An Empirical Path Loss Model for HVAC Duct Systems

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Abstract— **In this paper, we present a simple path loss prediction model for link budget analysis in indoor wireless local area networks (LANs) that use heating, ventilation, and air conditioning (HVAC) ducts. The model we propose predicts the average power at each location in an HVAC duct network. This prediction model greatly simplifies the analysis for a complex duct network, making it a convenient and simple tool for system design. Our prediction model is verified by experimental measurements.**

I. INTRODUCTION

Radio communications can offer convenient and cost effective solutions for providing broadband wireless access in indoor environments [1]-[3]. However, the performance of conventional methods for indoor wireless communications suffers from unpredictable and variable attenuation by the intervening structures and obstructions in buildings such as walls, partitions, elevators, etc. [3]. A new and promising approach for transmitting and receiving RF signals in indoor environments is the use of heating, ventilation, and air conditioning (HVAC) ducts which was recently reported [2].

Published work on the topic of indoor radio propagation channel dates back to 1959 [4]. However, most of the measurements and modeling work have been carried out in the last two decades with few exceptions. This coincides with the worldwide success of cellular mobile communication systems. Previous research dealt with measurements and modeling of the analog and digital radio propagation within and into buildings. Modeling of radio propagation via HVAC ducts has been reported in [6], where the authors consider only straight ducts as communication channels.

Previous analysis showed that indoor wireless networks using HVAC ducts can support data rates in excess of 1 Gbps for distances up to 500 m [5] when multicarrier transmission is used. These estimates were made using a propagation model verified with channel measurements on 0.3 m diameter spiral ducts. This propagation model deals with straight duct networks (S-networks), where the network has been considered as an overmoded waveguide and simple monopole probes were used to transmit and receive the RF signal in the ducts. Frequency measurements were done in the ISM band, 2.4 to 2.5 GHz, and it was shown that the propagation model predicts a frequency response that matches very well with the measurements. Extension of this model to more complex elements of the network; i.e., tees, wyes, etc., appears to be, at this point in time, a complex and difficult task. From a practical point of view, however, it may not be necessary to find the exact solution to the frequency response of cylindrical tees, wyes, etc. It is adequate to determine the average power loss of the received signal in a duct network that has tees, wyes, etc. Our ultimate goal is to find a simple model to predict propagation path loss in HVAC ducts.

The remainder of the paper is organized as follows. Characterization of the path loss model for different duct components is done in Section II. Experimental results for composite networks involving tees, wyes, etc. and discussions are presented in Section III. The path loss model is described in Section IV, while a large-scale experimental verification is presented in Section V.Finall y, conclusions are provided in Section VI.

II. CHARACTERIZATION OF PATH LOSS MODEL FOR DUCT COMPONENTS

A practical HVAC network consists mostly of straight sections, bends, wye-junctions, tee-junctions, etc. Therefore, in order to characterize the path loss model for a complex HVAC network, we need to characterize the path loss for each duct component.

A. Measurement Procedures

Wide band signal strength measurements were made with a system identical to the one used in [2]. We used cylindrical ducts 0.3 m in diameter made of galvanized steel with conductivity $\sigma = 10^6\ S/m$. The signal was transmitted through the duct by a monopole antenna of 3.1 cm length (approximately quarter wavelength) placed inside the cylindrical ducts. The receiver uses the same antenna as the transmitter. Both antennas are connected to an Agilent E8358A Vector Network Analyzer (VNA) via coaxial cables (see Figure 1). Measurements of frequency and time response were done using the VNA in the 2.4-2.5 GHz frequency band. The frequency measurements were then averaged over the frequency band, thus giving the average power loss for each measurement. In all of the measurements described below,the ends of the duct networks were open, approximating matched loads. Reflections from an open end of a multimode cylindrical waveguide are generally very small when the number of modes is sufficiently large, as demonstrated in [6].

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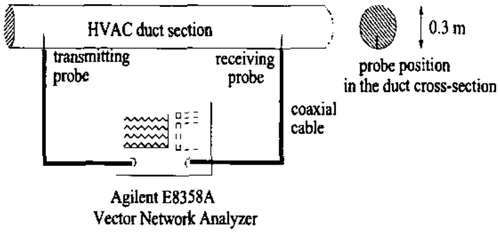

Fig. 1. Experimental setup after [6]. HVAC duct section shown in the figure is a generic representation and in different experiments different composite duct network configurations with different components (wyes, tees, bends, and straight ducts) were used (see, for example, Sections III and V of the paper).

