A Simple Path-Loss Prediction Model for HVAC Systems

Ozan K. Tonguz, *Member, IEEE*, Ariton E. Xhafa, *Member, IEEE*, Daniel D. Stancil, *Senior Member, IEEE*, Ahmet G. Cepni, *Student Member, IEEE*, Pavel V. Nikitin, *Member, IEEE*, and Dagfin Brodtkorb, *Member, IEEE*

***Abstract*—In this paper, we present a simple path-loss prediction model for link budget analysis in indoor wireless local area networks that use heating, ventilation, and air conditioning (HVAC) cylindrical ducts in the 2.4–2.5-GHz industrial, scientific, and medical 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 link budget 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.**

***Index Terms*—Heating, ventilation, and air conditioning (HVAC) systems, indoor wireless local area networks (WLANs), Internet access, path-loss prediction model.**

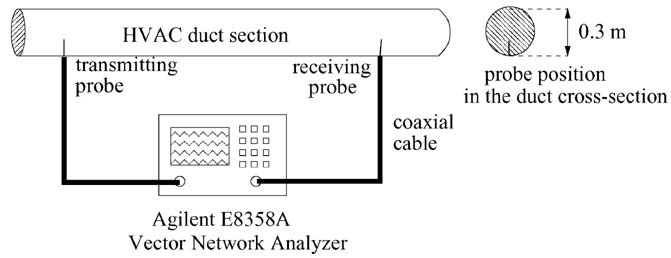

Fig. 1. Experimental setup after [8]. The HVAC duct section shown in the figure is a generic representation; in different experiments, different composite duct network configurations with different components (wyes, tees, bends, and straight ducts) were used (see, for example, Section IV of this paper).

I. INTRODUCTION

RADIO communications can offer convenient and cost-effective solutions for providing broad-band wireless access in indoor environments [1], [2]. 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. [2]–[4]. A new and promising approach for transmitting and receiving radio frequency (RF) signals in indoor environments is the use of heating, ventilation, and air conditioning (HVAC) ducts, which was recently reported [5]–[11].

Published work on the topic of an indoor radio-propagation channel dates back to 1959 [12]. However, most of the measurements and modeling work have been carried out in the last two decades with few exceptions, which coincides with the worldwide success of cellular mobile communication systems. Previous research dealt with measurements and modeling of the radio propagation within and into buildings [1], [2], [12]–[20]. The work presented here, however, is more related to the work done on path-loss prediction models in tunnels [21]–[26]. Modeling of radio propagation via HVAC ducts has been reported in [8], where the authors consider only straight ducts.

Previous analysis has shown that indoor wireless networks using HVAC ducts can support data rates in excess of 1 Gb/s for distances up to 500 m [7]. 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. Frequency measurements were done using simple monopole probes in the 2.4–2.5-GHz industrial, scientific, and medical (ISM) band and it was shown that the propagation model predicts a frequency response that very well matches the measurements [8]. Extension of this model to more complex elements of the network, i.e., tees, wyes, etc., should be possible with techniques such as cascaded scattering matrices [27]. 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 only the average power loss of the received signal in a duct network that has tees, wyes, etc. In this paper, a simple path-loss prediction model was developed for HVAC duct communication systems operating in the 2.4–2.5-GHz ISM band. This allows for a simple and accurate link budget analysis in complex HVAC duct communication systems.

The remainder of the paper is organized as follows. The problem statement is described in Section II and 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

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O. K. Tonguz, D. D. Stancil, and A. G. Cepni are with Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA 15213-3890 USA (e-mail: tonguz@ece.cmu.edu; stancil@cmu.edu; acepni@andrew.cmu.edu).

A. E. Xhafa is with the Communications Systems Laboratory, Texas Instruments, Inc., Dallas, TX 75243 USA (e-mail: axhafa@ti.com).

P. V. Nikitin is with Department of Electrical Engineering, University of Washington, Seattle, WA 98195-2500 USA (e-mail: nikitin@ee.washington.edu).

D. Brodtkorb is with Asea Brown Boveri Corporate Research, Billingstad N-1735, Norway (e-mail: dagfin.brodtkorb@no.abb.com)

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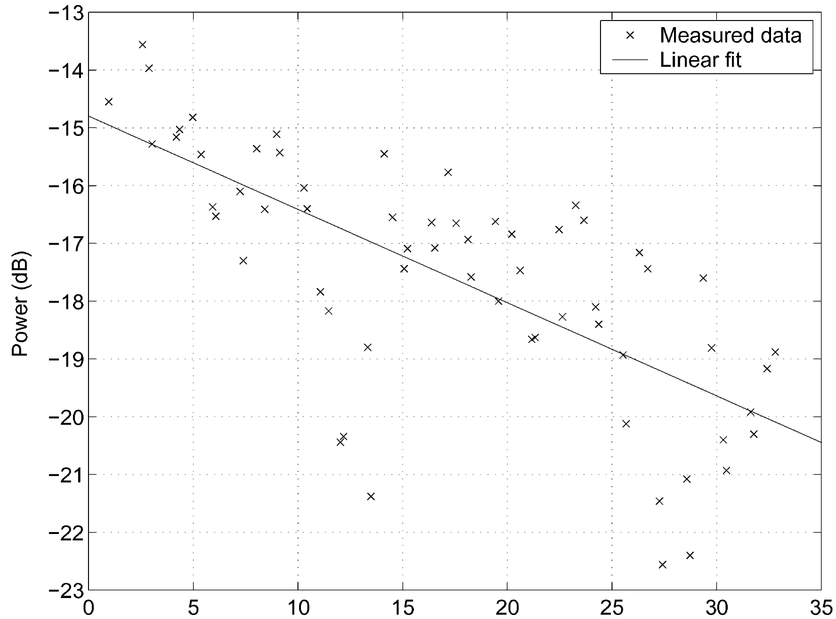

