On the Capacity Limits of HVAC Duct Channel for High-Speed Internet Access

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Abstract—In this paper, we report theoretical and experimental channel-capacity estimates of heating, ventilation, and air conditioning (HVAC) ducts based on multicarrier transmission that uses M-ary quadrature amplitude modulation and measured channel responses at the 2.4-GHz industrial, scientific, and medical band. It is shown theoretically that data rates in excess of 1 Gb/s are possible over distances up to 500 m in *straight ducts* in which reflections have been suppressed. Our experimental results also show that even in the case of *more complex HVAC duct networks* (i.e., HVAC duct networks that include bends, tees, etc.) data rates over 2 Gb/s are possible. Our estimations in this case are valid for distances of up to 22 m, which was the maximum distance of our experimental setup. These experimental results, measured with a large-scale testbed set up at Carnegie Mellon University, Pittsburgh, PA, albeit limited in terms of transmitter–receiver separation distance, provide further evidence on the potential of HVAC systems as an attractive solution for providing communications in indoor wireless networks.

Index Terms—Heating, ventilation, and air conditioning (HVAC) systems for wireless transmission, indoor propagation, internet access, multicarrier transmission, orthogonal frequency-division multiplexing (OFDM).

I. INTRODUCTION

HIGH-SPEED Internet access in buildings (residential, office, and commercial) is one of the most important challenges that next-generation wireless networks face today. Traditional indoor wireless communication systems transmit and receive signals through the use of a network of transmitters, receivers, and antennas that are placed throughout the interior of a building [1]–[3]. However, the placement of transmitters, receivers, and antennas (communication systems) in an indoor environment is still largely a process of trial and error [4], [5]. Also, wires and cables (for example, fiber and coax) are costly to install and may require expensive upgrades when their capacity is exceeded, or when new technology requires different types of wires and cables than those already installed.

An alternative approach to providing a communication infrastructure in buildings is to recognize that every building is already equipped with a microwave distribution system: the heating, ventilation, and air conditioning (HVAC) ducts [6], [7]. These ducts are designed to carry air to and from all parts of the building, but can also function as hollow waveguides for microwave signals. While the concept and preliminary results on this approach have been reported in [6]–[8], in this paper, we quantify, *for the first time*, theoretical estimates of HVAC duct channel capacity based on multicarrier transmission that uses M-ary quadrature amplitude modulation (M-QAM) and measured channel responses at the 2.4-GHz industrial, scientific, and medical (ISM) band.

Our results show that in *"matched"*[1] *straight ducts*, data-transmission rates in excess of 1 Gb/s are possible over distances up to 500 m. For more complex HVAC duct networks, one tends to think that the channel capacity will reduce drastically due to the power loss in the tee-junctions, wye-junctions, etc. However, our results show that for more complex HVAC duct networks (that contains tees and bends) with distances of up to 22 m, data-transmission rates in excess of 2 Gb/s are possible. The results reported in this paper show that HVAC systems can be used as an alternative technology for indoor wireless networks, which could enhance the speed of wireless internet access substantially. While from an engineering perspective, much research work remains to be done to implement this technology, from a theoretical standpoint, the capacity limits of HVAC duct channels point to the tremendous potential this technology has.

The remainder of this paper is organized as follows. In Section II, we describe briefly the experimental setup for channel measurement and preliminaries. In Section III, performance analysis of the HVAC duct channel is provided when multicarrier transmission is used as the transmission technology. Results and a discussion of their implications are presented in Section IV, while Section V concludes the paper. Auxiliary material is relegated to the appendix.

II. CHANNEL MEASUREMENTS AND PRELIMINARIES

The ultimate capability of the HVAC system for wireless transmission systems and networks depends on the channel characteristics of the HVAC duct channel, which is a waveguide. To determine this, we have made extensive channel-response

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[1]One can think of "matched" ducts as radio-friendly ducts, since "matching" can, in principle, eliminate multipath reflections in HVAC ducts.
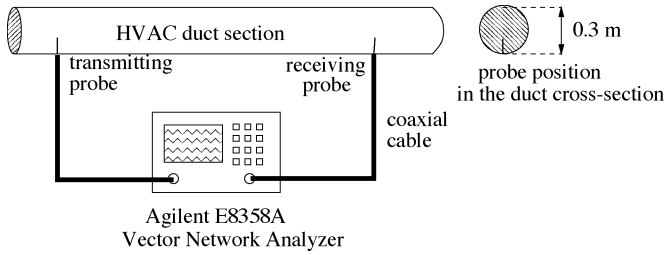
Fig. 1.   Experimental setup used for measurements. HVAC duct section shown is a generic representation, and in different experiments, different composite duct network configurations with different components (wyes, tees, bends, and straight ducts) were used.

measurements on various HVAC duct networks [9]–[12]. Next, we summarize the procedure used for these measurements.