B. Bends

The HVAC duct bend used had a radius of curvature of 0.51 m, as shown in Figure 2. In this experiment, the values (distance and path loss) reported in Table I are average values found as follows: 5 separate measurements were done where the transmitter was kept fixed while the receiver was positioned at 5 different points in the duct, each new position being half an inch away from its neighbor. The average distance between the transmitter-receiver pair distances is reported in the tables. Also, the path loss values are the average values of the 5 different measurements. The same procedure is followed for the characterization of tees and wyes (Section II.C and II.D, respectively).

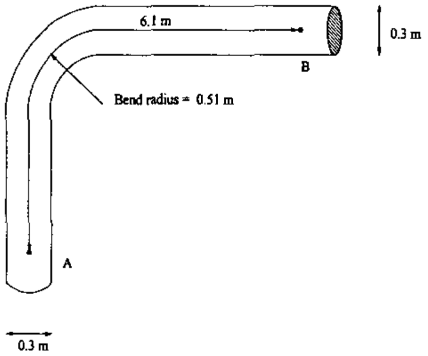

Fig. 2. The B-network used in our measurements. A and B denote the placements of the transmitting and receiving antennas in the duct. The ends were left open.

The power loss comparison between a B-network and S-network is given in Table I. In a straight network, our measurements showed an antenna coupling loss of 16 dB and an attenuation value of 0.066 dB/m. The results given in Table I suggest that the impact of a gradual curved bend in the channel response is negligible.

C. Tees

In case of T-networks (similar to the one shown in Figure 3), the path loss comparison is given in Table II. The transmitter-receiver distances are equal to 5.6 m for all reported paths. Based on equal power splitting, one would expect that the power loss in the straight duct section of the T-network, or the perpendicular duct section of the T-network should be 3 dB less than the power loss in an S-network having the same distance. However, the results in Table II indicate that the power loss in the straight section of the T-network (i.e., AB) is 8.6 dB, while in the perpendicular section of the T-network (i.e., BC) is 11.2 dB. Presently our hypothesis is that the explanation behind this phenomenon is that in case of the T-network, the energy is redistributed between the modes due to a mode conversion caused by the T-junction. Since the antennas used in the measurements can capture only certain modes, redistribution of the energy between modes results in increased path loss. Mode conversion is akn own phenomenon that happens in multimodal waveguides with any non-uniformity (bend, tee, cross-section change, etc.) [7]. Experiments we are currently conducting are continuing to verify this explanation. Also observe that the power loss in the straight section of the tee is less than the power loss in the perpendicular section of the tee (e.g., compare the power loss for AB and BC). This can be explained with the fact that there is a line-of-sight for the transmitter-receiver pair placed in the straight section of the tee (i.e., path AB), while no line-of-sight exists for the transmitter-receiver pair that uses path BC.

TABLE I

AVERAGE POWER LOSS (dB) COMPARISON BETWEEN A B-NETWORK AND S-NETWORK WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

Av. Power (dB) (B-networks)	Av. Power (dB) (S-networks)
-17.0 ±0.2	-16.7 ±0.1

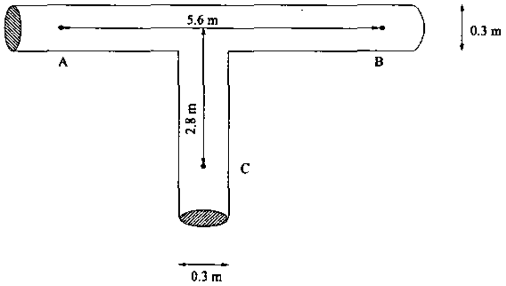

Fig. 3. The T-network used in our measurements. A, B, and C denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

D. Wyes

The experimental setup for a Y-network is shown in Figure 4. Measurements were made using the VNA in the ISM band, 2.4-2.5 GHz.

