# Impulse Response of the HVAC Duct as a Communication Channel

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***Abstract*—Heating, ventilation, and air conditioning (HVAC) ducts in buildings behave as multimode waveguides when excited at radio frequencies and thus, can be used to distribute radio signals. The channel properties of the ducts are different from the properties of a usual indoor propagation channel. In this paper, we describe physical mechanisms which affect the HVAC channel impulse response and analyze their influence on the delay spread. Those mechanisms include antenna coupling, attenuation, and three types of dispersion: intramodal, intermodal, and multipath. We analyze each type separately and explore the behavior of the delay spread as a function of distance in straight ducts. Experimental channel measurements taken on real ducts confirm the validity of our model.**

***Index Terms*—Dispersive channels, indoor radio communication, multimode waveguides, wireless local-area network (LAN).**

## I. Introduction

The heating, ventilation, and air conditioning (HVAC) duct system in most buildings consists of interconnected hollow metal pipes of rectangular or circular cross-section, which act as waveguides when driven at radio frequencies (RFs). This complex waveguide network may have multiple propagating modes and contain various nonuniformities (bends, tapers, T-junctions, etc.). It can be used as a communication channel with potentially high data-transmission capacity [1]. There are several advantages of using an HVAC duct system for signal distribution in buildings. First, the HVAC duct system, used as a communication infrastructure, is already present in almost any building. Second, the HVAC duct channel is a time-invariant channel, which is electrically shielded from the rest of the indoor environment. Third, the path loss in the straight HVAC duct is lower compared with a coaxial cable and with free-space propagation.[1] Fourth, various transmitting powers or frequencies can potentially be used inside HVAC ducts without violating emittance and interference regulations, provided that leakage from the duct system into the building space is negligible or can be controlled.

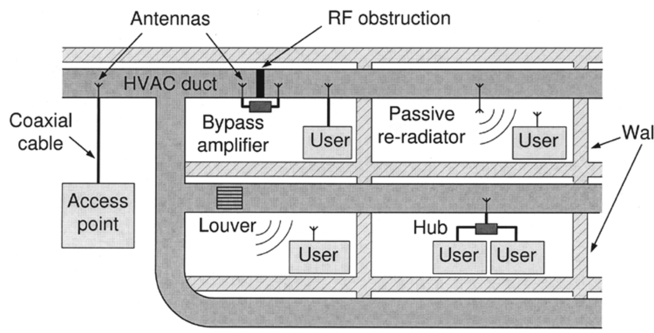


Fig. 1. HVAC duct system used for providing network access to offices.

An example of an HVAC system used for providing high-speed internet access to offices is shown in Fig. 1. The access point is connected to an antenna which excites waveguide modes in the duct system that carry the signal to the offices. Users access the system either directly (via a cable connected to the office antenna) or wirelessly (passive office antenna or duct louver reradiate into the office space). Coupling around various RF obstructions can be achieved with bypass amplifiers. One can see that HVAC ducts can serve as an independent transmission medium (in addition to indoor wireless or cable) and can enhance the capacity and coverage of the building data network system.

The characteristics of a traditional (free space) indoor radio propagation channel have been extensively studied by several researchers [2]–[5]. An excellent overview of this topic can be found in [2]. Indoor channel performance strongly depends on the specifics of the environment. In a typical office environment, the delay spread increases with the distance from the transmitter and can vary between a few tens and few hundreds of nanoseconds. The signal level decays with the path loss exponent whose value depends on the environment (typically, this

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[1]The loss in free space is proportional (in decibels) to the log of the path length, whereas in straight waveguides, the mode loss is linear with distance. The path loss in ducts is smaller compared to the free space until a certain distance from the transmitter where the two become equal. For a mode traveling in a straight duct with a loss of 0.1 dB/m and a free-space propagation at a frequency of 2.45 GHz, this distance is 1000 m. In a networked duct system, this distance would be smaller due to power splitting at joints.

value is between two and four). For example, Hashemi [3] reports root mean square (rms) delay spreads of 10–40 ns and path loss of 40–110 dB for antenna separations of 5–30 m in a large office building at frequencies between 900 and 1300 MHz. Tan [4] reports similar findings. The main advantage of the HVAC medium compared to indoor wireless propagation is that HVAC ducts penetrate all building floors and present a reliable channel whose performance is not affected by time-varying factors such as moving people or rearrangement of furniture. Since the HVAC channel has low attenuation, its data transmitting capability is limited mostly by the rms delay spread of the duct impulse response.

