Multi-carrier Signal Transmission through HVAC Ducts: Experimental Results for Channel Capacity

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***Abstract*—In this paper, we report, for the first time, experimental results on channel capacity of heating, ventilation, and air-conditioning (HVAC) ducts based on multi-carrier transmission technique and measured channel frequency responses in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. Experiments using actual synthesized signals through a building HVAC duct system demonstrate the ability to transmit with a spectral efficiency of 3.74 bps/Hz, corresponding to over 300 Mbps transmission rate within 2.4 GHz ISM band. The experimental results are within 80% of theoretical maximums reported in [1]. For the transmission schemes employed, these results confirm the potential of using the HVAC duct channel for indoor wireless networks.**

***Index Terms*—Multi-carrier transmission; indoor propagation; Heating, Ventilation, and Air Conditioning (HVAC) Systems for wireless transmission.**

I. INTRODUCTION

THE increased demand for broadband communications in buildings is bringing fundamental changes to indoor wireless networks. Future indoor wireless networks will provide not only voice communications, but also data, video, and high-speed Internet access. However, traditional indoor wireless communication systems are unable to keep up with the increased demand for bandwidth. In addition, the design of an indoor wireless network is still a complex task due to the nature of indoor propagation. An alternative approach to providing the communication infrastructure in buildings is to recognize that most buildings are already equipped with a microwave distribution system: the heating and ventilation ducts [2]. 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. The concept and preliminary results on this approach have been reported in [3]. In [1] theoretical estimates of duct channel capacity based on multi-carrier transmission with adaptive power loading that uses M-QAM modulation and measured channel responses in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band were reported. It was shown that data transmission rates in excess of 1 Gbps are possible over distances up to 500 m in “matched” straight ducts.

While the studies in [1] reported theoretical limits of the capacity of HVAC duct channels, in this paper, *for the first time*, we compare theoretical limits with experimental results based on multi-carrier transmission technique with uniform power distribution among carriers. Measured capacity results in these experiments are within 80% of theoretical maximums reported in [1] over a frequency range of 15 MHz. These results experimentally verify the potential of using the HVAC duct channel for indoor wireless networks.

The remainder of this paper is organized as follows. In Section II, we outline the main results of the analysis of the HVAC duct channel when multi-carrier transmission is used as the transmission technology [1]. The experimental setup is described briefly in Section III. Results and discussion are presented in Section IV, while Section V concludes the paper.

II. ANALYSIS

Signal transmission via HVAC duct channels suffers from inter-symbol interference (ISI), which is caused by multi-mode propagation and reflections of the signal in the ducts. To overcome this, it has been reported that one should use multi-carrier transmission as the transmission technology in HVAC ducts [1].

Since the details of the analysis for channel capacity of HVAC ducts based on adaptive multicarrier transmission was reported in [1], in this section we summarize the calculation of channel capacity using multicarrier modulation with uniform power distribution among the carriers.

In our analysis, we calculate the attainable bit rate of the HVAC duct channel at a given symbol error probability and under the restriction that the total transmitted power P be limited.

We consider the use of multi-carrier transmission with M-QAM modulation used for each carrier. Since each carrier could transmit a different number of bits per symbol, say n_i, and assuming that carrier bandwidth is Δf, then the total bit rate R transmitted via the HVAC duct channel is:

$$R = \sum_{i=1}^{S} n_i \Delta f. \tag{1}$$

where S is the number of carriers. In case of M-QAM modulation and high SNR, the probability of symbol error in the i-th carrier P_{se_i} is given as [4]:

$$P_{se_i} = K_{n_i} Q \left(\sqrt{\frac{3E_{av}}{(M_i - 1)N_0}} \right) \tag{2}$$

where M_i is the M-QAM modulation in the i-th carrier, E_{av} is the average energy per symbol, $Q(\cdot)$ is the error function and $N_0 = 2N(f)$, where $N(f)$ is the double-sided power spectral density of the additive white Gaussian noise (AWGN). 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 with a channel frequency response of $H(f)$, the total bit rate is given as [1]:

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

where P is the transmitted signal power and W is the channel bandwidth. In case of multi-carrier transmission, approximating the channel transfer function $H(f)$ by a staircase function and summing over all tones/carriers, one finds that the total bit rate is equal to [5]:

$$R = \sum_{i=1}^{S} \Delta f \cdot log_2 \left[1 + \frac{3P_{carrier}/(N_0 \Delta f)|H_i(f)|^2}{[Q^{-1}\{P_{se_i}/K_{n_i}\}]^2} \right], \tag{4}$$

where R is the total transmission rate, $P_{carrier}$ is the power allocated to each carrier and Δf is the carrier bandwith such that W=$S.\Delta f$. Assuming uniform power distribution

$$P_{carrier} = P/S. \tag{5}$$

Next, we briefly describe the experimental setup used for measurements of HVAC duct channel capacity.