Measurements were done on the second floor of Roberts Hall and National Robotics Engineering Consortium (NREC) on the Carnegie Mellon University (Pittsburgh, PA) campus. Wideband signal strength measurements were made with a system identical to the one used in [8]. Measurements of frequency and time response were done using an Agilent E8358A Vector Network Analyzer (VNA) in the 2.4–2.48 GHz frequency band. We used cylindrical ducts of 30.5 cm and cylindrical pipes of 15 cm in diameter, both made of steel. The signal was transmitted through the duct by a monopole antenna of 3.1 cm in length (approximately quarter wavelength at 2.45 GHz) placed inside the cylindrical ducts. The receiver used the same type of antenna as the transmitter. Both antennas were connected to the VNA via coaxial cables (see Fig. 1).

At the moment, we do not have the capability of making measurements for complex HVAC duct networks that have high transmitter–receiver separation distance (e.g., greater than 25 m). Therefore, in our analysis and results, we make use of the propagation model reported in [9]. In [9], it has been shown that the transfer function of an HVAC duct system, which is used for radio frequency (RF) communications in indoor environments, is given as

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

(1)

where K_Z is the coefficient that accounts for the impedance mismatch loss and depends on the impedances of the transmitter, the receiver, and the antenna; Z_n is the complex antenna impedance due to mode n; $\gamma_n = \alpha_n + j\beta_n$ is the complex propagation constant of mode n (α_n is the attenuation constant and β_n is the propagation constant); L is the distance between the transmitter and the receiver; and L_1 and L_2 are the distances from the antennas to the respective terminated ends with reflection coefficients equal to Γ. This propagation model deals with a straight duct network and can be used for various frequencies and various configurations of ducts (rectangular, cylindrical, etc.). Extension of this model to more complex elements of the network, i.e., tees, bends, wyes, etc., should be possible with techniques such as cascaded scattering matrices [13].

III. ANALYSIS

The performance of data-transmission systems is usually analyzed and measured in terms of the probability of error at a
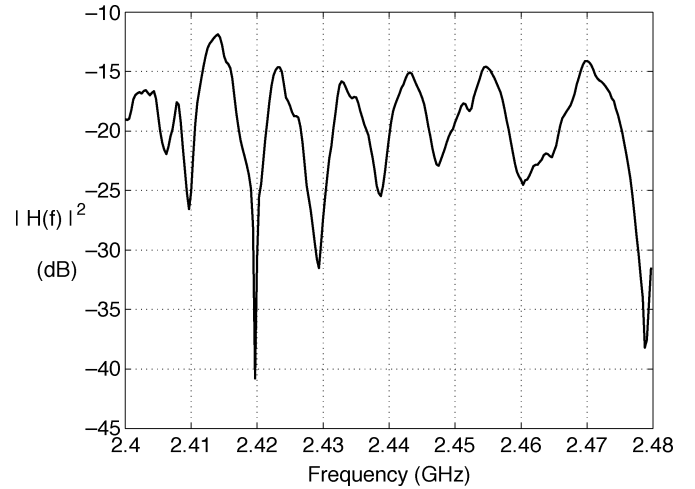

Fig. 2.   Channel frequency response of 11.7-m long, 30.5-cm diameter straight HVAC duct.

given bit rate and signal-to-noise ratio (SNR). However, in practice, more often than not, the total transmitted power is limited. Therefore, for a practical HVAC system, it is more appropriate to calculate the attainable bit rate at a given error rate and under the restriction that the total power P be limited.