The topic of wave propagation in multimode waveguides has been addressed before. In the early 1950s, Bell Labs researchers explored the feasibility of using straight multimode waveguides for long-distance communications [6]. Later, impulse responses of some extremely overmoded structures have been studied, e.g., in application to propagation in road tunnels [7]. In addition to that, electromagnetic waves in multimode waveguides have also been analyzed, e.g., from the power flow and distribution perspective [8], [9]. However, impulse response characteristics of a general multimode waveguide network, such as HVAC ducts, have not yet been studied from a wireless communications perspective. In this paper, we concentrate on the properties of a simple HVAC system in the form of a straight duct terminated on both ends. All physical mechanisms affecting the impulse response of an arbitrary HVAC duct system can be explored with this simple system.

The remainder of the paper is organized as follows. Section II presents the impulse response model for a straight terminated duct. The relative importance of different physical mechanisms is analyzed in Section III. Section IV explores the behavior of the rms delay spread as a function of transmitter–receiver separation distance. Comparison of the model with experimental data is presented in Section V. Section VI contains the discussion. Conclusions are given in Section VII.

## II. Impulse Response of a Straight Terminated Duct

Consider a straight terminated duct with two antennas as shown in Fig. 2, where $L$ is the distance between the transmitter and the receiver, and $L_1$ and $L_2$ are the distances from the antennas to the respective terminated ends with reflection coefficients equal to $\Gamma$ (which, for simplicity, are assumed to be constant for all modes and frequencies). Fig. 2 shows qualitatively all three types of dispersion in the straight duct system (only two propagating modes are kept for illustration). Drawing a vertical line allows one to determine the arrival times of the power delay profile components at any given position along the duct.

In [10], we have shown that the transfer function of such a system can be written as

$$H(\omega) = K_Z \sum_{n=1}^{N} Z_n e^{-\gamma_n L} \frac{(1+\Gamma e^{-2\gamma_n L_1})(1+\Gamma e^{-2\gamma_n L_2})}{1-\Gamma^2 e^{-2\gamma_n (L+L_1+L_2)}} \tag{1}$$

where $K_Z$ is the coefficient that accounts for the impedance mismatch loss and depends on the impedances of the transmitter, the receiver, and the antenna; $Z_n$ is the complex antenna

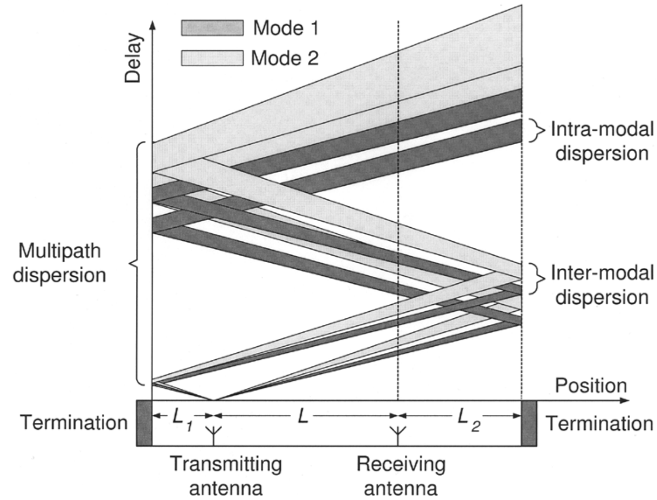


Fig. 2. Propagation of two modes in a straight terminated duct with three types of dispersion present.

