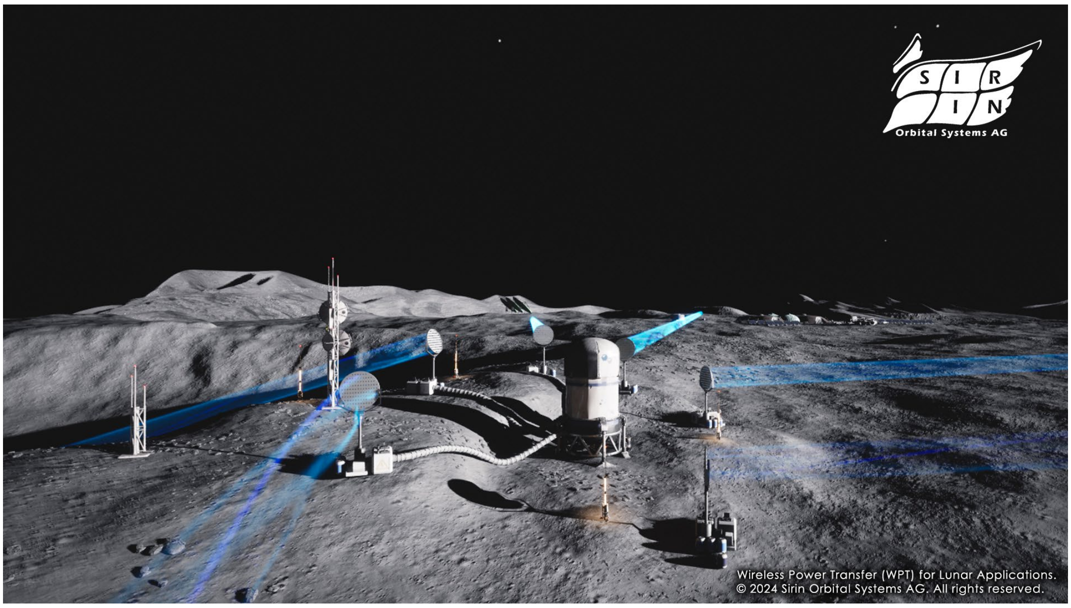


Development of Millimetre Waves Wireless Power Transfer (WPT) System for Lunar Rover Explorations: mmWaves WPT

Executive Summary Report (ESR)

Early Technology Development

Open Space Innovation Platform (OSIP) campaign, "New Ideas for Solar Power from Space"

Affiliation(s): ***Sirin Orbital Systems AG (Prime, CH), Lucerne University of Applied Sciences and Arts HSLU (Sub 1, CH)***

Activity summary:

This activity aimed at design and preliminary development of a millimeter waves – 35GHz – Wireless Power Transfer (WPT) system for lunar rover explorations. The project focused on the development of key enabling technologies – i.e. transmitting antenna that enables high transmission efficiency, efficient rectenna, and efficient microwave amplifier on the transmitter side that is suitable for use in space – for wireless energy transmission from a fixed station to a vehicle. A rover-like vehicle on the surface of the moon was assumed for the definition of the system parameters.

Publishing Date: **30.06.2024**
Contract Number: **4000135862**
Implemented as ESA EXPRESS PROCUREMENT – EXPRO

→ THE EUROPEAN SPACE AGENCY

ESA Discovery & Preparation
From breakthrough ideas to mission feasibility. Discovery & Preparation is laying the groundwork for the future of space in Europe
Learn more on www.esa.int/discovery
Deliverables published on https://nebula.esa.int

Development of Millimetre Waves Wireless Power Transfer (WPT) System for Lunar Rover Explorations

Abstract

The space-based generation of solar power and wireless transmission to the load require special solutions. Microwave technology offers itself as a key technology. The mm-wave range in particular is an attractive alternative for mobile applications, as the selected frequency has a direct influence on the size of the transmitting and receiving antennas. As part of the project, various methods and technologies were analysed and preliminary system architecture concepts were developed. Furthermore, the advantages and disadvantages of a phased array antenna solution for the generation of a flat-top beam were analysed. As heat can only be radiated in space to a very limited extent, electrical losses in the various systems must be avoided as far as possible. In order to achieve this in the phase shifter, a waveguide-based, mechanical variant was developed. A WPT demonstrator was used to demonstrate the feasibility of energy transmission using a 35 GHz radiolink. A rectenna array with more than 1000 individual rectifier circuits was designed and manufactured for this purpose.