A summary of the average power loss from the experimental results is given in Table III. It is interesting to note that the average power loss for AC is -29.3 dB, while the power loss in the other branches of the Y-network are

TABLE II

AVERAGE POWER LOSS (dB) COMPARISON BETWEEN T-NETWORK AND S-NETWORK WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

	Av. Power (dB) (T-networks)	Av. Power (dB) (S-networks)
AB	-25 ±0.3	-16.4 ±0.2
BC	-27.6 ±0.1	-16.4 ±0.2
AC	-27.6 ±0.1	-16.4 ±0.2

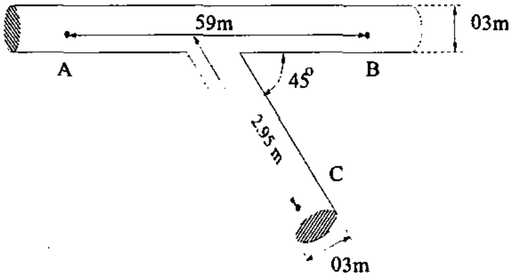

Fig. 4. The Y-network used in our measurements. A, B, and C denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

-23.9 dB and -21.4 dB. Again, these results can be potentially explained with the aforementioned mode conversion phenomenon.

TABLE III

AVERAGE POWER LOSS (dB) IN A Y-NETWORK WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

	Av. Power (dB) (Y-s)	Av. Power (dB) (S-netowrk)
AB	-21.4 ±0.2	-16.5 ±0.1
BC	-23.9 ±0.1	-16.5 ±0.1
AC	-29.3 ±0.1	-16.5 ±0.1

III. COMPOSITE NETWORKS: EXPERIMENTAL RESULTS AND DISCUSSIONS

In this section, we describe experiments performed with composite networks and discuss the implications of the experimental results obtained.

A. Composite Network 1: Network of Tees

The experimental setup for the composite network of tees is shown in Figure 5. The difference between the power loss of an S-network that has the same distance as the points of measurement and the measured average power loss between these points is taken to be the power loss due to tees. For example, let us assume that we want to calculate the power loss due to tees between points Z and S (there are 3 tees between these points). The measured average power loss is -32.7 dB. The power loss of an S-network that has the same distance as AZ (i.e., 14.8 m) was measured to be -17 dB. The difference between the measured power loss and the S-network is -15.7 dB.

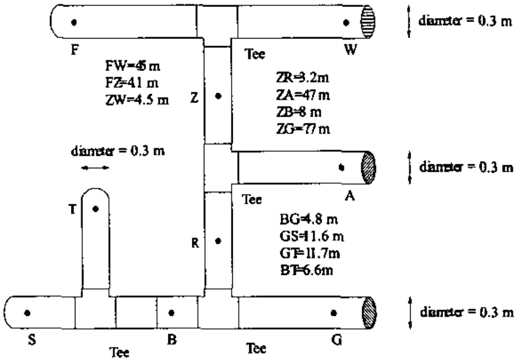

Fig. 5. The experimental setup for composite network of tees. A, F, Z, W, R, G, B, S, and T denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

To calculate the power loss for each tee, we averaged the power level for 1, 2, 3, and 4 tees. We found that one tee introduces a power loss of 8.7 dB with a standard error of 2.5 dB; two tees introduce a power loss of 11.9 dB with a standard error of 2.1 dB; three tees introduce a power loss of 15.6 dB with a standard error of 2.9 dB; and four tees introduce a power loss of 18.9 dB with a standard error of 0.9 dB. It is interesting to note that after the first tee, any additional tee added to the network will introduce an additional power loss of approximately 3 dB. A possible explanation of this is that mode conversion and scattering in the first tee results in increased path loss. The redistribution of energy occurs to a much lesser extent after the first tee, so that additional loss is simply the 3 dB loss from equal power division at the tees. Hence, the first tee in the cascade of tees behaves as a "mode filter".

B. Composite Network 2

In this experiment, we combined different duct segments (wyes, tees, and bends) and measured the channel frequency response using the VNA over the 2.4-2.5 GHz frequency range. The experimental setup is shown in Figure 6.

The expected power level between two points is found as a linear combination of the attenuation, power loss in each element, and the coupling loss. For example, the path from A to F includes one wye, one tee, and one bend; hence, the expected power loss for AF is given as:

$$P_{r_{AF}}(dB) = -\alpha l_{AF} - Y_d - T_d - B_d - C_L \qquad (1)$$

where $P_{r_{AF}}$ is the power loss at F when A is transmitting; α is the attenuation loss, l_{AF} is the distance between A and F; B_d is the power loss due to the bend; Y_d is the power loss due to the Y-junction; T_d is the power loss due to the tee-junction; and C_L is the antenna coupling loss. Note that Y_d depends on the geometry of the path between transmitter-receiver pair. Substituting $\alpha = 0.066\ dB/m$

