Millimeter-Wave Identification—A New Short-Range Radio System for Low-Power High Data-Rate Applications

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Abstract—The radio-frequency identification (RFID) concept is expanded to millimeter-wave frequencies and millimeter-wave identification (MMID) in this paper. The MMID concept and a comparison with UHF RFID are presented, showing the limitations and benefits of MMID. Three feasible applications are suggested for MMID, which are: 1) wireless mass memory; 2) an automatic identification system with pointing functionality; and 3) transponder communication with automotive radar. To demonstrate the feasibility of the MMID system, experimental results for both downlink and backscattering-based uplink are presented at 60 GHz.

Index Terms—Backscattering, millimeter waves, millimeter-wave identification (MMID), RF identification (RFID).

I. INTRODUCTION

TODAY, applications of radio-frequency identification (RFID) are widespread [1]. Inductive RFID systems, that operate at low-frequency (LF) and high-frequency (HF) bands are widely adopted, especially for access control, where short operational range and low data rate are sufficient, even desirable. In recent years, the ultra high-frequency (UHF) band has also been utilized for RFID. The UHF RFID systems are radiative, unlike the near-field-based systems at LF and HF, and they offer an operational range of a few meters with low-cost batteryless transponders. This makes UHF RFID tempting for logistics applications, e.g., for tracing postal packages. For some applications, such as tracking the location of transponders, microwave frequencies at the 2.45-GHz industrial–scientific–medical (ISM) band are used. These real-time locating systems (RTLSs) usually require an active transponder, i.e., a transponder with a battery.

Clearly, a tendency to move to ever higher frequencies is seen here. Herein, we propose using millimeter waves for identification applications. Here we call the millimeter RFID millimeter wave identification (MMID).

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There are several advantages of MMID over RFID. At millimeter waves, e.g., 60 GHz, high data-rate communications with even gigabit data rates can be implemented. Here, an interesting application would be batteryless wireless mass memories that can be read in a few seconds with high data rates. Furthermore, at millimeter waves, directive antennas are small. A reader device with a small directive antenna would provide the possibility of selecting a transponder by pointing toward it. This is not possible in today's UHF RFID systems because directive antennas are too large. A directive reader antenna would help in locating transponders in high-density sensor networks or other places where transponders are densely located, e.g., in item level tagging. Finally, there are already applications where millimeter-wave radars are used, as in automotive radars. These radars could, in principle, be used as MMID reader devices that could communicate with the transponders. Imagine a transponder in a child's clothing that gives a warning to oncoming cars, thus preventing a fatal accident.

There has been some research on RFID at microwaves, at 24 GHz [2], and by the authors at millimeter waves, i.e., at 60 [3] and 77 GHz [4]. These papers, however, focus only on one component of the MMID system, namely, the design and fabrication of a transponder. In this paper, the possibilities and limitations of the MMID system are thoroughly presented.

This paper is organized as follows. In Section II, the overall characteristics of the system are explained and the basic equations for its operation are derived. These equations are then used to identify the three applications suggested. After a more detailed discussion on the system components, an experimental verification of backscattering communication at 60 GHz is presented.

II. GENERAL CHARACTERISTICS

An MMID system consists of two main components, as presented in Fig. 1: a reader device and a transponder or tag.

The basic operation of the system is similar to that of any other RFID system. The transmitter in the reader sends out a modulated continuous wave signal (downlink). The transponder receives the signal, operates according to the detected command, and responds to the reader device (uplink). The response is detected by the receiver of the reader device. This description applies to almost every radio link, but it is the transponder powering and uplink realization that make the RFID and MMID systems unique.
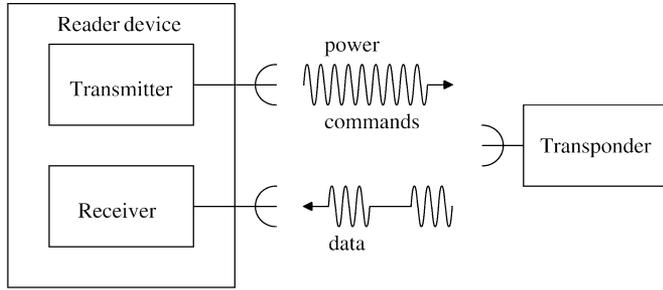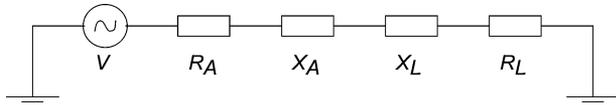
Fig. 1. Components of an MMID system.

