A Simple Path Loss Prediction Model for HVAC Systems

O. K. Tonguz, D. D. Stancil, A. E. Xhafa, A. G. Cepni, P. V. Nikitin[†], and D. Brodtkorb[‡]

Carnegie Mellon University, Department of Electrical and Computer Engineering
Pittsburgh, PA 15213-3890, USA

[†]University of Washington, Department of Electrical Engineering
Seattle, WA 98195-2500, USA

[‡]Asea Brown Boveri Corporate Research, Bergerveien 12, P.O.Box 90
N-1735 Billingstad, NORWAY

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) cylindrical ducts in 2.4-2.5 GHz frequency band. The model we propose predicts the average power loss between a transmitter-receiver pair 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. The accuracy of our prediction model is verified by an extensive set of experimental measurements.

Keywords

Path Loss Prediction Model, Internet Access, HVAC Systems, Indoor Wireless LAN's.

I. Introduction

Radio communications can offer convenient and cost effective solutions for providing broadband wireless access in indoor environments [1]-[4]. 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. [4]-[6]. 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], [3].

Published work on the topic of indoor radio propagation channel dates back to 1959 [7]. 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 [8]-[18]. Modeling of radio propagation via HVAC ducts has been reported in [13], 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 [12]. These estimates were made using a propagation

This work was funded by Asea Brown Boveri (ABB), Inc. of Europe.

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. Frequency measurements were done using simple monopole probes 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 [13]. 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 at 2.4-2.5 GHz frequency band.

The remainder of the paper is organized as follows. The problem statement is described in Section II. Duct channel characterization and some preliminary work is presented in Section III. Characterization of the path loss model for different duct components is done in Section IV. Experimental results for composite networks involving tees, wyes, etc. and discussions are presented in Section V. The path loss model is described in Section VI, while an illustrating example based on a large-scale experimental testbed is given in Section VII. Finally, conclusions are provided in Section VIII, while auxiliary material is relegated to the Appendix.

II. Problem Statement

In conventional wireless networks, the impulse response approach is useful in characterizing the detailed frequency response of the channel, while average path loss models are used in determining the size of the coverage area for indoor radio communications and in selecting optimum locations for the access points. It is well known that in wireless communications simple path loss propagation models (large-scale models), such as Hata model, Erikson model, etc., have been used to predict the received power level in urban areas, indoors, etc., [5], [6]. Most of the existing models in wireless communications have been found empirically by fitting curves or analytical expressions that regenerate a set of measured data. Our goal in this paper is also to find an empirical model that can accurately predict the path loss for any complex HVAC duct network in 2.4-2.5 GHz frequency band.

A practical HVAC network consists mostly of 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. The path loss for each duct component is found by averaging the frequency response magnitude over the frequency band of interest (2.4-2.5 GHz ISM band). The total loss of an HVAC network can be found by adding losses due to each component. In the next section, we give proof-by-examples as to why characterization of each duct component alone is sufficient for characterizing the path loss model for more complex HVAC networks.

III. PRELIMINARIES

In this section, we describe our experimental measurements used to find the attenuation and the antenna coupling loss in the HVAC ducts.

A. Attenuation

The attenuation between two points in a cylindrical HVAC duct is a function of of the modal mix and the attenuation per unit length. The attenuation in the 0.3 m diameter straight cylindrical HVAC ducts is found analytically as follows: For the single mode case, the mode power in the cylindrical HVAC duct decreases exponentially as the distance increases [23]. For a multimode pack, the multimode power is the sum of single modes powers. In the single mode case, one can define the attenuation constant as:

$$\alpha = -\frac{1}{2}\frac{dP(x)}{P(x)} \tag{1}$$

where $P(x)$ is the single mode power, x is the distance, and α is the attenuation constant. Similarly, one can define the multimode attenuation constant to be:

$$\alpha_m = -\frac{1}{2}\frac{dP_m(x)}{P_m(x)} \tag{2}$$

where the variables are the same as in Eqn.(1) and the index m stands for the multimode pack. The multimode attenuation constant for the 0.3 m diameter straight cylindrical HVAC ducts at a given distance is calculated analytically via the propagation model reported in [13]. Our calculations show that the multimode attenuation constant is given as:

$$\alpha_m(dB) = 5.64 - 0.04x \tag{3}$$

where x is the distance between the transmitting and the receiving antennas.

B. Antenna Coupling Loss

A theoretical approach in calculating the antenna coupling loss has been reported in [13], however, here we will use our experimental measurements to obtain the antenna coupling loss.

For this purpose, wide-band signal strength measurements were made at 2.4 GHz with a system identical to the one used in [3]. We used straight 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 (see Appendix A for a justification of this procedure). Since we already know the attenuation in the ducts, we calculated the antenna coupling loss to be -16 dB, which is in very good agreement with the theoretical approach reported in [13]. In all of the measurements described, 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 [13].

