RF propagation in an HVAC duct system: impulse response characteristics of the channel

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1 Introduction

Usually, the heating, ventilation, and air conditioning (HVAC) duct system in buildings is a complex network of hollow metal pipes of rectangular or circular cross-section which behave as multimode waveguides when driven at RF and microwave frequencies of common interest. HVAC ducts can be used as a wireless communication channel for providing high-speed network access to offices [1]. An example of an HVAC system used for signal distribution is shown in Figure 1. The access point is connected to an antenna which excites waveguide modes in the duct system. These modes propagate through the duct system with different group velocities and attenuation constants, experiencing multiple reflections from terminations and non-uniformities, and are received by the office antenna. Users access the system either directly (via a cable connected to the office antenna) or wirelessly (the office antenna re-radiates into the office space).

To design such a system, a knowledge of channel propagation properties, including the impulse response, is very important. The impulse response characteristics of a traditional ("free-space") indoor radio propagation channel have been studied extensively by several researchers [2, 3]. To the best of the authors' knowledge, impulse response characteristics of HVAC ducts (which can be thought of as multiple probe multimode waveguides) have not been studied yet from a wireless communications perspective. In this paper we describe different types of physical mechanisms (mode coupling, attenuation, and three types of dispersion) which affect the impulse response in straight HVAC ducts and analyze their relative importance. We explore the behavior of the RMS delay spread as a function of distance in long ducts and validate it with experimental measurements.

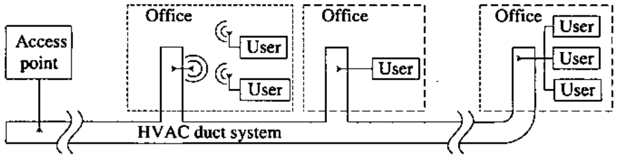

Figure 1: HVAC duct system for wireless access in buildings.

2 Physical mechanisms

There are several physical mechanisms that affect the HVAC duct channel's impulse response. In the following, we briefly describe these mechanisms. ***Probe coupling*** is due to

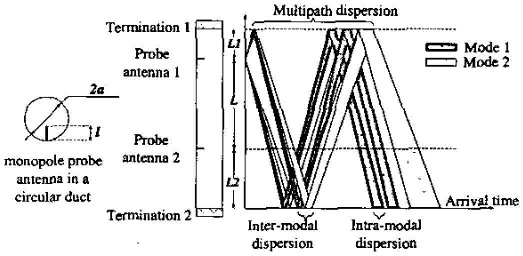

Figure 2: Propagation of two modes in a straight duct with three types of dispersion.

the fact that the transmitting antenna excites various modes differently and the receiving antenna responds differently as well. ***Attenuation*** is due to the finite conductivity of the duct walls and losses at each reflection from non-uniformities in the duct system. ***Dispersion*** is due to the fact that different components of a signal arrive at the receiver at different times. There are three different types of dispersion observed in the duct system: ***multipath dispersion*** is due to multiple echoes caused by reflections from non-uniformities (bends, tapers, T-junctions, Y-junctions, terminations, etc.), ***intermodal dispersion*** is due to the fact that different modes travel with different velocities, and ***intramodal dispersion*** (also known as chromatic waveguide dispersion) is due to the fact that velocities of spectral components of each mode are frequency-dependent.

3 Impulse response of a straight duct

Consider a straight circular duct with two probe antennas as shown in Figure 2, where l is the length of the probe antenna, a is the radius of the duct, 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 coefficient Γ. A coaxially fed monopole probe is a simple way to couple in and out of a waveguide [4]. In [5], we have shown that the transfer function of such a system is

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

where K_Z is a constant which depends on the impedances of the transmitter, the receiver, and the antenna; R_n is the radiation resistance of the antenna due to mode n; and γ_n is the complex propagation constant of mode n. In wireless communications, the transceiver bandwidth is usually limited, and the quantity typically analyzed is the power delay profile $p(t)$ related to a narrow-band impulse response $h(t)$ as

$$p(t) = |h(t)|^2 = \left| \int_{\omega_1}^{\omega_2} H(\omega) e^{j\omega t} d\omega + c.c. \right|^2, \qquad (2)$$

where ω_1 and ω_2 are the lower and the upper frequencies of the transceiver band. Depending on approximations made, $p(t)$ in a straight duct can be found in closed form. Figure 2 shows qualitatively all three types of dispersion in the straight duct system (only two propagating

Table 1: The RMS delay spread σ_τ due to different types of dispersion.