Fig. 2. Series model of a loaded antenna.

A transponder can be powered up in three ways. A passive transponder receives power from the reader transmission. In practice, a rectifier in parallel with the detector is used for generating dc power from the carrier sent by the reader. A semipassive transponder relies on a dc power source, such as a battery, but still uses backscattering for communication. This enables longer operational range than with a passive transponder, while providing a long battery lifetime, because the device does not draw any current from the battery in the absence of the reader. An active transponder is similar to an active radio: it uses a battery for powering an active detector and has an active radio for the uplink.

In RFID or MMID, the uplink is usually realized by modulation of backscattering. Lately, however, active radios have also been referred to as active RFID, when the link has been used for identification applications. This paper will concentrate on backscattering-based uplink.

The backscattering modulation is achieved by modulating the load of the transponder antenna. Thus, the reader receiver and transmitter must be operating simultaneously at the same frequency. The reader device can also be considered a radar: the uplink signal is a faint echo of the reader transmission.

A. Operation Principles

To understand the possibilities and limitations of an MMID system, one can shortly derive a few basic equations of the passive RFID with a backscattering uplink. The derivation is presented in more detail in [5] and [6]. Let us model the transponder as a series model of a reactive antenna (subscript A) and a reactive load (subscript L). The voltage source V in Fig. 2 presents the incoming RF radiation.

The current in the circuit is easily calculated from voltage and impedance. In a conjugate matched case, the power dissipated in load R_L is the transferred power in the Friis equation

$$\frac{V^2}{8R_A} = \frac{G_A \lambda^2}{4\pi} S \qquad (1)$$

where S is the power intensity created by the reader device at the transponder and G_A is the transponder antenna gain. The power transfer to the transponder is described by the effective

the aperture of the transponder A_e. The aperture A_e is defined as the ratio of power dissipated in the load to the power intensity S, i.e.,

$$A_e = \frac{\frac{1}{2}R_L|I|^2}{S}. \qquad (2)$$

Similarly, the scattered power from the transponder is described by the radar cross section σ, which is the ratio of power dissipated in the antenna to the power intensity

$$\sigma = \frac{\frac{1}{2}G_A R_A|I|^2}{S} \qquad (3)$$

where the gain G_A represents antenna losses and directivity as the scattered power is reradiated.

To combine (1)–(3), a reflection coefficient Γ is defined as [7]

$$\Gamma = \frac{Z_L - Z_A^*}{Z_L + Z_A} \qquad (4)$$

where $*$ denotes a complex conjugate. The equations for effective aperture and radar cross section can then be written as

$$A_e = \frac{G_A \lambda^2}{4\pi}(1 - |\Gamma|^2)$$
$$\sigma = \frac{G_A^2 \lambda^2}{4\pi}|1 - \Gamma|^2. \qquad (5)$$

The equations are similar in form. They consist of almost similar terms describing the maximum aperture or cross section, multiplied by a distinct mismatch term.

From (5), it seems evident that minimizing the mismatch between the antenna and load gives the best results, but backscattering modulation for the uplink requires us to have two different load impedances at the transponder. Assuming a square wave modulation between two impedance states, namely, Γ_1 and Γ_2, another set of equations can be written as follows:

$$A_e^m = \frac{G_A \lambda^2}{4\pi}\left(1 - \frac{1}{2}[|\Gamma_1|^2 + |\Gamma_2|^2]\right)$$
$$\sigma^m = \sigma_0 + \sigma_m$$
$$= \frac{G_A^2 \lambda^2}{4\pi}\left|1 - \frac{1}{2}(\Gamma_1 + \Gamma_2)\right|^2 + \frac{G_A^2 \lambda^2}{16\pi}|\Gamma_1 - \Gamma_2|^2 \qquad (6)$$

where a superscript m is added to denote the modulated state. The first term (σ_0) of the radar cross section describes scattering at the carrier frequency, and the other term (σ_m) describes scattering that carries information at the sideband frequencies. Now, the contradiction between good matching and high modulation is evident. The higher the difference between the modulation states, the higher the scattered power is, but the lower the power transferred to the load.

