Theoretical Estimates of HVAC Duct Channel Capacity for High-Speed Internet Access

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Abstract— **In this paper, we report theoretical channel capacity estimates of heating, ventilation, and air-conditioning (HVAC) ducts based on multi-carrier transmission that uses M-QAM modulation and measured channel responses at 2.4 GHz Industrial, Scientific, and Medical (ISM) band. It is shown that, data rates in excess of 1 Gbps are possible over distances up to 500 m in "matched" ducts (one can think of "matched" ducts as user-friendly ducts, since "matching" can, in principle, eliminate all the multi-path reflections in HVAC ducts). Our work also shows that data rates in excess of 300 Mbps are possible over distances up to 500 m even in the presence of significant multi-path reflections.**

Keywords—**Internet access; indoor propagation; Heating, Ventilation, and Air Conditioning Systems for wireless transmission.**

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]. However, the placement of transmitters, receivers, and antennas (communication systems) in an indoor environment is still largely a process of trial and error [2], [3]. Many communication systems are thus implemented inefficiently. 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 [1].

An alternative approach to providing the communication infrastructure in buildings is to recognize that every building is already equipped with a microwave distribution system: the heating and ventilation ducts [4]. 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 [1], in this paper we quantify theoretical estimates of heating, ventilation, and air conditioning (HVAC) duct channel capacity based on multi-carrier transmission that uses M-QAM modulation and measured channel responses at 2.4 GHz Industrial, Scientific, and Medical (ISM) band.

Our results show that data transmission rates in excess of 1 Gbps are possible over distances up to 500 m in "matched" ducts. It is also shown that data rates in excess of 300 Mbps are possible over distances up to 500 m even in the presence of significant multi-path reflections.

The remainder of this paper is organized as follows. In Section II we describe briefly the channel measurement setup. In Section III, analysis of HVAC duct channel when multi-carrier transmission is used as the transmission technology is given. Results and discussion are presented in Section IV, while Section V concludes the paper.

II. CHANNEL MEASUREMENTS

Measurements were done on the second floor of Roberts Hall on Carnegie Mellon University's campus. Wide band signal strength measurements were made at 2.4 GHz with a system identical to the one used in [1]. 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 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 2.4-2.48 GHz frequency band.

III. ANALYSIS

The performance of data transmission systems is usually analyzed and measured in terms of the probability of error at a given bit rate and signal-to-noise ratio (SNR). However, for a practical HVAC system it is more appropriate to calculate the attainable bit rate at a given error

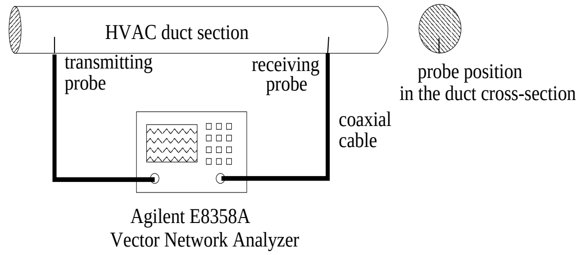

Fig. 1. Experimental setup used for measurements. HVAC duct section shown in the figure is a generic representation and in different experiments different composite duct networks with different components (wyes, tees, bends, and straight ducts) were used.

rate and under the restriction that the total power P be limited.

Next, we derive the maximum transmission rate of the HVAC channel when multi-carrier transmission with M-QAM modulation is used. The symbol error rate for each of the tones (frequencies) is assumed to be constant. First we introduce some terms and notations that we will need during the capacity derivation of the HVAC duct channel.

In case of M-QAM modulation and high signal-to-noise ratio, the probability of symbol error is given as [6]:

$$P_{se} = 4\left(1 - \frac{1}{\sqrt{2^n}}\right) Q\left(a\sqrt{\frac{2}{N_0}}\right), \qquad (1)$$

where n (even) is the number of bits per symbol and $Q(\cdot)$ is the error function defined as:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-y^2/2} dy, \qquad (2)$$

and $N_0 = 2N(f)$, where $N(f)$ is the double-sided power spectral density of the additive white gaussian noise (AWGN). The parameter a is related to the average symbol energy E for even n via the equation [6]:

$$a^2 = \frac{3E}{2(2^n - 1)}. \qquad (3)$$

Below we provide a brief outline for the derivation of the capacity of an HVAC duct channel. Denoting the channel frequency response as $H(f)$, the total bit rate for a single tone channel can be written as [5]:

$$R = W \cdot log_2\left[1 + \frac{3P/(N_0 W)|H(f)|^2}{[Q^{-1}\{P_{se}/K_n\}]^2}\right], \qquad (4)$$

where P is the signal power, W is the channel bandwidth, and K_n is a constant dependent on the number of bits per symbol such that $2 \leq K_n \leq 4$. In case of multi-carrier transmission, approximating the channel transfer function by a staircase function and summing over all tones/carriers (for which $log_2(\cdot) > 2$), one finds that the total bit rate is equal to [5]:

$$R = \sum_{i=0}^{N-1} \Delta f \cdot log_2\left[1 + \frac{3k_i P/(N_0 \Delta f)|H_i(f)|^2}{[Q^{-1}\{P_{se}/K_n\}]^2}\right], \qquad (5)$$