Fig. 2. Measured data (power loss) and the linear fit as a function of transmitter–receiver separation (in meters).

experimental test bed is given in Section VII. Finally, a conclusion is 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 to determine 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 the Hata and Erikson models, have been used to predict the received power level in urban areas, indoors, etc. [3], [4]. 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 to show that it also is possible to find (based on extensive measurements) an empirical model that can accurately predict the path loss for complex HVAC duct networks in the 2.4–2.5-GHz ISM 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 (2.45-GHz ISM band). The total loss of an HVAC network can be found by adding losses due to each component. In Section V, we present data showing that the characterization of each duct component alone is sufficient for characterizing the approximate path-loss model for more complex HVAC networks. The physical mechanisms affecting a modulated signal that propagates through the duct is reported in [9]; therefore, we omit these details in this paper.

III. Preliminaries

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

A theoretical approach in calculating the antenna-coupling loss and attenuation loss has been reported in [8]; however, here we will use our experimental measurements to determine these parameters. For this purpose, wide-band signal-strength measurements were made at the 2.4–2.5-GHz ISM band with a system identical to the one used in [6]. We also used straight cylindrical ducts 0.3 m in diameter, made of galvanized steel. The signal was transmitted through the duct by a monopole antenna of 3.1-cm length (approximately a 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 Fig. 1). Measurements of frequency and time response were done using the VNA in the 2.4–2.5-GHz ISM band. Frequency measurements were then averaged over the frequency band, thus giving the average power loss for each measurement (see the Appendix for a justification of this procedure). A frequency spectrum plot is also given in the Appendix (see also [8]). 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 [8].

To find the total attenuation per unit length, we used the "cutback" or differential method [28], whereby a set of power measurements over the required spectrum were taken, in this case 2.4–2.5 GHz, using a long duct. Losses due to cabling were removed by network-analyzer calibration. Eleven straight duct sections with a length of 3 m each were used to construct a duct path of length 33 m. After power measurements over a 33-m duct were made, the last 3-m duct section was removed

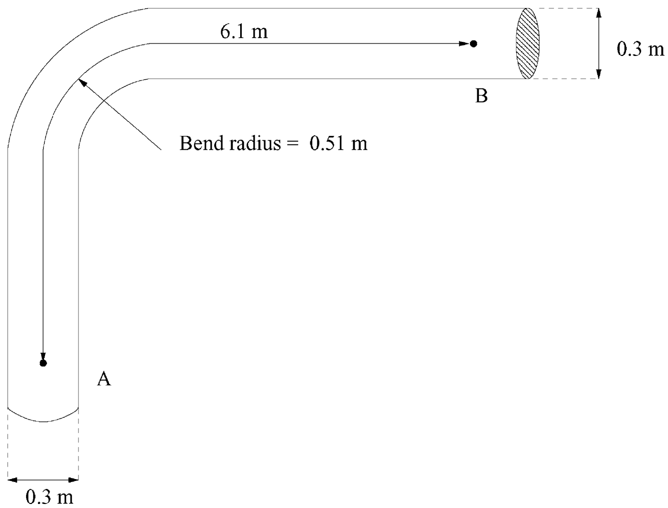

Fig. 3. B network used in our measurements. A and B denote the placements of the transmitting and receiving antennas in the duct. The ends were left open.

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

Points	Distance (m)	Av. Power Loss (dB) (B-networks)	Av. Power Loss (dB) (S-networks)
AB	6.1	17.02 ±0.2	16.7 ±0.1

from the measurements and we continued with the remaining ones, which yielded a long duct of length 30 m. This procedure (known as the "cut-back" or differential method) was repeated for different duct lengths and a total of 62 measurements were made. A linear fit was used for the measured data to extract the attenuation and antenna coupling loss (see Fig. 2). The attenuation loss was found to be 0.16 dB/m, while the antenna coupling loss was found to be 14.8 dB.

IV. CHARACTERIZATION OF PATH-LOSS MODEL FOR INDIVIDUAL DUCT COMPONENTS

The measurement procedure for bends, tees, and wyes junctions was similar to that reported in the previous section. The minimum separation between the transmitter and the receiver antennas was 3.2 m. This distance is much larger than the decay length for the closest evanescent mode, TE_{32}, which is 0.2 m. The frequency measurements made via VNA were then averaged over the frequency band, thus giving the average power loss for each measurement.

A. Bends

The bends used had a radius of curvature of 0.51 m, as shown in Fig. 3. In this experiment, the values (distance and path loss) reported in Table I are the average values found as follows: five separate measurements were made with the transmitter fixed while the receiver was positioned at different points in the duct, each new position being 1.3 cm away from its neighbor. The average distance between the transmitter–receiver pairs was 6.1 m. The same procedure was followed for a straight duct (S network) for comparison and for the characterization of tees and wyes (see Sections IV-B and IV-C, respectively).