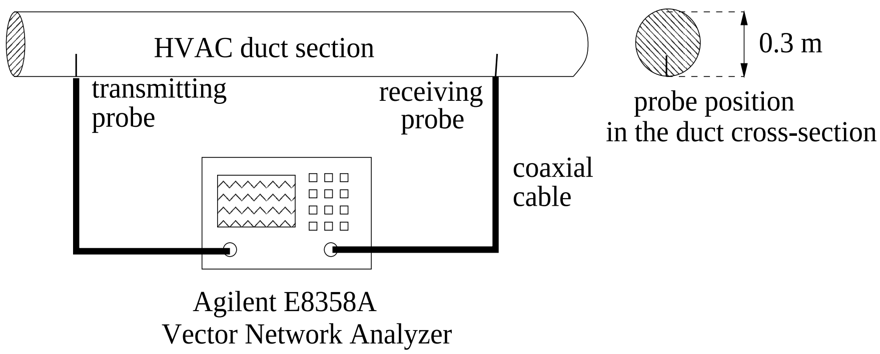

Fig. 1. Experimental setup after [13]. HVAC duct section shown in the figure is a generic representation and in different experiments different composite duct network configurations with different components (wyes, tees, bends, and straight ducts) were used (see, for example, Section IV of the paper).

IV. Characterization of path loss model for individual duct components

Measurement procedures were the same as the one reported Section III, however, we used bends, tees, and wyes-junctions along with straight cylindrical ducts. The minimum separation between the transmitter and the reciever antennas is 3.2 meters. This distance is larger than the decay length for the closet evanescent mode, TE_{32}, which is 0.2 meters. The frequency measurements made via VNA were then averaged over the frequency band, thus giving the average power loss for each measurements.

A. Bends

The bends 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 the average values found as follows: 5 separate measurements were made where the transmitter was kept fixed while the receiver was positioned at 5 different points in the duct, each new position being 1.3 cm away from its neighbor. The average distance between the transmitter-receiver pairs is 6.1 m. The same procedure is followed for the characterization of tees and wyes (see Section IV.B and IV.C, respectively).

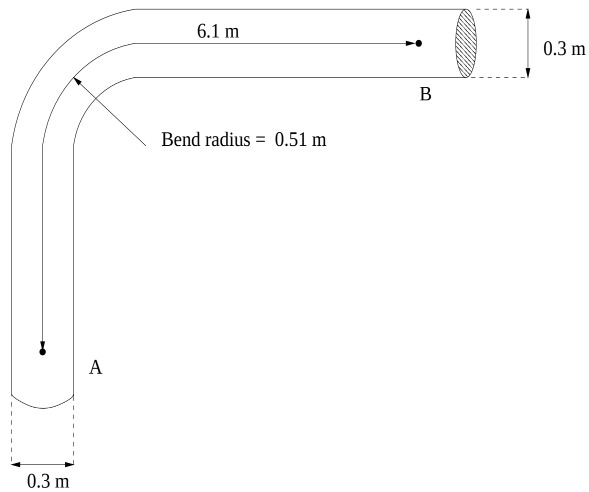

Fig. 2. The B-network used in our measurements. A and B denote the placements of the transmitting and receiving antennas in the duct. The ends were left open.

The power loss comparison is given in Table I. These results suggest that the impact of a gradual curved bend in the channel response is negligible.

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

Points	Distance (m)	Av. Power (dB) (B-networks)	Av. Power (dB) (S-networks)
AB	6.1	-17.02 $\pm$0.2	-16.7 $\pm$0.1

B. Tees

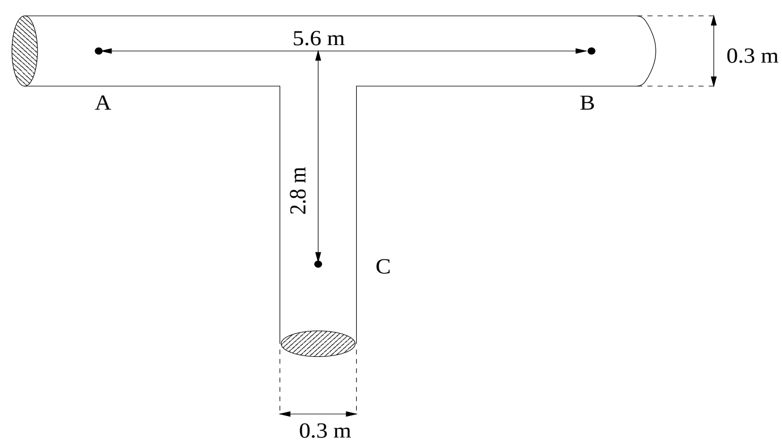

Fig. 3. The T-network used in our measurements. A, B, and C denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