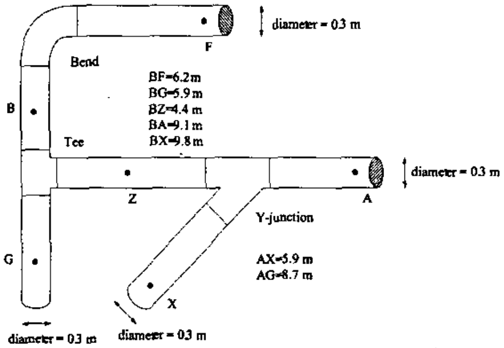

Fig. 6. The experimental setup for composite network 2. A, X, Z, G, B, and F denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

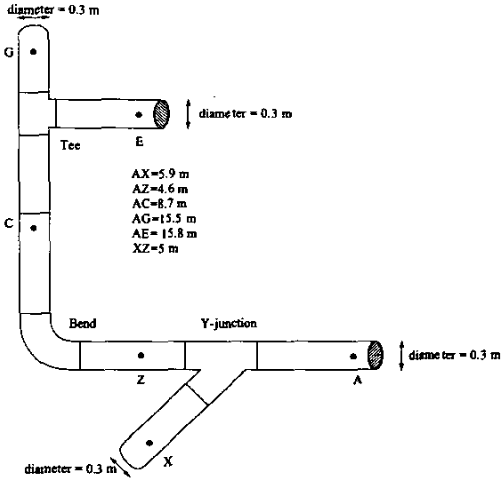

Fig. 7. The experimental setup for composite network 3. A, X, Z, C, G, and E denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

[2], $Y_d \approx 4.9\ dB$, $T_d \approx 8.7\ dB$, $B_d \approx 0.3\ dB$, and $C_L \approx 16\ dB$, one gets that $P_{r_{AF}} \approx -30.9\ dB$. The measured power loss was found to be -29.4 dB. Thus, the accuracy of the prediction was within 1.5 dB. For all transmitter-receiver pairs, the standard deviation of the absolute value of the difference between the results of the prediction model and the measurements was calculated to be 1.3 dB (the difference values are in the range -3.2 to 4.8 dB) with an absolute mean value of 1.6 dB. One can conclude that the path loss prediction model is in good agreement with the measured power loss values. Thus, these results show that if we know the power loss for each individual component, we can find the total loss of the composite network by adding the loss of each element.

C. Composite Network 3

In this experiment, the same duct components as in Section III-B are used, however, *the order of their placement* in the network has been changed (see Figure 7).

Proceeding as we did in the previous subsection, for all transmitter-receiver pairs, the standard deviation of the absolute value of the difference between the results of the prediction model and the measurements was calculated to be 1.3 dB (the difference values are in the range -4.7 to 2.2 dB) with an absolute mean value of 1.8 dB. This experiment again verifies the fact that we can predict the average power loss of the composite network if the individual power loss of each network component is known.

IV. THE PATH LOSS MODEL

Generally speaking, we expect the path loss for cylindrical ducts to depend on the frequency of transmission, distance between transmitter-receiver pair, the radius of the duct, antenna length and orientation, geometry and the material of the duct network. The goal is to minimize the power loss in the duct, subject to air flow constraints. This problem can be formulated as a linear constrained optimization problem. The two major constraints are the air pressure in the duct and the number of excited modes both of which are directly influenced by the radius of the HVAC duct. Further research is needed to formulate this optimization problem in a formal manner.

From the experimental results, we have found the power loss in bends, tees, and wyes of a network of cylindrical ducts 0.3 m in diameter made of galvanized steel and excited by 3.1 cm monopole probe antennas. We have also found that an insertion loss of two antennas is -16 dB.

A summary of the power loss levels from our experimental results is given in Table IV. In a composite network; i.e., a duct network consisting of bends, tees, wyes, and straight duct sections, power level loss at a given location can be found as a sum of power level loss of each component in the path between the transmitter-receiver. This idea is illustrated via a large-scale experimental setup in the next section.

TABLE IV

POWER LOSS (dB) IN BENDS, TEES, AND Y-JUNCTIONS WITH 0.3 M DIAMETER CYLINDRICAL DUCTS AND 3.1 CM ANTENNAS AND IN 2.4-2.5 GHZ FREQUENCY BAND.