Index Terms

Wireless power transmission, beam forming, phased array, rectenna array, rectenna, mm-waves

1. Introduction

With his work in the 1960s, Goubau worked out the essential relationships of power transmission in the radiating near field [1]. Based on his work, various microwave WPT experiments were carried out in the 2.4GHz frequency range. In the "Goldstone experiment", for example, 30kW DC power was transmitted over a distance of 1.5km [2]. In all these experiments, parabolic reflectors or horn radiators were used as transmitting antennas. There have been more recent microwave WPT contributions, mostly in the frequency range at 2.45GHz or 5.8GHz. Applications include wireless charging of cars, vans and drones. The transmitting antennas used are phased arrays, which enable beamforming with the aim of generating a uniform power density distribution at the receiver. The distances between the transmitter and receiver were between 1 and 6.5 metres. The array sizes ranged from 6x6 to 42x42. In the last ten years, technology development for WPT has been intensified, particularly in Japan, South Korea, China and the USA. The successful demonstration of a WPT experiment took place in 2015 after a six-year construction period. Four phased array panels were used to emit a power of 1.8kW at a frequency of 5.8GHz. The rectified power at a distance of 54m was 340W [3].

2. Wireless power transfer in the radiating near field

The electromagnetic field of an antenna can be conceptually divided into a near field and a far field. In the near field of an antenna, the electromagnetic field is described by spherical waves and the field components present depend on the type and structure of the antenna. The individual field components decay to varying degrees with increasing distance from the antenna. At a sufficiently large distance, only an E-field and a B-field component of the radiated field remain. This is referred to as the far field. A high degree of efficiency for wireless power transmission can only be achieved in the radiating near field. The transmission efficiency depends on the geometric mean value of the aperture area A_t of the transmitting antenna and the aperture area A_r of the rectenna at the receiving location. It can be described with the Beam Collection Efficiency BCE.

$$BCE = 1 - e^{-\tau^2} \tag{1}$$

where the parameter τ represents this geometric mean, normalised by the wavelength λ and the distance D.

$$\tau = \frac{\sqrt{A_t A_r}}{\lambda\, D} \tag{2}$$

A_r: Total area of the receiving antenna

A_t: Total area of the transmitting antenna

λ: Wavelength

D: Distance

If the value of τ is greater than 2, then the BCE is close to 100%. Goubau showed that the optimal beam has spherical phase fronts at the transmitting and receiving locations with a radius of curvature that corresponds to the distance D. The power density distributions p_t and p_r over A_t and A_r are shown in Figure 1 for circular apertures and for different values of τ. The distribution functions are identical at the transmitting and receiving locations, only the scales along the abscissa differ.

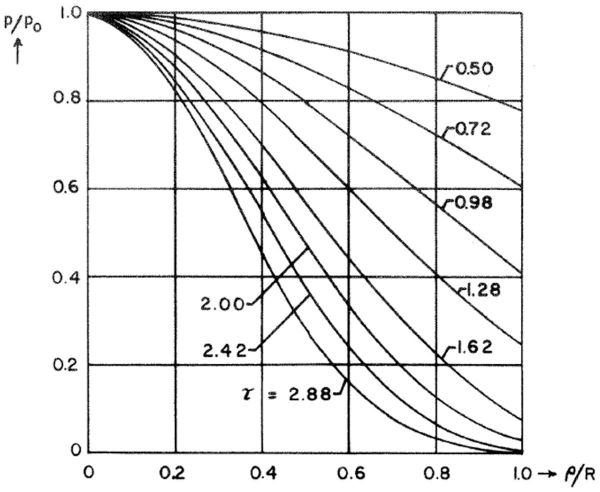


Figure 1. Relative cross-sectional energy density distribution in a beam with optimum field distribution at the transmitting antenna (p/p_{t0}, ρ/R_t) and at the rectenna (p/p_{r0}, ρ/R_r) for various values of τ. ρ is the radial distance from the center of the antenna, R_t and R_r are the corresponding aperture radii. [1]

3. WPT System Overview

The wireless power transfer system can be broken down into several sub-function blocks in a system view. A possible system concept is shown in Figure 2. The interfaces at the system boundaries, reference points A and E, is the power transfer in the form of a direct current. The function block "mm-Waves Power Source" represents the conversion between the direct current power and the high frequency power. Reference point B describes the high-frequency interface to the "Beam Shaping" function block. This subsequent block enables the optimisation of the power transmission on the transmitter side by influencing the directional characteristic of the antenna. The function block "Array Antenna" comprises a single or multi-element antenna structure and a suitable feeder network for it. The reference point D represents the wireless interface. The function block "Array Rectenna" enables the reception of the high-frequency power and converts it into a DC power. Ideally, this block also provides information to the controller regarding optimisation of the power transmission on the receiver side. The "System Control" function block enables and controls the operation and optimisation of the system's power transmission. The interfaces Fn describe the control flows between the individual function blocks and the control system.