A T-network is shown in Figure 3. The power loss comparison is given in Table II. 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) it is 11.2 dB. Presently our hypothesis is for 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 a known phenomenon that happens in multimodal waveguides with any non-uniformity (bend, tee, cross-section change, etc.) [19]-[21]. Extensive measurements based on different experiments we are currently conducting verify this explanation. Also, simulation results for tee-junctions and wye-junctions were made using High Frequency System Simulator (HFSS) by Ansoft. These simulation results showed that the straight through response of tee-junctions have a better frequency response (see Figure 4). 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 in Table II). 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 II

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

Points	Distance (m)	Av. Power (dB) (T-networks)	Av. Power (dB) (S-networks)
AB	5.6	-25 $\pm$0.3	-16.4 $\pm$0.2
BC	5.6	-27.6 $\pm$0.1	-16.4 $\pm$0.2
AC	5.6	-27.6 $\pm$0.1	-16.4 $\pm$0.2

C. Wyes

The experimental setup for a Y-network is shown in Figure 5. 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 Tables 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 -23.9 dB and -21.4 dB. Again, these results can be potentially explained with the aforementioned mode conversion phenomenon. Thus, the energy is redistributed between the modes due to a mode conversion caused by the Y-junction, which leads to the differ-

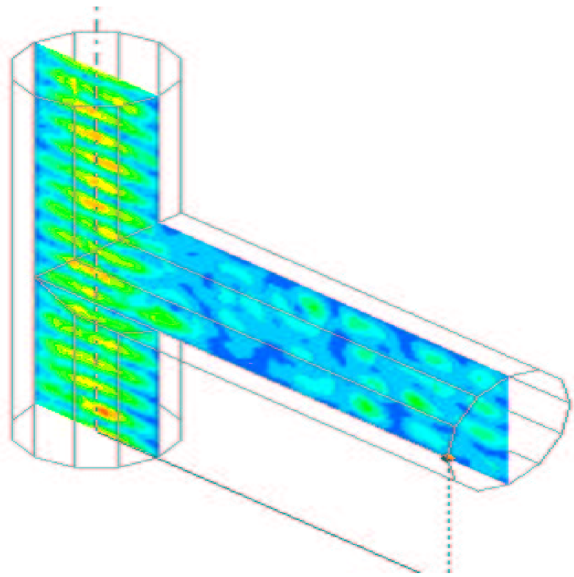

Fig. 4. The field propagation in a tee-junction (HFSS simulation results). The diameter of the ducts in the simulation is 0.3 m, the communication frequency range is 2.4-2.5 GHz, and antennas of length 3.1 cm were used.

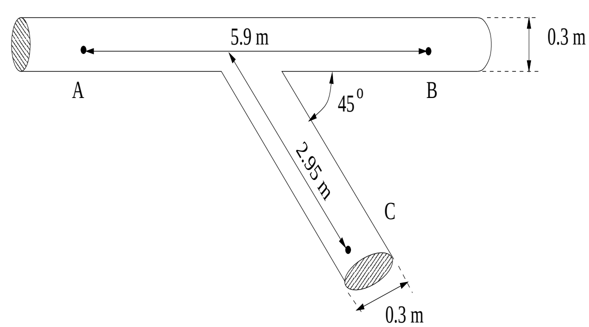

Fig. 5. The Y-network used in our measurements. A, B, and C denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

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

Points	Distance (m)	Av. Power (dB) (Y-s)	Av. Power (dB) (S-network)
AB	5.9	-21.4 ±0.2	-16.5 ±0.1
BC	5.9	-23.9 ±0.1	-16.5 ±0.1
AC	5.9	-29.3 ±0.1	-16.5 ±0.1

ences measured in the path loss.

V. 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 6. 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. The measured average power loss is -32.7 dB. The power loss of an S-network that has the same distance as ZS (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.

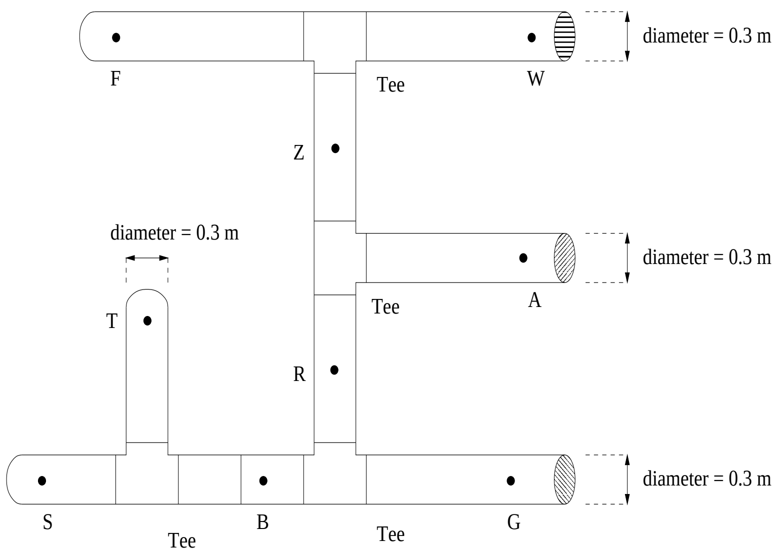

Fig. 6. The experimental setup for composite network of tees. A, F, Z, W, R, G, B, S, and T denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

TABLE IV
AVERAGE POWER LOSS (dB) DUE TO TEES IN COMPOSITE NETWORK WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

Number of Tees	Power loss (dB)
1	8.7 $\pm$2.5
2	11.9 $\pm$2.1
3	15.6 $\pm$2.9
4	18.9 $\pm$0.9

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 18.6 dB with a standard error of 0.9 dB (see Table IV). 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 7.

