INVITED PAPER

Long Range Passive UHF RFID System Using HVAC Ducts

To provide a potential communications channel, HVAC ducts can function as electromagnetic waveguides; a 30-m read range has been achieved within a free space range of 6 m.

By Pavel V. Nikitin, *Senior Member IEEE*, Darmindra D. Arumugam, *Member IEEE*, Matthew J. Chabalko, *Member IEEE*, Benjamin E. Henty, *Member IEEE*, and Daniel D. Stancil, *Fellow IEEE*

ABSTRACT | In this paper, the use of hollow metal heating, ventilating, and air-conditioning (HVAC) ducts as a potential communication channel between passive ultrahigh-frequency (UHF) radio-frequency identification (RFID) readers and tags is studied. HVAC ducts behave as electromagnetic waveguides with much lower signal attenuation compared to free-space propagation. This low-loss electromagnetic environment allows one to greatly increase the communication range of passive UHF RFID systems and build, for example, a long range passive sensor network spanning an entire infrastructure such as a large building. In this work, it is shown both theoretically and experimentally that the read range of passive UHF RFID systems can be increased by multiple times compared to operation in a free-space environment.

KEYWORDS | HVAC duct communications; radio frequency identification tags; wireless sensor networks

I. INTRODUCTION

Recently, there has been significant interest in the theory, design, and implementation of passive ultrahigh-frequency (UHF) radio-frequency identification (RFID) systems [1]–[3] which operate in the 902–928-MHz band in North and South America and in various other bands throughout different regions in the world (866–869 MHz in Europe, 950–956 MHz in Japan and many Asian countries, etc.). A typical UHF RFID system includes readers (interrogators) and passive tags which consist of two main elements: the tag antenna and an application-specific integrated circuit (ASIC, also known as tag IC, or simply chip). The RFID reader transmits a carrier-wave signal which powers up the tag chip. The chip sends back the data by switching its impedance between two states and thus modulating the backscatter.

Passive RFID tags with sensing capabilities can be very promising for sensor networks because they are compact, inexpensive, and require no maintenance. Wirelessly powered sensors have been a subject of intense interest and research in recent years [4]. The key challenge is that the range of most current passive UHF RFID systems (maximum distance at which tags can be read or written to) is limited to a large extent by the path loss from the reader to the tag. For example, current passive UHF RFID tags can have a maximum read range of about 15 m in free space. Practical read ranges for these tags depend on application scenarios and can be much smaller, e.g., 5 m or less. Fundamental tag read range limitations have been studied previously [5], [6] and are defined by the reader output power, reader antenna gain, tag antenna gain, and impedance match to the chip, chip sensitivity, the object to which the tag is attached, and the path loss of the propagation environment.

In general, the path loss between the two communicating antennas strongly depends on the propagation environment and the radiation patterns of each of the two communicating antennas. A typical RFID use case scenario involves an indoor multipath environment (e.g., a warehouse) with the line-of-sight and several reflections. Such environments have been extensively studied in wireless communications [7], [8]. The path loss can be approximated to be log-linear with

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P. V. Nikitin is with Intermec Technologies Corporation, Everett, WA 98203 USA (e-mail: pavel.nikitin@intermec.com).
D. D. Arumugam and **M. J. Chabalko** are with Carnegie Mellon University, Pittsburgh, PA 15213 USA (e-mail: darumugam@cmu.edu; mchabalk@andrew.cmu.edu).
B. E. Henty is with the Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723 USA (e-mail: henty@eirp.org).
D. D. Stancil is with North Carolina State University, Raleigh, NC 27695 USA (e-mail: ddstancil@ncsu.edu).

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distance. For example, in free space, the path loss exponent is 2, and the loss is 20 dB/decade.

An obvious way to significantly increase the tag read range is to change the propagation environment to one where the path loss is much lower than in free space. An example of such an environment is a transmission line (coaxial cable or waveguide, etc.) where the energy can propagate along one direction and the losses with distance can be very small [9]. Of course, laying out long lengths of cable or waveguide may not be economically practical.

As it turns out, in many places, there already exists a man-made low-loss waveguide environment. This environment is hollow metal heating, ventilating, and air-conditioning (HVAC) ducts, which are an integral part of most multiple story buildings. The use of these ducts for general RF communication has been proposed before [10], [11], and propagation characteristics of duct waveguides have been studied for the 2.4–2.5-GHz band [12]. Tagging short metal pipes with RFID tags for identification purposes has also been independently studied [13].