Fig. 2 shows the frequency response of the HVAC duct channel for an 11.7–m long and 30.5-cm diameter *straight duct*. The root mean square (RMS) delay spread for this channel was measured to be 57 ns, resulting in a coherence bandwidth B_c of 0.35 MHz (for 90% signal correlation). If one uses the whole bandwidth spectrum (i.e., single carrier) for data transmission, it is clear that since the transmission bandwidth is much larger than the coherence bandwidth (compare 80 MHz with 0.35 MHz), intersymbol interference (ISI) will appear at the receiver side. One way to achieve ISI-free transmission is to use multicarrier transmission of the signals, where the signal bandwidth transmitted in each tone/carrier is limited by the coherence bandwidth of the channel. A more efficient use of bandwidth can be obtained with a multicarrier system if the spectra of the individual subchannels are permitted to overlap, while specific orthogonality constraints are imposed to facilitate separation of the subchannels at the receiver [14]–[17]. This technique is known as orthogonal frequency-division multiplexing (OFDM), and was first proposed by Bell Labs researchers R. W. Chang and R. A. Gibby in the 1960s [14], [15]. It has been shown that OFDM and its extensions (e.g., vector OFDM [20]) provide substantial performance improvements over single-carrier modulation [17]–[20].

In multicarrier transmission, the number of carriers (N) used can be found as the minimum number of carriers needed for ISI-free transmission of the signal. For example, if the coherence bandwidth of the channel is B_c and the available transmission band is B_t, then the number of carriers used for ISI-free signal transmission is given as

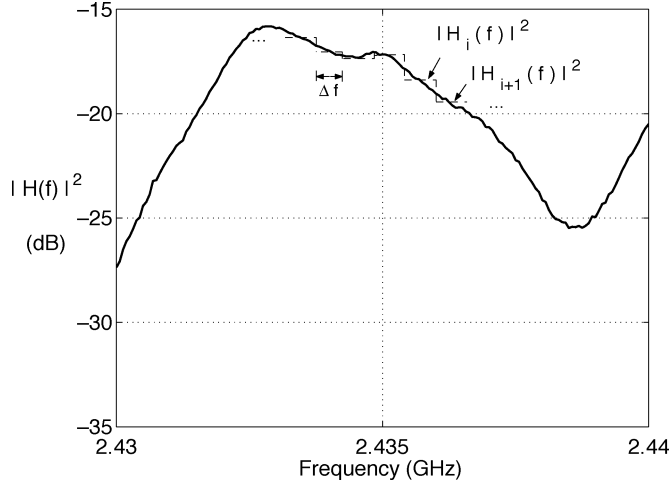$$N = \left\lceil \frac{B_t}{B_c} \right\rceil.$$

(2)

Fig. 3. Approximation of the channel-frequency response of 11.7-m long, 30.5-cm diameter straight HVAC duct via a staircase function for 2.43–2.44 GHz. Note that the figure is for illustration purposes, and that in the band 2.43–2.44 GHz, approximately 32 carriers are used.

In our analysis, we consider the use of multicarrier transmission with M-QAM[2] used for each carrier. Since each carrier could transmit a different number of bits per symbol, say n_i, and assuming that ISI-free bandwidth for each carrier is Δf, then the total bit rate R transmitted via the HVAC duct channel is

$$R = \sum_{i=1}^{N} n_i \Delta f. \qquad (3)$$

In case of M-QAM and high SNR, the symbol-error probability (SEP) in the ith carrier P_{se_i} is given as [21]

$$P_{\mathrm{se}_i} = 4 \left(1 - \frac{1}{\sqrt{M_i}}\right) Q\left(\sqrt{\frac{3E_{\mathrm{av}}}{(M_i - 1)N_0}}\right) \qquad (4)$$

where M_i is the M-QAM in the ith carrier, E_{av} is the average energy per symbol, $Q(\cdot)$ is the error function defined as $Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-y^2/2} dy$, and $N_0 = 2N(f)$, where $N(f)$ is the double-sided power spectral density of the additive white Gaussian noise (AWGN). The SEP can also be expressed as [21]

$$P_{\mathrm{se}_i} = K_{n_i} Q\left(\sqrt{\frac{3E_{\mathrm{av}}}{(M_i - 1)N_0}}\right) \qquad (5)$$

where K_{n_i} is a constant that depends on the number of bits per symbol, such that $2 \leq K_{n_i} \leq 4$. In case of single-carrier transmission over a linear distorted channel of bandwidth W, and assuming ISI-free transmission over this channel, the number of bits per symbol (when M-ary modulation is used) is given as

$$n = \log_2 M. \qquad (6)$$

We also assume that M-QAM is used for single-carrier transmission. The number of bits per symbol will be lower bounded if $K_n = 4$, and upper bounded if $K_n = 2$. After some algebraic

[2]One can consider other M-ary modulations; however, in this paper, we study the performance of a multicarrier transmission system that uses M-QAM.