III. EXPERIMENTAL SETUP

Experiments were done on the second floor of Roberts Hall on Carnegie Mellon University's campus. Two sets of experiments were made with the configuration shown in Fig. 1. In the first experiment, we configured a test duct network that included tees and straight sections (see Fig. 2a). The path between transmitter and receiver was 9 m. The duct components had a diameter of 0.3 m and were made of galvanized steel with conductivity $\sigma = 10^6 S/m$. Both ends were closed with caps lined with matched absorbers, resulting in a relatively flat channel frequency response. In contrast, the exploration of the signal propagation characteristics through existing HVAC duct systems in buildings gives useful information as to whether legacy HVAC duct systems can be used for high-speed data transmission. For that purpose, various communication signals were transmitted through the building HVAC system of the second floor of Roberts Engineering Hall (see Fig. 2b). The path between the transmitter and receiver was 16 meters and the duct system included cylindrical and rectangular ducts along with other common duct components. Thus, this system represented a realistic HVAC duct network that could be encountered in buildings.

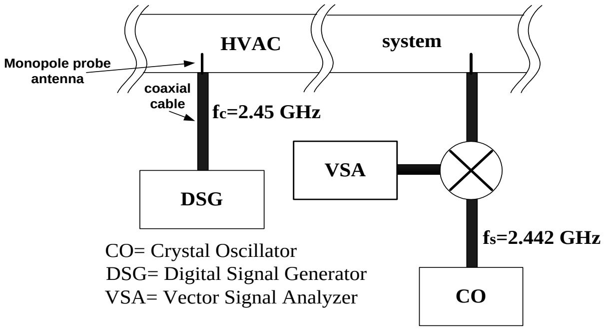
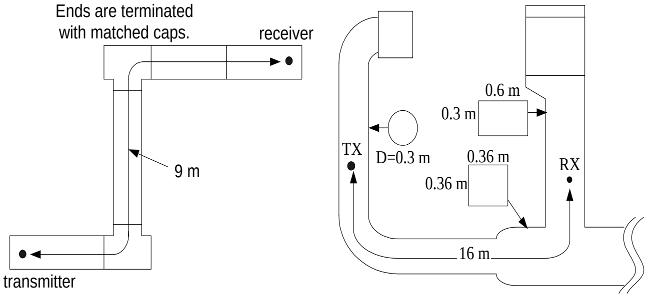


Fig. 1. Measurement scheme for multi-carrier transmission.



a) Test duct network

b) HVAC system of 2nd floor of Roberts Hall (REH220), Carnegie Mellon University

Fig. 2. Experimental setups: (a) Test duct network, (b) section of HVAC duct in Roberts Engineering Hall.

First, wideband channel measurements were made in the 2.4-2.5 GHz ISM band using an Agilent E8358A vector network analyzer (VNA). The antennas were monopole probe antennas 3.1 cm long. For the modulation experiments, a carrier separation of 300 kHz was chosen to approximate the conditions encountered by the IEEE 802.11a standard. 50 carriers were used in all the experiments corresponding to a 15 MHz channel.

The transmitted data rate depends on the modulation type and the pulse-shaping filter. In our experiments, M-PSK and M-QAM modulation schemes were used along with an $\alpha = 0.35$ raised cosine filter. The symbol rate R_s that can be passed through a passband raised cosine filter with absolute bandwidth B is $R_s = B/(1 + \alpha)$. With a carrier spacing of 300 kHz, R_s is therefore limited to 220 ksps. Multi-carrier signals were generated with an Agilent E4433B digital signal generator and demodulated with an Agilent 89610A vector signal analyzer. The signals were transmitted at 2.45 GHz, then down-converted to 8 MHz using a Wilmanco crystal oscillator that has an oscillation frequency of 2.442 GHz and a Narda 8825 double balanced mixer. The output power of the transmitter was varied for different SNR values [6].