impedance due to mode $n$; and $\gamma_n = \alpha_n + j\beta_n$ is the complex propagation constant of mode $n$ ($\alpha_n$ is the attenuation constant and $\beta_n$ is the propagation constant). Quantities $K_Z$, $Z_n$, and $\gamma_n$ are all functions of frequency $\omega$. Equation (1) describes a coherent sum of the propagating modes at the receiving antenna. The term $e^{-\gamma_n L}$ accounts for mode propagation between the transmitter and the receiver in a straight duct. The fraction containing $\Gamma$, $L_1$, and $L_2$ appears as the result of the summation of multiple reflections from the terminated ends. The propagation constant is defined as

$$\beta_n = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2} \tag{2}$$

where $\omega_c$ is the cutoff frequency of the mode. In cylindrical waveguides, the cutoff frequency is

$$\omega_c = \frac{c\,g}{a} \tag{3}$$

where $c$ is the velocity of light, $a$ is the duct radius, $g = p_{nm}$ is the $m$th zero of the Bessel function $J_n(x)$ for transverse magnetic (TM) modes, and $g = p'_{nm}$ is the $m$th zero of the Bessel function derivative $J'_n(x)$ for transverse electric (TE) modes.

In wireless communications, the transceiver bandwidth is usually limited, and the quantity typically analyzed is the power delay profile $p(t)$ related to a narrowband impulse response $h(t)$ as $p(t) = |h(t)|^2$. Often, the impulse response is calculated via a discrete Fourier transform (DFT) from the frequency response $H(\omega)$, which is measured or modeled at a discrete set of frequencies in a given band. An important characteristic of the channel is the rms delay spread of the power delay profile. With no diversity, equalization, or coding, the maximum attainable data rate is strongly related to the coherence bandwidth, which is inversely proportional to the rms delay spread. The latter is typically computed using only values above a certain threshold with respect to the maximum signal level in the impulse response. In our analysis, we use a threshold of $-20$ dB, typically used in the literature [3].

The HVAC channel frequency response $H(\omega)$ measured between the ports of two antennas coupled into the duct system

TABLE I
CUTOFF FREQUENCIES AND NUMBER OF MODES IN CYLINDRICAL DUCTS OF VARIOUS DIAMETER AT FREQUENCIES 915 MHz, 2.4835 GHz, AND 5.825 GHz

| Duct diameter | Cutoff frequency | Number of modes | | |
|---|---|---|---|---|
| | | 915 MHz | 2.484 GHz | 5.825 GHz |
| 15.25 cm (6 in.) | 1.154 GHz | - | 5 | 24 |
| 30.48 cm (12 in.) | 577 MHz | 2 | 17 | 91 |
| 45.72 cm (18 in.) | 385 MHz | 6 | 40 | 197 |

strongly depends on antenna mode sensitivity, which defines what modes are excited the most by the transmitting antenna and what modes are sensed the best by the receiving antenna. Hence, the channel impulse response $h(t)$ obtained from $H(\omega)$ inherently includes the antenna effects. Note that the traditional indoor wireless channel response also depends on antenna properties. Directive gains of the transmitting and receiving antennas define how much power is radiated or received from a certain angular directions. For that reason, indoor measurements are typically performed with omnidirectional antennas which give birth to many multipath components.

## III. RELATIVE IMPORTANCE OF DIFFERENT PHYSICAL MECHANISMS

There are several physical mechanisms that affect the HVAC duct channel impulse response. *Antenna coupling* is due to the fact that transmitting and receiving antennas excite and sense various modes differently. *Attenuation* is due to the finite conductivity of the duct walls and losses at each reflection from nonuniformities in the duct system. *Dispersion* can be classified into three types: *intramodal dispersion*, due to different velocities of various spectral components within each mode; *intermodal dispersion*, due to different velocities of various modes; and *multipath dispersion*, due to multiple reflections from nonuniformities. The manifestation of the aforementioned mechanisms strongly depends on the number and relative amplitudes of propagating modes and usually is nonlinear with respect to frequency.

In this section, we describe the aforementioned mechanisms and examine their effects individually on the example of cylindrical ducts, most commonly used in HVAC systems. Table I presents the cutoff frequencies of cylindrical ducts of several common diameters and the maximum number of modes that can propagate in them at typical frequencies used in wireless communications.