steps, one can show that the transmission rate over a channel with bandwidth W and ISI-free transmission is given as

$$R = W \cdot \log_2 \left[1 + \frac{\frac{3P}{(N_0 W)}}{\left[Q^{-1}\left\{\frac{P_{\mathrm{se}}}{K_n}\right\}\right]^2}\right] \qquad (7)$$

where P is the transmitted signal power. In case of multicarrier transmission, approximating the channel-transfer function $H(f)$ by a staircase function (see Fig. 3) and summing over all tones/carriers, one finds that the total bit rate is given as [18], [19]

$$R = \sum_{i=0}^{N-1} \Delta f \cdot \log_2 \left[1 + \frac{\frac{3k_i P}{(N_0 \Delta f)|H_i(f)|^2}}{\left[Q^{-1}\left\{\frac{P_{\mathrm{se}_i}}{K_{n_i}}\right\}\right]^2}\right] \qquad (8)$$

where N is the number of carriers, and k_i's are such that

$$\sum_{i=0}^{N-1} k_i = 1, \quad k_i > 0. \qquad (9)$$

Assume that the symbol-error rate for each of the tones/carriers is the same, and equal to P_{se}. We also use K_n instead of K_{n_i}; hence, $K_n = 4$ or $K_n = 2$ will lower bound or upper bound the transmission bit rate. Since each QAM signal requires at least one bit in each dimension, then in (8), one should have $\log_2[\cdot] > 2$. Maximizing R means that the power distribution has to be optimized over different frequency channels, given the constraint for k_i's. After some steps (see the Appendix for more details), one gets

$$R_{\max} = \sum_{i=0}^{N-1} \Delta f \cdot \log_2 \left[\frac{\nu}{ln2} K_0 |H_i(f)|^2\right] \qquad (10)$$

where $K_0 = 3P/(N_0[Q^{-1}\{\cdot\}]^2)$ and $\nu = -1/\lambda$ is the Lagrangian multiplier.

Next, we present numerical results using different HVAC duct channel-frequency response measurements made in the laboratory.

IV. RESULTS AND DISCUSSION

In our calculations, we use the frequency response of an HVAC duct channel measured via the VNA. The measurements were taken using open-ended straight ducts. When multiple modes are present, reflections from open-ended ducts are small and the ducts can be considered to be "matched." It was previously verified in our measurements that the difference in the channel frequency response between closed-ended ducts with absorbers and open-ended ducts was insignificant [9]. To obtain the impulse response of the channel (that is used to calculate the coherence bandwidth of the channel), an inverse Fourier transform is performed on the frequency response of the channel. The coherence bandwidth of the channel is calculated for 90% signal correlation. Since the complexity of a practical multicarrier transmission system increases with the number of carriers, the minimum number of carriers for ISI-free signal transmission is used in the 2.4–2.48 GHz ISM band, so that complexity is kept at the minimum possible level. Also, the number of carriers should be such that when the quantization
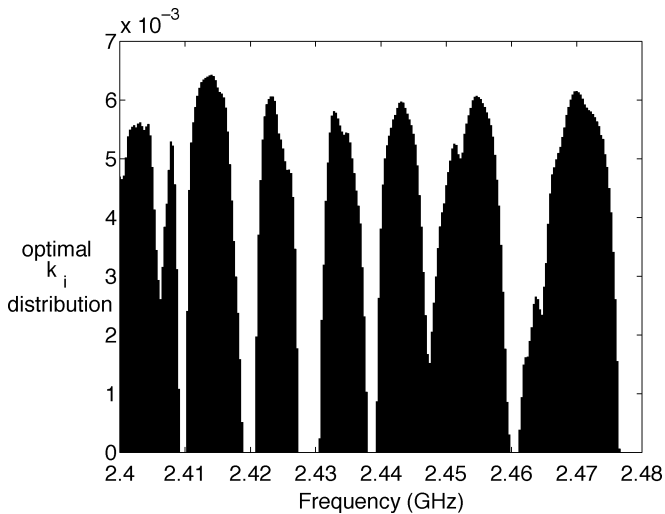
Fig. 4. Distribution of optimal values of k_i's for the channel frequency response of an 11.7-m long and 30.5-cm diameter straight HVAC duct.
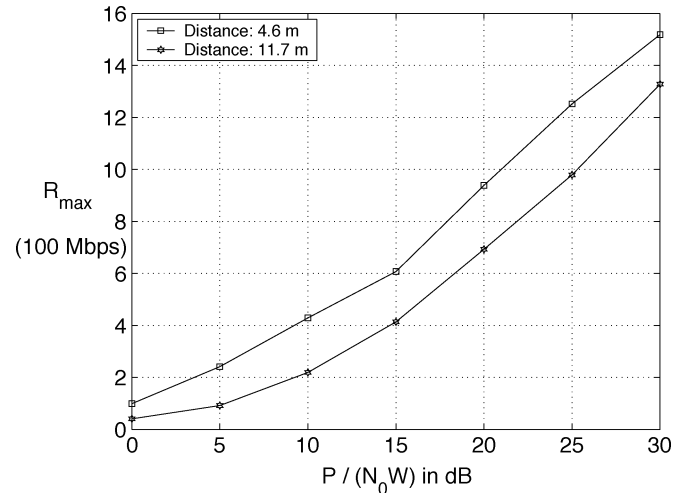

