Wideband mmWave Wireless Power Transfer: Theory, Design and Experiments

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***Abstract*—A new type of wireless power transfer system is presented with wideband mmWave transmitters and rectennas. The proposed system transmits a beam formable and beam steerable signal by exploiting the inherent frequency-dispersive nature of a passive leaky wave antenna, thereby eliminating the need for active phased array and other costly control methods. Multiple nodes can be wirelessly powered simultaneously by using a wideband mmWave rectenna to harvest the frequency scanning signals. A 24-34 GHz rectenna was designed in a highly integrated fashion and has been tested to show its high conversion efficiency of >50% at the frequency and power levels of interest. We have presented a system demonstration for remotely charging diverse nodes at > 1 m distance by using the proposed system with feedback control for the multi-tone frequency modulation and sweeping of the transmitting signals. Our work has showcased the passive beamforming and multi-node tracking of mmWave WPT system using significantly reduced cost and complexity.**

***Index Terms*—mmWave, leaky wave antennas, rectennas, wireless power transfer.**

I. Introduction

Far-field wireless power transfer (WPT) via radio waves is a promising way for remote charging. However, the radiative wireless power could be largely scattered in open areas whilst the path loss of radio waves propagating in free space is significant; consequently, the end-to-end efficiency of the far-field WPT system is relatively low (less than 1%). This has been the main challenge for traditional radiative power transfer. To improve the WPT link efficiency, high directivity antenna arrays with beamforming capabilities are preferred to transmit power effectively. State-of-the-art research has shown the feasibility of using phased array [1-3] and digital meta-surfaces [4] for wireless power beamforming, such that the power beam could be focused sharply while the beam direction is switchable toward several receiver locations. But the phased array essentially needs active phase shifters and array feeding networks which will introduce significant power loss (more than 6 dB) and increases the costs tremendously. Similarly, digital meta-surface beamformers will need the massive integration of PIN diodes and costly semiconductor varactors thereby reducing the WPT efficiency and charging distances (lower than 2% within 0.5 m). The beam scanning range, number of beam directions and beam scanning resolution of both technologies are directly determined by how many active phase shifters and switches are integrated to the design. These significant drawbacks in terms of high complexity, high power loss, and high cost have become the bottleneck when applying such far-field WPT in real world applications.

Node Tracking is crucial when wirelessly remote charging a moving target. This will need the feedback information sent from the receiver to effectively control the wireless power beamforming at the transmitter. Existing studies have demonstrated the use of retrodirective antenna array (RDA) for node tracking [5, 6] whereas the RDA automatically retransmits a signal towards a source without prior knowledge of the incoming signal. Due to the need of phase conjugation to realize retro-directivity, RDAs typically consist of signal mixers, sub-arrays and multiple power amplifiers (PAs) and bandpass filters [6]. This will bring in extra costs, power loss and complexity for the WPT systems. Time reversal (TR) is another emerging technology for selectively delivering wireless power to the targeted nodes. Different from the phased array that relies on phase shifting, TR transmitting array operates in a switching manner where only one element transmits at a time [7, 8]. The node selectivity is accomplished by measuring the feedback beacon signal sent from the receiver and correspondingly selecting the optimal transmitting antenna element. But both RDA and TR technologies will need large active antenna arrays consists of multiple antenna elements, PAs and complex feedings, they still need to be actively controlled and/or switched which inherently has higher cost and higher power loss compared to the conventional passive transmitting antenna.

In this paper, we will present a brand-new wireless power transfer system by using mmWave signals with relaxed radiating power levels. Importantly, we will propose a passive beamforming method by exploiting the inherent frequency dispersion nature of leaky wave antennas, thereby eliminating the need for active phased array transmitter which exhibits extremely high cost and high-power loss at mmWave frequency ranges. At the receiver end, we will present a newly designed wideband mmWave rectenna to efficiently capture the spectrum-sweeping signals transmitted from the leaky wave antenna. We will also present the multiple node tracking system by establishing a closed control loop using the the DC power monitor for the rectenna, feedback beacon signals and multi-frequency modulation and sweeping for the mmWave signals.