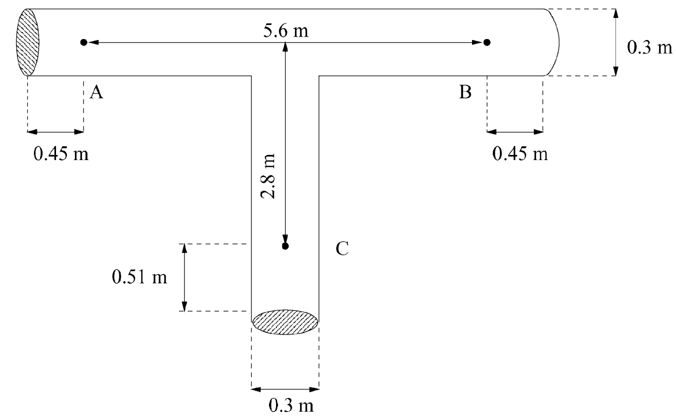

Fig. 4. T network used in our measurements. A, B, and C denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

TABLE II
AVERAGE POWER LOSS (DECIBELS) COMPARISON BETWEEN A T NETWORK AND AN S NETWORK WITH 0.3-M DIAMETER CYLINDRICAL DUCTS

Points	Distance (m)	Av. Power Loss (dB) (T-networks)	Av. Power Loss (dB) (S-networks)
AB	5.6	25 ±0.3	16.4 ±0.2
AC, BC	5.6	27.6 ±0.1	16.4 ±0.2

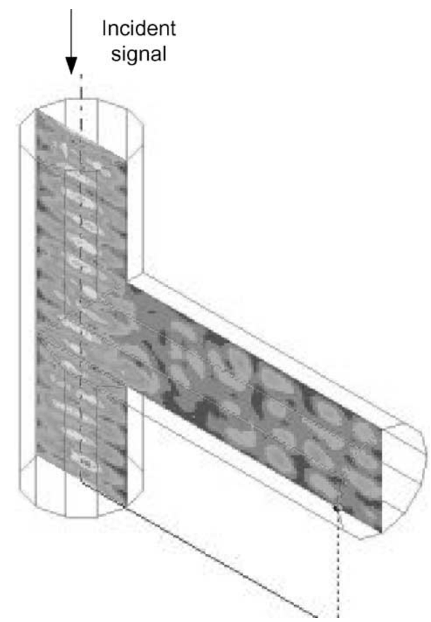

Fig. 5. Field propagation in a tee junction with 17 equally excited modes (HFSS simulation results). The diameter of the ducts in the simulation is 0.3 m and the frequency is 2.45 GHz.

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 very small. In a practical scenario, the HVAC duct network might include a large number of bends and, hence, their impact on predicting the path loss between the transmitter and receiver cannot be neglected.

B. Tees

A T network is shown in Fig. 4 and 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

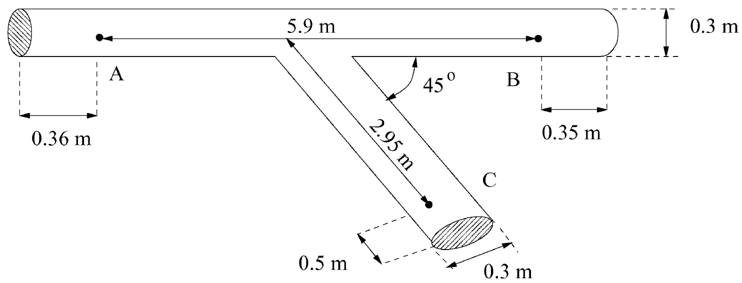

Fig. 6. Y network used in our measurements. A, B, and C denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

the T network or the perpendicular duct section of the T network should be 3 dB greater than the power loss in an S network that has the same distance. However, the results in Table II indicate that the additional 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 for the explanation of this phenomenon is that, in the 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 nonuniformity (bend, tee, cross-section change, etc.) [29]–[31]. Simulation results for tee and wye junctions, excited via waveguide ports, obtained with the High Frequency System Simulator (HFSS) by Ansoft also support this explanation. These simulation results show that the straight through loss of tee junctions is smaller than the loss through the perpendicular section, in qualitative agreement with the measurements (see Fig. 5).

C. Wyes

The experimental setup for a Y network is shown in Fig. 6. Measurements were made using the VNA in the 2.45-GHz ISM band.

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 23.9 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 differences measured in the path loss.

Simulation results for wye junctions excited via coaxial probes, obtained with HFSS, also support this explanation. We could not obtain exact agreement for the power loss in a wye junction, probably because of many approximations in HFSS simulation, such as hollow coax, ideal matching open end, and no impedance mismatch between transceivers and antennas. However, our simulations endorsed our measurements in the sense that path BC (7.4-dB loss in HFSS simulations) is better than AC (7.9-dB loss in HFSS simulations) and both are worse than AB (7-dB loss in HFSS simulations). Fig. 7 shows the path loss obtained via HFSS simulations.

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

Points	Distance (m)	Av. Power Loss (dB) (Y-s)	Av. Power Loss (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

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 a composite network of tees is shown in Fig. 8. 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 estimated to be 17.2 dB by using the results of Section III. The difference between the measured power loss and the S network is 15.5 dB. This difference is associated with the power loss due to the three tees that exists between points Z and S. In the same fashion, we calculated the power losses that are associated with the number of tees along the path between the transmitter and receiver pairs. Then, the minimum mean-square error (mse) criterion was used to calculate the power loss due to one, two, three, and four tees in the network.

We found that one tee introduces a power loss of 8.2 dB with a standard error of 2.4 dB, two tees introduce a power loss of 12.6 dB with a standard error of 1.9 dB, three tees introduce a power loss of 15.5 dB with a standard error of 2.6 dB, and four tees introduce a power loss of 18.0 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 may behave as a "mode filter."