IV. RESULTS AND DISCUSSION

In our experiments, the synthesized signals occupied a 15 MHz band centered at 2.45 GHz. There were 50 carriers in the band, each 300 kHz wide with a symbol rate of 220 ksps. The symbol error probability was taken to be 10^{-5}.

As indicated in [1], [6], multipath effects are significant in HVAC duct systems. Experiments with duct networks configured with straight sections, tees, wyes and bends showed that the maximum delay spread is about 250 ns [6]. This indicates that in terms of delay spread characteristics, the HVAC channel is between typical indoor and outdoor wireless channels.

The reflections can be minimized by placing RF absorbing materials on the ends. The test duct network configured in the lab (see Fig. 2a) had matched terminations, resulting in a reasonably flat channel. Fig. 3 shows the frequency response of this channel in the 2.4-2.5 GHz band. The RMS delay spread of this channel is 60 ns, which corresponds to a 3.3 MHz coherence bandwidth with 50 % signal correlation. The average path loss of this HVAC duct channel within the 2.4-2.5 GHz frequency interval is 38.3 dB. This includes the coaxial cable loss that is approximately 8.8 dB total. Fig. 4 shows the frequency correlation function of the frequency response shown in Fig. 3. The correlation curve indicates that with 0.5 correlation, the coherence bandwidth is 4.7 MHz, which is close to the value obtained via RMS delay spread.

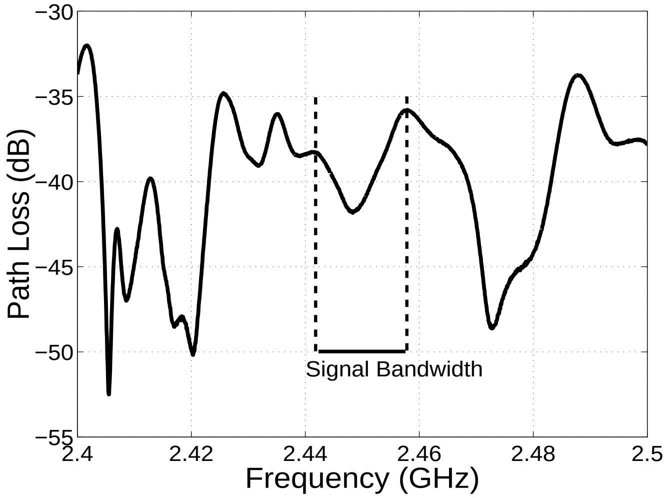


Fig. 3. The frequency response of test duct network given in Fig. 2a.

TABLE I

MULTI-CARRIER TRANSMISSION PERFORMANCE OF TEST DUCT NETWORK GIVEN IN FIG. 2A. WITH SNR=30 DB

Mod. type	Data rate per carrier (Mbps)	Number of successfully demod. carriers among 50	Total trans. rate (Mbps)
64-QAM	1.32	50	66
256-QAM	1.76	35	61.6

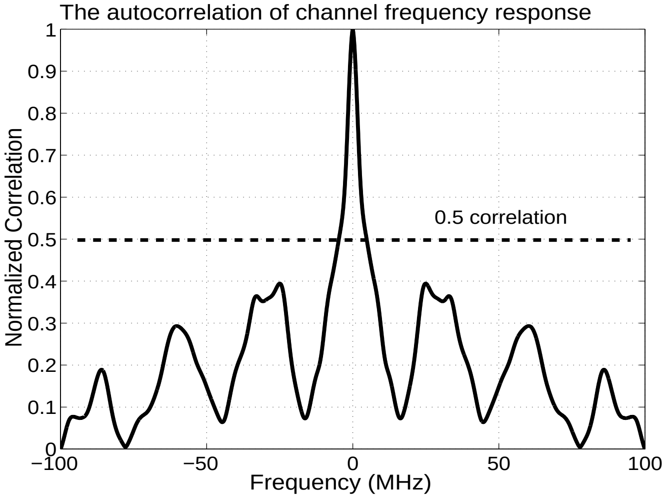


Fig. 4. Frequency correlation function of channel given in Fig. 3.