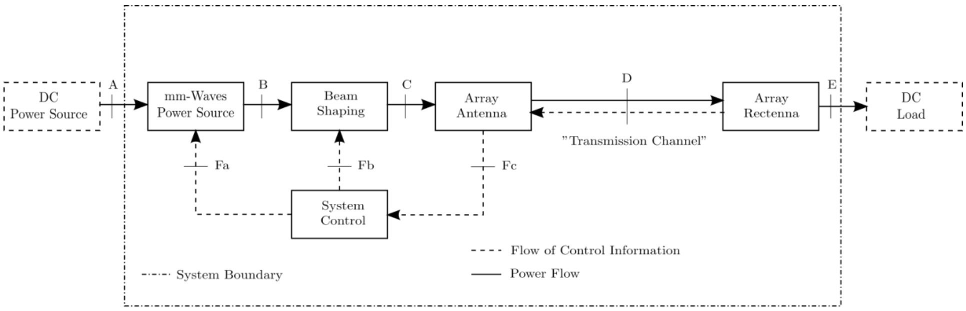


Figure 2. System Concept

The system parameters in Table 1 served as the starting point for the project.

Table 1: System parameters of the mm-waves wireless power transfer system.

Parameters	Symbol	Unit	Value	Remarks
Frequency	f	GHz	24/35	-
Transmitting antenna aperture	A_t	m	2	Diameter
Distance	D	m	100	-
Rectenna aperture	A_r	m	1	Diameter
Transmission power	P_t	kW	1.3	-
Transmission efficiency	BCE	%	75	Beam collection efficiency

Section 2 showed that efficient power transmission in the near-field range leads to a non-constant power density distribution. If the receiver is realised with a rectifier array, the individual rectifier systems would receive different input powers. This leads to greater complexity in the implementation. A constant power density distribution at the receiver location in the form of a flat-top beam would therefore be ideal. For mobile applications, it would also be advantageous if the beam could be focussed within a certain distance range and electronically deflected.

4. Beam forming using a phased array antenna

The Fourier transform provides an analytical relationship between an array excitation and the beam pattern. In 1D, since the pattern in this case is a rectangular function, the Fourier transform is known by the $sinc$ function. To ensure that the beam is always focussed on the receiver and delivers a constant power, two aspects must be controlled: the beam width and the beam amplitude. Two parameters τ and α are introduced to control the beam width and amplitude. For a desired beam width bw, the sine excitation coefficients can be expressed as follows:

$$a_n = \alpha(bw)\,\tau(bw)\,\mathrm{sinc}\left(\tau(bw)\left(n - \frac{N+1}{2}\right)\right), n \in [1, N] \quad (3)$$

Here, τ is the parameter with which the width of the sine function can be varied and α controls the amplitude. Both are functions of the desired beam width. N is the number of array elements. Given a 2m Tx antenna array (N=333) and a 1m rectenna, for variable transmission distances of 20 to 100m, the $tau(bw)$ function can be found empirically as follows [4]:

$$\tau(bw) = 0.7414bw + 0.028,\ \ bw \text{ in rad} \quad (4)$$

If the receiver moves closer to the transmitter, the beam width must be increased. At the same time, the beam amplitude must be reduced in order to keep the total power in the beam constant. This determines the parameter $\alpha(bw)$.

$$\alpha(bw) = \frac{\alpha_0}{\sqrt{bw}} \quad (5)$$

Here, α_0 is a constant that can be selected to set the beam amplitude/power to a specific value. Figure 3 shows the resulting excitation coefficients and beam patterns for distances of 100m and 20m.

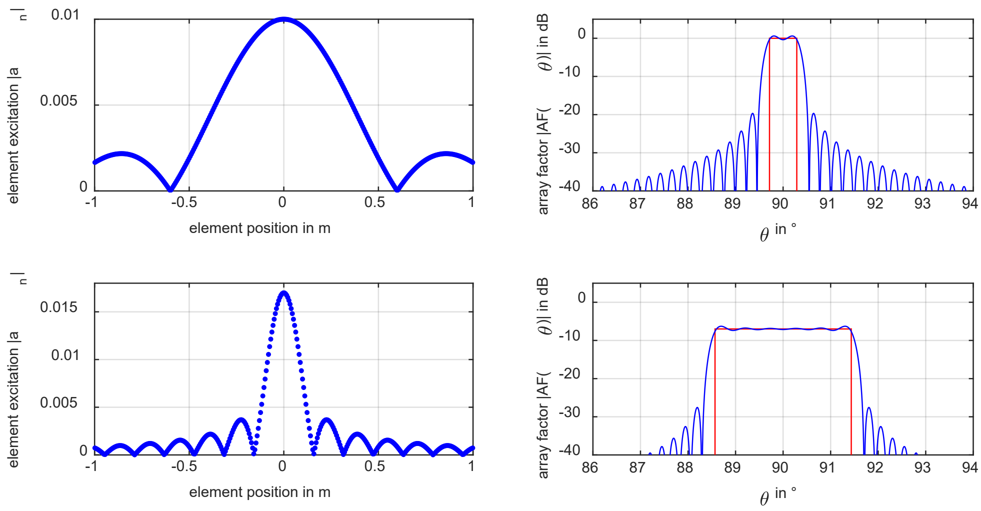


Figure 3. Array excitation and beam pattern for different receiver distances at 100m (top) and at 20m (bottom).