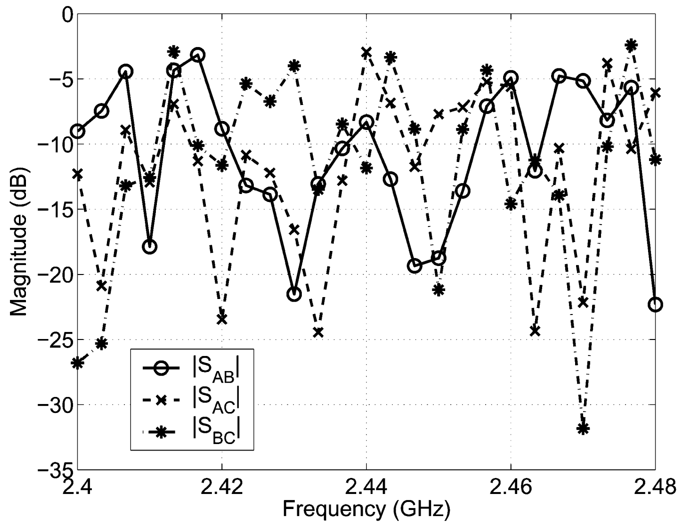

Fig. 7. Channel-frequency response for the wye junction obtained via HFSS simulations.

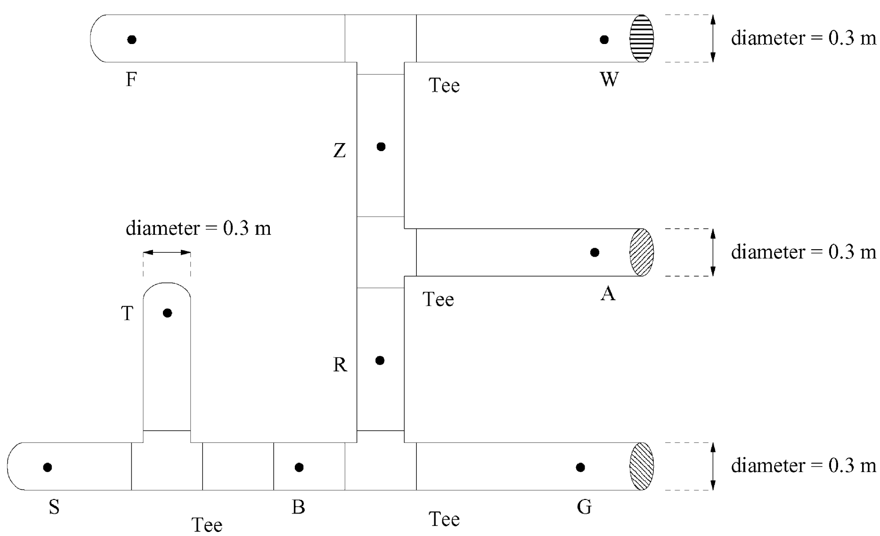

Fig. 8. Experimental setup for a composite network of tees. A, F, Z, W, R, G, B, S, and T denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

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 Fig. 9.

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 Fig. 9, while the second column gives the distance between these points. The measured average power loss is given in the third column and 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 antenna-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

$$P_{l_{\mathrm{AF}}}(\mathrm{dB}) = \alpha_m l_{\mathrm{AF}} + Y_d + T_d + B_d + C_L \qquad (1)$$

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

Number of Tees	Power loss (dB)
1	8.2 ±2.4
2	12.6 ±1.9
3	15.5 ±2.6
4	18.0 ±0.9

where $P_{l_{\mathrm{AF}}}$ 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 the transmitter–receiver pair. Substituting $Y_d \approx 4.9$ dB, $T_d \approx 8.2$ dB, $B_d \approx 0.3$ dB, and $C_L \approx 14.8$ dB, one gets that $P_{l_{\mathrm{AF}}} \approx 30.7$ dB. The last column shows the difference between the results of the measurements and the prediction model.

TABLE V
AVERAGE POWER LOSS (DECIBELS) IN COMPOSITE NETWORK 2 WITH 0.3-M DIAMETER CYLINDRICAL DUCTS

Points	Distance (m)	Av. Power (dB)	Expected Power (dB)	Difference (dB)
AX	5.9	-28.9	-28.5	0.4
AZ	4.6	-24.4	-20.4	-4.0
AG	8.7	-29.1	-29.3	0.2
AB	9.1	-29.4	-29.4	0.0
AF	15.3	-29.4	-30.7	1.3
XZ	5	-25.9	-23.0	-2.9
XG	9.1	-29.2	-31.9	2.7
XB	9.8	-27.9	-32.0	4.1
XF	15.6	-30.9	-33.0	2.3
ZG	4.1	-25.7	-23.7	-2.0
ZB	4.4	-24.6	-23.8	-0.9
ZF	10.6	-26.4	-25.0	-1.4
GB	5.9	-23.5	-24.0	0.5
GF	12	-26	-25.2	-0.8
BF	6.2	-17.8	-16.1	-1.7