The power P_{tag} transferred from the reader to the transponder can be calculated from the Friis equation

$$P_{\text{tag}} = A_e^m \frac{G_{\text{tx}} P_{\text{tx}}}{4\pi d^2} \qquad (7)$$

where subscript tx denotes reader transmitter and d is the distance between the transponder and reader. The minimum power
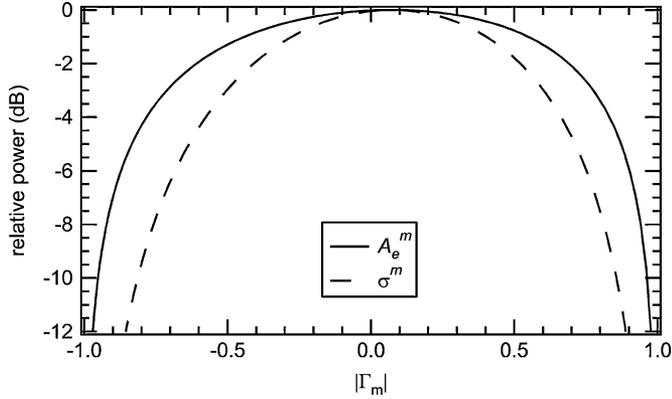
Fig. 3. Effect of mismatch Γ_m to the antenna aperture A_e^m and modulated radar cross section σ^m. Both are scaled to 0 dB at peak value. Values used in calculation: $R_A = R_L = 10\ \Omega$, modulation $\Delta Z = \pm 5\ \Omega$, mismatch purely resistive.

TABLE I
SYSTEM VARIABLES FOR UHF RFID AND MMID

Variable	UHF RFID passive	MMID passive	MMID semipassive
λ	347 mm	5.0 mm	5.0 mm
G_A	0 dBi	0 dBi	0 dBi
$G_{tx}P_{tx}$	33 dBm (erp)	33 dBm (erp)	33 dBm (erp)
G_{rx}	8 dBi	20 dBi	20 dBi
P_{tag}^0	-20 dBm	-20 dBm	-100 dBm
p_{rx}^0	-150 dBm/Hz	-150 dBm/Hz	-150 dBm/Hz
Δf	100 kHz	100 kHz	100 kHz
P_{rx}^0	-100 dBm	-100 dBm	-100 dBm

required by the transponder to operate is referred to as P_{tag}^0. At UHF, P_{tag}^0 can be as low as 10 μW [5], [8].

The power P_{rx} received by the reader is given by the radar equation

$$P_{\text{rx}} = \sigma_m \frac{\lambda^2 G_{\text{tx}} P_{\text{tx}} G_{\text{rx}}}{(4\pi)^2 d^4} \qquad (8)$$

where subscript rx denotes the reader receiver.

There are, however, four real life phenomena that diminish the operational range from the theoretical limits given by these equations, which are: 1) transmitter noise; 2) mismatch; 3) fading; and 4) polarization.

1) Transmitter Noise: The sensitivity of a radio receiver is usually determined by the thermal, of Johnson noise, of the receiver. The noise is proportional to the noise figure F and bandwidth Δf of the receiver, i.e., $P_n = 4kT\Delta fF$.

In case of backscattering communication, the transmitted signal couples to the receiver through near-field effects in the reader and its antennas and other environment. The attenuation in the coupling can be as low as -30 dB. The transmitted signal carries amplitude and phase noise originating in the oscillator and power amplifier, which can then dominate over the Johnson noise of the receiver.

In the worst case, the order of magnitude of the RF noise can be estimated as follows: a typical phase-locked loop (PLL) oscillator gives a noise floor of -120 dBc/Hz. This signal is amplified to 30 dBm and then coupled to the receiver with -30-dB coupling. Hence, the noise level at the receiver is -120 dBm/Hz, even 50 dB over the Johnson noise. To eliminate this, high isolation between the transmitter and receiver should be achieved.

2) Mismatch: As seen from (6), a certain amount of mismatch is necessary to implement backscattering communication, although good matching is still required. In fact, matching is even more important than usual: the achieved modulation deteriorates faster with growing mismatch than power transfer. This is shown in Fig. 3, where a mismatch $\Gamma_m = \Gamma_m(Z_m)$ is added to (6): $Z_A = Z_L^* + Z_m(\Gamma_m)$.

A typical source of mismatch is a change in the environment within the antenna near field. In general, a change in transponder antenna surroundings affects the antenna input port impedance. This can dramatically diminish the operational

range of the system. This has led to the design of platform-tolerant antennas, especially antennas that can be mounted on dielectric or metal housing [10]. The design goal of these antennas is to minimize the effect of the antenna surroundings on the input impedance of the antenna.