Creating a 2D pattern can be done in different ways. The straightforward way is to build a rectangular NxN planar array of antenna elements by placing N linear arrays of size N next to each other. Each linear array is excited with the 1D excitation patterns and across the linear arrays the amplitude of each array is multiplied by the excitation pattern again. This method is simple and allows to extend 1D patterns to 2D. The concept and formulas are elaborated in [5]. In the resulting 2D pattern, the original 1D pattern can be found on the x- and y-axis. The values in between the axis are defined by the multiplication of the x- and y-pattern. They therefore do not exactly match the 1D pattern.

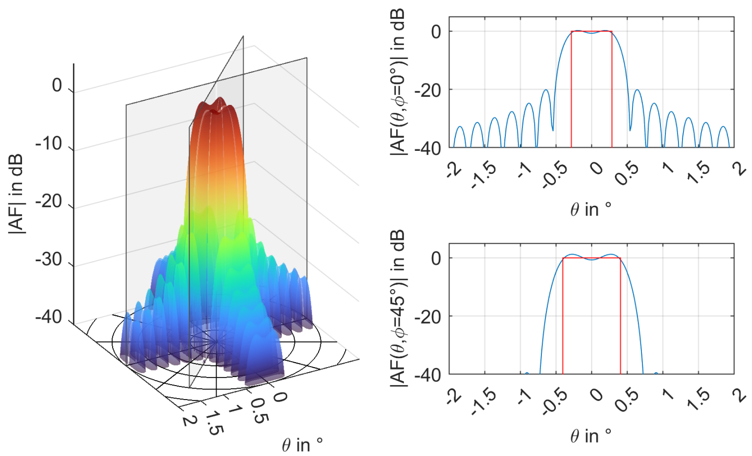
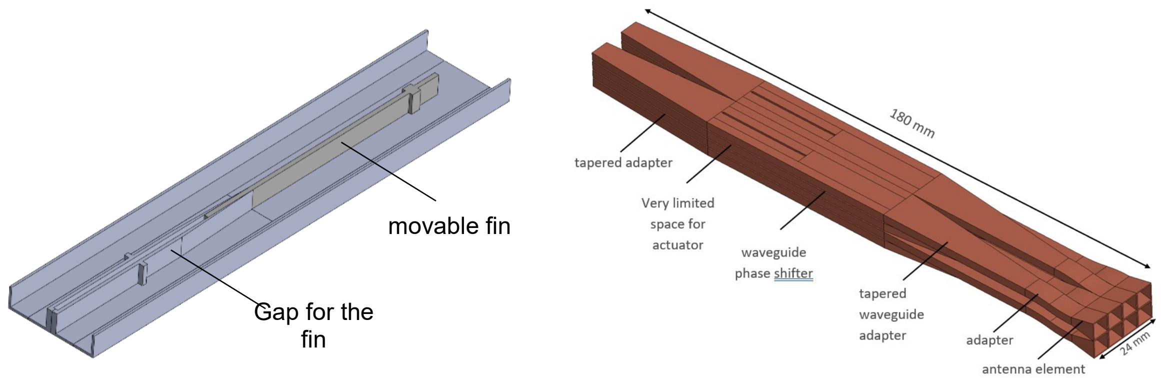


Figure 4. Cuts of the 2D pattern at ϕ=0° (along the x-axis) and ϕ=45° (diagonal between x- and y-axis).

5. Precise and efficient phase shifter

Phase shifter elements are required to electronically control the alignment of the main beam of a phased array antenna. There are various solutions for phase shifters, whereby a mechanically adjustable solution in the waveguide system directly in front of the radiating element best fulfils the requirements in terms of efficiency and accuracy. The mechanical structure of the phase shifter is shown in Figure 5. The adjustment of the fin requires a low-power drive mechanism. In order to guarantee the required phase resolution of 10°, a mechanical manufacturing tolerance of +/- 35um must be maintained [4]. The space in the array configuration is very limited. The distance between the individual antenna elements is 0.7λ, which also determines the dimensions for the phase shifter.



a) Mechanical phase shifter, shown without cover.

b) Each phase shifter feeds one antenna. This solution enables a scanning range of +/- 20°.

Figure 5. Mechanical phase shifter with sliding fin.