Table I shows the performance of multi-carrier communication signals through the test duct system for SNR of 30 dB as determined from the VSA measurement of error vector magnitude. The available throughput through the HVAC duct network given in Fig. 2a is 81.4 Mbps if we use the adaptive loading approach. 35 carriers can be successfully demodulated with 256-QAM, and 15 more carriers with 64-QAM. The corresponding spectral efficiency is 5.42 bps/Hz. The symbol error probability was taken to be 10^{-5}. The analytical approach outlined in Eqn.(1) to (5) predicts a maximum data rate of 100 Mbps for the same frequency band. This corresponds to a spectral efficiency of 6.7 bps/Hz (see Fig. 5). Thus the experimental results are within 80 % of the maximum achieved capacity for the 15 MHz channel. Fig. 5 shows the experimental and analytical spectral efficiencies as a function of SNR. In our analytical results, the SNR, the symbol error probability, and carrier separation have the same values as the ones in the experiments. In the experiments the most aggressive modulation scheme used was 256-QAM, but the analysis assumes the best available modulation possible for the carriers, and perfect matched receiver operation.

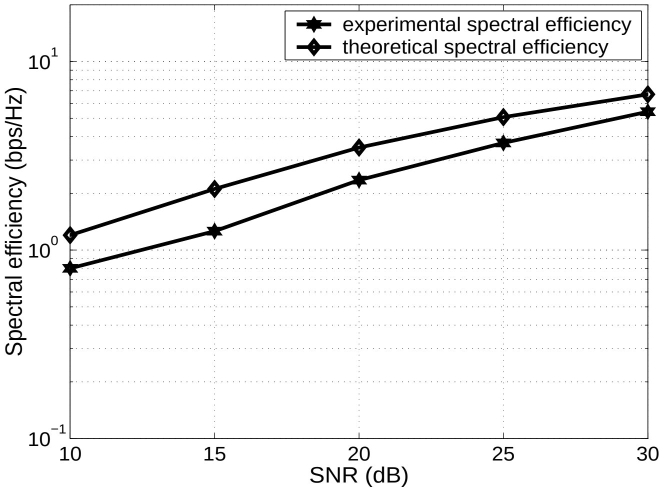


Fig. 5. The normalized capacity vs SNR for 2.4425-2.4575 GHz band using the setup shown in Fig. 2a.

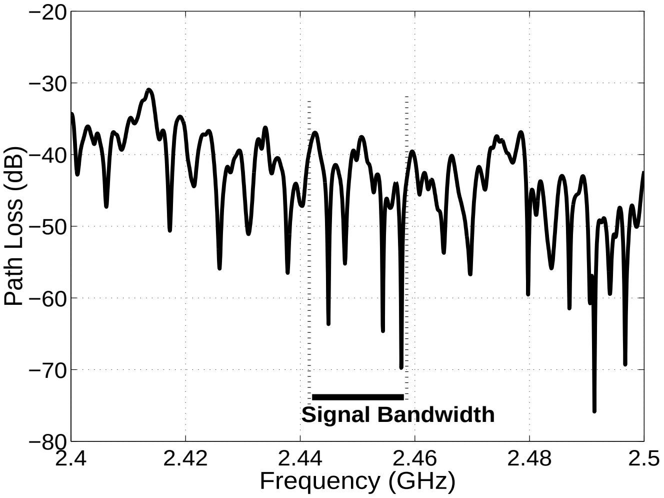


Fig. 6. The frequency response of the buliding HVAC system as shown in Fig. 2b.

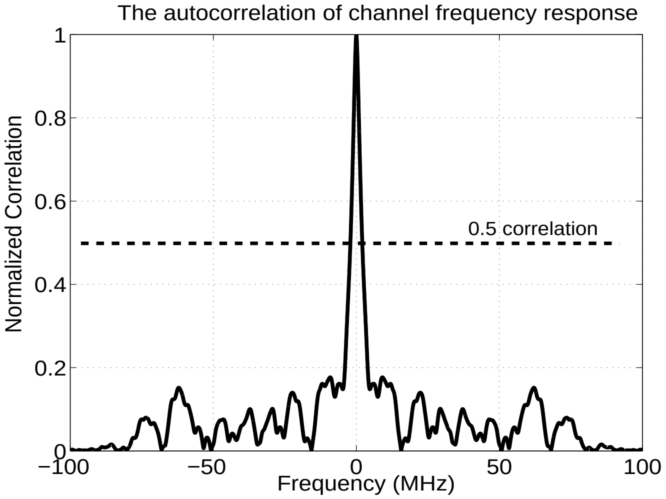


Fig. 7. Frequency correlation function of channel given in Fig. 6.