3) Fading: Since the environment is full of reflectors and scatterers, signals arrive at the same point using different paths. This multipath propagation leads to interference. The signals can interfere destructively to create areas of diminished RF field. Measurements on fading in backscattering communication at 2.45 GHz can be found in [11].

4) Polarization: The signal and power transfer are affected by the transponder and reader antenna polarizations. At UHF, usually linearly polarized transponder antennas and circularly polarized reader antennas are used. This ensures operation regardless of polarization, but introduces a loss of -3 dB due to polarization mismatch. The effect of polarization is considered thoroughly in [7].

These four phenomena are highly dependent on the actual implementation of the MMID system. In this study, these phenomena are omitted to give theoretical upper limits to the RFID and MMID operational range. Thus, the Johnson noise is used as a limiting value for reception, and reader sensitivity is assumed to be $p_{\text{rx}}^0 = -150$ dBm/Hz, which is 20 dB higher than room-temperature Johnson noise. A more thorough treatment of required signal-to-noise (SNR) is presented in [12].

B. Comparison of MMID and UHF RFID

The carrier frequency of the system affects the components that can be used. Especially at millimeter waves, the small wavelength allows very directive antennas, but also diminishes the antenna effective aperture and radar cross section. This affects the modulation index that should be implemented in the transponder, as well as the feasible applications of the system. Hence a comparison of power transfer and backscattered power in widely adopted UHF RFID and MMID systems is presented. The typical system variables that are used in the comparison are presented in Table I. The main differences in the two systems are the wavelength and reader antenna gain.

The received power P_{rx} and power transferred to the transponder P_{tag} at UHF are presented in Fig. 4 as a function of distance d with several values of the modulation index $|\Gamma_1 - \Gamma_2|$. The horizontal line represents the theoretical limiting power level (P_{tag}^0, P_{rx}^0) for both of the scales. Thus, the maximum operational range is reached at the first point of intersection. The modulation is assumed to be ideal so that $\Gamma_1 = -\Gamma_2$.
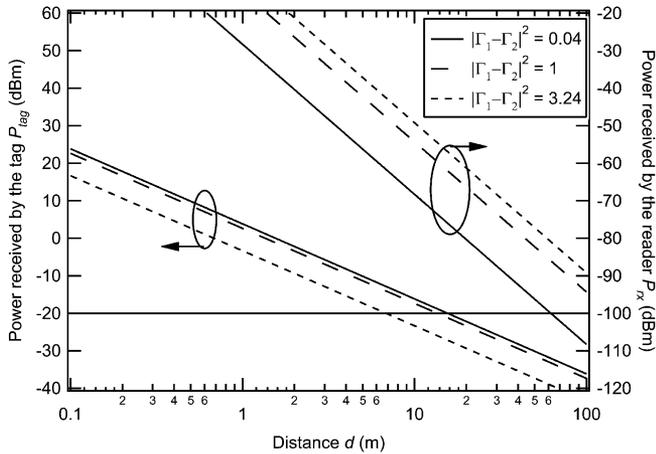
Fig. 4.   Limiting factors on the UHF RFID range.
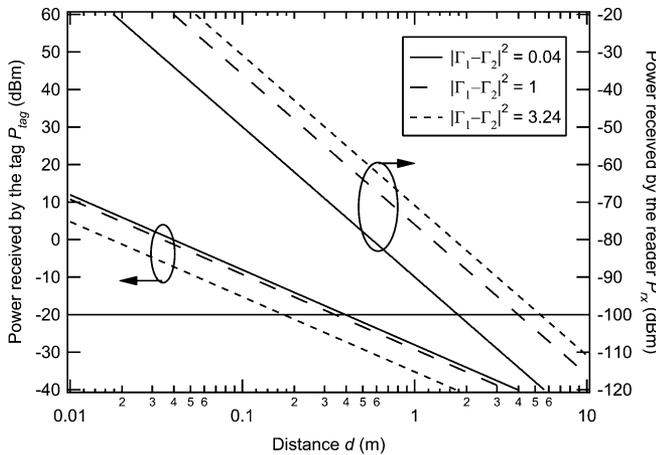

