Design of an Overmoded-Waveguide Directional Antenna for Use in In-Building Ventilation Duct Wireless Networks

Jessica C. Hess and Daniel D. Stancil
Electrical and Computer Engineering
Carnegie Mellon University
Pittsburgh, PA 15213, United States.
Email: jessica.hess@gmail, stancil@cmu.edu

Benjamin E. Henty
i5wireless, LLC.
Northbrook, IL, 60062, United States.
Email: henty@eirp.org

***Abstract*— We present an adaptation of a Yagi-Uda antenna design for use inside the overmoded waveguide environment of building ventilation ducts. We obtain experimentally the element size and spacing of a reflector and driven element that can be used for IEEE 802.11b/g/n signals in a cylindrical duct to provide 3.1 dB of gain and a front-to-back ratio of 9.1 dB compared to a simple monopole antenna. We also discuss the usefulness of such an antenna in a duct network used to distribute wireless signals in a building.**

***Index Terms*— Yagi-Uda, Multimode waveguides, Waveguide antennas**

I. Introduction

One of a modern business' most valuable assets is its communications infrastructure: without it, there is no connection to the outside world, no way to interface with customers, and no way to move data to where it needs to go. As the need for fast and convenient communication increases, the cost of wiring buildings and providing mobility for individual employees is also increasing. Over time more businesses are employing high-speed wireless technology, either in addition to their wired infrastructures or in place of them; however, attempting to use conventional wireless products and methodologies to meet all communication needs can be problematic. Significant effort is needed to design multi-AP layouts, and building structure can cause holes in coverage areas.

A promising method for easier-to-design wireless networks with better coverage is to use heating, ventilation, and air conditioning (HVAC) ducts as electromagnetic waveguides for distributing RF (radio-frequency) signals. The nature of ventilation ducts is such that the signal they deliver will be strongest in areas where employees spend most of their time–offices and conference rooms–because this is where vents open, both ventilating the room and allowing transference of wireless signals. Significant research into this idea has been published in the literature (see for example [1]).

Prior work on ventilation duct based RF distribution has developed monopole antennas that can provide a good match for exciting ventilation ducts [2]. The size of typical ventilation ducts implies that the ventilation ducts will be overmoded waveguides. For example, a commonly used cylindrical ventilation duct with a 30.5 cm (12 inch) diameter will have 17 propagating modes. Thus, significant research has been undertaken to model the duct channel and antenna effects [3].

In many HVAC systems, the use of a directional antenna rather than a simple monopole could improve performance significantly: a monopole placed in a duct transmits in both directions, which can be unnecessary, as in the case when only one section of a building needs to be illuminated, and signal transmitted in the other direction is "wasted." Further, in a non-duct channel, an increased gain antenna can decrease the delay spread of a channel by decreasing the strength of multipath components received by the antenna. Similarly, a directional antenna used in a highly resonant duct environment could reduce a channel's multipath by directing power away from dead ends and towards intended users. For instance, the most convenient placement of an antenna may be near air-handling equipment, tapers, end caps, or other features of the duct which could disrupt the signal. A reflection from one of these features will be offset in time and phase from the signal that was originally transmitted, making reception and decoding of the original signal more difficult. If, however, a directional antenna is used, then not only will there be an increase in the amplitude of the original signal, but the amplitude of the reflected signal will decrease, perhaps enough so that the reflected signal can be ignored by the receiver.

II. Experiments

For this project, we designed a two-element directional antenna for use with IEEE 802.11b/g/n equipment connected to HVAC ducts. The goal was to maximize the average forward gain, given a pre-chosen driven element (i.e. a previously designed monopole antenna) and a single additional element acting as a reflector. Such an antenna mounted inside a duct is shown in Fig. 1. The length of the monopole, driven element, l_d, was determined first without the reflector element to provide a good impedance match. Then, in order to maximize forward gain, we experimentally varied the length of the reflecting element,