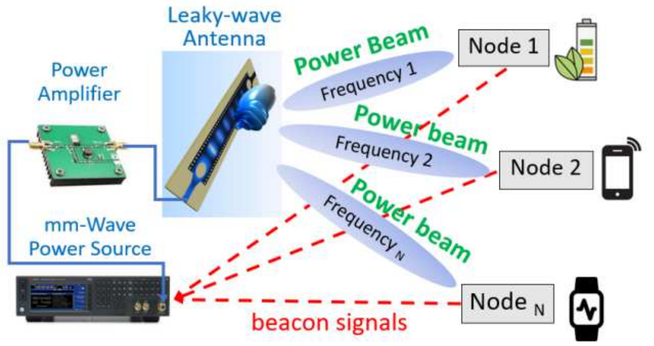


Fig. 1. Wideband mmwave WPT system with low-cost passive beamforming and multi-node tracking.

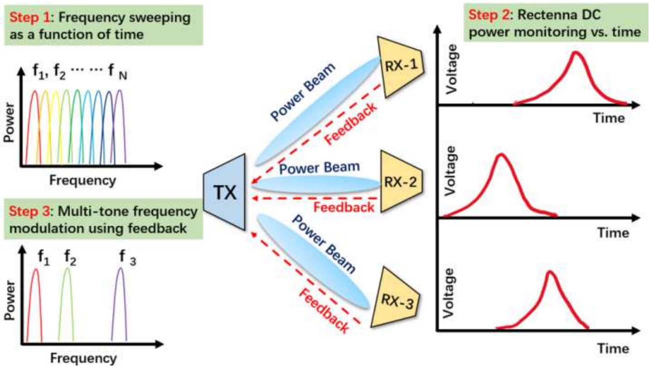


Fig. 2. Beamforming and multi-node tracking by using rectenna DC power monitoring and multi-tone freqeuncy modulation and sweeping.

II. WIDEBAND MMWAVE WPT SYSTEM AND THEORY

A. Why use mmWave?

Compared to low-frequency microwaves (< 6 GHz), the EIRP limit of mmWave band is increased from 36 dBm to 75 dBm (according to FCC and 3GPP) [9]. This means that the mmWave power transmitter could radiate significantly enhanced power (about 39 dB higher) in domestic environments within safety human exposure constraints. In addition, mmWave antennas could realize higher directivity (> 25 dBi) using a given aperture size while the overall size of mmWave RF devices will be naturally smaller than that of microwave devices (around 10 times smaller). Hence, a high directivity mmWave WPT system may have better end-to-end efficiency as well as much higher deliverable wireless power at the identical distances compared with microwave systems. The free space path loss can be greatly mitigated by high directivity and high aperture efficiency of mmWave antennas whilst the transmitting power is enhanced by the relaxed EIRP regulations. However, the major challenges for mmWave WPT are that the cost, power loss and efficiency of mmWave PAs, phase shifters and active switches are unfavorable. It is overly expensive to build the power beamforming and node tracking capabilities for the remote charging system at mmWave frequencies using conventional technologies and for this reason it has not yet been substantially explored [10].

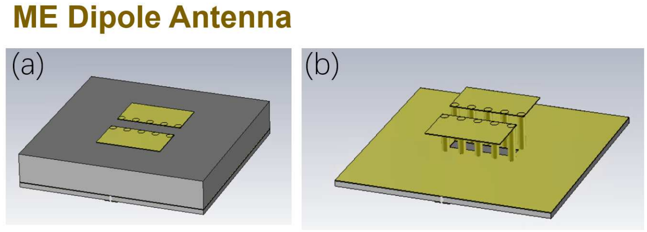


Fig. 3. Wideband ME dipole antenna at mmWave frequency. (a) With substrate. (b) without substrate.

B. Why need wideband?

The proposed system is presented in Fig. 1. Here we will consider a special type of passive beam-scannable and beam-formable antenna – the leaky wave antenna (LWA), which has very high radiation efficiency (>90%) at mmWave frequency bands [11]. Due to the frequency dispersive nature of LWA, its radiation pattern and beam scanning is a function of frequency. This might be the drawback when applying LWA in typical wireless communications (frequency aligned), but we can take advantage of this feature in WPT, that is, a wideband wide-beam rectenna (power receiver) could be developed to receive diverse frequency-dependent power beams radiated from the LWA transmitter. By doing so, the beamforming of LWA power transmitter could be simply achieved by changing the frequency of mmWave signals, thereby significantly reduce the power loss, cost, and complexity compared with conventional active beam scanning and other WPT beamforming methods.