TABLE II

MULTI-CARRIER TRANSMISSION PERFORMANCE OF BUILDING HVAC DUCT SYSTEM WITH SNR=30 DB.

Mod. type	Data rate per carrier (kbps)	Number of successfully demod. carriers among 50	Total trans. rate (Mbps)
BPSK	220	47	10.34
QPSK	440	46	20.24
16-QAM	880	43	37.84
64-QAM	1320	38	50.16

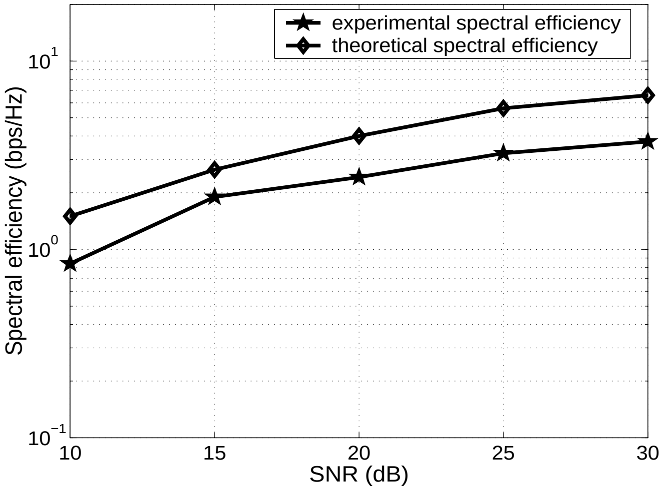


Fig. 8. The normalized capacity vs SNR for 2.4425-2.4575 GHz band using the setup shown in Fig. 2b.

The frequency response of the building HVAC duct system is shown in Fig. 6. The RMS delay spread of this channel is 112 ns, which corresponds to 1.8 MHz coherence bandwidth with 50 % signal correlation. The average path loss within the 2.4-2.5 GHz frequency interval is 40.2 dB. Fig. 7 shows the frequency correlation function of the building HVAC duct network. The figure indicates that with 50% correlation, the coherence bandwidth is 2 MHz, which is close to the value obtained from the RMS delay spread.

Referring to Table II, we see that 38 carriers can be successfully demodulated at 1.32 Mbps (64-QAM), 5 more carriers can be demodulated at 880 kbps (16-QAM), 3 more can be demodulated at 440 kbps (QPSK), and 1 more can be demodulated at 220 kbps (BPSK). Thus, the maximum capacity that can be achieved if adaptive loading is used in our experiment is 56.1 Mbps corresponding to a spectral efficiency of 3.74 bps/Hz. The SNR for demodulation was 30 dB. The symbol error probability was taken to be 10^{-5}. The analytical approach for the same frequency band predicts a data rate of 98.2 Mbps. This corresponds to a spectral efficiency of 6.55 bps/Hz (see Fig. 8). Fig. 8 shows the experimental and theoretical spectral efficiencies as a function of SNR.

Based on the data rate values achieved in our experiments, it can be seen that that there is a good agreement between the analytically predicted values and the experimental values achieved in our laboratory. These results confirm that HVAC system is a practical and viable option for broadband access in indoor wireless networks.

V. CONCLUSIONS

Multi-carrier signal transmission is a promising technique to achieve high throughput when using HVAC duct systems for wireless communications. The initial experiments showed that without any equalization and error control coding one can achieve a 56.1 Mbps data rate in a 15 MHz bandwidth in a representative building HVAC duct system with RMS delay spread of 112 ns. For the measured building HVAC channel (see Fig. 2b), the analytical capacity prediction based on multicarrier transmission with uniform power distribution among carriers yields a maximum data rate of 98.2 Mbps for the same 15 MHz channel centered at 2.45 GHz ISM band. The experimental measurements are approximately 65% of the theoretical maximums averaged across different SNR values. If the duct components are made radio friendly (i.e., absorbers are used to eliminate reflections), the throughput will increase significantly. Our experiments showed 80% of the theoretical capacity in a laboratory system using end absorbers. The next generation wireless LAN systems that make use of Orthogonal Frequency Division Multiplexing (OFDM) (e.g., IEEE 802.11a) are expected to offer robust indoor wireless access when HVAC ducts are used as a communication channel.

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