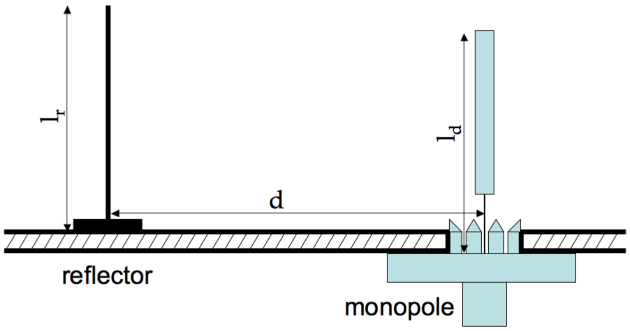
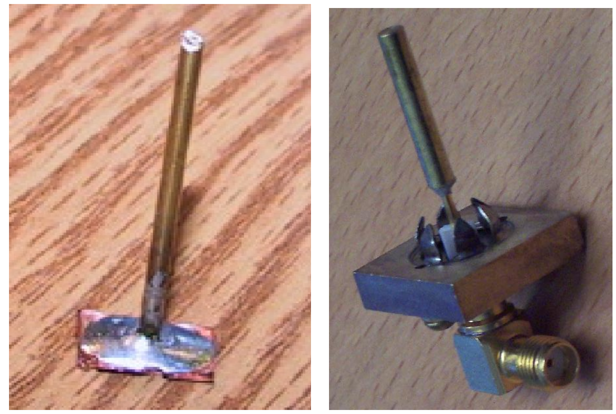


Fig. 1. Schematic of Directional Antenna Design.



(a) Reflector Element (b) Monopole Driven Element

Fig. 2. Pictures of Directional Antenna Elements

Fig. 3. Hole Cut in Duct with Neck Piece.

l_r, as well as the distance between it and the driven element, d.

The goal of this design was to create a two-element directional antenna, inspired by the Yagi-Uda design [4], [5], which would improve the strength and quality of an IEEE 802.11b/g/n signal being transmitted through an HVAC duct system. However, because of the multimode character of the duct environment, the free-space dimensions could not be assumed. Consequently, the design progressed as a series of “experiments,” iteratively determining the best combination of distance between elements and reflector length. The first experiment consisted of variation over inter-element distance, d; the second consisted of variation over reflector length, l_r; and the third consisted of variation over separation distance, d again.

The monopole, driven element, pictured in Fig. 2(b), used in the directional antenna, is constructed from SMA female, right-angle panel mount connectors with extended dielectric, screwed to brass bases with holes through the center. Metal “teeth,” intended to snap the fixture into a ten millimeter hole in the side of a duct, have been placed into the base, around the dielectric. The dielectric has been cut down to be level with the brass base, leaving the center conductor exposed. A brass cylinder with a diameter of 0.32 cm (1/8 inch) with a hole in it has been fitted onto the end of the center conductor. The monopole antenna was tuned by placing it in a duct and varying its length–changing the amount by which the center conductor and cylinder overlapped–until the length that gave the minimum return loss between 2.4 and 2.5 GHz was found. Once the proper overlap was determined, silver epoxy was used to connect the cylinder and center conductor in the correct configuration. The resulting driven element length, l_d, is 2.7 cm. The measured average return loss over the 2.4 GHz ISM band is more than 10.0 dB over the frequency range.

The reflector is made up of a piece of 0.16 cm (1/16 inch) diameter welding rod, soldered to a piece of copper tape, which is attached with adhesive to a magnet, as shown in Fig. 2(a). The copper tape is wrapped around the magnet carefully, so that it makes electrical contact with the duct edge. The copper tape is necessary not just to ensure electrical contact but to prevent loss of magnetism by the application of heat for the solder. Although welding rod on a magnet is not what would be used in a real installation, it is a convenient solution for performing experiments in which the reflector must be moved many times.

For the experiments, we used 30.5 cm (12 inch) diameter by 3.05 meter (10 foot) long sections of cylindrical steel HVAC ducts, connected end to end. One section had a 19 cm diameter hole cut out of its side at ninety degrees off the antennas’ axis. A metal neck piece was attached to the duct like that shown in Fig. 3. The purpose of the hole was to cause mode-scattering as it exists in large duct-networks in order to make the resulting antenna design more useful in a real-world system, where features such as T-junctions and bends are common.

The authors of [6] developed a technique for extracting the mode content excited by an antenna in an overmoded duct. In the same work, the mode content excited by a quarter-wavelength monopole probe in a 30.5 cm cylindrical ventilation duct was determined. The authors report that the 3 most excited modes in such a duct in decreasing order are TE_{61}, TE_{51} and TE_{41}. In [7] we studied the mode filtering caused by a duct hole like the one shown

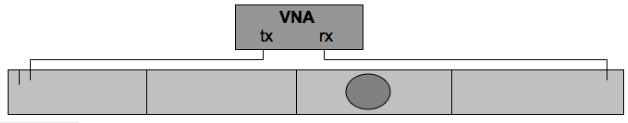


Fig. 4. Experimental Setup

in Fig. 3 using the same monopole antennas used in this work. In the work we showed that the TE_{61} mode excited by the monopole antenna was significantly reduced by the presence of a hole in the duct. The same hole had appeared to have little effect on the TE_{51} and TE_{41} modes. As a result, we expect that TE_{61} is largest amplitude mode in a duct without a hole, while TE_{51} is the largest amplitude after passing by a 190mm diameter hole in a duct.