### A. Antenna Coupling

To couple signals in and out of the HVAC system, one needs to insert an antenna, such as coaxially fed monopole probe [11], into the duct. Antenna coupling can be characterized by the radiation resistance of each mode, which determines how much of the transmitted power is carried away by a given mode. Mode radiation resistances define the excited mode distribution and the weights of the different spectral components of each mode. Mode radiation resistance depends on mode type, antenna parameters, waveguide cross-section dimension and geometry, and excitation frequency.

Expressions for radiation resistances of TE and TM modes excited by a thin monopole probe in cylindrical waveguide are given in [10]. For example, in 30.5-cm cylindrical ducts, mode $\mathrm{TE}_{61}$ is excited the most at 2.5 GHz by a 3.5-cm monopole probe, whereas modes $\mathrm{TE}_{\mathrm{on}}$ are not excited at all.

### B. Attenuation

In a straight duct, the power in each mode drops exponentially with the distance. Attenuation due to losses in the duct walls defines the decay rate of different modes in a propagating mode distribution as well as the decay rate of individual frequency components. The mode attenuation constant depends on mode type, waveguide cross-section dimension and geometry, duct wall material properties (conductivity $\sigma$ and permeability $\mu$), and excitation frequency. Attenuation constants of TE and TM modes in cylindrical waveguides are given by [12]

$$\alpha_n = \frac{AR_s}{\eta\, a\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}} \tag{4}$$

where $A = 1$ for TM modes, $A = (\omega_c/\omega)^2 + n^2/({p'_{nm}}^2 - n^2)$ for TE modes, and $R_s = \sqrt{\omega\mu/(2\sigma)}$ is the wall surface resistance. In our experiments, the attenuation constants (at 2.5 GHz) of the three most excited modes were 0.117 dB/m ($\mathrm{TE}_{61}$), 0.055 dB/m ($\mathrm{TE}_{51}$), and 0.035 dB/m ($\mathrm{TE}_{41}$).

The total power carried by propagating modes is a sum of powers carried by each mode. The effective decay rate of the traveling mode pack depends on the relative power in each mode, which varies with distance from the transmitter. Loss due to nonideal reflections from nonuniformities and power splitting at joints introduces an additional attenuation to the received signal.

### C. Dispersion

Dispersion arises when different signal components travel with different speed. Let us examine the power delay profiles in the situations when each of the dispersion types (intramodal, intermodal, and multipath) is predominant. Consider a straight cylindrical duct excited by monopole antennas with characteristics described in Section V. Assume the following geometrical parameters for the system shown in Fig. 2: $L = 25$ m, $L_1 = 0.3$ m, and $L_2 = 0.3$ m.

*Intramodal dispersion* is due to the fact that velocities of spectral components of each mode are frequency dependent. The mode group velocity is given by $v_n = c\sqrt{1-(\omega_c/\omega)^2}$. The arrival time delay for distance $L$ can be calculated as $t_a = L/v_n$.