C. How to track nodes?

Different from the RDA and TR technology, the LWA wireless power transmitter does not need complex antenna arrays, phase shifters, signal mixers and active semiconductor switches. The beamforming is achieved by software-controlled frequency modulation. A simplified node tracking could therefore be realized by firstly sweeping the frequency of transmitting (TX) signal at a known rate over a defined time-period, then the receiving (RX) node DC power from the rectenna could be real-time monitored over the identically time-synchronized period of the transmitter. When the peak DC output is detected, the receiver sends a beacon signal back to the transmitter, thereby localizing the time instance for the optimal TX signal frequency to perform beamforming. More importantly, multi-target moving nodes tracking could be realized by using multitone frequency modulation and sweeping (see Fig. 2).

III. WIDEBNAD MMWAVE RECTENNA DESIGN

For the proposed system, it is evident that a highly efficient wideband mmWave rectenna will be the key component to receive the DC power and charge devices. To cope with the wide frequency range of the frequency-dependent passive beam scanning of the LWA, an efficient broadband rectenna will be needed, however, it is relatively challenging to design

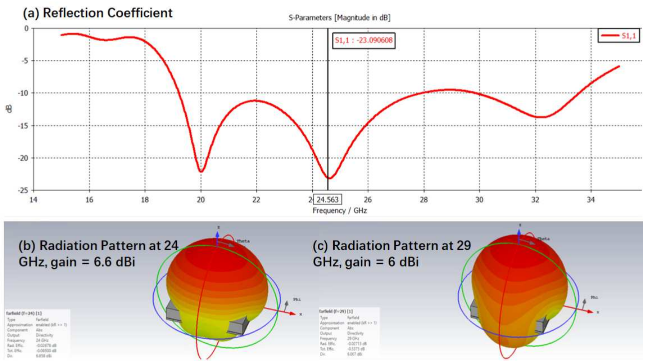


Fig. 4. (a) S_{11} (b) raidaion pattern at 24 GHz and (c) raidation pattern at 29 GHz.

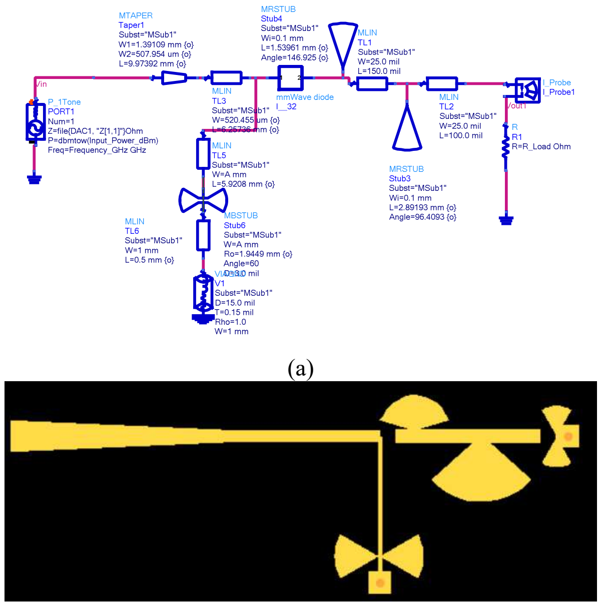
wideband rectennas at mmWave frequency band as the power loss of high-frequency diodes (e.g., MA4E1317), surface mounted devices (SMD) and chips becomes significant at such frequency bands (over 10 GHz). Here we will showcase our latest rectenna design to address the above-mentioned challenges.

A. Wideband ME-dipole Antenna

We firstly present a wideband magnetoelectric (ME)-dipole antenna design fed by a slot aperture, as shown in Fig. 3 (a). The shorting wall of magnetic dipole was achieved using substrate integrated waveguide (SIW) vias across a single layout of Rogers 5880 substrate of 1.575 mm thickness (see Fig. 3 (b)). The electric dipole arms are directly printed on the PCB without the need of additional spacers. On the bottom layer, an alternative layer (0.3 mm thickness) of RT5880 was inserted below the slot and was used to accommodate the feed line of antenna. The overall size of the antenna was only 10 mm × 10 mm × 1.86 mm. Such a slot fed ME-dipole could simultaneously have small size, wide bandwidth and high gain, as demonstrated in our recent work [12]. According to the simulated S_{11}, the proposed ME dipole antenna covers 19 – 34 GHz for reflection coefficient < -10 dB (see Fig. 4 (a)). It is also shown than the ME dipole realizes over 4.9 dBi gains across the frequency band of interest. The radiation pattern generally agrees to the desired shape of complementary antennas of ME dipole, in which the beam width is over 93 degrees for all frequencies with antenna gain over 6 dBi (Fig. 4 (b)-(c)).