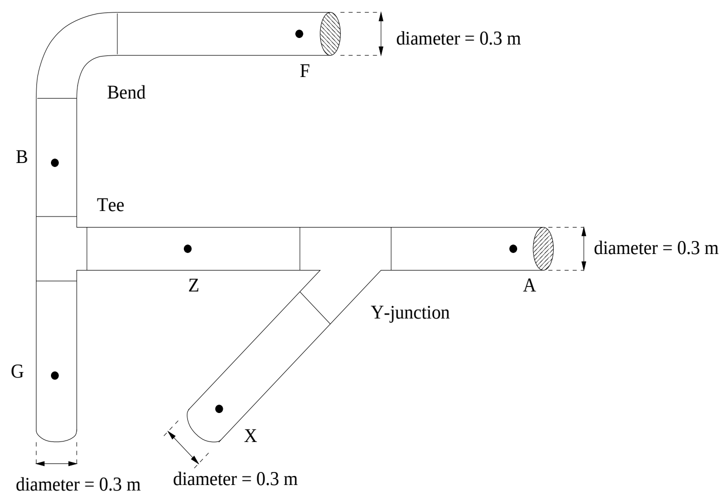

Fig. 7. The experimental setup for composite network 2. A, X, Z, G, B, and F denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

Measured average power levels between different measurement points are given in Table V. The first column in the table gives the points of measurement as depicted in Figure 7, while the second column gives the distance between these points. The measured average power loss is given in the third column. The fourth column gives the expected power level between these two points, which 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 the wye, the tee, and the bend; hence, the expected power loss for AF is given as:

$$P_{r_{AF}}(dB) = -\alpha_m l_{AF} - Y_d - T_d - B_d - C_L \tag{4}$$

where $P_{r_{AF}}$ is the power loss at F when A is transmitting; α_m is the multimode 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

TABLE V

AVERAGE POWER LOSS (dB) IN COMPOSITE NETWORK I WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

Points	Distance (m)	Av. Power (dB)	Expected Power (dB)	Difference (dB)
AX	5.9	-28.9	-29.3	0.4
AZ	4.6	-24.4	-21.1	-3.3
AG	8.7	-29.1	-30	0.9
AB	9.1	-29.4	-30	0.6
AF	15.3	-29.4	-30.7	1.3
XZ	5	-25.9	-23.6	-2.3
XG	9.1	-29.2	-32.6	2.6
XB	9.8	-27.9	-32.5	4.4
XF	15.6	-30.9	-33.2	2.3
ZG	4.1	-25.7	-25	-0.7
ZB	4.4	-24.6	-25	0.4
ZF	10.6	-26.4	-25.6	-0.8
GB	5.9	-23.5	-25.1	1.6
GF	12	-26	-25.6	-0.4
BF	6.2	-17.8	-16.7	-1.1

$Y_d \approx 4.9\ dB$, $T_d \approx 8.7\ dB$, $B_d \approx 0.3\ dB$, and $C_L \approx 16\ dB$, one gets that $P_{r_{AF}} \approx -30.7\ dB$. The last column shows the difference between the results of the the measurements and the prediction model. Looking at the data in Table V, 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 V-B are used, however, *the order of their placement* in the network has been changed (see Figure 8).

Measured average power levels between different measurement points are given in Table VI. In constructing this table, the same guidelines as for Table V were followed. 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.

VI. THE PATH LOSS MODEL

Generally speaking, we expect the path loss for cylindrical ducts to depend on the following parameters:

- frequency of transmission

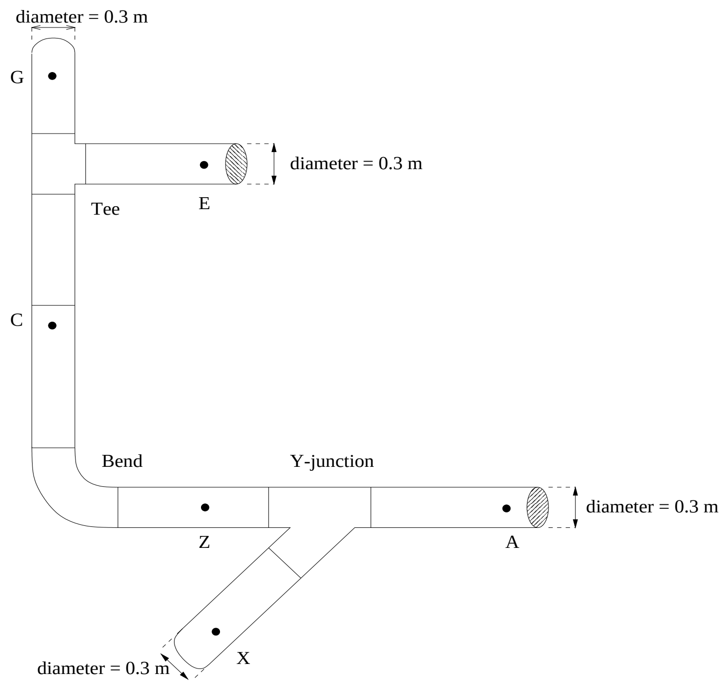

Fig. 8. The experimental setup for composite network 3. A, X, Z, C, G, and E denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

TABLE VI

AVERAGE POWER LOSS (dB) IN COMPOSITE NETWORK II WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

Points	Distance (m)	Av. Power (dB)	Expected Power (dB)	Difference (dB)
AX	5.9	-29.6	-29.3	-0.3
AZ	4.6	-24.3	-21.1	-3.2
AC	8.7	-26.5	-21.6	-4.9
AG	15.5	-28.7	-30.7	2.0
AE	15.8	-33.1	-30.7	-2.4
XZ	5	-24.3	-23.6	-0.7
XC	10.1	-26.9	-24.2	-2.7
XG	15.9	-33.6	-33.2	-0.4
XE	16.2	-31.4	-33.2	1.8
ZC	5.1	-17.1	-16.5	-0.6
ZG	10.9	-27.7	-25.6	-2.1
ZE	11.2	-28.3	-25.6	-2.7
CG	5.7	-25.4	-25.1	-0.3
CE	6.1	-23.4	-25.1	1.7

- distance between transmitter-receiver pair
- the radius of the duct
- antenna length and orientation

- geometry of the duct network
- material of the duct

The goal is to minimize the power loss in the duct, subject to air flow constraints[1]. 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 antenna loss is -16 dB. A summary of the power loss levels from our experimental results is given in Tables VII and VIII.

TABLE VII
SINGLE ELEMENT CHARACTERIZATION OF POWER LOSS (dB) IN BENDS, TEES, AND Y-JUNCTIONS WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

Geometry	Power loss AB (dB)	Power loss AC (dB)	Power loss BC (dB)
Bends	-0.3	NA	NA
1 Tee	-8.7	-11.2	-11.2
Y-s	-4.9	-12.8	-7.4

TABLE VIII
AVERAGE POWER LOSS (dB) IN TEES IN A COMPOSITE NETWORK WITH 0.3 M DIAMETER CYLINDRICAL DUCTS.

Geometry	Power loss AB (dB)	Power loss AC (dB)	Power loss BC (dB)
1 Tee	-8.7	-8.7	-8.7
Any additional Tee	-3	-3	-3

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:

$$P_{ri}(dBm) = P_t(dBm) - \alpha_m(r,\sigma,l_i)l_i - \sum_{j=1}^{n_{Ti}} T_j(r,\sigma) - \sum_{j=1}^{n_{Yi}} Y_j(r,\sigma) - n_{Bi}B(r,\sigma) - C_L \qquad (5)$$

where P_{ri} denotes the power received in dBm for user in office i; $\alpha_m(r,\sigma,l_i)$ denotes the multimode attenuation coefficient in the duct which depends on the radius r of the duct, the conductivity, σ,

[1]It is well known that one could reduce, for example, the number of modes in HVAC ducts by using pipes with smaller diameter. However, from a heating, cooling, and ventilation viewpoint, this could be problematic.

of the material, and the distance, l_i, between the transmitting and the receiving antennas; 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 VIII.

It is worth mentioning here that for other frequency bands, duct diameter, and antenna length, values given in Table VIII will have to be re-measured before using them in our path loss model.

VII. AN ILLUSTRATIVE BUILDING HVAC SYSTEM: CASE STUDY

To illustrate how the path loss model works, the duct network shown in Figure 9 was constructed at the National Robotics Engineering Consortium Laboratory of 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.

Table IX 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 VIII and an antenna coupling loss of 16 dB is assumed. 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 3 dB of the experimental results.