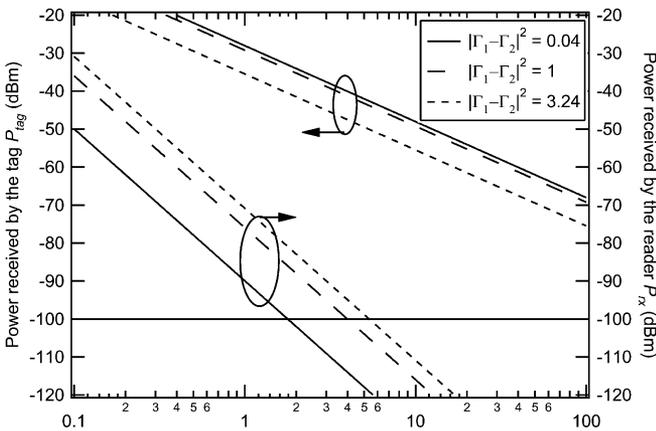Fig. 5.   Limiting factors on the passive MMID range at 60 GHz.

Fig. 6.   Limiting factors on the semipassive MMID range at 60 GHz.

Clearly, the UHF RFID is power transfer limited, i.e., the transponder powering limits the operational range. The maximum range is approximately 5 m, and the passive operation of the transponders calls for a relatively shallow modulation.

A similar analysis for passive and semipassive MMID at 60 GHz is presented in Figs. 5 and 6, respectively. Three possible applications for MMID can be seen. A completely passive

MMID is power transfer limited to a range of approximately 15 cm. To maximize the operational range of passive MMID, the modulation depth should be very shallow. At very short distances, i.e., at a few centimeters, the SNR of the received signal is very high. Excess SNR enables widening of the signal bandwidth. At a distance of a few centimeters, the SNR is over 10^4 with $\Delta f = 100$ kHz. This scales to a gigahertz bandwidth with unity SNR. However, smaller antennas with lower directivity are needed to satisfy the far-field criterion for the Friis and radar equations [see (7) and (8)] at short ranges. Since a wide bandwidth can be used at 60 GHz, a possible application of passive MMID could be a very short-range communication link, similar to near-field communication (NFC) with very high bandwidth, e.g., passive wireless mass memories.

In semipassive MMID, the transponder is powered by a battery, but the uplink is realized by backscattering. The downlink is limited only by the sensitivity of the transponder detector. A diode detector is efficiently Johnson noise limited, thus a sensitivity of $P_{\mathrm{tag}}^0 = -100$ dBm is used.

The limiting factor is the power received by the reader, which gives a maximum operational range of approximately 5 m in Fig. 6. For maximum range, the modulation depth should be maximized. The range could be extended by diminishing the signal bandwidth. This could provide an application similar to the UHF RFID of today—a short (today, typically 96 bit) ID code is transmitted over a distance of a few meters.

At UHF, the reader transmission cannot be efficiently directed and nearby transponders cannot be distinguished spatially. Here, MMID could provide pinpoint accuracy by high gain reader antennas, which provide narrow beam. The cost here is a battery in the transponder, but in sensor nodes or data loggers, the battery is needed for continuous operation also in the absence of the reader.

The operational range of an active MMID is only limited by signal detection at the transponder. Thus, a range of even a hundred meters is feasible, as seen from Fig. 6. This operation mode comes very close to a traditional radio link. This type of an active transponder could be used, for example, to communicate with automotive radars: the radar provides the location of the transponder and the transponder sends back additional information about the object. The system becomes almost symmetrical. The transponder is equipped with an active transmitter, which consumes a lot of power.

III. SYSTEM COMPONENTS

A. Transponder

A transponder has four main parts, which are: 1) an antenna; 2) a millimeter-wave front end; 3) a state machine; and 4) a functional block (such as a memory or sensor). The state machine controls the active block as commanded by the reader, e.g., accesses a memory address and streams its contents to the reader. The antenna can be very small in millimeter waves, and it would be tempting to use a high gain antenna in the transponder to increase the operational range. This, however, makes the transponder also directive, i.e., hard to access from any other direction than the main beam—and the direction of the main beam is seldom a fixed parameter in any application.
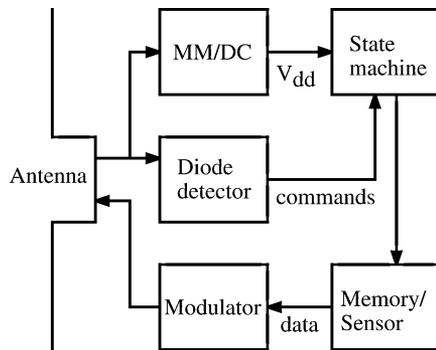
Fig. 7. Block diagram of a possible MMID transponder.