B. Wideband mmWave Rectifier

For mmWave rectifiers, it is important to reduce the loss of power due to circuit elements used in matching networks and DC output networks. Therefore, here we propose a novel rectifier without using lumped elements and SMD components, to prevent the decay of Q factor over high frequency bands of chip inductors and nominal value variations of lumped elements. The ME-dipole antenna in Section III-A was fed through an aperture coupled transmission line that is directly linked to the rectifier printed



(a)

(b)

Fig. 5. (a) Schematic and (b) layout of wideband mmWave rectifier.

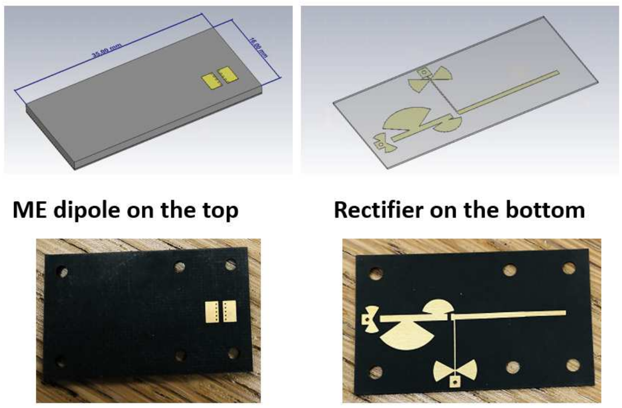


Fig. 6. Fabricated prototype of the proposed rectenna.

on the back side of the antenna. We will leverage the authors' previous success in broadband rectenna design, in particular, the integrated co-design methodology of wideband antenna and rectifier will be employed [13]. Ideally, the entire wideband rectenna is solderless (excepting the high-frequency diode), which removes the loss caused by antenna-rectifier interconnections. The rectifier circuit components (e.g., low-pass and DC filters) will be largely converted into microstrips to substitute the SMD devices, thereby reducing the loss due to soldering and inherent packaging loss in real-world prototypes. The schematic and layout of the rectifier are shown in Fig. 5 (a)-(b). It can be clearly seen that there are only 2 gaps on the PCB layout, one is used to solder a single high frequency diode MA4E1317 (up to 80 GHz) and another is proposed for a chip resistor of 200 ohms. All other matching network elements, DC filters, output matching and harmonic termination are wisely converted into either shunt stubs or radial stubs with corresponding electrical size against its wavelength.

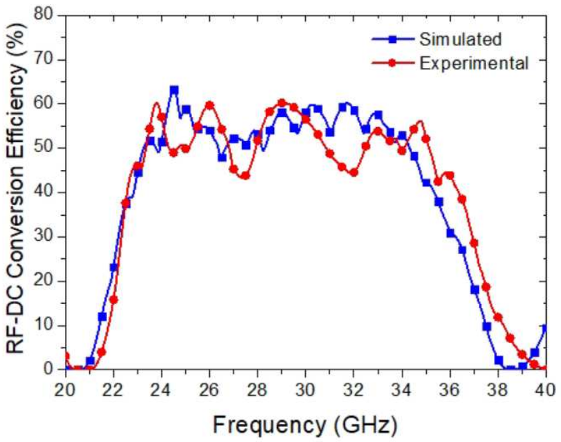


Fig. 7. RF-DC conversion effciency vesus frequency.