TABLE IX
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	-28.5	-1.3
B	11.1	-34.3	-31.6	-2.7
C	14.6	-35.1	-34.7	-0.4
D	18	-39.3	-37.9	-1.4
E	21.7	-36.9	-38.2	1.3

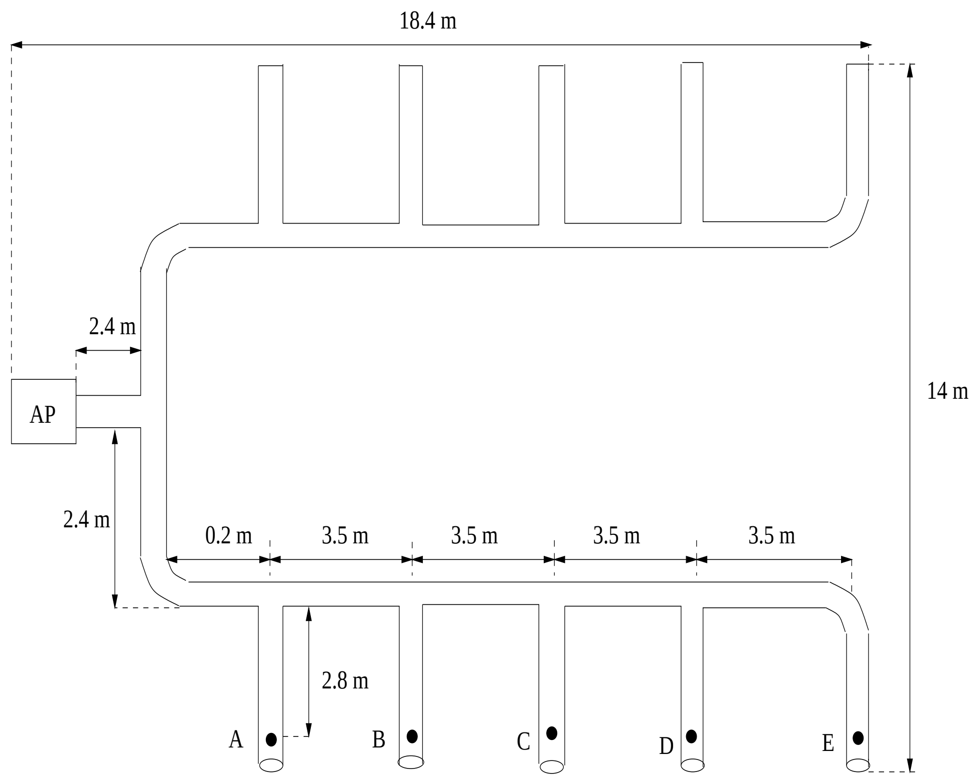

Fig. 9. The floor plan considered in the experimental setup.

To check the effect of the spatial variations across this large-scale testbed, we proceeded as follows: we used 6 transmitting antennas at the access point, each 5 cm apart from each-other, as well as 6 receiving antennas at point E, each also 5 cm apart from each-other. Then, 36 measurements were made for each possible combination of the transmitter-receiver pair. The average power loss of these measurements had a mean of 36.6 dB and a standard deviation of 2.2 dB. The predicted power loss between the access point and point E is 39.7 dB, which is within 3 dB range of the measured spatial average power loss. Another observation is that the power loss measured by using just one transmitting antenna and one receiving antenna is 36.9 dB, which is within 3 dB of the measured spatial average power loss. We also measured the spatial average power loss between points A and E as follows: we used 3 transmitting antennas at point A, each 5 cm apart from each-other, as well as 3 receiving antennas at point E, each also 5 cm apart from each-other. Then, 9 measurements were made for each possible combination of the transmitter-receiver pair. The average power loss of these measurements was 35.96 dB with a standard deviation of 1.9 dB. The predicted power loss between these two points is calculated to be 36.3 dB, which is within 0.4 dB of the spatial average power loss. Thus, one can see that the effect of the spatial variations across the HVAC ducts is negligible.

In conclusion, it is clear that for such a large-scale experimental testbed this is an excellent agreement which verifies the simple path loss prediction model developed in this paper. This allows for a simple and accurate link budget analysis of complex HVAC systems.

VIII. Conclusions

In this paper, we described an approximate path loss model based on measurements made on cylindrical HVAC ducts at 2.4-2.5 GHz, 0.3 m in diameter, made of galvanized steel, and excited by 3.1 cm monopole probe antennas.

Via the extensive experiments conducted it was shown that the impact of *bends* in an HVAC duct network is negligible. The path loss in this case was approximately 0.3 dB. It was also shown that at 2.4-2.5 GHz, one tee introduces an 8.7 dB loss in either section of a T-network, while each additional tee introduces approximately 3 dB loss in either direction. These findings imply that the use of HVAC ducts for RF transmission in buildings is a very promising technique.

Our measurements in a large-scale experimental testbed showed an excellent agreement between the path loss predicted by the model developed in this paper and the measured path loss. This allows for a simple and accurate link budget analysis in more complex HVAC systems that include bends, tees, wyes, etc.

In summary, a path loss model which can predict the power level at any location in the HVAC duct system has been presented. 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.

Appendix A: Justification of Power Averaging over the 2.4-2.5 GHz ISM Band

In this appendix, we justify the use of our averaging approach of the power loss in HVAC ducts. The voltage delivered to the load connected to the receiving antenna can be written in the form:

$$V_r(\omega) = \sum_m A_m e^{-j\phi_m(\omega)}, \tag{A.1}$$

where A_m and $\phi_m(\omega)$ are the amplitude and phase respectively of the contribution from the m-th mode.