In this paper, we discuss the use of HVAC ducts for long range passive UHF RFID systems. Some advantages of using ducts include greatly reduced path loss and the fact that maximum equivalent isotropic radiated power (EIRP) in such shielded environments may not be limited by the Federal Communications Commission (FCC) regulations. Section II presents a theoretical analysis of using HVAC ducts as a propagation medium. Section III presents experimental results. Applications to HVAC sensor networks are presented in Section IV. Conclusions are provided in Section V.

II. HVAC DUCTS AS A PROPAGATION MEDIUM

A. System Concept

The system concept is very simple—HVAC ducts can be used as the propagation medium between an RFID reader and tags as illustrated in Fig. 1 for the monostatic reader case (i.e., the same transmit/receive antenna). Tags can be located inside or outside the duct system. The RF signals can propagate outside the duct system via intentional or unintentional passive reradiators (such as louvers).

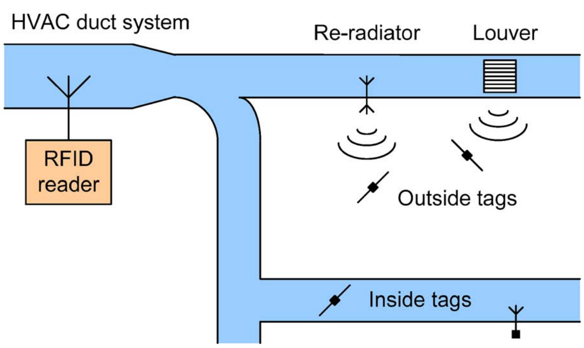

Fig. 1. ***RFID system using HVAC duct waveguides for communication.***

Table 1 Minimum Cutoff Dimensions of Waveguides

Waveguide	Minimum dimension	900 MHz	2.4 GHz
Rectangular	$a_{\min} = \frac{c}{2f}$	16.7 cm	6.3 cm
Circular	$D_{\min} = \frac{1.841c}{\pi f}$	19.5 cm	7.3 cm

B. HVAC Duct Cutoff Sizes

As is well known, the waveguide cross-section shape and size define a cutoff frequency below which signals cannot propagate inside the waveguide. Table 1 gives cutoff dimensions for rectangular waveguide of wide dimension a (fundamental mode is TE_{10}) and circular waveguide of diameter D (fundamental mode is TE_{11}). These dimensions define the minimum cross-section size that is required to carry different UHF signals.

As one can see, standard circular HVAC ducts that have diameters on the order of 12 in (approximately 30 cm) can easily be used as waveguides for UHF RFID systems operating above 900 MHz.

C. Link Budget and Maximum Range

In general, the power P_{abs} absorbed by the RFID tag chip can be expressed as

$$P_{\text{abs}} = P_t \tau_t L \tau \tag{1}$$

where P_t is the output power of the reader, τ_t is the impedance matching coefficient between the reader and its antenna, L is the power transmission loss between the reader and the tag antenna terminals, and τ is the impedance matching coefficient between the tag IC (chip) and its antenna. When P_{abs} is higher than the chip threshold power sensitivity P_{chip}, the chip is powered up and responsive.

In free space, the power transmission loss can be found from the well-known Friis formula [14]

$$L_{\text{free space}} = G_t \left(\frac{\lambda}{4\pi d}\right)^2 G \tag{2}$$

where G_t is the gain of the reader antenna, G is the gain of the tag antenna, λ is the wavelength, and d is the distance between the reader and the tag (perfect polarization efficiency between the antennas is assumed).

In a waveguide (duct) with two probe antennas, the power transmission loss has been analyzed in [12]. It is defined by the coupling loss of waveguide antennas and the weighted sum of all propagating modes. Assuming that the monostatic reader and the RFID chip are each connected to the coupling antennas inserted into the long duct with matched ends (no reflections and/or end caps), the power transmission loss can be written for the single-mode scenario as

$$L_{\text{duct}} = C_t e^{-\alpha d} C \tag{3}$$

where C_t is the coupling loss of the reader antenna for a particular mode, α is the attenuation loss for a particular mode, C is the coupling loss of the tag antenna for a particular mode, and d is the distance between the antennas. For multimode scenario, summation over the number of propagating modes needs to be performed.