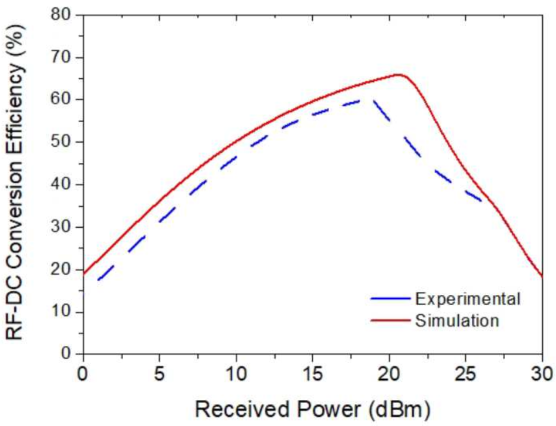
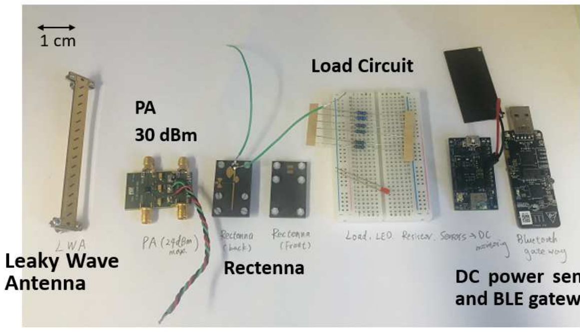


Fig. 8. RF-DC conversion effciency vesus received power.

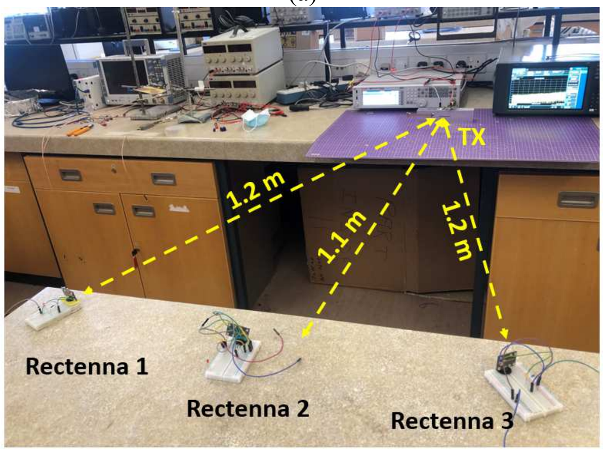
IV. PERFORMANCE OF THE RECTENNA

We have fabricated the proposed rectenna with ME-dipole and integrated rectifier, as shown in Fig. 6. The overall dimension is 35 mm × 16 mm × 1.86 mm with two layers of PCBs for top antenna and bottom rectifier respectively. The measurement of the rectenna was conducted in the Anechoic Chamber where the received power transmitting from mmWave signal generator N5183B was calculated using the antenna far-field gain and Friis formula at the far-field distance of 70 cm.

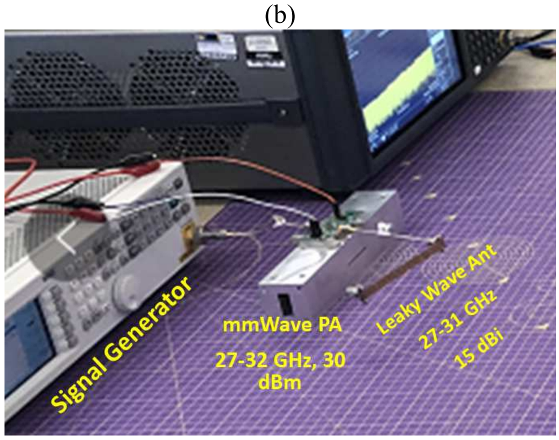
The simulated and measured RF-DC conversion efficiency is compared in Fig. 7 as a function of frequency. It has been shown that the wide frequency range between 24 GHz and 34 GHz is well matched thereby realizing a stable efficiency around 50-60%. The input power has been tuned to 20 dBm by manipulating the TX power from the signal generator and PA. If we plot the conversion efficiency against the received power at 29 GHz (see Fig. 8), it can be seen than peak efficiency is around 65% at 22 dBm RF power whilst the overall conversion efficiency is above 50% for 10 - 25 dBm. These results have demonstrated the effectiveness of the proposed rectenna of high conversion efficiency and a wide operational frequency band to cope with the proposed wideband mmWave WPT system.



(a)



(b)



(c)

Fig. 9. (a) Prototype of the proposed mmWave wideband WPT system. (b) Test setup for wireless charging three nodes at different locations. (c) The leaky wave antenna and PA for the transmitter.