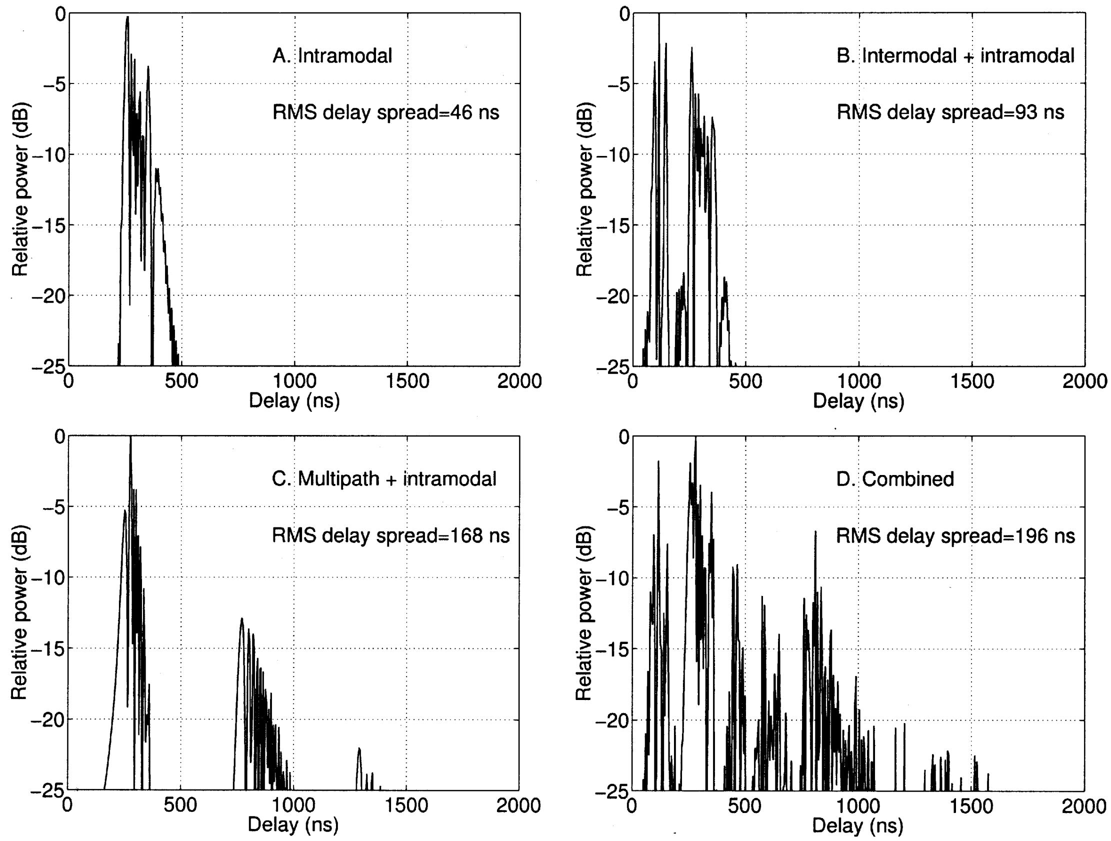


Fig. 3. Different types of dispersion in the calculated power delay profiles for 30.5-cm diameter cylindrical ducts, 3.5-cm monopole antennas, and 2.4–2.5-GHz frequency band. (A) Intramodal for mode $\mathrm{TE}_{61}$. (B) Intermodal and intramodal for all modes. (C) Multipath and intramodal for mode $\mathrm{TE}_{61}$. (D) Combined for all modes. Other parameters are $L = 25$ m, $L_1 = 0.3$ m, and $L_2 = 0.3$ m.

The intramodal time spread per unit distance, $\Delta\, t_a$, can be found by differentiating $t_a$

$$|\Delta t_a| = \frac{\omega_c^2 \Delta\omega}{c\left[1 - \left(\frac{\omega_c}{\omega}\right)^2\right]^{3/2} \omega^3} \tag{5}$$

where $\Delta\omega$ is the width of the frequency window. The significance of the intramodal time spread can be understood in comparison with $t_a$. For lower order excited modes, $\Delta t_a$ is very small, compared with the arrival delay time ($\Delta t_a / t_a = 0.002$ for $\mathrm{TE}_{11}$ mode). For higher order modes, these times are of comparable magnitude ($\Delta\, t_a / t_a = 0.567$ for $\mathrm{TE}_{61}$ mode).

To see the effect of the intramodal dispersion, assume that there are no multipath reflections from the terminated ends (set $\Gamma = 0$) and only the mode $\mathrm{TE}_{61}$ propagates. The normalized calculated power delay profile in this case is shown in Fig. 3(a). The intramodal dispersion manifests itself as broadening of the original transmitted pulse.

The 3-dB width of the narrowest pulse that can be transmitted is finite and is on the order of 10 ns with 100 MHz of bandwidth for a rectangular frequency window. The intramodal dispersion effect is inherently present on all Fig. 3 plots, which were obtained using a frequency band 2.4–2.5 GHz.

*Intermodal dispersion* is due to the fact that different modes travel with different velocities. To analyze the intermodal dispersion, assume again that there are no multipath reflections from the terminated ends (set $\Gamma = 0$). The normalized calculated power delay profile is shown in Fig. 3(b). The fastest mode that arrives first is $\mathrm{TE}_{11}$.