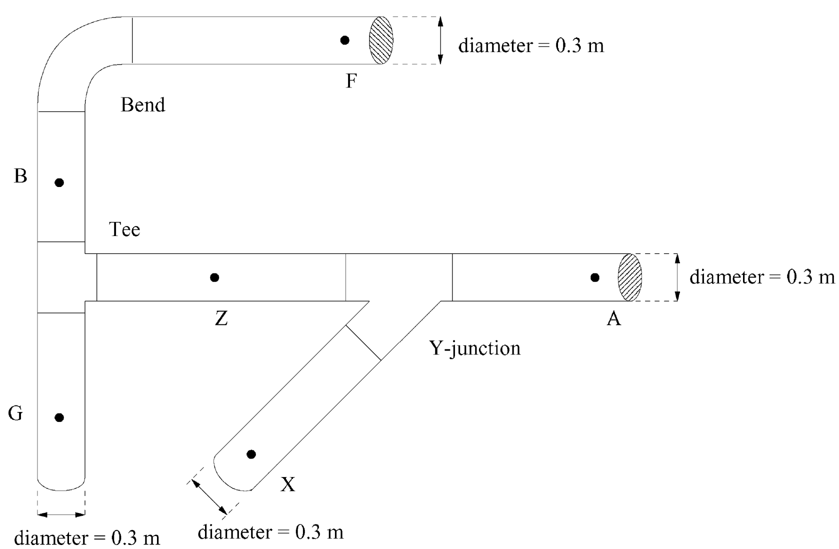

Fig. 9. Experimental setup for composite network 2. A, X, Z, G, B, and F denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

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 Fig. 10).

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. PATH-LOSS MODEL

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

- frequency of transmission;
- distance between transmitter–receiver pair;
- 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

[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.

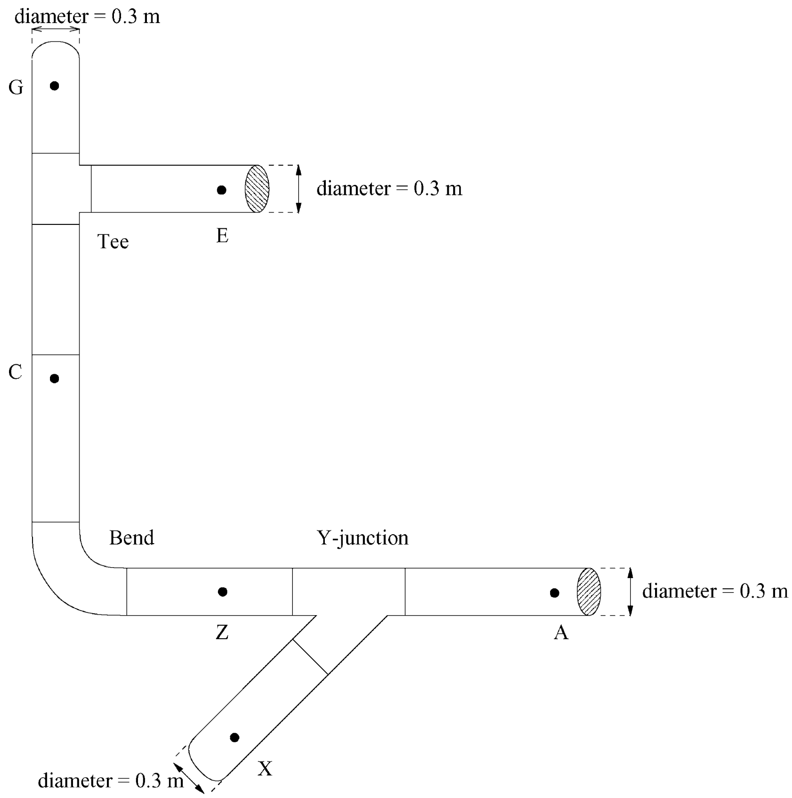

Fig. 10. Experimental setup for composite network 3. A, X, Z, C, G, and E denote the placements of transmitting/receiving antennas in the duct. The ends were left open.

TABLE VI
AVERAGE POWER LOSS (DECIBELS) IN COMPOSITE NETWORK 3 WITH 0.3-M DIAMETER CYLINDRICAL DUCTS

Points	Distance (m)	Av. Power (dB)	Expected Power (dB)	Difference (dB)
AX	5.9	-29.6	-28.5	-1.1
AZ	4.6	-24.3	-20.4	-3.9
AC	8.7	-26.5	-21.4	-5.1
AG	15.5	-28.7	-30.7	2.0
AE	15.8	-33.1	-30.7	-2.4
XZ	5	-24.3	-23.0	-1.3
XC	10.1	-26.9	-24.1	-2.8
XG	15.9	-33.6	-33.3	-0.3
XE	16.2	-31.4	-33.3	1.9
ZC	5.1	-17.1	-15.9	-1.2
ZG	10.9	-27.7	-25.1	-2.6
ZE	11.2	-28.3	-25.1	-3.2
CG	5.7	-25.4	-23.9	-1.5
CE	6.1	-23.4	-24.0	0.6

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 14.8 dB. A summary of the power-loss levels from our experimental results is given in Table VII.

TABLE VII
SINGLE-ELEMENT CHARACTERIZATION OF POWER LOSS (DECIBELS) 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	8.2	8.2	8.2
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 [see (2) at the bottom of the page] where P_{ri} denotes the power received in dBm for the user in office i; $\alpha_m(r, \sigma)$ denotes the multimode 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 the office; n_{Ti} , n_{Yi}, and n_{Bi} denote the number of tees,

Fig. 11. Experimental setup at the NREC, Carnegie Mellon University.

wyes, and bends from the AP to the user; $B(r,\sigma)$ denotes the power loss in decibels in the bends; C_L is the antenna coupling loss; and $T_j(r,\sigma)$ and $Y_j(r,\sigma)$ denote the power loss due to the jth tee and wyes, respectively, given in Table VII.