A suitable actuator must be used to bring the fin of the phase shifter into the desired position. The power consumption of the actuator may only be a few μW, as the phased array antenna system contains more than 100,000 individual antennas. The effective power dissipation ultimately depends on the frequency of phase control and the necessary switching speed. Such demands on power consumption, as well as the limited space available, require a micro-electromechanical system (MEMS) as a linear drive. The mode of operation of the phase shifter can be illustrated with the aid of Figure 6, which shows the distribution of the electric field. If the length of the fin is increased, fewer waves fit into the waveguide section between the input port and the output port. The propagation delay is reduced. This is because the wavelength of the TE01 mode increases in the smaller waveguide cross-section in the area of the fin. The opposite happens when the length of the fin is reduced. More wavelengths of the mode fit into the waveguide section and therefore the propagation time between the ports is increased.

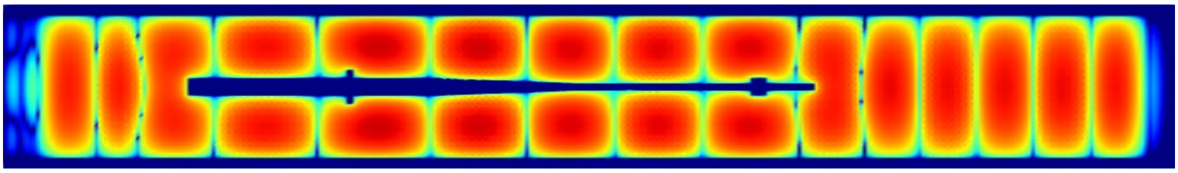


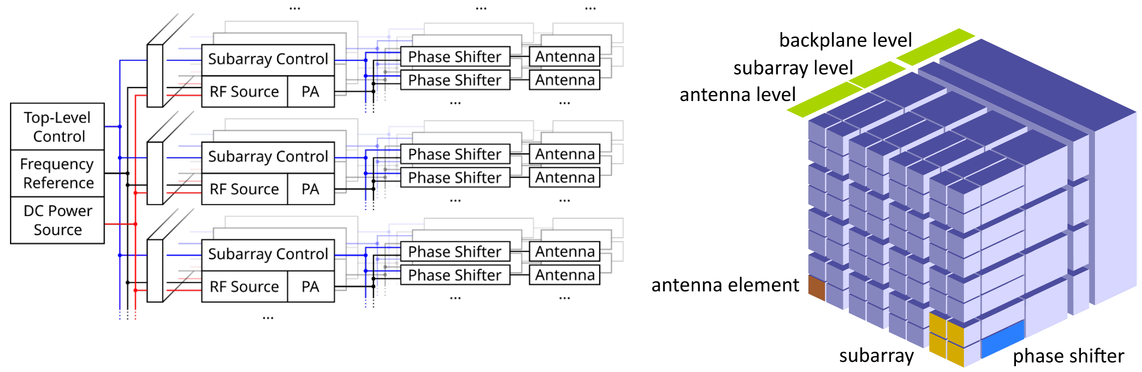
Figure 6. Electric field distribution across the waveguide phase shifter ($\boldsymbol{TE_{10}}$ mode).

6. Possible Structure of the transmitting antenna system

The system is built and controlled in a hierarchical structure from top (control & source) to bottom (antenna element). Three hierarchy levels exist:

- Backplane level: Top-Level Control, Frequency Reference, DC Power Source
- Subarray level: Subarray Control, RF Source, Power Amplifier
- Antenna level: Phase Shifter, Antenna Element

Figure 7 shows a symbolic drawing of the 3D structure of the transmitter antenna system with three hierarchical levels (size and number of elements were chosen for visualisation purposes).



a) System control concept

b) 3D structure of transmitter antenna system (symbolic drawing)

Figure 7: System control concept

To summarise, the simulated system for a phased array antenna as a transmitting antenna includes the following characteristics:

Table 2: Performance of the simulated transmitting system

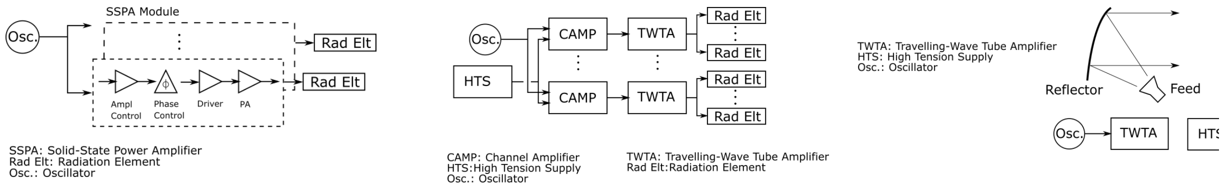
Parameters	Simulation results	Remarks
Frequency band	35GHz	
Antenna element distance	0.7 λ	
System size	<2 m.	
WPT distance	20-100m	Distance range for focussing the beam
Beam collection efficiency (BCE)	>76% unscanned, >70.8% scanned to 20°	
Beam scan angle	±20°	±3° with a single phase shifter for two antenna elements
Phase control	Phase control on element level required.	for a scanning range of +/- 20°
Scan angle resolution	the beam shaping system scan angle resolution is <0.01°, using a 11.25° phase resolution.	
Phase shifter resolution	<0.5°	
Beam width	0.573° ≤ beam width ≤ 2.86°	over the distance range of 100m...20m
Amplitude control	Amplitude control is required on a subarray level only.	
Beam uniformity	≤1.06 dB with 16x16 subarrays.	