Power transmission loss dependence on distance for multimode waveguide and free-space environments is illustrated in Fig. 2 for the frequency of 900 MHz. The free-space transmission loss is calculated using the Friis formula, and the waveguide transmission loss is calculated using the experimentally verified model described in [12]. In free-space case, the reader antenna gain is assumed to be 6 dBi, and the gain of the perfectly matched tag antenna is assumed to be 2 dBi. In the waveguide case, both reader and tag are assumed to be connected to monopole probes with coupling losses of −10 dB each, which are inserted into the straight infinite circular steel waveguide of 30.5-cm diameter.

In such waveguides at 900 MHz, only two modes can propagate: TE_{11} and TM_{01}. However, the TM_{01} mode has a circumferential electric field and is not excited by the radial monopole probe antenna. The theoretical attenuation of the TE_{11} mode in a smooth, steel, circular waveguide at 900 MHz is estimated to be 1 dB/100 m. Assuming single-mode propagation, the maximum range of the RFID tag in a duct waveguide can easily be found from (1) and (3) as

$$d_{\max} = \frac{1}{\alpha} \ln\left(\frac{P_t \tau_t C_t C \tau}{P_{\text{chip}}}\right). \tag{4}$$

For the multimode case, such a simple expression is not possible because one would have to sum the contributions from all modes, and the sum of exponentials with different powers does not have a simple analytical inverse function representation. However, (4) can still be used in many single-mode scenarios (such as a 900-MHz RFID system operating in 30.5-cm circular ducts with monopole probes exciting only the TE_{11} mode).

The maximum range of current passive UHF RFID systems is limited by the tag sensitivity in the forward link (powering up the tag). However, the sensitivity of modern Gen2 UHF RFID ICs is such (for example, the Impinj Monza 4 IC has sensitivity on the order of −18 dBm [15]) that current readers can barely read such tags at their maximum power-up range. Equation (4) assumes that the reader can read the tag as long as the tag is powered up. In that sense, a useful quantity to look at is the required sensitivity for the reader to be able to read a tag in an arbitrary propagation environment (medium between reader and tag antenna ports) at the maximum possible distance. The reader must be able to receive and decode the backscattered signal which propagates through the same medium as it arrived to the tag. From this, one can easily find that the reader sensitivity required to read an arbitrary tag at its maximum range is

$$P_{\text{reader}} = \frac{P_{\text{chip}}^2 M}{P_t \tau^2} \tag{5}$$

where the modulation factor M [5] shows how much of the RF power received by the chip from the antenna is "converted" into the modulated backscattered power. Note that the path loss dependence on distance for any particular channel is inherently embedded into (5), which is valid for any arbitrary propagation environment (HVAC duct system or any other).

The dependence given by (5) is illustrated in Fig. 3 for a reader with output power of 1 W (30 dBm), a modulation factor of −10 dB, and a tag impedance matching coefficient of 0 dB. Note that the tag range is different at different points on the line shown in Fig. 3.

Assuming that the RFID reader output power is 1 W (30 dBm), and the tag chip sensitivity is −15 dBm, there can be 45 dB of power transmission loss in order for the tag to still be powered up. As one can see from Fig. 2, this means that in free space the read range of such a tag will be

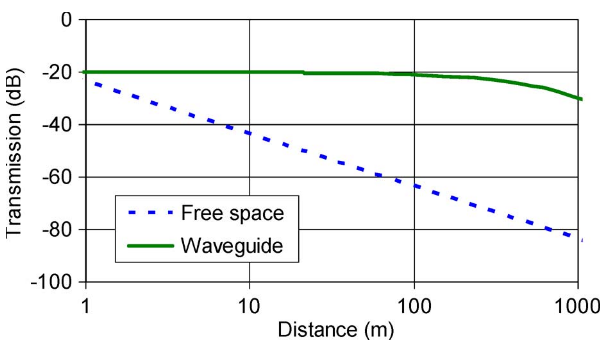

Fig. 2. ***Power transmission loss in a single-mode waveguide and free space at 900 MHz.***