It is worth mentioning here that, for other frequency bands, duct diameters, geometries, and antenna lengths, values given in Table VII will have to be remeasured before using them in our path-loss model.

VII. Illustrative HVAC System: Case Study

To illustrate how the path-loss model works, the duct network shown in Fig. 11 (a layout is also shown in Fig. 12) was constructed at the National Robotics Engineering Consortium (NREC) Laboratory, Carnegie Mellon University, Pittsburgh, PA. This experimental setup is representative of what might be used in office spaces in the U.S. 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 AP through the duct by a monopole antenna of 3.1-cm length. The receiver uses the same antenna as the transmitter and both antennas were connected to an Agilent E8358A VNA via coaxial cables (as in Fig. 1). Measurements of frequency response were made using the VNA in the 2.45-GHz ISM 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 objects.

Table VIII 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 VII and an antenna coupling loss of 14.8 dB is used. 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 3.2 dB of the experimental results.

To check the effect of the spatial variations across this large-scale test bed, we proceeded as follows. We used six transmitting antennas at the access point, each 5 cm apart from each other, as well as six 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 the 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 three transmitting antennas at point A, each 5 cm apart from each other, as well as three receiving antennas at point E, each also 5 cm apart from each other. Then, nine 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 test bed, this is an excellent agreement that verifies the validity of 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. Conclusion

In this paper, we described an approximate path-loss model based on measurements made on cylindrical HVAC ducts in the 2.4–2.5-GHz ISM band, 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 in the 2.4–2.5-GHz ISM band, one tee introduces an 8.2-dB loss in either section of a T network, while each additional tee introduces an 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 test bed 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.

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

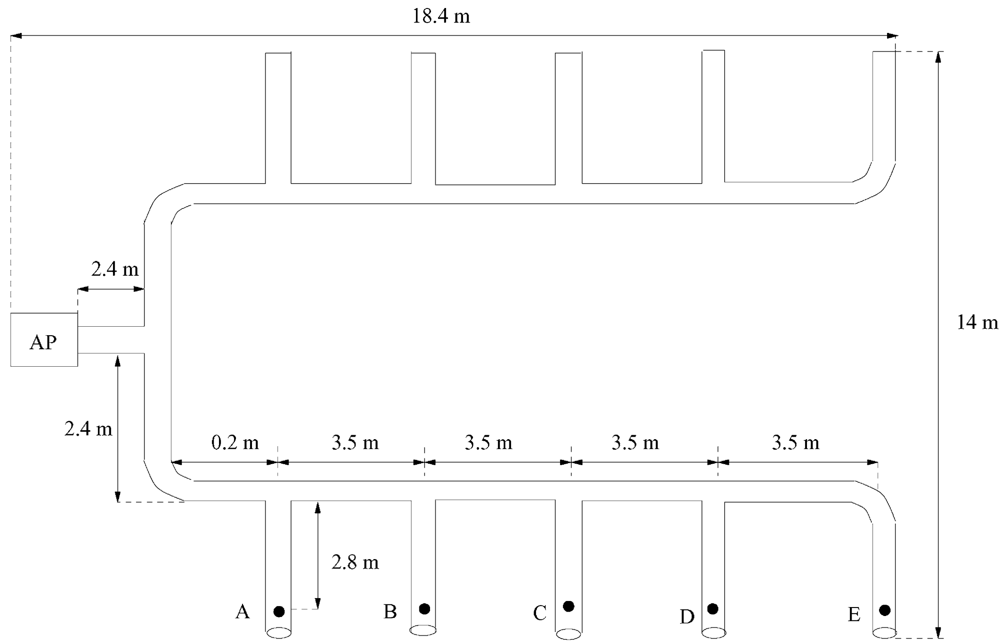

Fig. 12. Floor plan considered in the experimental setup.

TABLE VIII
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	-28.9	-0.8
B	11.1	-34.3	-32.5	-1.8
C	14.6	-35.1	-34.8	-0.3
D	18	-39.3	-39.3	-0.0
E	21.7	-36.9	-40.1	3.2

In summary, a path-loss model that 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 and also allows 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
JUSTIFICATION OF POWER AVERAGING OVER THE 2.45-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

$$V_r(\omega) = \sum_m A_m e^{-j\phi_m(\omega)} \tag{3}$$

where A_m and $\phi_m(\omega)$ are, respectively, the amplitude and phase of the contribution from the mth propagating mode.

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

- span of frequency covers many coherence bandwidths;
- $A_m \approx$ constant with frequency over the band of interest;
- $\phi_m(\omega)$ is a uniformly distributed random variable over the range $(-\pi, \pi]$.

To show that this is true, take the expectation over frequency of the magnitude squared of V_r

$$\begin{aligned} E\left[|V_r(\omega)|^2\right] &= E\left[\sum_{m,n} A_m A_n e^{-j(\phi_m(\omega)-\phi_n(\omega))}\right] \\ &= E\left[\sum_m A_m^2 \cos^2(\phi_m(\omega))\right] \\ &\quad +2E\left[\left\{\sum_{m\neq n} A_m A_n \cos(\phi_m(\omega))\cos(\phi_n(\omega))\right\}\right] \\ &= \frac{1}{2}\sum_m {A_m}^2 \end{aligned} \tag{4}$$

since ϕ_m ranges over $(-\pi, \pi]$ and are statistically independent; thus, $E[\cos(\phi_m)\cos(\phi_n)] = E[\cos(\phi_m)]E[\cos(\phi_n)] = 0$, since $E[\cos(\phi_m)] = E[\cos(\phi_n)] = 0$. Thus

$$E\left[|V_r(\omega)|^2\right] = \sum_m P_m = P_T \tag{5}$$

where $(1/2)A_m^2 = P_m$ is the power in the mth mode and the total power is simply the sum of the power in each mode.