7. Transmitter-side Architectures

Based on the results obtained, three different preliminary architecture concepts were described for the transmitter side.

Concept: "Maximum functionality"

This concept includes a phased array with more than 100,000 individual elements as a transmitting antenna. As a coherent system, it promises maximum functionality such as electronic beam steering, possible focussing of the beam on a distance range and a synthetic beam shape for a flat and sharply defined power density distribution at the receiver location. In order to realise this, individual amplitude and phase control as well as power amplification must be provided for each antenna element. However, the available space behind the individual antenna element is so small that an application-specific monolithic microwave integrated circuit (MMIC) would have to be developed for the electronics. The control of the mechanical phase shifter also requires a MEMS solution.



Concept: "Maximum functionality" Concept: "Sub-arrays with TWTA modules" Concept: "Moderate complexity"

Figure 8: Transmitter-side Architectures

Concept: "Sub-arrays with TWTA modules"

The solution includes a phased array antenna with more than 100,000 individual elements. If electronic beam steering and beam focussing over different distances is dispensed with, the phased array antenna can be realised with 400 sub-arrays of size 16x16. This variant allows the realisation of a flat-top beam. The space available behind a sub-array allows electronic solutions to be realised with commercially available components. The use of MEMS actuators for the phase shifters can also be avoided. Commercially available travelling wave tube amplifier (TWTA) modules could be used for power generation. As such a power module would be operated close to or in the saturation range in favour of higher efficiency, it would be necessary to implement phase correction on the output side. Otherwise, the beam shaping would be lost.

Concept: "Moderate complexity"

The system complexity on the transmitter side is greatly reduced if a reflector or lens antenna is used. In contrast to previous concepts, only one antenna element is used. The provision of a power density distribution at the receiver is therefore no longer achieved by superimposing different field components provided by individual antenna elements. This also eliminates the need for complex amplitude and phase control for a coherent antenna system. It would be a system as described by Goubau. The microwave power can be provided with TWTA modules or SSPA modules. As TWTA modules for the frequency range of 35 GHz are not available in the kilowatt range, the power of several modules must be combined via a waveguide combiner.

Table 3: Comparison of the three concept variants

	Concept variant		
Subject	**Maximum functionality**	**Sub-arrays with TWTA modules**	**Moderate complexity**
Complexity in the realisation	Very high	High to very high	moderate
Beam forming	- Flat-top beam - Beam focussing over a distance range - Beam scanning possible	- Flat-top beam possible - Electronic scan and focussing functions not possible	- Electronic beamforming not possible ("Goubau system")

Power generation	- Customised for each individual element, may require MMIC design	- Own design for the sub-array amplifier (CAMP) with COTS components - TWTA COTS modules available - High-voltage generation possibly available as COTS modules	- TWTA COTS modules available - High-voltage generation possibly available as COTS modules - requires a power combiner

8. Rectenna Array

The architecture to be realised results from the task to be solved (antenna, impedance matching, rectifier, output filter and DC bus system). Depending on the existing power density distribution at the receiver, one or more receiving antennas can be combined via a feeder network.

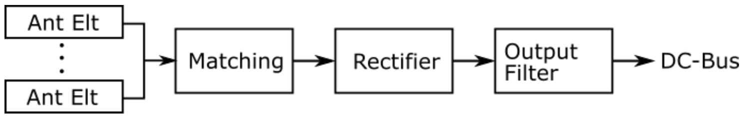
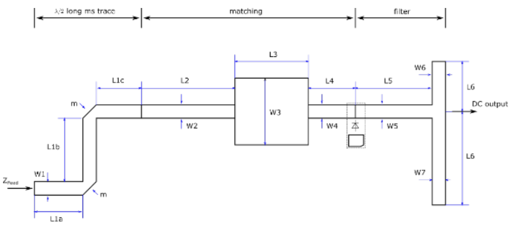
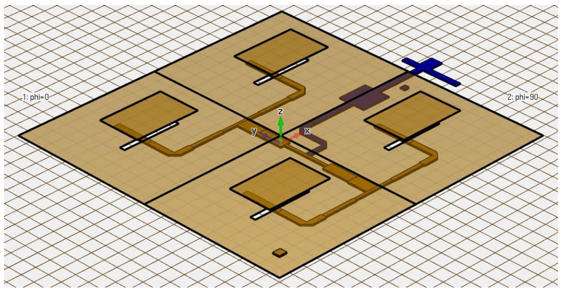


Figure 9. Block diagram of a rectifier on the Rectenna.