The total power in a frequency band can be estimated by averaging the amplitude squared of the received voltage over the band provided the following assumptions are satisfied:

- Span of frequency covers many coherence bandwidths,
- A_m ≈constant with frequency over the band of interest, and
- $\phi_m(\omega)$ is a uniformly distributed random variable over the range $(-\pi, \pi]$ with zero mean.

To show that this is true take the expectation of the magnitude squared of V_r:

$$\begin{aligned} E\left[|V_r(\omega)|^2\right] &= E\left[\sum_{m,n} A_m A_n e^{-j(\phi_m(\omega)-\phi_n(\omega))}\right] \\ = E\left[\sum_m A_m^2\right] &+ E\left[Re\left\{\sum_{m\neq n} A_m A_n e^{-j(\phi_m(\omega)-\phi_n(\omega))}\right\}\right] \\ &= \sum_m A_m^2 + E\left[\sum_{m\neq n} A_m A_n cos(\phi_m - \phi_n)\right] \end{aligned} \quad \text{(A.2)}$$

Since $E[\phi_m] = E[\phi_n] = 0$ and ϕ_m ranges over $(-\pi, \pi]$, it follows that $E[cos(\phi_m - \phi_n)] = 0$. Using this result in Eqn.(A.3) gives

$$E\left[|V_r(\omega)|^2\right] = \sum_m P_m = P_T, \quad \text{(A.3)}$$

where $A_m^2 = P_m$ is the power delivered to a 1 ohm load by mode m, and use has been made of the well-known orthogonality property of the normal modes of a cylindrical waveguide. Figure 10 shows the frequency response of a 5.3 m straight HVAC duct.

Using this procedure, we found out that the average power loss for a 5.3 meter straight HVAC duct is -15.4 dB.

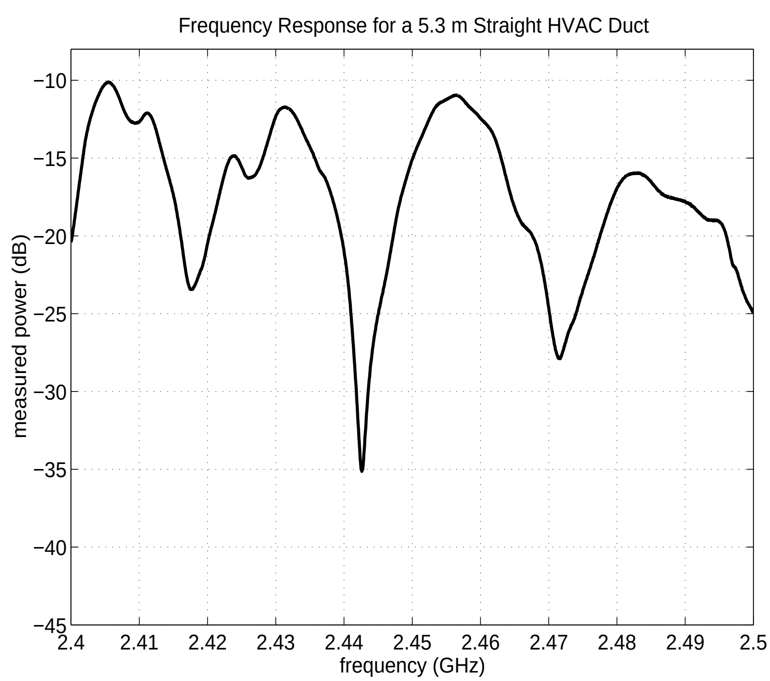

Fig. 10. Frequency response of a 5.3 m straight HVAC duct. Cylindrical ducts 0.3 m in diameter made of galvanized steel with conductivity $\sigma = 10^6\ S/m$ were used for this measurements. The signal was transmitted through the duct by a monopole antenna of 3.1 cm length.

The above frequency response has a coherence bandwidth of 6.22 MHz (20 dB threshold level was used in the impulse response to calculate the coherence bandwidth for 50% signal correlation). Thus, one can consider approximately 13 sub-bands over which the signal level remains constant. Hence, one can use the average approach to fing the average power loss for this frequency response. Our calculations, however, consist of approximately 1600 subbands which satisfy the requirements for power averaging. Using only 13 subbands, we found out that the average power loss calculated in this manner results in a value of -15.71 dB, which is 0.3 dB lower than the value that we found by averaging the power loss over all 1601 measurement points. Thus, the averaging process over all frequency measurement points is justified.

References

[1] D. Molkdar, "Review on radio propagation into and within buildings", *IEE Proc.*, vol. 138, no. 1, pp. 61-73, Feb. 1991.