*Multipath dispersion* is due to multiple echoes caused by reflections from nonuniformities. Assume that there are strong multipath reflections from the terminated ends (set $\Gamma = -0.9$), but only the $\mathrm{TE}_{61}$ mode propagates. The normalized power delay profile is shown in Fig. 3(c). One can clearly observe sets of periodic peak structures that correspond to reflections coming from the terminated ends. The intramodal dispersion causes the spreading of these structures with time. The spacing between the same peaks in different structures is the round-trip time of the corresponding spectral component of mode $\mathrm{TE}_{61}$ between the ends of the duct.

Fig. 3(d) shows the normalized power delay profile with all three types of dispersion present. The power delay profile shape and its rms delay spread depend on the mode composition and exact amplitudes and phases of each mode impulse response. One can see from Fig. 3(a)–(d) that the largest contribution to the rms delay spread in relatively short straight ducts with closed ends comes from multipath dispersion. Mitigating the reflections decreases the rms delay spread and makes ducts "radio friendly." When reflections are minimized, or the duct is very long, the dominant contribution comes from intermodal dispersion. Both intermodal and intramodal dispersion can be minimized by selectively exciting a single (or small number) of preferred modes.

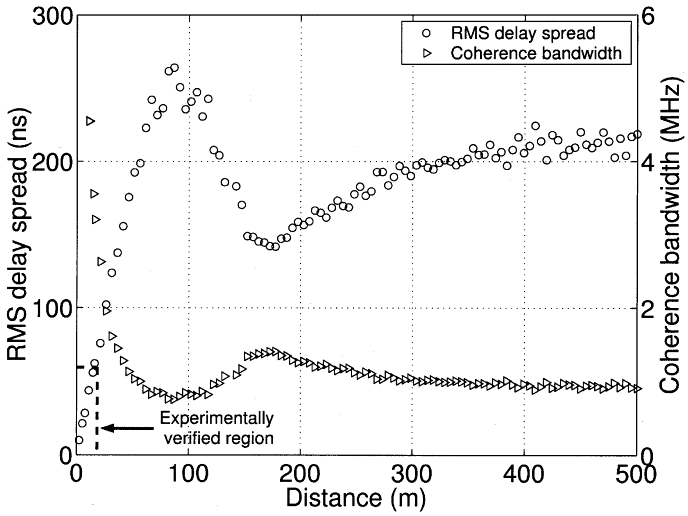


Fig. 4. Calculated rms delay spread (○ symbols) and coherence bandwidth (▷ symbols) as functions of transmitter–receiver separation distance in a straight "radio friendly" cylindrical steel duct 30.5 cm in diameter. Antennas are 3.5-cm monopole probes, frequency band is 2.4–2.5 GHz. The region inside the dashed box is shown in Fig. 6.

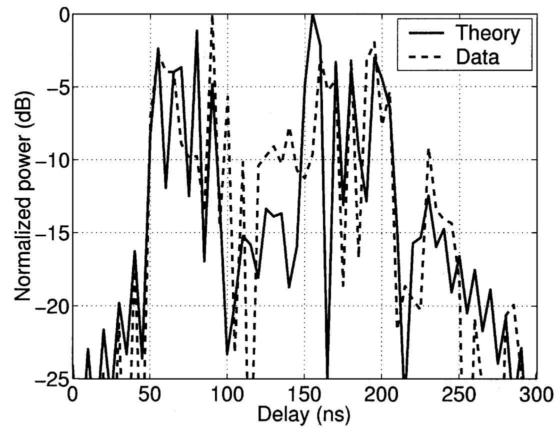


Fig. 5. Comparison of measured and calculated (with $\Gamma = 0$) power delay profiles in a straight "radio friendly" cylindrical steel duct 30.5 cm in diameter. Antennas are 3.5-cm monopole probes, frequency band is 2.4–2.5 GHz, $L = 14.62$ m.

## IV. RMS Delay Spread Versus Distance

Having an ability to investigate the rms delay spread dependence on the system parameters ($L$, $L_1$, $L_2$, $\Gamma$) could be very valuable for a system designer. From a system design point of view, the channel properties for long HVAC ducts ($\geq 50$ m) are of great interest. Obtaining experimental data for such distances is difficult, due to the size of the experimental testbed that would have to be constructed. Our impulse response model allows prediction of the rms delay spread behavior for any distance.