Fig. 5. Normalized capacity versus $P/(N_0W)$. Capacity calculations were done using *experimentally* measured CIRs for cylindrical ducts of 30.5-cm diameter in the 2.4–2.48 GHz ISM band. All 256 carriers in the 80-MHz channel bandwidth are used in the capacity calculations.

of the channel frequency response is done (or equivalently, the approximation of the channel frequency response by a staircase function), the quantization error is small. In another scenario, we consider the use of a fixed number of carriers (256), where each subchannel transmission bandwidth is taken to be the minimum between the carrier spacing and the channel coherence bandwidth. The SEP was taken to be 10^{-5}, while the value used for K_n was four, which gives a lower bound on the HVAC duct channel capacity when one uses multicarrier transmission with M-QAM. We also assume that $P/(N_0W)$ is given. The values of k_i's associated with each of the multicarriers were found by solving (9) and (16) simultaneously.

Fig. 4 shows the distribution of the optimal values for k_i's (at $P/(N_0W) = 30$ dB) of the channel frequency response of an 11.7-m long and 30.5-cm diameter straight HVAC duct. Comparing Fig. 4 with the channel frequency response shown in Fig. 2, one can see that the distribution of optimal values of k_i's follow the attenuation curve of the channel frequency response.

A. HVAC Networks With Straight Ducts

For straight ducts of 30.5-cm diameter, we used the setup shown in Fig. 1. Making use of the channel frequency response measured from the setup shown in Fig. 1, Fig. 5 shows the HVAC duct channel capacity (normalized) versus $P/(N_0W)$ for measurements made for transmitter–receiver pair distances of 4.6 and 11.7 m. For $P/(N_0W)$ greater than 25 dB, a transmission data rate of more than 1 Gb/s can be achieved for the given distances in the duct.

We repeated our experiment for straight ducts in cylindrical pipes with a diameter of 15 cm. Note that while transmitter and receiver were located on the straight pipe, both ends of the pipe were connected to the complex network that included bends, tees, wyes, etc. Thus, the presence of multipath reflections was much higher than the case when the network consisted of simply straight "matched" ducts (as was the case in Fig. 5). Fig. 6 shows the normalized capacity versus $P/(N_0W)$ for different distances between the transmitter–receiver pair. Here, with $P/(N_0W)$ greater than 30 dB, one could achieve 1 Gb/s
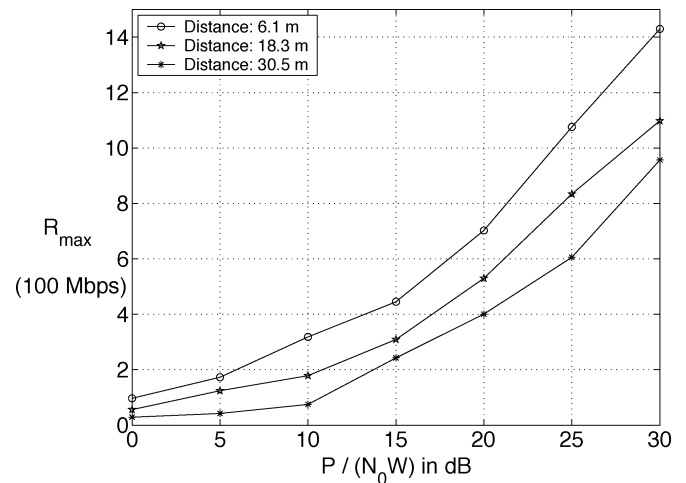