Fig. 8. Block diagram of a possible MMID reader at 60 GHz.

Thus, a relatively low gain antenna with a nearly uniform radiation pattern is preferred.

A passive transponder, as presented in Fig. 7, has the most complex millimeter front end since it requires a rectifier, detector, and modulator. When the incoming millimeter power is strong enough, the rectifier creates enough dc power from the field to power up a passive transponder. In a semipassive or an active transponder, a rectifier is not needed since a battery is used for dc power. At UHF, Schottky diodes and zero-bias transistors are used as rectifying elements. At millimeter waves, feasible elements could be Schottky and other diodes. The rectification is often quite inefficient because of low power and voltage levels. At UHF, the power conversion efficiency from RF to dc is in the order of 10% [13]. Similar efficiencies are to be expected also in MMID.

The modulator is used for changing the antenna load to achieve modulated backscattering for the uplink, as described earlier. This is used in passive and semipassive transponders, but not in active transponders, where an active radio sends the data to the reader. Best modulation depth can be acquired by switching between high- and low-impedance states. A fast switch, such as a diode or transistor-based switch, is required. A diode can also be applied as a modulator by changing the diode bias current. A microelectromechanical systems (MEMS) switch could deliver a very high on/off capacitance ratio, but tends to be quite slow [14].

The detector is required in all types of transponders. A diode is the optimal device because of its simplicity and low power consumption.

In fact, in a semipassive transponder, the front end can actually be simplified down to a single millimeter diode used for both detection and for uplink communication by implementing bias modulation. An optimal choice would be a zero-bias detector diode providing low power consumption while waiting for reader commands. In our proof-of-concept demonstration, we used a semipassive transponder with a Schottky diode [3], [4].

B. Reader Device

An UHF RFID reader usually uses a direct conversion architecture, where the same local oscillator is used for converting the baseband up in the transmitter and down in the receiver. This improves noise performance through noise correlation in down-conversion [15]. At millimeter waves, other solutions may also
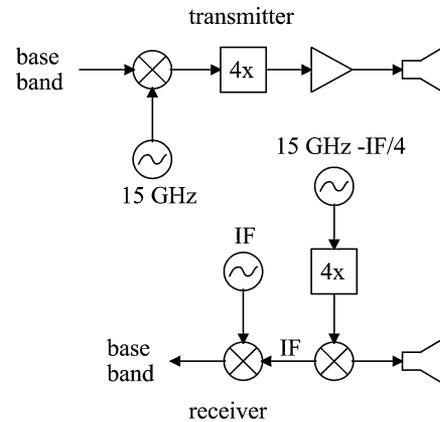
be useful and the actual reader architecture can vary depending on the MMID application. A possible architecture is presented in Fig. 8. The downlink utilizes amplitude modulation, but the uplink can also use phase modulation. Therefore, quadrature detection may be required.

The reader should have high isolation between the transmitter and receiver because the high-power transmission is present simultaneously at the same frequency as the weak received signal. The dynamic range is formidable: a typical transmission power could be several watts equivalent radiated power (erp). At the same time, the receiver should have as low a noise level as possible. Using the figures in Table I, we get dynamic range of 130 dB! Since this is clearly too much for any active circuit, high isolation between the transmitter and receiver is required.

An advantage of MMID over UHF RFID is the small size of directive antennas. A handheld reader at UHF typically has quite a big antenna, even as large as $(15 \text{ cm})^2$. This size can give approximately 6-dB gain. At millimeter waves, a small planar antenna of $(20 \text{ mm})^2$ can provide over 17-dBi gain (see, e.g., [16]). This enables smaller reader devices. Of course, transponders can also be similarly miniaturized.

IV. MEASUREMENT RESULTS

To demonstrate the MMID concept at millimeter waves, both downlink and backscattering measurements are needed. The downlink experiment shows that data can be sent from a reader to a transponder. The backscattering measurement demonstrates the MMID concept itself, showing that a signal transmitted by the reader is modulated by a transponder and a modulated signal is received by the reader.

The measurements demonstrate a semipassive transponder, i.e., the transponder was not remotely powered, but had an external dc power source. The millimeter-wave front end of the transponder (see Fig. 9) consisted of a 60-GHz Yagi–Uda antenna with a monolithically integrated Schottky diode, both supported on a 2-μm-thick GaAs membrane [3]. The device is optimized for a receiver application, but lends itself to demonstrating the MMID operation principle. For a practical MMID application, a less directional antenna with the main lobe orthogonal to the tag plane would be preferable, as in [4].