V. DEMONSRATION OF THE PROPOSED SYSTEM

The overall mmWave wideband WPT system has been fabricated, as depicted in Fig. 9 (a). It consists of a leaky wave antenna (27 -31 GHz, 15 dBi gain), an mmWave PA (30 dBm, 27-32 GHz), proposed rectennas, load bread boards and DC sensors for rectenna output monitoring. The DC power will be read by using a low-cost programmable BLE sensor platform (CYALKIT-E02 BLE Sensor Beacon). The TX will firstly send a frequency-sweeping signal from 27-32 GHz at a configurable time-period and step-width, then the DC sensor will record the rectenna voltage outputs over the same time interval. When the peak DC is detected, the beacon

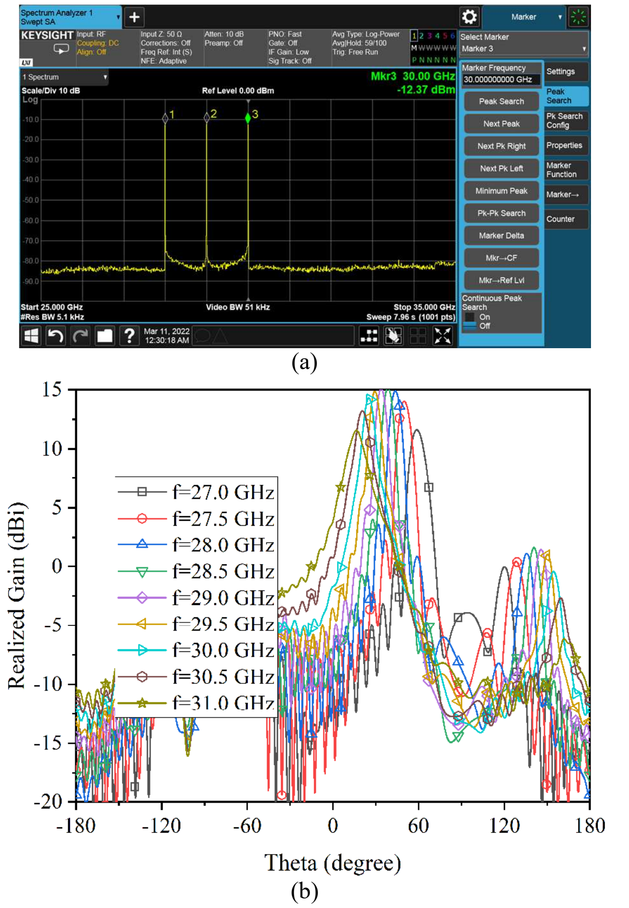


Fig. 10. (a) Tri-tone spectrum for multi-node tracking and wireless charging. (b) Beam scanning range and frequency dependence of the LWA.

signal will be sent back to the TX to localize the frequency at the time of generating peak voltages. When multiple nodes are sending beacon signals to the TX simultaneously, then a few frequencies will be identified for multi-tone frequency modulation and sweeping to track and remotely charge these nodes (see Fig. 9 (b)).

For tracking the three nodes shown in Fig. 9 (b) at around 60 degrees scanning range, the input signal has been modulated with 3 tones for the TX as depicted in Fig. 9 (c). An example of the tri-tone signal spectrum is shown in Fig. 10 (a) while the beam scanning range of the leaky wave antenna and its frequency dependence is given in Fig. 10 (b). When the target device is moving, the DC monitoring system will detect the drop/variation of voltage and send a beacon signal to re-enable the frequency sweeping of the LWA transmitter to identify new frequencies and new beam directions for remote charging and efficient tacking of these moving objects. The proposed rectenna can produce an output DC power up to 10 dBm at 0.5 m, 3 dBm at 1 m, and -6 dBm at 3 m distances to the transmitter (the TX power is fixed at 30 dBm).

VI. Conclusions

We have showcased a novel WPT system using wideband mmWave TXs and rectennas. The system was innovatively enabled by a new type of beam scannable and beam-formable millimeter waves, which were passively steered by exploiting the frequency dispersive nature of leaky wave antenna. We have proposed a highly efficient mmWave wideband rectenna (24-34 GHz, and an overall 50% conversion efficiency) to harvest the frequency diverse power beams radiating from the LWA transmitter. Such a radical combination has significantly reduced the cost, loss and complexity of conventional technologies that rely on phased array and other active components. Moreover, we have demonstrated the multi-node tracking by controlling the multi-tone modulation of mmWave signals via the feedback beacon signal and rectenna DC monitoring.

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