Fig. 13 shows the frequency response of a 5.3-m distance separation between the antennas in the HVAC duct. Using the aforementioned procedure, with 1601 frequency samples, we found that the average power loss for a 5.3-m (antenna separation) straight HVAC duct is 15.4 dB.

The above frequency response has a coherence bandwidth of 6.22 MHz (a 20-dB threshold level was used in the impulse response to calculate the coherence bandwidth for 50% signal correlation). Thus, one can consider approximately 16 subbands (in

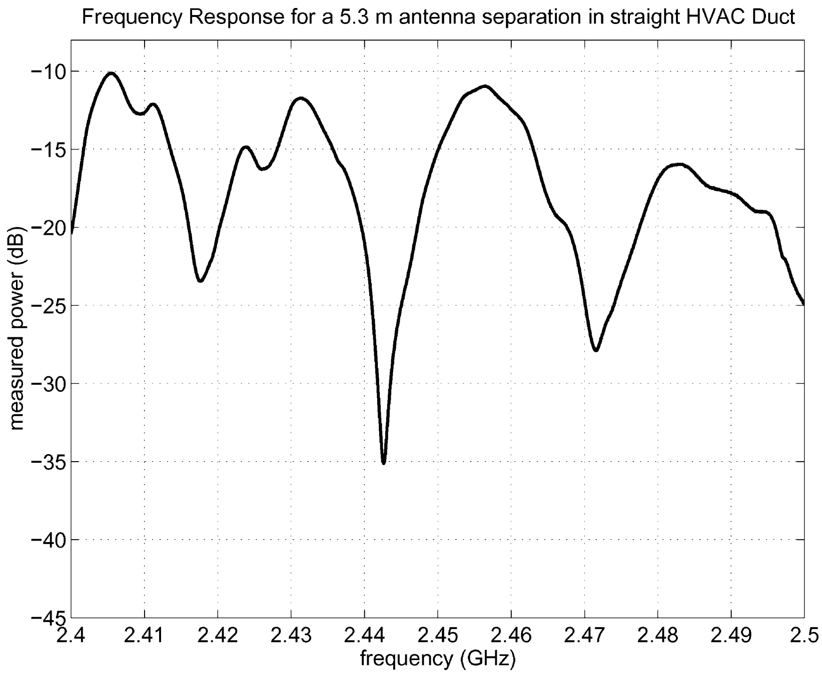

Fig. 13. Frequency response of a 5.3-m straight HVAC duct. Cylindrical ducts 0.3 m in diameter made of galvanized steel with conductivity $\sigma = 10^6$ S/m were used for this measurements. The signal was transmitted through the duct by a monopole antenna of 3.1-cm length.

fact, it is slightly higher than 16) for which the signal measurements are statistically independent. This is a large enough statistical sample to get a reasonable estimate of the expectation given in (4).

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Ozan K. Tonguz (S'86–M'90) was born in Nicosia, 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 Ph.D. degrees in electrical engineering from Rutgers University, New Brunswick, NJ, in 1986 and 1990, respectively.

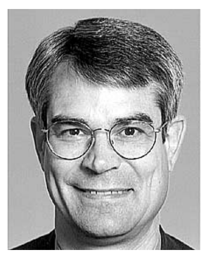
He is currently a tenured Full Professor in the Department of Electrical and Computer Engineering, Carnegie Mellon University (CMU), Pittsburgh, PA. Before joining CMU in August 2000, he was with the Electrical and Computer Engineering Department, State University of New York at Buffalo (SUNY). He joined SUNY in 1990 as an Assistant Professor, where he was granted early tenure and promoted to Associate Professor in 1995, and to Full Professor in 1998. Prior to joining academia, he was with Bell Communications Research (Bellcore), Red Bank, NJ, between 1988–1990, doing research in optical networks and communication systems. He has published in the areas of optical networks, wireless communications and networks, and high-speed networking. He is author or coauthor of more than 150 technical papers in IEEE journals and conference proceedings, and a book chapter (New York: Wiley, 1999). He is the author of *Ad Hoc Wireless Networks: A Communication-Theoretic Perspective* (New York: Wiley, 2004). His contributions in optical networks and wireless networks are internationally acclaimed. He was also the architect of the "High Performance Waveform (HPW)" that was implemented in Harris RF Communications' AN/PRC-117f multiband man-pack tactical radio. His industrial experience includes periods with Bell Communications Research, CTI, Inc., Harris RF Communications, Aria Wireless Systems, Clearwire Technologies, Nokia Networks, Asea Brown Boveri (ABB), and Intel. He currently serves as a consultant for several companies, law firms, and government agencies in the United States and Europe in the broad area of telecommunications and networking. He is also a Co-Director (Thrust Leader) of the Center for Wireless and Broadband Networking Research, CMU. More details about his research interests, research group, and publications can be found at http://www.ece.cmu.edu/~tonguz

Dr. Tonguz, in addition to serving on the Technical Program Committees of several IEEE conferences (such as INFOCOM, GLOBECOM, ICC, AND VTC) and symposia in the area of wireless communications and optical networks, currently serves or has served as an Associate Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE COMMUNICATIONS MAGAZINE, and the JOURNAL OF LIGHTWAVE TECHNOLOGY. He was a Guest Editor of the special issue of the JOURNAL OF LIGHTWAVE TECHNOLOGY and the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS on Multiwavelength Optical Networks and Technology, published in 1996.