Dispersion type	Intramodal	Intermodal	Multipath
Modes present	TE_{61}	all	TE_{61}
Γ	0	0	-1
σ_τ (ns)	20.2	55.7	158.4

modes are kept for illustration). Drawing a horizontal line allows one to determine the arrival times of the power delay profile components at any given position along the duct. One of the important characteristics of the channel that defines the maximum data rate is the RMS delay spread σ_τ of the power delay profile computed using a certain threshold with respect to maximum signal level. In our analysis we use a threshold of -20 dB.

Table 1 gives the RMS delay spread computed from Equations 1 and 2 for cases when different types of dispersion are present in a system ($L = 14.62$ m, $L_1 = 0.32$ m, $L_2 = 0.25$ m, $a = 15$ cm, $l = 3.5$ cm, $\omega_1 = 2\pi \times 2.4$ Grad/s, $\omega_2 = 2\pi \times 2.5$ Grad/s). Note that the intramodal dispersion is always present due to the finite transceiver bandwidth. Mode TE_{61} is chosen because it is excited the most by this monopole probe antenna. One can see that the main mechanism which determines the RMS delay spread in straight terminated ducts is the multipath dispersion. Mitigating the reflections decreases the RMS delay spread and makes ducts "radio-friendly."

4 RMS delay spread

Having an ability to investigate the RMS delay spread dependence on the system parameters (L, L_1, L_2, Γ) could be very valuable for a system designer. From a system design point of view, the channel properties for long HVAC ducts (≥ 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 $\Gamma = 0$). In this situation, only intermodal and intramodal dispersions are present. Figure 3 shows the RMS delay spread as a function of the transmitter-receiver separation distance calculated with our model. At short distances, 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 dispersion of a few lower order modes increases the delay spread again.

5 Comparison with experiment

To validate these theoretical results, we compared our calculated delay spread values with the experimentally measured ones over accessible distances in ducts with both ends open ($\Gamma \approx 0$). We used straight cylindrical ducts 30.5 cm in diameter made of galvanized steel excited by 3.5 cm long coaxially fed monopole probes. An Agilent E8358A network analyzer was used to measure the impulse response in 2.4 - 2.5 GHz band. Figure 3 shows that

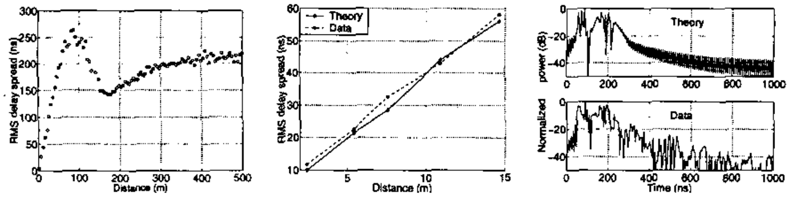

Figure 3: Theoretically computed RMS delay spread in a long "radio-friendly" duct as a function of distance (left), its comparison with experimental data (center), modelled and measured impulse responses for $L = 14.62$ m (right).

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.

6 Conclusions

The impulse response in the HVAC duct system used as a wireless communication channel is shaped by three physical mechanisms: probe coupling, attenuation, and dispersion. Three types of dispersion exist in this channel that affect the RMS delay spread. In the order of their importance, they are multipath reflections, intermodal dispersion, and intramodal dispersion. We presented a model for the power delay profile in a straight terminated duct which allows exploration of RMS delay spread parametric behavior. As an example, we calculated the delay spread as a function of distance in a straight duct and found it to be in good agreement with experimental data at distances up to 15 m. The real HVAC system has a complicated geometry, which may include bends, junctions, etc. Efficient modelling of its channel properties is still a challenging task. Our model for straight ducts should be perceived as a first step towards that goal.

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