Microwaves & RF

DESIGN FEATURE

Wireless Connectivity

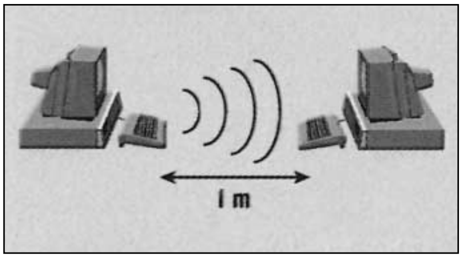
Modeling Systems Based On Bluetooth Wireless Connectivity

Accurate channel models and precise propagation simulations are needed to reasonably predict the performance of Bluetooth systems.

W. Robert Nichols II
Senior Design Engineer
Noise Products, Micronetics Wireless,
26 Hampshire Dr., Hudson, NH
03051; (603) 883-2900, FAX: (603)
882-8987.

Moeness G. Amin
Professor, Department of Electrical and Computer Engineering
Villanova University, Villanova, PA
19085; (610) 519-7305, FAX: (610)
519-4436.

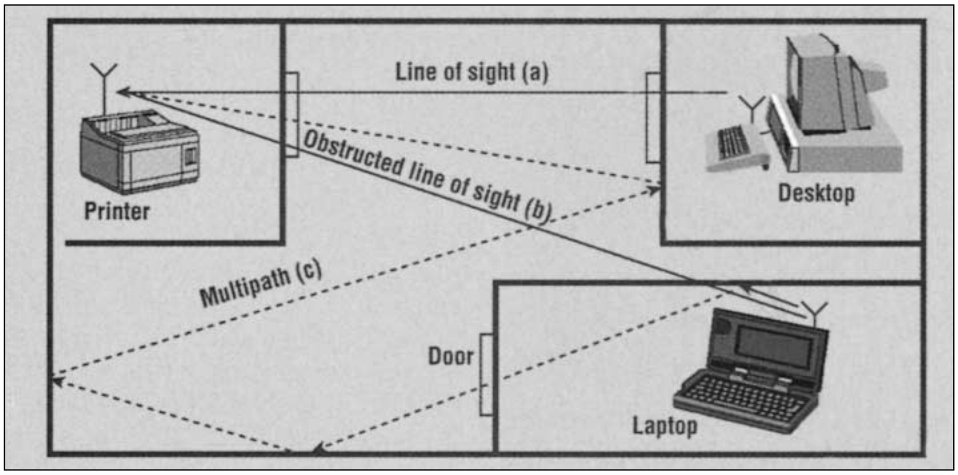
SHORT-RANGE wireless connectivity solutions for the home and office, such as Bluetooth, will simplify the transfer of control and data signals between electronic devices. As the number of devices equipped with wireless connectivity capability increases, it makes sense to evaluate the effects of multipath and Doppler shifts, due to reflectivity and mobility, on voice- and data-transmission quality. Identifying the sources of channel impairments on the signals transmitted and received with this enabling technology is important for proper use of any new devices which are designed for the underlying applications. In this article, residential homes and their short-range communication channel characteristics will be discussed. With small Doppler shifts and the absence of large delay spreads, testing and performance evaluations of the short-range wireless connectivity inside our homes may prove to be plain and simple when performed using designated RF faders and channel simulators.



1. A typical application for IrDA devices is the exchange of data between two closely spaced laptop computers.

Driven by declining prices for personal computers (PCs), free wireless phones equipped with the third-generation (3G) wideband-cellular-telephony technology, the boom in Internet usage, on-line trading, banking and shopping, recent trends in higher education that require college students to purchase and use their own computers, rapid increases in the number of home offices, and a drop in the percentage of corporate employees commuting to work, a typical home in the new millennium will be poised to house laptop and desktop computers, printers, scanners, pagers, and cordless wired and wireless telephones. Connectivity among these devices will become a necessity to share resources, such as scanners and printers, transfer e-mail, Internet, and video data among wired and wireless units. Connectivity must

Reprinted with permission, from Microwaves & RF, August 2000 by Reprint Services. 206204
For reorders call Reprint Services at 651-582-3800. For subscription information, call 201-393-6060.



