 | 9 | -7.2 | 0.190546072 | 0.436515832 |

**INDOOR OFFICE B** RMS Delay Spread = 100ns

| TAP | DELAY (ns) | DELAY n (n*1/88M) | AVG POWER (dB) | AVG. POWER (FRAC.) | VOLTAGE GAIN |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 |
| 2 | 50 | 4 | -1.6 | 0.691830971 | 0.831763771 |
| 3 | 150 | 13 | -4.7 | 0.338844156 | 0.582103218 |
| 4 | 325 | 29 | -10.1 | 0.097723722 | 0.312607937 |
| 5 | 550 | 48 | -17.1 | 0.019498446 | 0.139636836 |
| 6 | 700 | 62 | -21.7 | 0.00676083 | 0.082224265 |

**INDOOR OFFICE C** RMS Delay Spread = 450ns

| TAP | DELAY (ns) | DELAY n (n*1/88M) | AVG POWER (dB) | AVG. POWER (FRAC.) | VOLTAGE GAIN |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 |
| 2 | 100 | 9 | -0.9 | 0.812830516 | 0.901571138 |
| 3 | 150 | 13 | -1.4 | 0.72443596 | 0.851138038 |
| 4 | 500 | 44 | -2.6 | 0.549540874 | 0.741310241 |
| 5 | 550 | 48 | -5 | 0.316227766 | 0.562341325 |
| 6 | 1125 | 99 | -1.2 | 0.758577575 | 0.87096359 |
| 7 | 1650 | 145 | -10 | 0.1 | 0.316227766 |
| 8 | 2375 | 209 | -21.7 | 0.00676083 | 0.082224265 |

**INDOOR COMMERCIAL A** RMS Delay Spread = 55ns

| TAP | DELAY (ns) | DELAY n (n*1/88M) | AVG POWER (dB) | AVG. POWER (FRAC.) | VOLTAGE GAIN |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 |
| 2 | 50 | 4 | -2.9 | 0.512861384 | 0.71614341 |
| 3 | 100 | 9 | -5.8 | 0.263026799 | 0.512861384 |
| 4 | 150 | 13 | -8.7 | 0.134896288 | 0.3672823 |
| 5 | 200 | 18 | -11.6 | 0.069183097 | 0.263026799 |

**INDOOR COMMERCIAL B** RMS Delay Spread = 150ns

| TAP | DELAY (ns) | DELAY n (n*1/88M) | AVG POWER (dB) | AVG. POWER (FRAC.) | VOLTAGE GAIN |
|---|---|---|---|---|---|
| 1 | 0 | 0 | -4.6 | 0.34673685 | 0.588843655 |
| 2 | 50 | 4 | 0 | 1 | 1 |
| 3 | 150 | 13 | -4.3 | 0.371535229 | 0.609536897 |
| 4 | 225 | 20 | -6.5 | 0.223872114 | 0.473151259 |
| 5 | 400 | 35 | -3 | 0.501187234 | 0.707945784 |
| 6 | 525 | 46 | -15.2 | 0.030199517 | 0.173780083 |
| 7 | 750 | 66 | -21.7 | 0.00676083 | 0.082224265 |

**INDOOR COMMERCIAL C** RMS Delay Spread = 500ns

| TAP | DELAY (ns) | DELAY n (n*1/88M) | AVG POWER (dB) | AVG. POWER (FRAC.) | VOLTAGE GAIN |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 1 |
| 2 | 50 | 4 | -0.4 | 0.912010839 | 0.954992586 |
| 3 | 250 | 22 | -6 | 0.251188643 | 0.501187234 |
| 4 | 300 | 26 | -2.5 | 0.562341325 | 0.749894209 |
| 5 | 550 | 48 | -4.5 | 0.354813389 | 0.595662144 |
| 6 | 800 | 70 | -1.2 | 0.758577575 | 0.87096359 |
| 7 | 2050 | 180 | -17 | 0.019952623 | 0.141253754 |
| 8 | 2675 | 235 | -10 | 0.1 | 0.316227766 |

## References


[1] Chayat, Naftali, "Tentative Criteria for Comparison of Modulation Methods, *IEEE P802.11-97-96*, September, 1997.

[2] Nobles, P., and F. Halsall, "Delay Spread and Received Power Measurements Within a Building at 2GHz, 5GHz, and 17GHz', *IEEE Tenth International Conference on Antennas and Propagation*, Edinburgh, UK, April 14-17, 1997.

[3] Devasirvatham, D.M.J, M.J. Krain and D. A. Rappaport, "Radio Propagation Measurements at 850MHz, 1.7GHz and 4GHz Inside Two Dissimilar Office Buildings," *Electronics Letters*, Vol. 26, No. 7, pp. 445-447, March 29, 1990.

[4] Anderson, P. C., O.J.M Houen, K. Kladakis, K. T. Peterson, H. Fredskild and I. Zarnoczay, "Delay Spread Measurements at 2GHz," COST 231 TD (91)029.

[5] Johnson, I. T., and E. Gurdenelli, "Measurements of Wideband Channel Characteristics in Cells Within Man Made Structures of Area Less Than 0.2km$^2$," COST 231 TD(90)083.

[6] Kim, Seong-Cheol, Henry L. Bertoni and Miklos Stern, "Pulse Propagation Characteristics at 2.4GHz Inside Buildings," *IEEE Transactions on Vehicular Technology*, Vol. 45, No. 3, August 1996.

[7] Van Nee, Richard, Ramjee Prasad, *OFDM for Wireless Multimedia Communications*, Artech House, Boston, 2000.

[8] Pahlavan, K., Allan Levesque, Allen Levesque, *Wireless Information Networks*, Wiley-Interscience; ISBN: 0471106070, New York, 1995.




## Sales Office Headquarters


**NORTH AMERICA**
Intersil Corporation
7585 Irvine Center Drive
Suite 100
Irvine, CA 92618
TEL: (949) 341-7000
FAX: (949) 341-7123

Intersil Corporation
2401 Palm Bay Rd.
Palm Bay, FL 32905
TEL: (321) 724-7000
FAX: (321) 724-7946

**EUROPE**
Intersil Europe Sarl
Ave. C - F Ramuz 43
CH-1009 Pully
Switzerland
TEL: +41 21 7293637
FAX: +41 21 7293684

**ASIA**
Intersil Corporation
Unit 1804 18/F Guangdong Water Building
83 Austin Road
TST, Kowloon Hong Kong
TEL: +852 2723 6339
FAX: +852 2730 1433