The rectenna array is not a coherent antenna, but consists of individual systems for receiving and rectifying the available microwave power. The DC output power of the individual rectifiers is combined sector by sector and converted to a desired output voltage using DC/DC converters. The rectifier circuit developed consists of a 2x2 patch antenna array and a Schottky diode. All other functions were implemented using microstrip conductor circuits.



a) Drawing of the rectifier circuit with microstrip conductor technology.

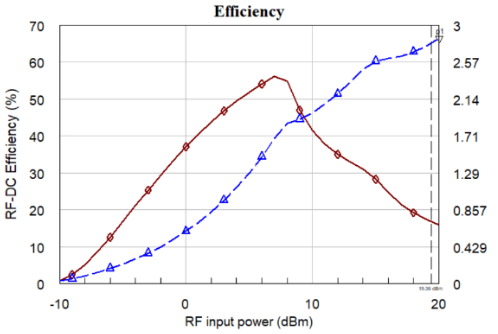


b) The layers with the substrate are not shown in the sketch.

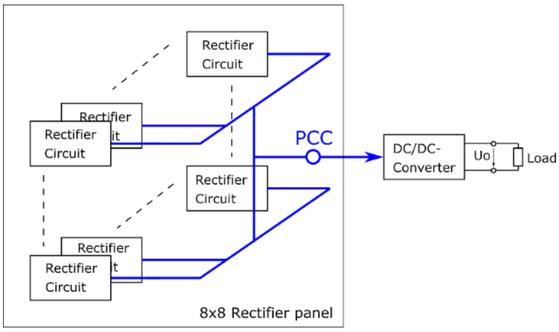
Figure 10. Rectifier circuit with receiving antenna.

The efficiency of the rectifier circuit essentially depends on the available input power and the optimum load. The developed circuit has an efficiency of 50% and better, if the input power is between 4...8dBm and a load of RL = 1000 Ohm is available.

For effective operation of the rectenna, the contributions of the individual rectifier circuits must be combined and made available to a load. A DC/DC converter is used to set the optimum load for the rectifiers at the common coupling point PCC on the input side. On the output side, a constant output voltage is provided for the load.



a) Rectifier efficiency with a load of 1000Ω



b) DC bus system for the power combination of the individual rectifiers.

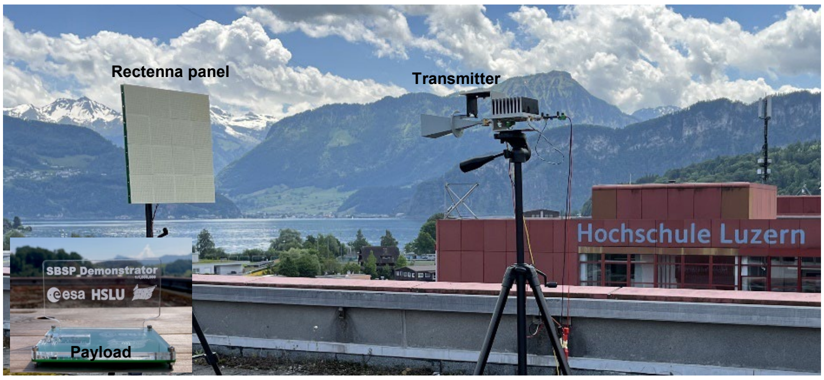
Figure 11. Rectifier circuit with receiving antenna.

9. mm-Waves WPT system demonstrator

A demonstrator was set up to show power transmission in the mm-wave range. A pyramidal horn antenna is used on the transmitter side, which generates a power distribution in the radiating near field as described by Goubau. On the receiver side, a rectenna consisting of 16 panels is used. Each panel contains 64 rectifiers. This allows individual panels to be connected in series or parallel so that the non-uniform power density distribution can be taken into account.

D1	C1	B1	A1
D2	C2	B2	A2
D3	C3	B3	A3
D4	C4	B4	A4

a) Front view of panel labelling.



b) Top view of the rectenna panel designation for the measurements.

Figure 12. Rectifier circuit with receiving antenna.

The efficiency was measured on a single panel with 64 rectifiers and compared with the simulation result. A transmission power of 2W was available in the laboratory for this purpose. The measurements yielded a result that was a factor of 2 lower than the simulation values (Figure 12). The measurement results of the individual panels are shown in the Table 4.