The bondwires are long, and may operate as antennas at millimeter waves. A low-pass filter isolates the wires from the diode

Fig. 9. Transponder used in measurements: on the left is the antenna. The Schottky diode is placed at the feed of the antenna, on the right side of which there is a low-pass filter. On the right, the baseband connector is seen. On the scale below, one tick is 1 mm.
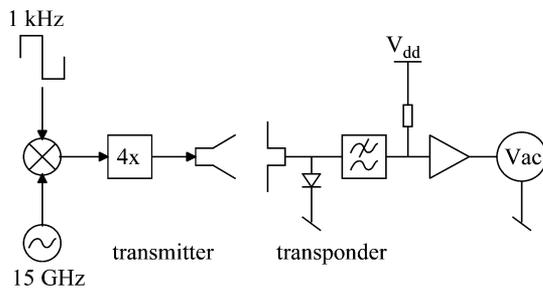

Fig. 10. Setup for downlink measurement.

at millimeter waves. The bondwires scatter, but this scattering is only at the carrier frequency, and does not affect the diode-related scattering at the information band.

A. Downlink

A modulated 60-GHz signal was transmitted to a transponder using a waveguide-based laboratory transmitter (see Fig. 10). The transmitter consisted of a modulated signal generator (Agilent E8257C), multiplier (HP83557A), and a horn antenna. The transmitted power at 60 GHz was 25-dBm erp.

An amplitude modulated signal was transmitted and it was received by the transponder. The detected voltage at the transponder and the transponder sensitivity are shown as a function of distance d between the transponder and the reader in Fig. 11. The detected voltage begins to saturate at low distance because the voltage is very high. This is seen as a drop in detector sensitivity.

The recorded waveforms can be seen in Fig. 12. The results show that downlink data transfer can be performed over a distance of at least 6 m with this measurement configuration. The range can be increased by transmitting more power, using a transponder with a more sensitive receiver and more antenna gain.
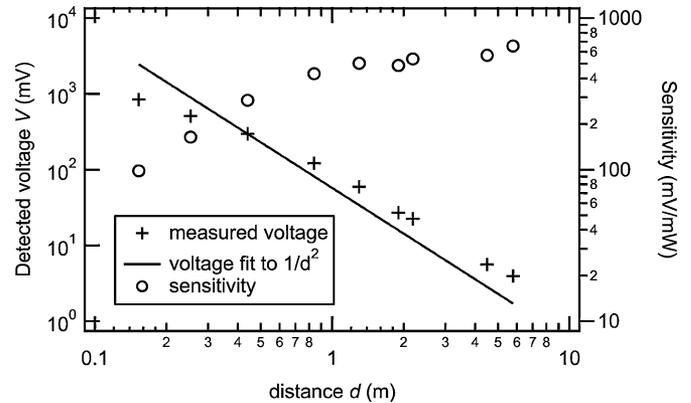

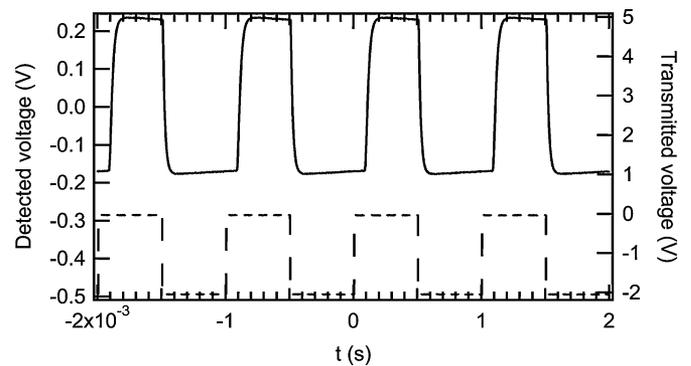Fig. 11. Voltage detected by the transponder and transponder sensitivity.

Fig. 12. Example of the waveforms in downlink measurement: detected voltage (solid line) and transmitted voltage (dashed line).
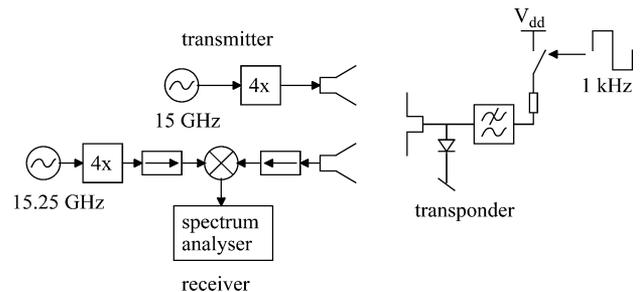

Fig. 13. Setup for uplink measurement.