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

$$\sum_{i=0}^{N-1} k_i = 1, \quad k_i > 0. \qquad (6)$$

The number of carriers N used for transmission can be found as the minimum number of carriers needed for intersymbol interference (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:

$$N = \lceil B_t/B_c \rceil. \qquad (7)$$

Maximizing R means that the power distribution has to be optimized over different frequency channels. It was shown that there is a solution to this problem and it is the same as the “water-pouring” solution described in information theory [5], [7]. Applying this to our problem yields:

$$k_i = \begin{cases} \frac{\lambda \Delta f}{ln2} - \frac{\Delta f}{K_0 |H_i(f)|^2} & k_i > 0 \\ 0 & \text{otherwise} \end{cases} \qquad (8)$$

where $K_0 = 3P/(N_0[Q^{-1}\{\cdot\}]^2)$, $\sum k_i = 1$, and λ is the Lagrangian multiplier. Therefore, the maximum bit rate (equivalently the maximum capacity) is given as:

$$R_{max} = \sum_{i=0}^{N-1} \Delta f \cdot log_2\left(\frac{\lambda}{ln2} K_0 |H_i(f)|^2\right). \qquad (9)$$

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 HVAC duct channel measured via the VNA. 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% of signal power correlation. We assume that the number of carriers used in 2.4-2.48 GHz ISM band is 256. If the transmission requires a higher number of carriers, the number (256 carriers) is kept the same, however the usable bandwidth is reduced to that of the coherence bandwidth so that ISI-free signal transmission is achieved. This number of carriers in 2.4-2.48 GHz band results in 0.3125 MHz carrier spacing. The symbol error probability was taken to be 10^{-5}, while the value used for K_n was 4 which gives a lower bound on the HVAC duct channel capacity when one uses multi-carrier transmission with M-QAM modulation. We assume that $P/(N_0W)$ is given. The values of k_i-s associated with each of the multi-carriers were found using the "water-pouring" algorithm. The measurements were taken using open- and closed-ended straight ducts.

For straight ducts of 30.5 cm in diameter we used the setup depicted in Figure 1. Making use of the channel frequency response measured from the setup described above, Figure 2 shows the HVAC duct channel capacity (normalized) versus $P/(N_0W)$ for measurements made for transmitter-receiver pair distances of 4.6 m and 11.7 m. For $P/(N_0W)$ greater than 25 dB, a transmission data rate of more than 1 Gbps can be achieved for the given distances in the duct.

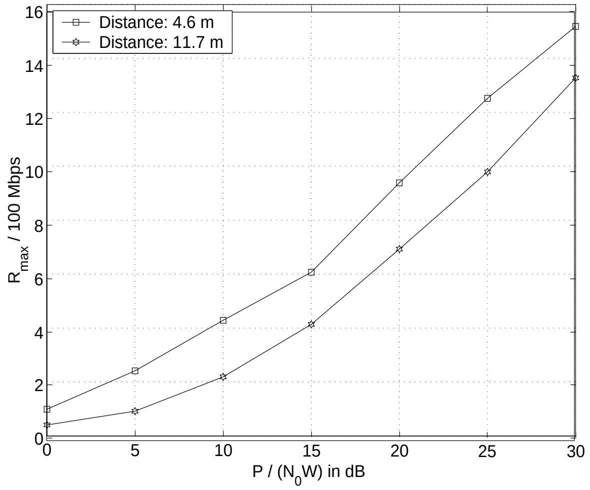

Fig. 2. Normalized capacity versus $P/(N_0W)$. Capacity calculations were done using experimentally measured channel impulse responses for cylindrical ducts of 30.5 cm in diameter in 2.4-2.48 GHz ISM band. All 256 carriers in the 80 MHz channel bandwidth are used in the capacity calculations.

We repeated our experiment for straight ducts in cylindrical pipes with a diameter of 15 cm. Note that while the measurements were done for the straight portion of the cylindrical pipes, the pipe network was more complex and included bends, tees, wyes, etc., thus, the presence of multi-path reflections is much higher than the case when the network consists of simply straight "matched" ducts (as was the case in Figure 2). Figure 3 shows the normalized capacity versus $P/(N_0W)$ for different distances between transmitter-receiver pair. Here, with $P/(N_0W)$ of greater than 30 dB, one could achieve 1 Gbps 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 Figures 2 and 3, one can see that slightly higher data transmission rate are achieved in the case of straight ducts of 30.5 cm in diameter (compare the transmission rates for distances of 4.6 m in Figure 2 and 6.1 m in Figure 3). However, the results shown in Figure 2 are for straight "matched" ducts, while the results shown in Figure 3 are for a realistic network configuration where no effort is made to reduce the multi-path reflections.