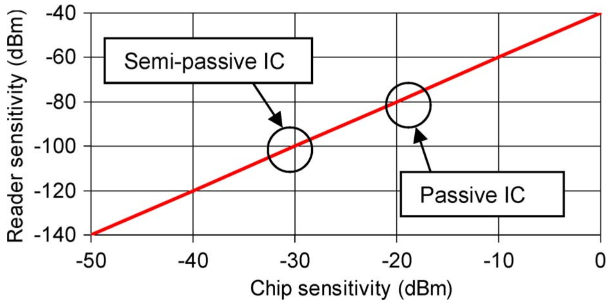

Fig. 3. *Reader sensitivity needed to read a tag with certain chip sensitivity at its maximum range.*

about 10 m, whereas in a waveguide such tags can be read up to about 4 km (the plot in Fig. 2 only shows the distances up to 1 km). Note, however, that this calculation assumes an ideal, smooth, cylindrical waveguide. Attenuation in actual ducts with surface oxidation, seams, joints, and louvers will be higher. However, it is likely that the practical range will be limited by multipath effects rather than attenuation.

III. EXPERIMENTAL RESULTS

To demonstrate the feasibility of using HVAC ducts for UHF RFID communications, we performed two types of measurements: channel measurements with a network analyzer and RFID tests with a commercial UHF Gen2 reader. Both measurements are described below.

A. Channel Measurements

Our experimental channel measurement setup was similar to the one used in [12] and is shown in Fig. 4. The diameter of the HVAC duct was 30.5 cm (12 in) and the duct ends were left open to minimize reflections.

The 30.6-m duct was placed on the floor in a long building corridor of the Electrical Engineering Department, Carnegie Mellon University, Pittsburgh, PA. Typical passive UHF RFID systems operating in the United States use the industrial, scientific and medical (ISM) band of 902–928 MHz. The probe monopole antennas were designed to be resonant at the center frequency of interest

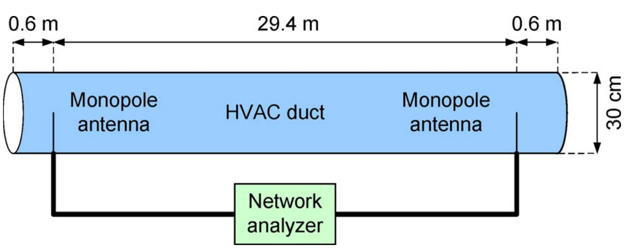

Fig. 4. *Channel measurement setup for the HVAC duct waveguide.*

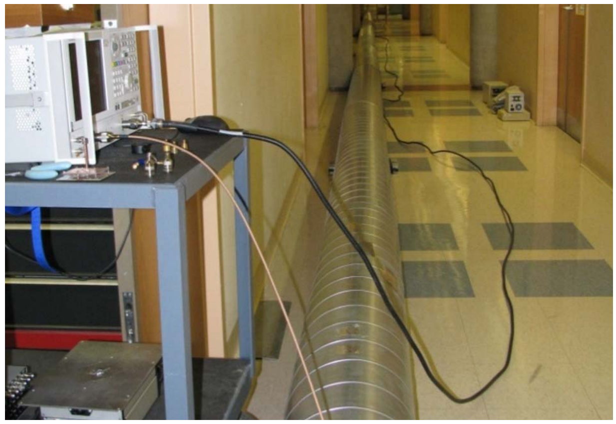

Fig. 5. *Experimental setup for duct channel testing.*

(915 MHz) and were 8.2 cm long. In the 860–960-MHz band, such a probe predominantly excites the TE_{11} mode owing to its radial electric field pattern. The network analyzer was an Agilent E8358A.

Figs. 5 and 6 show photographs of the actual test setup and the monopole antenna used for the testing.

The key parameters that characterize the wireless channel are the frequency response and power delay profiles. Fig. 7 shows the magnitude of the measured complex frequency response in the 860–960-MHz band. As an approximation to the power delay profile, Fig. 8 shows the impulse response calculated from that frequency response. One can see that the duct channel is more than suitable for passive UHF RFID systems.

Because of the relatively low data rate of the Gen2 RFID standard [16] (compared, e.g., to 802.11g), the RFID signals are narrowband (500-kHz instantaneous bandwidth), and the system performance is primarily affected by the channel loss rather than the delay spread.