[2] C. P. Diehl, B. E. Henty, N. Kanodia, and D. D. Stancil, "Wireless RF distribution in buildings using heating and ventilation ducts", *in Proc. of* 8^{th} *Virginia Tech/MPRG Symposium on Wireless Personal Communications*, pp. 61-70, June 1998.

[3] D. D. Stancil, O. K. Tonguz, A. Xhafa, A. Cepni, P. Nikitin, and D. Brodtkorb, "High-speed Internet access via HVAC ducts: A new approach", *in Proc. of IEEE Global Telecomm. Conf. (GLOBECOM'01)*, vol. 6, pp. 3604-3607, San Antonio, Texas, Nov. 2001.

[4] H. Hashemi, "The Indoor Radio Propagation Channel," *Proc. of the IEEE*, vol. 81, no. 7, pp. 943-968, July 1993.

[5] T. S. Rappaport, *Wireless Communications: Principles and Practice.* Prentice Hall, 1996.

[6] H. L. Bertoni, *Radio Propagation for Modern Wireless Systems*. Prentice Hall, 2000.

[7] L. P. Rice, "Radio transmission into buildings at 35 and 150 mc", *Bell Syst. Tech. J.*, vol. 38, no. 1, pp. 197-210, Jan. 1959.

[8] A. A. M. Saleh and R. A. Valenzuela, "A statistical model for indoor multipath propagation", *IEEE J. Sel. Areas in Commun.* vol. 5, no. 2, pp. 128-137, 1987.

[9] International Telecommunication Union, ITU-R Recommendation, pp. 1238: *Propagation data and prediction models for the planning of indoor radiocommunication systems and radio local area networks in frequency range 900 MHz to 100 GHz*, Geneva, 1997.

[10] W. Honcarenko, H. L. Bertoni, J. Dailing, and H. D. Yee, "Mechanisms governing UHF propagation on single floors in modern office buildings", *IEEE Trans. on Vehic. Tech.*, vol. 41, no. 4, pp. 496-504, 1992.

[11] S. S. Saunders, *Antennas and Propagation for Wireless Communication Systems.* John Wiley and Sons, 1999.

[12] A. Xhafa, O. K. Tonguz, A. Cepni, D. D. Stancil, P. Nikitin, and D. Brodtkorb, "Theoretical limits of HVAC duct channel capacity for high-speed Internet access", *IEEE Int. Conf. Commun. (ICC'02)*, vol. 2, pp. 936-939, New York, NY, May 2002.

[13] P. Nikitin, D. D. Stancil, O. K. Tonguz, A. Cepni, A. Xhafa, and D. Brodtkorb, "Propagation model for the HVAC duct as a communication channel", *IEEE Trans. Ant. Propag.*, to appear, May 2003.

[14] D. D. Stancil, O. K. Tonguz, P. Nikitin, A. Xhafa, and A. Cepni, "Assessment of building HVAC ducts as high-bandwidth communication channels", *Technical Report*, Carnegie Mellon University, July 2001.

[15] H. Hashemi and D. Tholl, "Statistical modeling and simulation of RMS delay spread of indoor radio propagation channels", *IEEE Trans. Vehic. Tech.*, vol. 43, no. 1, pp. 110-120, Feb. 1994.

[16] H. -J. Zepernick and T. A. Wysocki, "Multipath channel parameters for the indoor radio at 2.4 GHz ISM band," *in Proc. of IEEE Vehic. Tech. Conf. (VTC'99)*, vol. 1, pp. 190-193, 1999.

[17] J. T. E. McDonnell, T. P. Spiller, and T. A. Wilkinson, "RMS delay spread in indoor LOS environments at 5.2 GHz ," *IEE Electronics Letters* , vol. 34, no. 11, pp. 1149-1150, May 1998.

[18] S. Y. Seidel and T. S. Rappaport, "914 MHz path loss prediction models for indoor wireless communications in multifloored buildings", *IEEE Trans. Ant. Propag.*, vol. 40, no. 2. pp. 207-215, Feb. 1992.

[19] M-D. Wu et al. "Full-wave characterization of the mode conversion in a coplanar waveguide right-angled bend", *IEEE Tran. Microwave Theory Techniques*, vol. 43, no. 11, pp. 2532-2538, Nov. 1995.

[20] N. J. P. Frenette and J. C. Cartledge, "The effect of wavefront tilt on mode conversion in asymmetrical Y-branch waveguides", *IEEE J. Quantum Electronics*, vol. 25, no. 4, pp. 742-748, April 1989.

[21] J. M. Burke and W. M. Manheimer, "Mode conversion losses in highly overmoded waveguide cavitites", *IEEE Tran. Microwave Theory Techniques*, vol. 38, no. 10, pp. 1503-1509, Oct. 1990.

[22] S. Ramo, J. R. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics.* Wiley & Sons, Third Edition, 1994.

[23] N. N. Rao, *Elements of Engineering Electromagnetics.* Prentice Hall, Fourth Edition, 1994.