Fig. 6. Normalized capacity versus $P/(N_0W)$. Capacity calculations were done using *experimentally* measured CIRs for cylindrical pipe network of 15-cm diameter in the 2.4–2.48 GHz ISM band. All 256 carriers in the 80-MHz channel bandwidth are used in the capacity calculations.

or higher data-rate transmission. Observe that the channel capacity decreases as the distance between the transmitter and the receiver increases, which is the trend that one would expect. Comparing the results shown in Fig. 5 and Fig. 6, one can see that slightly higher data-transmission rates are achieved in the case of straight ducts of 30.5-cm diameter (compare the transmission rates for distances of 4.6 m in Fig. 5 and 6.1 m in Fig. 6). However, the results shown in Fig. 5 are for straight "matched" ducts, while the results shown in Fig. 6 are for a realistic network configuration, where no effort is made to reduce the multipath reflections.

It is of interest to plot the capacity versus distance for a given transmitter power. As an example, consider a long straight open-ended ("matched") duct system. Assume a transmit power of 1 W (+30 dBm), a total receiver noise power of −90 dBm, a probe coupling loss of 16 dB, and a SEP of 10^{-5}. Then, $P/(N_0W) = 104$ dB. Capacity calculations were done using the above assumptions and channel impulse responses
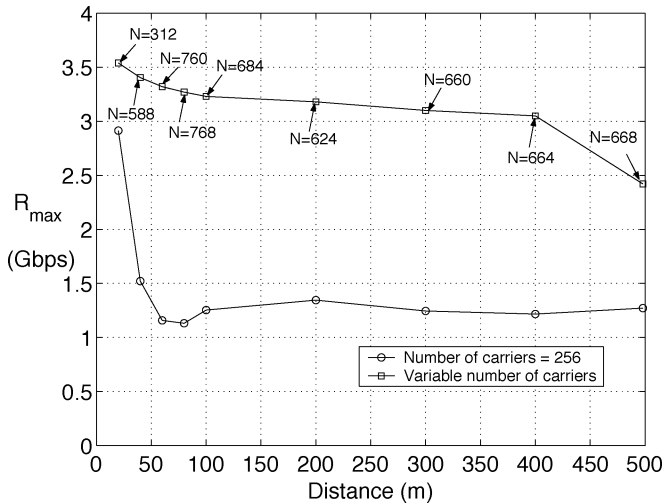
Fig. 7. Transmission rate as a function of transmitter–receiver separation distance for a transmit power of 1 W, a receiver noise power of -90 dBm, a probe coupling loss of 16 dB, and a SEP of 10^{-5}. Capacity calculations were done using CIRs extracted from our theoretical propagation model for cylindrical open-ended ducts of 30.5-cm diameter in the 2.4–2.48 GHz ISM band. Two cases are considered, fixed and variable numbers of carriers.

(CIRs) extracted from our theoretical propagation model [9] for different distances between the transmitter–receiver pair.

Plots of transmitted data rate as a function of distance for a fixed number of carriers (256) and a variable number of carriers are given in Fig. 7. The variable number of carriers is found as the minimum number of carriers needed for ISI-free signal transmission via an HVAC duct channel. Although the minimum number of carriers needed for ISI-free signal transmission is greater than 256, for the fixed number of carriers case, the signal transmission bandwidth is taken to be the channel-coherence bandwidth. Note that the usable bandwidth is the channel-coherence bandwidth, even in the case of a variable number of carriers. Thus, if the coherence bandwidth of the channel is less than $B_t/256$, in the case of a fixed number of carriers, a portion of 80 MHz is not used at all, but the complexity in this case is kept at a much lower level, compared with the case with a variable number of carriers. The shape of the curves in Fig. 7 can be explained with the behavior of the RMS delay spread for different distances [11]. Since measurements were made with open-ended ducts, the RMS delay spread results from dispersion between multiple propagation modes. At short distances, this delay spread increases monotonically with distance, thus the coherence bandwidth of the channel decreases. This results in the sharp initial decline in capacity for the case of a fixed number of carriers, shown in Fig. 7 (lower curve). At longer distances, the delay spread is limited by the decay time in the ducts and the RMS delay spread (or equivalently, the coherence bandwidth) and, therefore, the capacity stabilizes for both cases.

The important observation from this figure is that, with a fixed number of carriers (i.e., $N = 256$), bit rates in excess of 1 Gb/s should be possible over distances up to 500 m in straight ducts.