In the case of the duct channel, both channel loss and the delay spread are very low compared to conventional multipath environments. The average measured duct

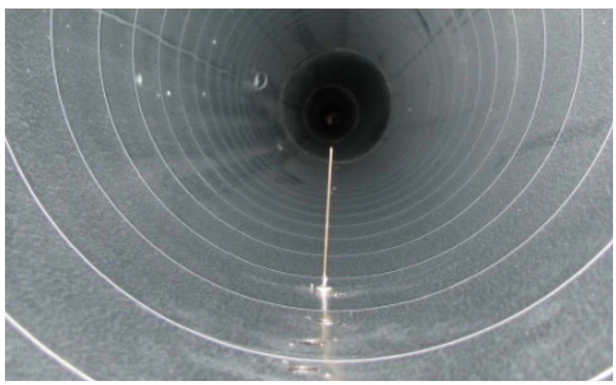

Fig. 6. *Monopole antenna in the duct used for channel testing.*

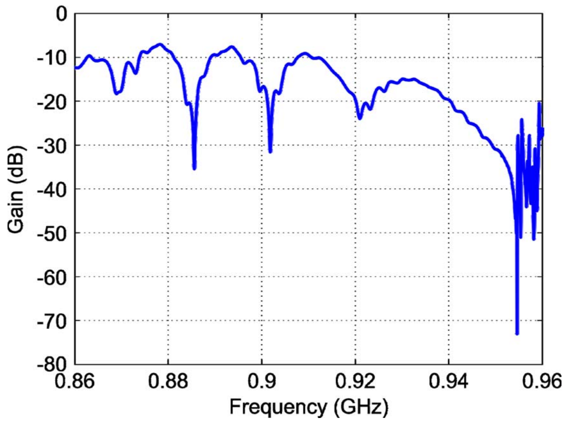

Fig. 7. ***Experimentally measured frequency response of the duct channel in the 860–960-MHz band.***

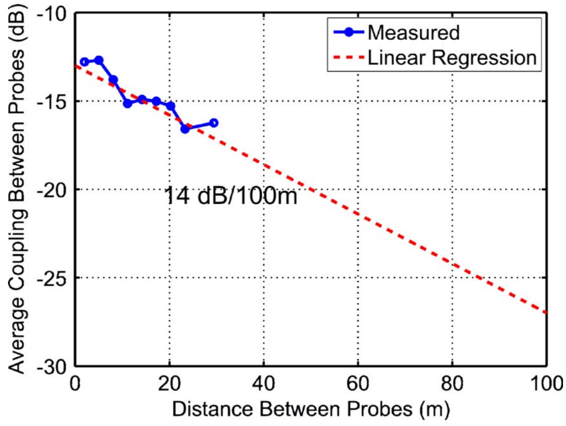

Fig. 9. ***Experimental average coupling between probes at varying distances in 860–960-MHz band.***

channel loss in the 902–928-MHz band is −13 dB, and the root mean square (RMS) delay spread is 29 ns.

The average measured loss of the HVAC duct channel is plotted as a function of distance in Fig. 9. In these measurements, one probe was fixed while the other was moved to different distances within the 30-m duct. A linear regression of this average loss within the 860–960-MHz band indicates that the average loss for the propagation is approximately 14 dB/100 m. This is an order of magnitude larger than that of an ideal single-mode steel waveguide as discussed in Section II-C, but is still much better than open air propagation for distances below a few hundred meters (see Fig. 2).

B. RFID Testing

We also tested the performance of commercially available UHF RFID systems in the duct environment. Our experimental RFID measurement setup is shown in Fig. 10. The passive UHF Gen2 RFID reader (Intermec IF4 [17]) was connected on one end to the same monopole antenna as in the previous setup. A commercially available dipole-like tag AD-431 [18] shown in Fig. 11 was used in testing. The normal read range of such a tag in free space with 4 W EIRP is about 6 m. The tag was placed on a foam block that was positioned at different distances from the reader antenna using nonconducting string as shown in Fig. 10.

The effects of the foam and the string on the RF propagation should be minimal, owing to the low density of the foam and small volume associated with the string. At all times, the tag was co-oriented with the reader monopole antenna. The measurements were taken every 8.2 cm.