Geometry	Power loss AB (dB)	Power loss AC (dB)	Power loss BC (dB)
Bends	-0.3	NA	NA
1 Tee	-8.7	-8.7	-8.7
Any additional Tee	-3	-3	-3
Y-s	-4.9	-12.8	-7.4

The power loss at the user in office i will be a function of attenuation in the duct, distance between the transmitter-receiver pair, the geometry of the duct, and the antenna coupling loss. Thus:

$$P_{ri}(dBm) = P_t(dBm) - \alpha(r,\sigma)l_i - \sum_{j=1}^{n_{Ti}} T_j(r,\sigma) - \sum_{j=1}^{n_{Yi}} Y_j(r,\sigma) - n_{Bi}B(r,\sigma) - C_L \quad (2)$$

where P_{ri} denotes the power received in dBm for user in office i; $\alpha(r, \sigma)$ denotes the attenuation coefficient in the duct which depends on the radius r of the duct and the conductivity, σ, of the material; l_i is the distance from the access point (AP) to the user in office; n_{Ti} , n_{Yi}, and n_{Bi} denote the number of tees, wyes, and bends from AP to the user; $B(r, \sigma)$ denotes the power loss in dB in the bends; C_L is the antenna coupling loss; $T_j(r, \sigma)$, and $Y_j(r, \sigma)$ denote the power loss due to the j-th tee and wyes, respectively, given in Table IV.

For other frequency bands, duct diameter, and antenna length, values given in Table IV will have to be re-measured before using them in our path loss model.

V. EXPERIMENTAL VERIFICATION

To illustrate how the path loss model works, the duct network shown in Figure 8 was constructed at the National Robotics Engineering Consortium Laboratory at Carnegie Mellon University. This experimental setup is representative of what might be used in office spaces in USA and Europe.

Cylindrical ducts 0.3 m in diameter made of galvanized steel with conductivity $\sigma = 10^6\ S/m$ were used for this setup. The signal was transmitted from the access point (AP) through the duct by a monopole antenna of 3.1 cm length. The receiver uses the same antenna as the transmitter. Both antennas were connected to an Agilent E8358A Vector Network Analyzer via coaxial cables (as in Figure 1). Measurements of frequency response were made using the VNA in 2.4-2.5 GHz frequency band. To find the average power level, the frequency measurements were then averaged over the frequency band. In this particular experiment, the ends of the duct network were terminated with absorbers to avoid reflections from the surrounding.

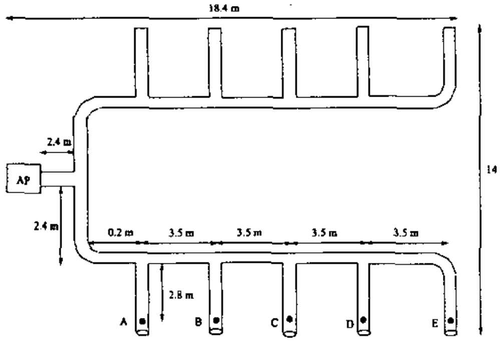

Fig. 8. The floor plan considered in the experimental setup.

Table V gives the received power for each user using the prediction model and the measured received power. The power loss in tees and bends are taken from Table IV and an antenna coupling loss of 16 dB is assumed. Based on the measurements made, attenuation in the duct is taken to be 0.066 dB/m. Comparing the experimental results with the predicted values via our path loss model, one can see that the accuracy of the path loss model is within 2 dB of the experimental results. This allows for a simple and accurate link budget analysis of complex HVAC systems.

TABLE V

MEASURED AND PREDICTED POWER LEVELS AT EACH USER FOR 1 W TRANSMITTED POWER WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

User	Distance from AP (m)	Measured power level(dB)	Predicted power level (dB)	Error (dB)
A	7.7	-29.8	-28.7	-1.1
B	11.1	-34.3	-31.9	-2.4
C	14.6	-35.1	-35.1	0
D	18	-39.3	-38.4	-0.9
E	21.7	-36.9	-39.1	2.2

VI. CONCLUSIONS

In this paper, we described an approximate path loss model based on measurements made on cylindrical HVAC ducts, 0.3 m in diameter, made of galvanized steel, and excited by 3.1 cm monopole probe antennas. The validity of this approximate path loss model is verified via a large-scale experimental setup constructed at Carnegie Mellon University. Predicted power levels are in excellent agreement with the measured power levels at different locations (accuracy within 2 dB).

The path loss model can predict the power level at any location in the HVAC duct system. This model uses experimentally determined parameters of duct system components. The methodology that we presented allows one to experimentally characterize any type of component used in HVAC duct networks excited by any type of antenna. This model will also allow a system designer to predict path loss contours for all types of HVAC duct network configurations, in an extremely simple and time-efficient manner.

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