Thus, if the experiments presented below had been done with a straight section of duct, without a hole, they would likely have ended in an antenna design that maximized TE_{61}. This would have been of little use in practice, as most duct systems have many branches, and maximization of TE_{61} would not lead to much gain, in general, as it would be filtered out upon passing duct holes.

The optimization experiments were set up in the duct configuration shown in Fig. 4, with four ducts connected end to end and a hole placed in the third. The directional antenna under test was used as the transmitter, and a monopole of the same type used as the directional antenna driven element was used as the receiver. Measurements were made with an HP 8714B vector network analyzer (VNA). 1601 magnitudes equally spaced across 100 MHz, from 2.4 to 2.5 GHz, were recorded and the average gain over the IEEE 802.11b/g/n spectrum, 2.4 to 2.4835 GHz, was computed for each measurement.

If data were to be taken only at one receiver position, we would end with an antenna design that was optimal for that specific placement but which would not necessarily work well in general. Because the goal was to design an antenna that would work well in most cases, rather than one that works for one specific case, we made ten holes for the receiving antenna, each approximately 12 cm apart, and measured the received signal at each one for every scenario under test. We then averaged the results from these ten receiver positions, to get one "average" result for each test scenario. A measurement of the channel using a monopole without a reflector for transmission served as a base case, from which we could determine how much gain a particular reflector configuration had achieved.

The first experiment involved varying the distance between the driven element and the reflector, d. For this iteration, we chose to make the reflector 5.5 cm long, approximately twice the length of the driven element. This length stayed constant throughout the experiment. We found that the closest we could reasonably get the reflector

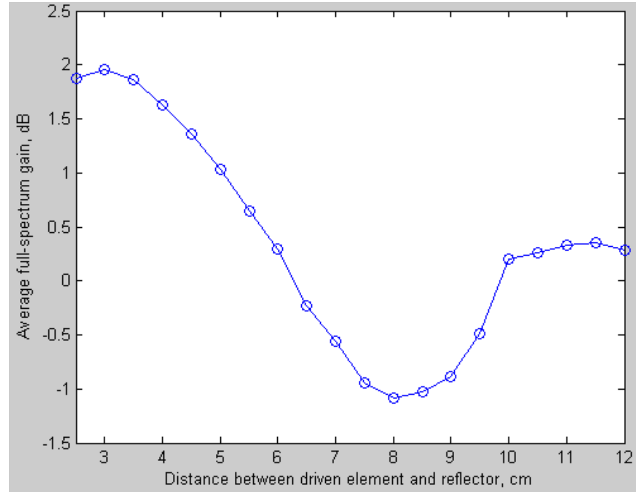


Fig. 5. Results of First Element Separation Variation Experiment

to the driven element was 2.5 cm, so this was our starting point. From there, we increased the distance by 0.5 cm each time, ending at 12 cm. The computed average gains over the 83.5 MHz bandwidth also averaged over all 10 receiver locations is plotted in Fig. 5. As seen in the figure, the best reflector separation distance was d =3 cm.

For the second experiment, we placed the reflector 3 cm from the driven element. The distance stayed constant throughout this iteration. Because we were using wire cutters on welding rod, we found that the best granularity available for element length was about a quarter centimeter. Therefore, we measured the channel, starting at a reflector length, l_r, of 5.25 cm, decreasing by 0.25 cm for each measurement, and ending at 2.5 cm, which was slightly less than the length of the driven element. The resulting average gains are plotted in Fig. 6. As shown, the length that provided the highest gain at a distance of 3 cm was 3 cm.