The experimental results for tag readability inside the metal HVAC duct and in free space (in the building corridor) are compared in Fig. 12. Since the measurements in the building corridor were conducted in the presence of the walls, ceiling, and floor, read nulls resulting from multipath can be seen in the free-space results. In contrast, the readability in the duct has much smaller fluctuations and falls off much more slowly. These results clearly show

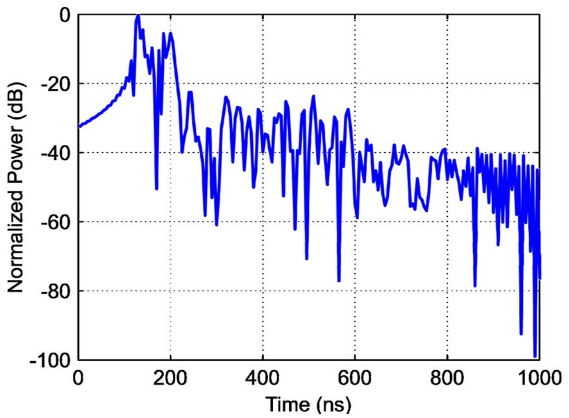

Fig. 8. ***Experimentally measured impulse response of the duct channel in the 860–960-MHz band.***

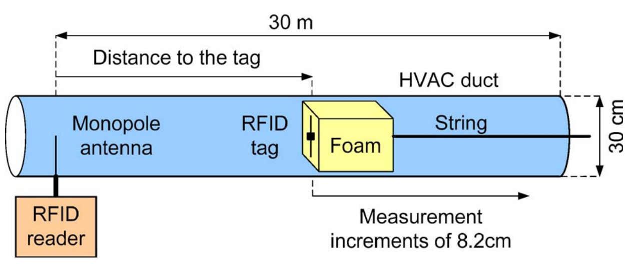

Fig. 10. ***Measurement setup for the HVAC duct waveguide used with the passive UHF RFID system.***

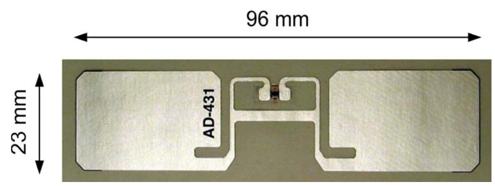

Fig. 11. *The AD-431 passive UHF RFID tag used in tests [18].*

that it is possible to read tags at a distance of order 30 m in the HVAC duct waveguide.

Note that the readability inside the duct is decreasing linearly with the distance. This behavior may be due to various Gen2 protocol artifacts (such as selection of protocol parameters, e.g., the expected number of tag responses) or tag response collisions (caused by multiple reflections from the open ends of the duct).

We also observed that the tag was readable for about 0.5 m beyond the HVAC duct—where the tag was removed from the duct but maintained within line-of-sight and moved further along on the same axis. This implies that it would be possible to bridge one system of duct waveguides to another system (using duct openings or reradiators), thus effectively enabling tags in the second duct system to be read by a reader in the first system.

Also note that once inserted into a waveguide, an antenna can no longer be characterized by its gain pattern but rather by the modes which it excites. One can design directional antennas for waveguides using, e.g., monopole arrays. Antenna impedance is also different in free space and in waveguides and is important for matching the RFID chip connected directly to the waveguide antenna.

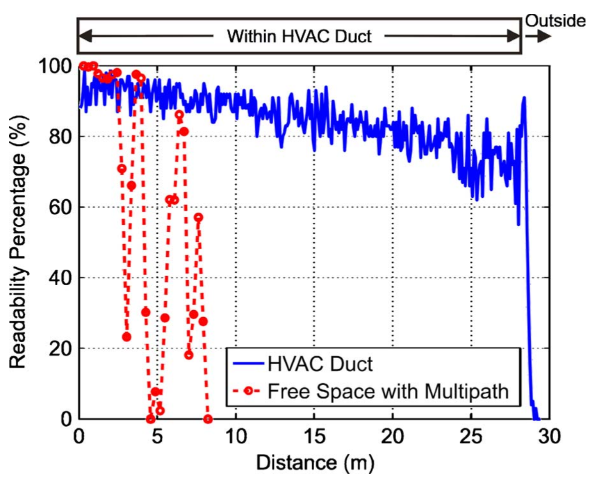

Fig. 12. *Readability of the passive UHF RFID tag within the HVAC duct waveguide as compared to free space (in the building corridor).*