2. In a typical home environment, RF transmissions can experience a variety of multipath conditions.

incorporate the mobility of pagers, wireless and cordless phones, as well as the immobility of PCs and the portability of laptop computers.

Home local-area networks (LANs) using telephone lines as a tool for connectivity are faced with difficult challenges due to variations in the lines' voltage levels and impedance, poor shielding, and improper line termination.[1] Furthermore, the use of phone lines, in general, limits mobility and does not lend itself to future integration of all electrical and electronic devices at home. It is foreseen that home appliances will soon be equipped with wireless transmission to communicate household information to PCs or wireless devices. The alternative to wired connectivity is the wireless short-range connectivity offered by Bluetooth technology at 2.4 GHz.

Short-range wireless connectivity between computer and telecommunication devices at home is within reach.[2] As more devices become available, this technology must be tested and evaluated using RF-channel faders and simulators which generate proper signal impairments for this application. As discussed in the following sections, due to the nature of human occupancy in residential homes and home sizes, Doppler and delay spread are minimal, causing the wireless indoor-communication channel to be either stationary or a very slowly varying Rician flat-fading channel.

Bluetooth[2] is a standard for short-range voice and data transfer through low-power RF transmission and reception. Bluetooth can transmit through solid, non-metal objects. Its nominal link range is from 10 cm to 10 m, but it can be extended to 100 m by increasing the transmitted power. It is based on a low-cost, short-range radio link, and facilitates ad-hoc connections for stationary and mobile-communication environments. This technology will enable users to connect to a wide range of computing and telecommunications devices without the need to buy, carry, or connect cables. It can be used in phones, pagers, modems, LAN-access devices, headsets, as well as notebook, desktop, and handheld computers.

Bluetooth generally operates in the license-free 2.4-GHz industrial-scientific-medical (ISM) band. It offers the capability of non-line-of-sight transmission and reception through walls and other solid objects with only moderate attenuation. This is in contrast to infrared (Ir) devices built according to the Infrared Data Association (IrDA) standards, which require a short direct nonobstructed path from the transmitter (Tx) to the receiver (Rx). Figure 1 shows a typical application of IrDA in exchanging business cards between two closely spaced laptop computers. The line-of-sight requirement limits connectivity, as it lacks the flexibility to connect a wireless device to a wired network, and thus reduces the options in placing a LAN-access point within the premises.

In contrast to IrDA, which requires that the Rx be within 30 deg. of a direct line of sight with the Tx, Bluetooth is omnidirectional. That is, the Tx signal is radiated with equal power in all directions, implementing point-to-multipoint propagation. In addition, Bluetooth offers 10 times the range of IrDA devices. Bluetooth uses frequency-hopping, spread-spectrum (FHSS) techniques to combat potential interlopers from baby monitors, garage-door openers, cordless phones, and microwave ovens, all of which operate in the same frequency band. Bluetooth can support up to eight devices in a piconet, and more devices can be added by linking piconets. It has built-in security, and supports isochronous and asynchronous services and easy integration of transmission-control protocol/Internet protocol (TCP/IP) for networking.[2]

Wireless communications channel-modeling and signal-fading characteristics in residential homes are guided by three fundamental factors—the nature of human occupancy, home design, and structural materials. While the first factor mainly determines ambient motions and subsequently sets the Doppler shifts and defines the time-varying characteristics of the communication channel, the other two factors are mostly responsible for the multipath-profile signature, delay spread, and path loss between the Tx and the Rx. Spatial information regarding the correlation of signals among multiple antennas, direction of arrivals, and multipath angle spread are key parameters describing the spatial channel for smart-antenna technology. At present, these parameters do not play an important role in single, omnidirectional Rx/Tx communications associated with short-range connectivity.