Table 4: DC output power for different ohmic loads on the panels.
The distance between transmitter and rectenna was 1m and the transmission power was 2W.

	Unit	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4
Pdc	Ω	--	180	39	180	120	33	18	33	180	27	18	27	--	180	27	120
RL var.	mW	0	0.5	5.5	0.6	0.6	10.5	42.7	10.1	0.6	11.9	37.6	10.7	0	0.5	5.8	0.8
Pdc @ RL=18Ω	mW	0	0.2	4.0	0.3	0.3	9.7	42.7	9.3	0.3	11.6	37.6	10.6	0	0.2	5.6	0.4
Pdc @ RL=56Ω	mW	0	0.4	4.4	0.5	0.4	9.6	33.3	9.6	0.6	10.7	30.8	9.7	0	0.5	5.3	0.7

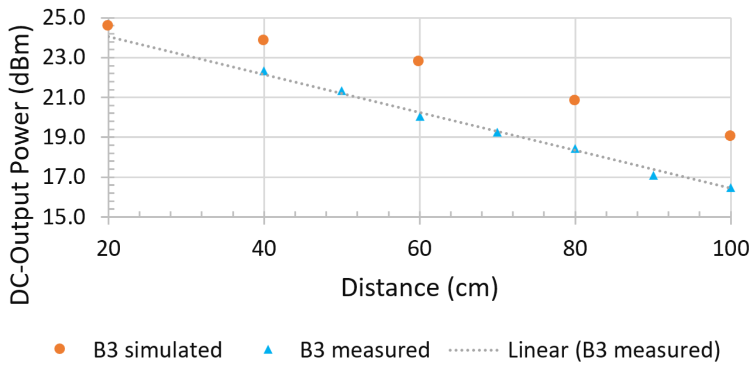


Figure 13. Comparison between the simulated and measured DC output power of a panel (P_t=2W).

The measured output power of the entire Rectenna was a factor of 3 lower than the simulated value.

Accumulated output power at...

- Optimum load RL variable: P_{dc} = 138.4mW
- Uniform load RL=18 Ohm: P_{dc} = 132.8mW
- Uniform load RL=56 Ohm: P_{dc} = 116.5mW

The simulated rectenna delivers a total power of P_{dc}= 440W with optimum matching and optimum loading of the panels. The measured DC output power of 138mW of the manufactured rectenna is considerably lower than the simulation result of 440mW. There are probably several reasons for this result.

- Impedance matching and efficiency calculation of the rectifier is based on the large signal equivalent circuit diagram of the diode, which may be too inaccurate.
- If the results of the individual panels are analysed, it is noticeable that only 6 panels of the rectenna out of a total of 16 panels contribute more than 10mW to the output power (Table 4). The current structure of the Rectenna with identical rectifiers across the entire surface is not ideal.
- The parallel connection of 64 rectifiers, which are driven differently, leads to a reduction in performance.

10. Conclusions

The aim of the project was to demonstrate the suitability of energy transmission in the mm-wavelength range for a WPT system used for experiments on the Moon. For efficient power transmission, such a system operates in the radiating near field. A phased array antenna on the transmitter side allows a flat-top beam on the receiver side. The rectenna array can then have a uniform structure. If a horn or parabolic reflector is used as the transmitting antenna, this reduces the complexity of the transmitter. However, the power density distribution on the receiver side is no longer constant across the aperture area. The Rectenna array would have to be set up non-uniformly in order to achieve better efficiency. The complexity is shifted somewhat from the transmitter side to the receiver side. Power transmission at 35 GHz was successfully shown with a WPT demonstrator.

References

[1] G. Goubau, “Microwave Power Transmission from an Orbiting Solar Power Station,” Journal of Microwave Power, vol. 5, no. 4, pp. 224-231, 1970.
[2] R. M. Dickinson, "Performance of a High-Power, 2.388-GHz Receiving Array in Wireless Power Transmission Over 1.54 km," in 1976 IEEE-MTT-S International Microwave Symposium, 1976.
[3] T. Takahashi et al., "Phased array system for high efficiency and high accuracy microwave power transmission," 2016 IEEE International Symposium on Phased Array Systems and Technology (PAST), Waltham, MA, USA, 2016, pp. 1-7, doi: 10.1109/ARRAY.2016.7832563.
[4] M. Joss et al., “mm-Waves Wireless Power Transfer System, Detailed design description,” Elect. Eng. Institute, Lucerne Univ. of Appl. Sciences and Arts, Horw, WPT-HSLU-1-1-Detailed design description Rep., 2022.
[5] C. A. Balanis, Antenna Theory - Analysis and Design, John Wiley & Sons, 2016.