The final experiment used a fixed reflector length, l_r of 3 cm as determined in the previous experiment. We again varied the distance between elements, d from 2.5 cm to 12 cm in half centimeter increments. The measured gain averaged over the bandwidth and receiver locations is plotted in Fig 7. As shown, the distance that provided the highest gain with this final iteration was 5 cm. Thus, we have an antenna design with l_d =2.7 cm, l_r =3 cm and d =5 cm. As shown in Fig. 7 the forward gain of such an antenna is 3.1 dB over the same monopole antenna without a reflector. These dimensions agree well with Yagi-Uda design rules which state that the reflector should be about 5 percent longer than the driven element and spaced a quarter-wavelength from the driven element [4], [5]. By these metrics, the ideal reflector length should be l_r =2.84 cm and the ideal separation distance, using the theoretical wavelength of TE_{51} in the waveguide,

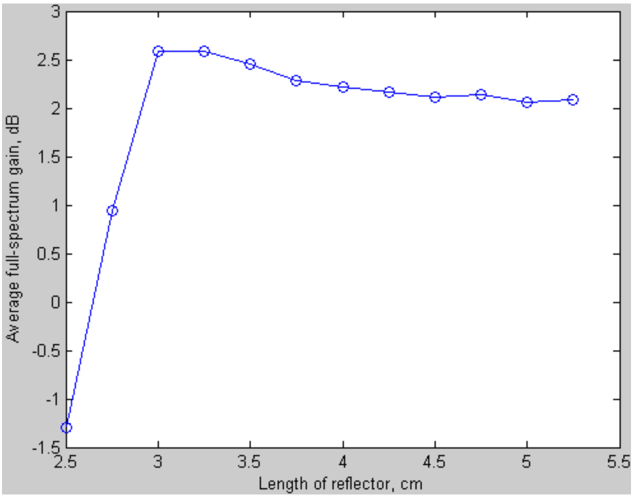


Fig. 6. Results of Reflector Length Variation Experiment

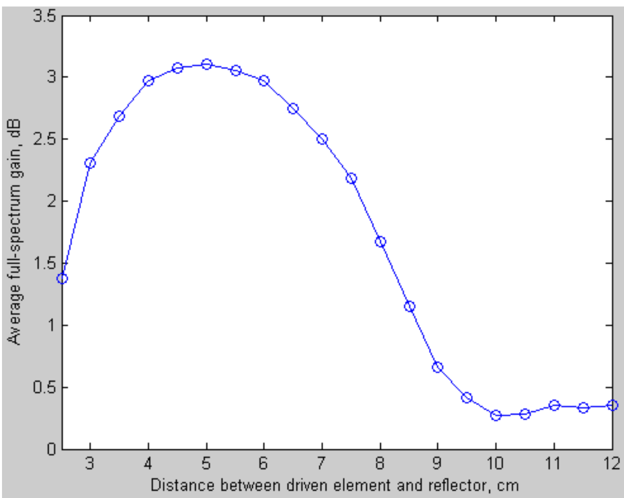


Fig. 7. Results of Second Element Separation Variation Experiment

should be d =5.15 cm. We use the guide wavelength of TE_{51} because we expect our optimization technique to be dominated by the performance of this mode.

In order to measure the front-to-back ratio of the antenna, the monopole antennas in the setup were left in place but the reflector element was moved to the other side of the driven element. This reverses the direction of radiation of the antenna so that power is being directed away from the receiving antenna. The measured gain for this setup was -6.0 dB over the 83.5 MHz bandwidth and 10 receiver locations, giving a front-to-back ratio of 9.1 dB.

It is somewhat unintuitive that this antenna would have a gain above 3 dB. If for example the reflector was working perfectly, we would expect that the reflector element could result in a doubling of the power delivered to the receiver for a gain of 3 dB. However, the reflector element also affects the impedance of the driven element and so may improve the matching of the feedline to the driven element, resulting in more power delivered to the receive antenna and accounting for the gain greater than 3 dB. We have confirmed this to be the case by measuring the return loss of monopole and of the directional antenna. The average return loss of the monopole alone is -10.0 dB while the average return loss of the directional antenna was -17.6 dB. This represents a significant improvement and accounts for some of the gain in the forward direction.

III. Conclusion

The design of the directional antenna presented in this work is a compelling option for use in HVAC-based RF distribution networks. The antenna provides a gain of 3.1 dB over a monopole antenna, has a front-to-back ratio of 9.1 dB, and is an excellent match to 50 ohm feedline. These attributes make the antenna an attractive component for improving the performance of wireless-in-duct systems. The high front-to-back ratio helps to reduce unwanted reflections and interference, while the gain of the antenna enables better signal strength in areas to be covered. The antenna dimensions are consistent with a waveguide-adapted Yagi-Uda antenna design, and the antenna described in this paper should be valuable for future wireless in-duct installations.

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