As an example, consider a straight "radio friendly" duct (both ends are terminated with matched loads, with $\Gamma = 0$, and all other parameters are the same as before). In this situation, only intermodal and intramodal dispersions are present. Fig. 4 shows the rms delay spread and the coherence bandwidth (estimated for 50% signal correlation as $B_c = 1/(5\sigma_\tau)$, where $\sigma_\tau$ is the delay spread) as functions of the transmitter–receiver separation distance calculated with our model. At short distances, the attenuation is small, and the delay spread increases linearly due to the intermodal dispersion. At longer distances, the mode attenuation decreases the number of modes with significant amplitudes, and the delay spread diminishes. At extremely long distances, the intermodal and intramodal dispersion of a few low-order modes increase the delay spread again. The specific slope of the rms delay spread curve strongly depends on the mode mix traveling in the duct and the duct end reflection coefficients $\Gamma$.

## V. Comparison With Experiment

To validate these theoretical results, we compared data and theory over accessible distances in straight cylindrical HVAC duct sections of different lengths with different antenna locations, and with both ends open or closed by end caps. The ducts were 30.5 cm in diameter made of galvanized steel. The distance $L_1$ was 0.32 m, the distance $L_2$ was in the range 0.28–1.24 m, and the separation $L$ was varied between 2.44 and 14.67 m. The antennas were thin copper monopole probes 3.5-cm long and 1 mm in diameter set on the straight line along the duct length. We used an Agilent E8358A network analyzer to measure the frequency response between the ports of antenna probes at 1601 discrete frequency points in the 2.4–2.5 GHz band. Further details of the experimental setup can be found in [10]. The duct on which we performed the experiments was elevated on the supports, and set up along the centerline of a long corridor. Although no special measures were taken to prevent coupling between two open ends, the good agreement between the theoretical and the measured frequency responses [10] indicated that this effect was not significant.

First, we compared impulse responses (computed from frequency responses via a DFT) predicted by the model and measured in ducts with open or closed ends. Although in reality, reflection coefficients of open and closed ends is mode and frequency dependent, we empirically found that a single value ($\Gamma = 0$ for open ends and $\Gamma = -0.9$ for closed ends) is a reasonable approximation that yields a good agreement between the measurements and the model. Typical measured and calculated power delay profiles for the duct with open ends are shown in Fig. 5, which contains the effect of both intramodal and intermodal dispersions. One can see that data and theory agree well. Differences are due to reflections from the open ends of the duct.

Then, we calculated the delay spread values and compared them with the experimentally measured ones. Fig. 6 shows the rms delay spread as function of distance. The graphed points represent one sample. Because the duct is a time-invariant channel, samples repeated over time yield the same value. One can see that theoretical results agree well with experimental data for distances up to 15 m. Although validation at longer distances is ultimately needed as well, this result gives confidence in the basic elements of the model, which can be used for estimating the rms delay spread of the straight duct communication channel.

## VI. Discussion

The impulse response model that we presented provides insight into the parametric behavior of the rms delay spread as a function of distance or any other system parameter ($L$, $L_1$,

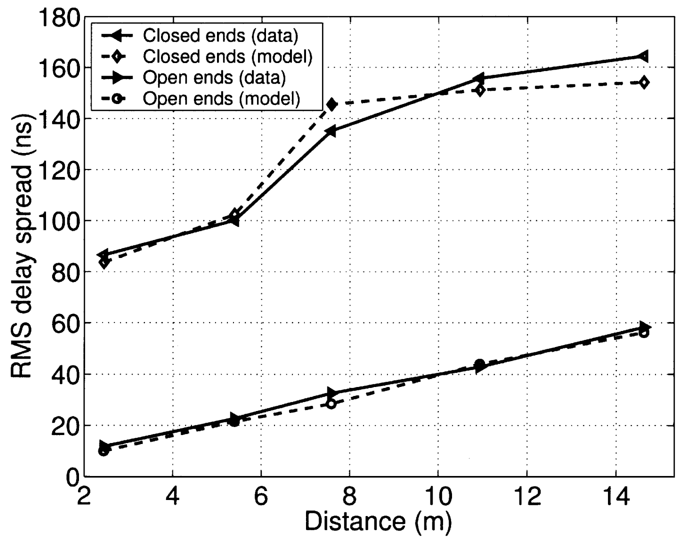


Fig. 6. Rms delay spread: comparison of theoretical model for closed ends (◇ symbols) and open ends (○ symbols), with experimental data for closed ends (◁ symbols) and open ends (▷ symbols) for 30.5-cm diameter cylindrical ducts with open and closed ends. Antennas are 3.5-cm monopole probes, frequency band is 2.4–2.5 GHz.