However, the HVAC network in buildings does not consist of just straight ducts, but also tees, bends, wyes, etc. Thus, one has to estimate the capacity of complex HVAC duct networks. In the next section, we investigate the capacity of complex HVAC duct networks.

Fig. 8. Experimental setup at NREC.

B. HVAC Networks With Tees and Bends

To estimate the capacity of HVAC channels for realistic scenarios, the duct network shown in Fig. 8 (a layout is also shown in Fig. 9) was constructed at the National Robotics Engineering Consortium (NREC) Laboratory of Carnegie Mellon University. This experimental setup is representative of what might be used in office spaces in the US 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 VNA via coaxial cables (as in Fig. 9). Measurements of frequency response were made using the VNA in the 2.4–2.5 GHz frequency band. These measurements were used to calculate the data-transmission rate capabilities of this network. Assume a transmit power of 1 W (+30 dBm), a total receiver noise power of -90 dBm, a probe coupling loss of 16 dB, and a SEP of 10^{-5}. Then, $P/(N_0 W) = 104$ dB. Fig. 10 shows the data-rate transmission versus transmitter–receiver separation distance for different APs (see Fig. 9). As one can see, data transmission rates over 2 Gb/s are possible for distances up to 22 m, even in the case of *complex HVAC duct networks* that include tees and bends (in addition to straight ducts). These capacity estimates are slightly lower than those of straight HVAC duct networks that have the same distance. There are two reasons for this. The first is that the power loss in a complex HVAC duct network is higher than in the straight duct networks; and the second reason is that the RMS delay spread is also higher, since more reflections are present in the complex HVAC duct networks. At the moment, we do not have the capability of making measurements for complex HVAC duct networks that have higher transmitter–receiver separation distance; however, we believe that for practical separation distances (in today's buildings, that translates into distances of up to 100 m), the data-transmission capabilities of complex HVAC duct networks will also be in the gigabits-per-second range.

Our results (see Fig. 7 and Fig. 10) suggest that HVAC technology can be used as a distribution system for wireless internet
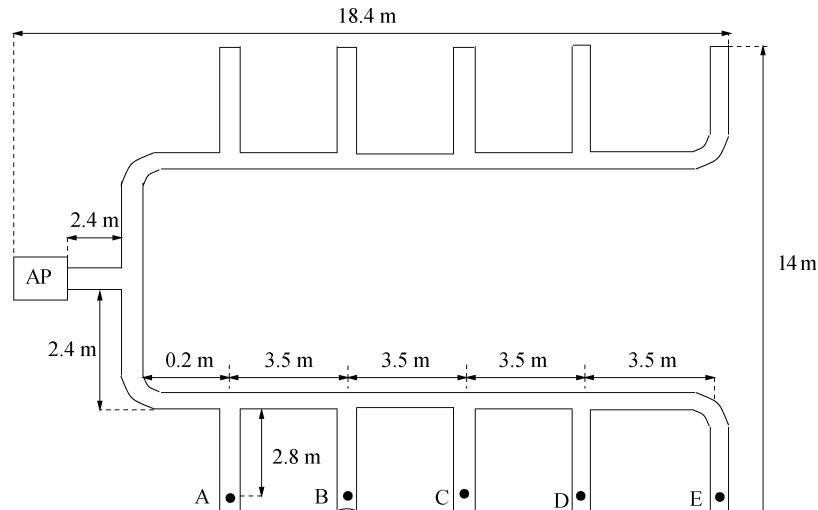
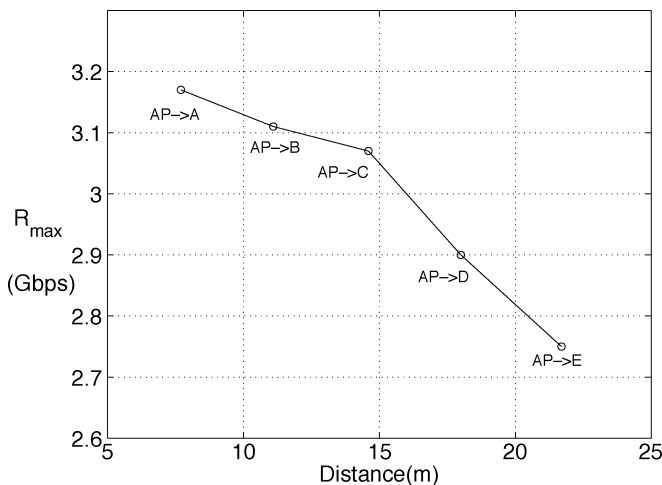Fig. 9.   Floor plan considered in the experimental setup [10].