B. Uplink

The uplink experiment has been used for demonstrating the MMID concept in a similar manner as illustrated in Fig. 1. The goal was to demonstrate modulated backscattering from the transponder. The reader consisted of a waveguide-based transmitter and receiver. The transmitter was the same as in the downlink experiment. The receiver consisted of a signal generator (HP83650A), a multiplier (Spacek Laboratories AV-4XW), a mixer (Spacek Laboratories PV-VB), isolators, and a horn antenna (Fig. 13).

A 60-GHz continuous wave signal transmitted by the reader was modulated with by transponder and the backscattered signal received again with the reader. The received signal was downconverted to 1 GHz and measured with the spectrum analyzer.
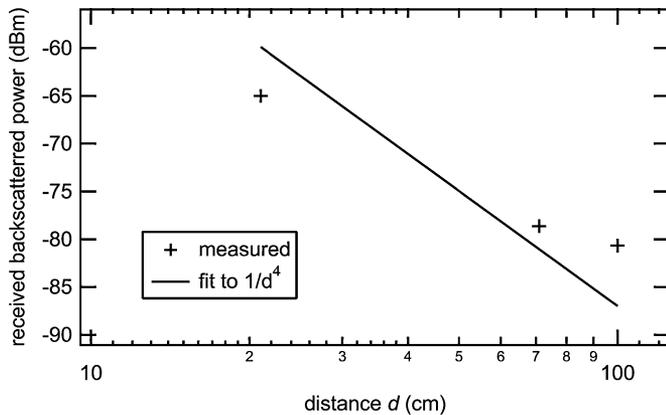
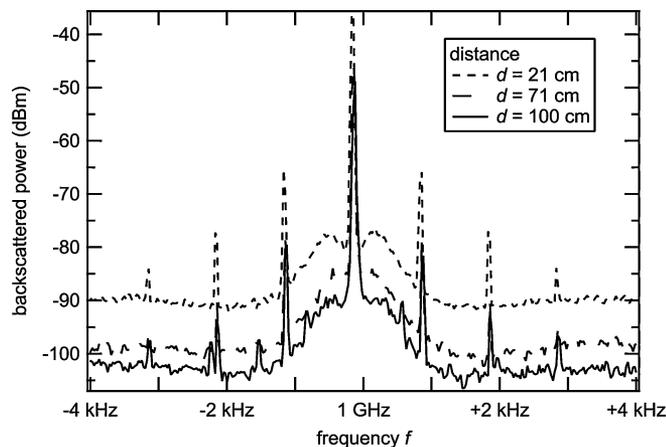Fig. 14. Backscattered power received by the reader.

Fig. 15. Measured backscattered spectra. Resolution bandwidth was 100 Hz and averaging 100.

The received backscattered power as a function of distance d is shown in Fig. 14 and the measured spectrum is shown in Fig. 15.

The measurements prove that backscattered power can be used for data transmission at 60 GHz. The bandwidth used here, however, is inconveniently small, which is due to nonoptimal modulation and matching at the transponder. In our previous study related to 77-GHz transponder development, we have demonstrated a similar measurement in [4], where SNR of 20 dB was achieved with 330-kHz modulation, 10-kHz resolution bandwidth, and no averaging.

V. CONCLUSION

MMID, i.e., backscattering-based communication at millimeter waves, was studied. The general characteristics and limitations of MMID were illustrated: the theory of operation was explained by deriving fundamental equations for remote powering and backscattering-based communication.

A comparison between UHF RFID and MMID showed that MMID will not replace RFID: at UHF, remote powering is feasible to approximately 5 m, which suits today's RFID applications well. Remote powering is limited to tens of centimeters at millimeter waves, but at short range, very wide, even gigabit, data bandwidth can be realized.

Finally, experimental verification of the derived theory was provided at 60 GHz with laboratory equipment. Data transfer from reader to transponder was demonstrated at 6 m. Modulated backscattering was received with small bandwidth up to a of 1 m.

The presented theoretical and experimental considerations prove that backscattering can be used for data transmission at millimeter waves, and thus MMID is feasible.

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