$L_2$, $\Gamma$, etc.). It allows a designer to determine which system parameters must be adjusted to obtain the desired performance characteristics. Other power delay profile characteristics (e.g., mean excess delay) can be analyzed with our model in a similar fashion.

While in this paper we considered an HVAC channel in the form of a straight duct, the real HVAC duct system is more complicated, as it may contain tapers, bends, T-junctions, etc. Efficient modeling of the path loss and impulse response characteristics in such a system is a challenging task [13], [14]. Our measurements indicate that rms delay spread behavior in the duct system with small nonuniformities, such as smooth cylindrical bends, is almost identical to the rms spread behavior in the straight ducts. Severe nonuniformities, such as T-junctions and Y-junctions, cause a more pronounced effect on the rms delay spread by introducing reflections and mode conversion phenomena.

## VII. Conclusions

The HVAC duct system is an interesting and promising propagation channel for indoor wireless communication. We have described the following physical mechanisms that affect the impulse response of this channel: probe coupling, attenuation, and dispersion. Three types of dispersion exist in this channel: multipath reflections, intermodal dispersion, and intramodal dispersion. We have analyzed their effect on the delay spread with the example of a straight terminated duct, for which we have presented a model and explored the parametric behavior of the rms delay spread as a function of distance. The model agreed well with experimental measurements at accessible distances up to 15 m. Our model should be perceived as a first step toward predicting the rms delay spread in ducts when designing an HVAC signal distribution system.

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Dr. Stancil received a Sigma Xi Research Award from North Carolina State University in 1985, and was a leader in the development of the CMU Electrical and Computer Engineering Department's Virtual Laboratory, which was a finalist for a 1996 Smithsonian Computerworld Award. In 1998, he coreceived a Science Award for Excellence from the Pittsburgh Carnegie Science Center, an IR 100 Award, and a Photonics Circle of Excellence Award for the development and commercialization of electro-optics technology. He is a Past President of the IEEE Magnetics Society.

**Ozan K. Tonguz** (S'86-M'90) was born in Cyprus, in May 1960. He received the B.Sc. degree from the University of Essex, Colchester, U.K., in 1980, and the M.Sc. and the Ph.D. degrees from Rutgers University, New Brunswick, NJ, in 1986 and 1990, respectively, all in electrical engineering.

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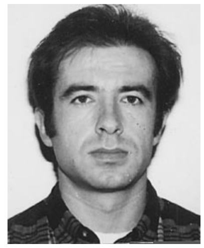
In addition to serving on the Technical Program Committees of several IEEE conferences and symposia in the area of wireless communications and optical networks, Dr. Tonguz currently serves or has served as an Associate Editor for the IEEE Transactions on Communications, *IEEE Communications Magazine*, and IEEE Journal of Lightwave Technology. He was a Guest Editor of the special issues of the IEEE Journal of Lightwave Technology and the IEEE Journal on Selected Areas in Communications on Multiwavelength Optical Networks and Technology, published in 1996.



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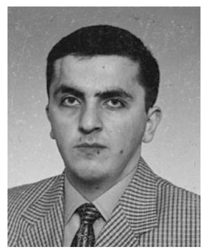
From 2000 until 2001, he was a Visiting Researcher at CMU, doing research on design and performance analysis of communication systems. Since 2002, he has been a Research Assistant at the Telecommunications Research Group at CMU. His current research and interests include design and performance analysis of wireless networks, scheduling, resource allocations and queuing theory, and handover management and quality of service in communications networks.

Mr. Xhafa is a student member of IEEE Communications Society, IEEE Vehicular Technology Society, and IEEE Computer Society.



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