There are fewer occupants in any residential home compared to the two cases of an office building or a commercial area. The latter includes manufacturing floors, shopping malls, storage places, and transportation stations. Often, people inside their homes are either sitting down or standing up. Furthermore, since it is not a standard practice to buy new furniture or move furniture around the house, home furniture and appliances should be considered in constant stationary modes and viewed as fixed reflectors of electromagnetic (EM) waves.

In indoor settings, PCs, laptop computers, printers, and other computer devices and equipment are not typically used while in motion. Subsequently, the only potential mobile Rxs or Txs in residential areas are typically cordless and wireless telephones and personal digital assistants (PDAs). Within the home, it is unlikely that a person would continuously walk during an entire call. Their movements would most likely be characterized by repeated patterns of moving and then being stationary. Therefore, Doppler spreads associated with the use of wireless units, caused by holding these mobile units or reflecting their signals, are smaller in residential homes when compared to other indoor-propagation environments.

In fact, Doppler spreads in homes will hardly reach the maximum frequency recommended by the Personal Communications Services (PCS) Joint Technical Committee for indoor pedestrian-communication environments. This frequency is 9.6 Hz for services operating at 2 GHz. By examining the nature of human occupancy, it is safe to assume negligible Doppler spreads in a typical residential home over long periods of daytime, and zero Doppler spread during the night.

Residential homes represent the smallest sites for indoor communications. For short-range connectivity and by the virtue that the Tx and Rx are contained in the same home, there is modest path loss due to the distance traveled in free-space at home compared to outdoor propagation. If the loss in the first meter is 30 dB,[3] and a free-space loss of 6 dB per octave is factored in, then a house that is 24 m long will attenuate the signal by 54 dB, as it propagates from one end of the home to the other. The signal-power attenuation is also caused by losses associated with signals traveling through exterior and interior building structures. Residential homes are typically wooden-framed, low-ceilinged, single-family units with one or two stories. The interior walls are usually covered with a thin layer of plaster inside cardboard. The exterior frame is often filled with insulation and covered by layers of plywood and wooden or aluminum (A1) siding or brick. In contrast to indoor-office areas, houses are not usually built using metallic studs and concrete frames and their floors often do not contain large amount of metal and concrete. There are almost no, or very few, large metal objects or cubicles, for which there is no application or use at home. The table shows typical partition losses that were measured in office buildings.[4] Comprehensive tables for average signal-loss measurements reported by various researchers for radio paths obstructed by common building material are given in Ref. 5. The first four measurements in the table were gained at 815 MHz, whereas the last two measurements in the table were performed at 9.6 MHz.

The last three values in the table apply to residential-home indoor communications and show losses possibly up to a maximum of 7 dB per interior partition. Signals penetrating the exterior walls are sufficiently attenuated to be considered a distressing source of interference to nearby homes. Conversely, it is maintained that, unlike commercial areas, residential homes have several glass windows that may remain open most of the summer and spring seasons. Signals escaping one home to a neighboring home in very close proximity through open windows can be considered a worrisome source of interference that can be eliminated only if FHSS-communication protocols are different in the two homes. More typical and fundamental interference sources in short-range communications in residential areas are caused by the microwave oven and garage-door openers.

Detailed statistical modeling and computer simulation of indoor radio channels can be found in refs. 6-8. The formula for path loss in a residential home of a signal traveling within the same floor is given by:

$$L_p = L_o + 10n\log_{10}d + \sum_{m=1}^{N} P_m \qquad (1)$$

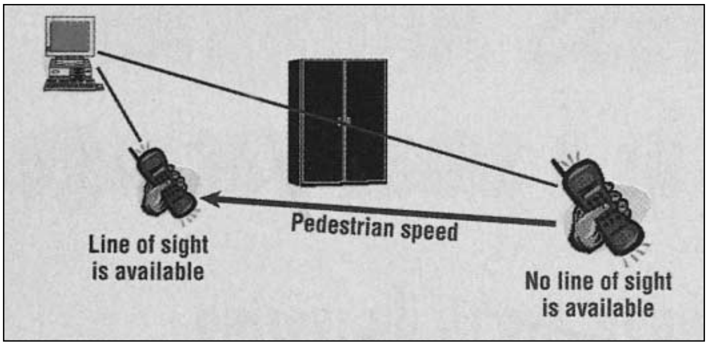
where:

n = 2 for the underlying short-range applications, L_o is the drop in power in decibels at 1 meter, d is the overall distance between two communicating devices. The last term in Eq. 1 represents the drop in power due to path obstruction by N home interior walls. The terms in the summation in Eq. 1 may be considered equal, as the interior walls do not vary much in texture and thickness.

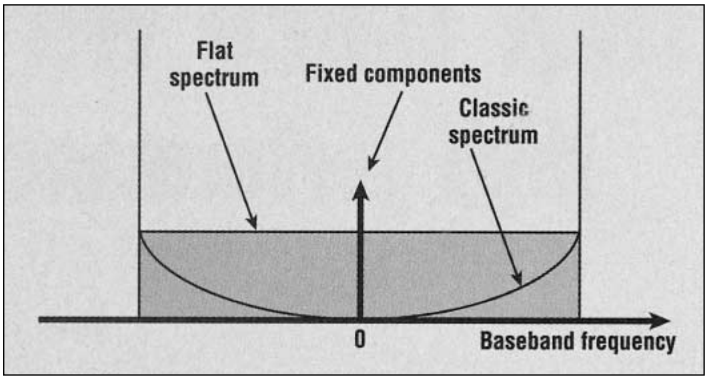
Figure 2 shows one possible short-range connectivity setting that includes a laptop, PC, and a printer, each in a separate room. With the room doors open, the PC has a line of sight to the printer (a). In this case, only the first term of the path loss in Eq. 1 applies. Conversely, the laptop and the printer can only communicate either through an obstructed line of sight or multipaths. With the transmitted signal power dropping 6 dB per octave, and considering typical room and hallway sizes in residential homes, it is easily realized that the transmitted signal along path (b) obstructed by a plywood wall is received at the printer with higher power than the signal along multipath (c). The latter looses power due to the long distance traveled and also due to the attenuation incurred from the reflections against the interior walls.

BECAUSE OF POTENTIAL MULTIPATH CONDITIONS WITHIN INDOOR HOME AND OFFICE ENVIRONMENTS, IT IS IMPORTANT IN BLUETOOTH APPLICATIONS TO FIND “BLIND SPOTS” AS WELL AS OPTIMUM LOCATIONS.

It should be mentioned that there are several other possible multipaths in the specific home structure depicted in Fig. 2 that could connect the printer to the two computers through reflections from walls, floors, and ceilings. Many of those multipaths, after a certain number of reflections and transmissions through walls are sufficiently attenuated and their effects on signal fading are therefore negligible. It is also important to



3. When a Tx and/or Rx moves within the home environment, new conditions of multipath can be created and line-of-sight signal paths can be obstructed.



4. The classic of U-shaped Doppler spectrum is shown in contrast to a flat-shaped Doppler spectrum.

point out that Fig. 2 only shows one example of specular multipath. This is because at approximately 2-GHz center frequency, most surfaces of reflection in homes are relatively smooth and the scattered media that produces diffuse reflections are minimal. Therefore, diffuse multipaths for short-range connectivity applications in homes can be ignored.

As mentioned previously, the bit rate used in Bluetooth is 10 Mb/s (i.e., the bit duration is 100 µs). EM propagation travels at the speed of light, or 3 x 10^8 m/s, so one bit is approximately 30 m long. Frequency-selective fading responsible for intersymbol interference would occur if the path differences inside the residential home were significant portions of 30 m. Propagation experiments conducted for small buildings show that the maximum delays are in the order of 100 ns (this value will become smaller when specifically considering residential homes). The distance traveled over the aforementioned maximum delay spread is 30 m. Not counting the loss due to reflections, this 30-m distance causes an approximate 30-dB drop in power relative to a signal that is received one meter away from the Tx. This drop is significant and causes any resolvable multipath to be weaker than the first signal arrival. As a result, Bluetooth-signal propagation inside residential homes is primarily guided by a flat fading channel, where all effective multipaths arrive within the information symbol.