Fig. 10.   Transmission rate as a function of transmitter–receiver separation distance between different APs (see Fig. 9) for a transmit power of 1 W, a receiver noise power of -90 dBm, a probe coupling loss of 16 dB, and a SEP of 10^{-5}.

access in buildings. Fig. 7 also shows that by choosing a variable number of carriers at each distance for ISI-free transmission, one can, in principle, provide data rates larger than 1 Gb/s (see the upper curve in Fig. 7). However, to change the number of carriers for different transmitter–receiver distances over the same floor plan seems impractical and prohibitive from a complexity standpoint.

It is worth mentioning that while HVAC duct-channel capacity is an important measure for the capacity of an HVAC network, the total capacity of the network should be treated as the capacity of the *compound channel*, HVAC duct channel and the channel consisting of the receiving antenna pair on the duct and the user terminal. Hence, further research is needed to quantify the theoretical capacity of the compound channel.

V. CONCLUSIONS

We have quantified the theoretical channel-capacity limits of the HVAC ducts when multicarrier transmission with M-QAM is used as the transmission technology. These estimates of

channel capacity based on multicarrier transmission and measured/predicted channel responses indicate that with 256 carriers in the 2.4–2.48 GHz ISM band, data rates in excess of 1 Gb/s are possible over distances up to 500 m for HVAC straight ducts. For more realistic scenarios, our estimates show that data rates in excess of 2 Gb/s are possible over distances of up to 22 m. It is clear that the theoretical capacity estimates for HVAC channels reported in this paper suggest a new distribution technology for indoor wireless networks which could provide cheaper and faster wireless internet access to indoor environments. Thus, these theoretical capacity estimates provide further evidence on the potential of HVAC systems as an attractive and viable option for broadband wireless communications in new systems, as well as legacy systems.

APPENDIX
MAXIMUM BIT RATE OF HVAC SYSTEMS

In this appendix, we justify the maximum bit rate given in (10).

Maximizing R means that the power distribution has to be optimized over different-frequency channels, given the constraint for k_i's. More formally, this optimization problem can be formulated as

$$\max . R = \sum_{i=0}^{N-1} \Delta f \cdot \log_2 \left[1 + \frac{\frac{3 k_i P}{(N_0 \Delta f)|H_i(f)|^2}}{\left[Q^{-1} \left\{ \frac{P_{\mathrm{se}_i}}{K_{n_i}} \right\} \right]^2} \right] \qquad (11)$$

subject to the constraint that

$$\sum_{i=0}^{N-1} k_i = 1, \quad k_i > 0. \qquad (12)$$

The solution to this convex optimization problem is called the "waterpouring" solution [18], [22], and can be found using the Lagrange multiplier technique. Let R' denote a new function that is given as

$$R' = R + \lambda \sum_{i=0}^{N-1} k_i. \qquad (13)$$

Finding the values of k_i for which R is maximized implies that R' is minimized. Hence

$$\frac{\partial R'}{\partial k_i} = 0. \qquad (14)$$

Substituting for R' yields

$$\frac{\partial}{\partial k_i}\left(\sum_{i=0}^{N-1}\Delta f\cdot\log_2\left[1+\frac{\frac{3k_iP}{(N_0\Delta f)|H_i(f)|^2}}{\left[Q^{-1}\left\{\frac{P_{\rm se}}{K_n}\right\}\right]^2}\right]+\lambda\sum_{i=0}^{N-1}k_i\right)=0 \qquad (15)$$

which, after some algebraic steps, yields

$$k_i = \begin{cases} \frac{\nu\Delta f}{ln(2)} - \frac{\Delta f}{K_0|H_i(f)|^2}, & k_i > 0 \\ 0, & \text{otherwise} \end{cases} \qquad (16)$$

where $K_0 = 3P/(N_0[Q^{-1}\{\cdot\}]^2)$, $\sum k_i = 1$, and $\nu = -1/\lambda$ is the Lagrangian multiplier. The Lagrangian ν and k_i's are found by solving (12) and (16) simultaneously. Substituting for k_i's in (8), the maximum bit rate is given by

$$R_{\max} = \sum_{i=0}^{N-1}\Delta f\cdot\log_2\left[\frac{\nu}{ln2}K_0\,|H_i(f)|^2\right] \qquad (17)$$

which establishes (10) of the manuscript.

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