IV. APPLICATIONS TO HVAC SENSOR NETWORKS

The measurements presented in the previous sections verify the low-loss propagation of electromagnetic waves in HVAC ducts. A promising application suggested by this result is the use of HVAC ducts as a communication backbone for future passive sensor networks. To illustrate this idea, consider the concept presented in Fig. 1 where RF power is delivered to transponders throughout a chain of HVAC ducts spanning an entire building. Imagine, for example, multiple passive RF-powered temperature, humidity, and airflow HVAC sensors plugged into ducts throughout a building. A variety of such sensors has recently been described in the literature (see e.g., [19]). When powered up through energy harvesting techniques (such as passive UHF RFID), these sensors would then backscatter their measurements to a central location (reader, connected to all main HVAC controls for heater, blower, air conditioner, etc.). This network of passive sensors could help optimally maintain proper operation of HVAC systems in large buildings or monitor conditions in a building that are of interest. With the 30-dBm transmitter, one can see from Fig. 9 that at distances of several tens of meters a few milliwatts of power should be available to operate low-power sensors (temperature, humidity, and others).

Another application is intelligent buildings, where wireless sensor motes are already being used [20]. In such buildings, the use of the HVAC ducts would provide improved flexibility and reduced cost of both installation and maintenance.

V. CONCLUSION

In this paper, we have proposed to use HVAC ducts as a low-loss propagation medium and power grid to enable powering up and communicating with passive UHF RFID tags that can be located far away from the reader. Using the latest passive Gen2 (ISO-18000 6C) UHF RFID ICs with a sensitivity on the order of −18 dBm [15], such a system should enable a range many times the typical operating range of UHF RFID systems in free space. If semipassive (battery-assisted) chips are used that have sensitivities on the order of −30 dBm [21], the operating range can be extended even further.

We derived the expression for the maximum tag range in the waveguide and for the required reader sensitivity. We also provided measurements indicating that passive UHF RFID systems in their current technological state could operate very well at long distances. Experimentally, a 30-m read range was confirmed for the tag whose normal read range in free space is only 6 m.

The described concept of long range passive RFID operation in electromagnetic waveguides can also be applied to other environments such as gas mains, oil pipes, and tunnels. ■

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ABOUT THE AUTHORS

Pavel V. Nikitin (Senior Member, IEEE) received 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, Logan, in 1998, and the Ph.D. degree in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, PA, in 2002.

He is currently a Lead Engineer with Intermec Technologies, Everett, WA, where he is involved in the research, design, and development of RFID systems. His professional experience includes working with the Ansoft and IBM corporations and a postdoctoral position with the University of Washington. He has authored over 50 technical publications in journals and conferences. He has more than 20 patents pending or issued.

Darmindra D. Arumugam (Member, IEEE) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Texas at Arlington in 2005 and 2007, respectively. Currently, he is working towards the Ph.D. degree at the Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA.

He joined the Antenna & Radio Communications (ARC) Group within the Department of Electrical and Computer Engineering, Carnegie Mellon University in 2009. His research interests are in electromagnetic theory, wave propagation, electro-quasi-static and magneto-quasi-static fields, and antenna theory.

Matthew J. Chabalko (Member, IEEE) received the B.S. degree in electrical engineering from Lehigh University, Bethlehem, PA, in 2006 and the M.S. degree in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, PA, in 2008, where he is currently working towards the Ph.D. degree at the Electrical and Computer Engineering Department.

He joined the Antenna and Radio Communication (ARC) group in the Electrical and Computer Engineering group at Carnegie Mellon in fall 2006. His research interests are optical devices, subwavelength optical devices (plasmonic devices), antenna theory, and electromagnetic wave propagation.

Benjamin E. Henty (Member, IEEE) received the Ph.D. degree from Carnegie Mellon University, PIttsburgh, PA, in December 2006.

He is currently a Senior Research Engineer at the Applied Physics Laboratory, Johns Hopkins University, Laurel, MD.

Daniel D. Stancil (Fellow, IEEE) 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 in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, in 1978, 1979, and 1981, respectively.

He is the Alcoa Distinguished Professor and Head of the Electrical and Computer Engineering Department, North Carolina State University, Raleigh. From 1981 to 1986, he was an Assistant Professor of Electrical and Computer Engineering at North Carolina State University. From 1986 to 2009, he was an Associate Professor, then Professor of Electrical and Computer Engineering at Carnegie Mellon University, Pittsburgh, PA. He returned to North Carolina State as Head of the Electrical and Computer Engineering Department in 2009. His research interests include wireless communications and applied electrodynamics.

Dr. Stancil is a Past-President of the IEEE Magnetics Society.