An indoor wireless channel is often described by Rician fading, where the probability-density function of received signal envelope x is given by:

$$f(x) = \frac{x}{\sigma^2} e^{-(x^2+A^2)/2\sigma^2} I_0\left(\frac{Ax}{\sigma^2}\right),$$

$$\text{with } K = \frac{A^2}{2\sigma^2} \qquad (2)$$

where:

$I_0(.)$= the modified Bessel function of the first kind and zero order. Parameter A is greater or equal to zero and denotes the peak-to-zero value of the specular radio signals comprised of the superposition of the dominant line-of-sight signal and the time-invariant scattered signals reflected from walls, ceilings, and stationary objects. Parameter σ^2 represents the average power of the signal received over paths that vary with time due to people moving within the house. Parameter K is the Rician distribution. When K equals infinity, the channel is Gaussian, whereas K = 0 defines the Rayleigh channel. A value of 3 dB for K is typical for modeling indoor radio-channel amplitude fluctuations.

If the Tx and Rx are stationary with no pedestrian movements, as in the case depicted in Fig. 2, the communication channel is constant with time-invariant impulse response and zero Doppler. In this case, the channel is deterministic and its multipath characteristics remain constant over a long period of time. Depending on the locations of the Tx and the Rx antennas inside the home, the multipath components may add constructively or destructively. As such, the received signals may be amplified by a constant factor or remain in a deep fade. It is therefore important in Bluetooth applications to find "blind spots" as well as optimum locations. An example of this is a laptop computer in each room of the house which communicates with a fixed printer that is stationary in a specific room. These locations should be determined in most likely propagation scenarios, that is, they should not be influenced by Doppler shifts but rather should be identified in stationary settings when most of the house occupants are away, or in "stand-still" positions.

With no randomness induced in the communication channel, the ratio of the square of the mean to the variance in Eq. 2 becomes extremely high and K can be simply approximated by a positive infinity.

In the second type of propagation environment, the Tx and Rx are stationary, but there are some ambient motions of people within the house. This causes the communication channel to be slowly time-varying. In this case, the multipath components can be divided into two different categories. The first category is comprised of the dominant line of sight signal, if it exists, in addition to all time-invariant scattered signals reflected from the stationary objects such as walls, ceilings, furniture, and appliances. The other category consists of the multipaths whose first- or higher-order reflection patterns include at least one path that bounces from a nonstationary source in the house. While the lifetime of the multipath signals in the first category is very long and may last until the signal transmission is terminated, multipath signals in the second category may cease to exist shortly after they became established. The contribution of the first category of multipaths to the signal-fading environment is deterministic with zero Doppler, whereas the effect of the second multipath category is stochastic and changes the signal correlation and frequency characteristics. The combined categories yield Rician fading described by Eq. 2 with σ assuming nonzero values.

In the third type of propagation environments, either the Rx and/or the Tx are in motion. This, indeed, introduces Doppler effects on the transmitted signal with frequency changing up to approximately 10 Hz. The movement, as well as displacement of the antennas inside the house, may create a new line of sight or obstruct an already existing one (Fig. 3). It may also change the signal, scattering propagation profiles near the Txs and the Rxs, and may consequently give rise to random scattering that defines the probability-density function of Eq. 2.