Ariton E. Xhafa (S'98–M'04) was born in Karbunar, Vlore, Albania. He received the B.S. degree in electrical and electronics engineering and physics from Eastern Mediterranean University, North Cyprus, Turkey, in 1997, the M.S. degree in electrical engineering from the State University of New York, Buffalo (SUNY/Buffalo), in 1999, and the Ph.D. degree in electrical and computer engineering from Carnegie Mellon University (CMU), Pittsburgh, PA, in 2003.

He was a Visiting Researcher at CMU From 2000 to 2001, doing research on the design and performance analysis of communications systems. He was a Research Assistant with the Telecommunications Research Group, Center for Wireless and Broadband Networking, CMU, from 2002 to 2003, doing research on design and performance evaluation of wireless networks. He was a Research Associate with CMU from January to April 2004, doing research on scheduling, handover management, and resource allocation in wireless networks. Currently, he is a Member of Technical Staff with the Communications Systems Laboratory, Texas Instruments Inc., Dallas, TX. His current research interests include design and evaluation of multiple-access (MAC) protocols, handover management, and quality of service (QoS) in wireless networks.

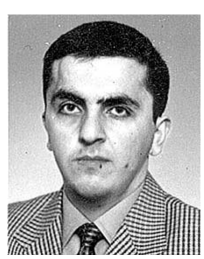
Dr. Xhafa is a Member of Eta Kappa Nu and of the IEEE Communications, Vehicular Technology, and Computer Societies.



Daniel D. Stancil (S'75–M'81–SM'91) received the B.S. degree in electrical engineering from Tennessee Technological University, Cookeville, in 1976, and the S.M., E.E., and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, in 1978, 1979, and 1981, respectively.

From 1981 to 1986, he was an Assistant Professor of electrical and computer engineering with North Carolina State University, Raleigh. In 1986, he was an Associate Professor with Carnegie Mellon University (CMU), Pittsburgh, PA, where he currently is a Professor with the Department of Electrical and Computer Engineering and leads the Antenna and Radio Communications Group and heads the newly established Center forWireless and Broadband Networking.

Dr. Stancil was President of the IEEE Magnetics Society and was the Recipient of a 1985 Sigma Xi Research Award, presented by North Carolina State University. He was a Corecipient of a 1998 Science Award for Excellence, presented by the Pittsburgh Carnegie Science Center, a Research and Development 100 Award, and a Photonics Circle of Excellence Award for the development and commercialization of electrooptic technology. In 1996, he cofounded the Applied Electro-optics Corporation, Pittsburgh, PA, and was a leader in the development of the Virtual Laboratory, Electrical and Computer Engineering Department, CMU, which was a finalist for a 1996 Smithsonian Computerworld Award.



Ahmet G. Cepni (S'01) received the B.S. degrees in electrical and electronics engineering and physics from Bogazici University, Istanbul, Turkey, in 2000, and the M.S. degree in electrical and computer engineering from Carnegie Mellon University (CMU), Pittsburgh, PA, in 2002, where he is currently working toward the Ph.D. degree.

Since January 2001, he has been a Research Assistant with the Antenna and Radio Communications Research Group, CMU, and has been involved with indoor wireless communications via the HVAC duct project. His research interests include intelligent radio architectures, RF/microwave systems, and propagation models.

Pavel V. Nikitin (S'98–M'02) was born in Ashkhabad, U.S.S.R., in March 1974. He received the B.S. degree in electrical engineering from Utah State University, Logan, in 1994, the B.S. degree in physics from Novosibirsk State University, Novosibirsk, Russia, in 1995, the M.S. degree in electrical engineering from Utah State University in 1998, and the Ph.D. degree in electrical and computer engineering from Carnegie Mellon University (CMU), Pittsburgh, PA, in 2002.

He was a Research Assistant with the Antenna and Radio Communications Group, Center for Wireless and Broadband Networking, CMU. He currently is a Research Associate with the Department of Electrical Engineering, University of Washington, Seattle. His research interests include applied electromagnetics, wireless communications, and computer-aided design of integrated circuits and systems.

Dr. Nikitin is a member of Phi Kappa Phi and was a recipient of the 2000 Electrical and Computer Engineering Teaching Assistant of the Year Award, presented by CMU.

Dagfin Brodtkorb (M'81) was born in Norway in July 1947. He received the M.S. and Ph.D. degrees in electrical engineering from the Norwegian Institute of Technology, Trondheim, in 1970 and in 1976, respectively.

From 1971 to 1980, he was a Research Engineer and Project Manager with the Norwegian Defense Research Establishment, Kjeller, where he was involved with radar and microwave systems. From 1977 to 1978, he was a Postdoctoral Researcher with the Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, where he was involved with surface acoustic wave (SAW) technology. From 1980 to 1984, he was with A/S Informasjonskontroll, Asker, Norway, as a Manager of the Remote Sensing Group. From 1984 to 1995, he was Managing Director of MIROS A/S, Asker, Norway. Since 1995, he has been with the ABB Corporate Research Center, Billingstad, Norway, initially as a Senior Research Manager, then as a Technology Program Manager and as a Department Manager, and currently as Vice President (Research Director). He has authored several technical papers.