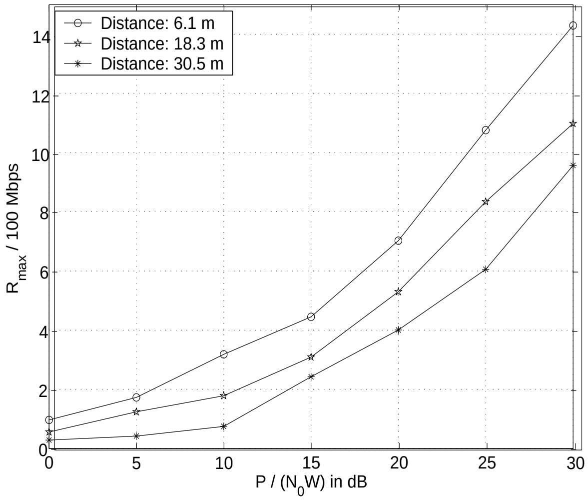

Fig. 3. Normalized capacity vs $P/(N_0W)$. Capacity calculations were done using experimentally measured channel impulse responses for cylindrical pipe network of 15 cm in diameter in 2.4-2.48 GHz ISM band. All 256 carriers in the 80 MHz channel bandwidth are used in the capacity calculations.

It is of interest to plot the capacity versus distance for a given transmitter power. As an example, assume a transmit power of 1 W (+30 dBm), a total receiver noise power of -90 dBm, a probe coupling loss of -15 dB, and a symbol error probability of 10^{-5}. The $P/(N_0W)$ is given as:

$$\begin{aligned} P/(N_0W)(dB) &= +30 - 15 + 90 \\ &= 105 \end{aligned} \qquad (10)$$

Capacity calculations were done using Eqn. (10) and channel impulse responses extracted from our theoretical propagation model [8] for different distances between the transmitter-receiver pair.

Plots of transmitted data rate as a function of distance for best case (open ends duct) and worst case (closed ends duct) are given in Figure 4. The shape of the curves in Figure 4 can be explained with the behavior of the RMS delay spread for different distances. For example, with open ends, 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 shown in Figure 4 (upper 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. In the case of closed ends, the RMS delay spread results from reflections as well as dispersion between multiple propagation modes. Therefore, it has higher values than the open end case, which results in lower values for coherence bandwidth. At short distances, the RMS delay spread increases (coherence bandwidth decreases) slightly with distance owing to the contribution from multi-mode dispersion as before. This results in an initial decrease in capacity as shown by the lower curve in Figure 4. At longer distances, the effect of reflections diminishes due to attenuation in the duct and power loss at each reflection. Hence, the RMS delay spread *decreases* slowly at higher distances, leading to an increase in capacity (see Figure 4). As one would expect, at long distances (above 500 m), open and closed end ducts have the same transmission capacity. The important observation from this figure is that bit rates in excess of 300 Mbps should be possible over distances up to 500 m for both scenarios.

It is worth mentioning that while HVAC duct channel capacity is an important measure for the capacity of 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. Thus, 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 multi-carrier transmission with M-QAM modulation is used as the transmission technology. These estimates of channel capacity based on multi-carrier 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 Gbps are possible over distances up to 500 m. 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.

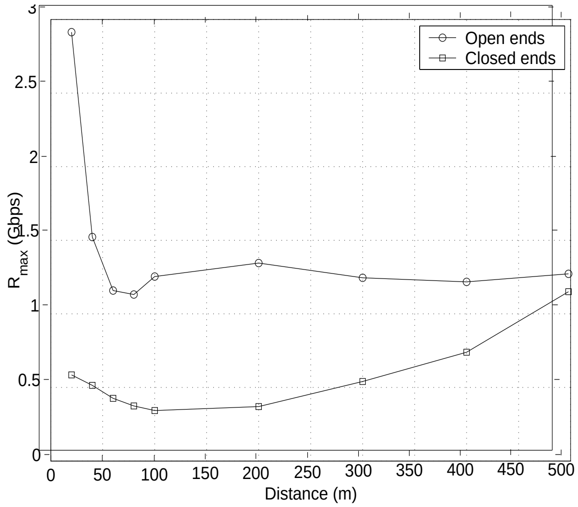

Fig. 4. Transmission rate as a function of transmitter-receiver separation distance for a transmit power of 1 W, a receiver noise power of -90 dBm, a probe coupling loss of -15 dB, and a symbol error probability of 10^{-5}. Capacity calculations were done using channel impulse responses extracted from our theoretical propagation model for cylindrical ducts of 30.5 cm in diameter in 2.4-2.48 GHz ISM band. All 256 carriers in the 80 MHz channel bandwidth are used in the capacity calculations.

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