The correlation of the fading envelope is determined by the relative power carried by the different scatterers and their corresponding angles of arrival. In isotropic scattering, the power is uniformly distributed over 360 deg. This leads to a U-shaped spectrum (Fig. 4), which is known as the classic Doppler spectrum. While the classic spectrum is often assumed in outdoor propagation, a flat Doppler spectrum is shown to be characteristic of indoor communications.[3] In the flat Doppler spectrum, the uniformity is encountered across frequencies rather than over the angles of arrivals. This type of spectrum is caused by random movements of scattering elements in the area of the communication path, from random movement of the Tx or Rx causes. A flat Doppler spectrum is also shown in Fig. 4, where the impulse represents the presence of the line-of-sight signal path that can be associated with the classic and flat Doppler spectra. The impulse location at zero frequency indicates, among other possibilities, the orthogonality between the direction of motion of the Rx and the line connecting the Rx and transmitting antennas.

FADING SIMULATORS

New RF techniques in channel simulation can work well for testing and characterizing short-range indoor-radio modules. These techniques employ combinations of programmable phase shifters, attenuators, and vector modulators to achieve the desired fading profiles. The RF-channel simulators are simpler in design complexity than their digital-signal-processing (DSP)-based counterparts and are typically less costly and easier to program and operate. In contrast to DSP solutions, an RF-channel simulator does not require signal downconversion and upconversion and, as such, does not introduce distortion products and frequency-conversion errors into a channel which otherwise would not exist. There are several factors that favor a channel simulator where the signal processing is performed at RF.

A flat-fading channel with one or two resolvable multipaths can be achieved easily and cost effectively. An RF-channel simulator requires that the incident signal be split into a number of resolvable multipath components appropriate for simulating a particular operating environment. Each signal component is faded independently and undergoes its own signal processing. The multipath signals are then recombined. While this can become cumbersome with twelve multipaths, for the underlying indoor applications, it can be performed using a simple power splitter, combiner, and two signal-processing components.

The short propagation delays associated with indoor communication can be easily handled by a channel simulator using RF signal processing. Delays are typically short when they can be achieved using simple, commercially available delay lines.

The demand for bandwidth in wireless LAN (WLAN) systems is increasing. In addition, techniques that employ direct-sequence spread spectrum (DSSS) with frequency hopping are being developed to combat potential interference generated from home appliances and shared spectrum users. Effective interference suppression requires large spreading of the transmitted signal bandwidth. A channel simulator which performs signal processing at RF is only band-limited by the RF control components processing the signal. The extent of signal bandwidth at the 2.4- and 5.8-GHz ISM bands may become unsuitable for even the most-powerful DSP-based commercially available channel simulators.

In conclusion, new short-range wireless connectivity technologies that are cable-free and allow electronic devices to talk to each other with little user intervention are within reach. The home environment is seen as a major growth area and the principal host of these technologies. This is mainly due to the increase in information appliances and Internet-borne services. Testing and evaluating the performance of present and future short-range wireless connectivity can be achieved by a new generation of simple RF faders and channel simulators designed for this purpose. ●●

References

1. G. Mlnasslan, “Home Phone Line Networks: The Next Challenge,” *Communications System Design*, pp. 42-46, February 1999.
2. Bluetooth Website, http://www.bluetooth.com.
3. K. Pajlavan and A. Levesque, *Wireless Information Networks*, John Wiley & Sons, Inc., New York, NY, 1995.
4. R. Morrow, “Site-Specific Engineering For Indoor Communications,” *Applied Microwave & Wireless*, pp. 30-38 March 1999.
5. T. Rappaport, *Wireless Communications*, Prentice Hall, Inc., Upper Saddle River, New Jersey, 1996.
6. Saleh and R. Valenzula, “A Statistical Model For Indoor Multipath Propagation,” *IEEE Journal On Selected Areas In Communications*, Vol. 5, pp. 128-137, February 1987.
7. R. Ganesh and K. Pahlavan, “Statistical Modeling And Computer Simulation Of Indoor Radio Channel.” *IEEE Proceedings*, Vol. 138, pp. 153-161, June 1991.
8. H. Hashemi, “The Indoor Radio Propagation Channel,” *Proceedings Of The IEEE*, pp. 941-968, July 1993.