TELSIKS 2017 Serbia, Niš, October 18 - 20, 2017

Near- and Far-Field Wireless Power Transfer

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Abstract— **This paper presents and overview of near and far-field wireless power transfer at RF and microwave frequencies for a variety of applications, ranging from near-field capacitive kW-level powering for cars in motion at MHz frequencies, to harvesting very low statistically-varying power densities (<1μW/cm²) across the microwave range and a study of directive beaming for space applications. In all applications, the primary consideration is both transmit and receive power efficiency, but at higher power levels, other factors such as safety regulations, become relevant and require new approaches. Specific examples are given for a near-field phased array at 6.78 MHz for vehicle powering, an airborn 4.3GHz harvester and a study for a microwave large array lunar directive beaming scenario.**

***Keywords*— wireless power transfer, energy harvesting, rectifier, antennas, rectennas, phased array.**

I. Introduction and Motivation

There are a number of reasons where wireless power transfer (WPT) is desired, ranging from high power levels to harvesting at very low incident power densities. Sometimes, the motivation is consumer convenience, such as charging of phones, which will always be lower-efficiency than a wired solution. In other cases, there are no other efficient alternatives, such as in the case of unattended sensors in environments with no reliable light and/or vibration, or for devices in motion. Fig.1 illustrates the various types of wireless powering found in practice and in the literature.

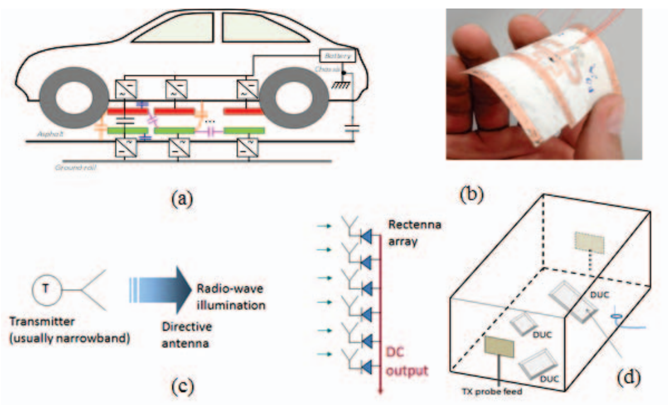

Fig.1. Illustration of different types of wireless power transfer: (a) near-field (inductive/capacitive); (b) far-field harvesting; (c) far-field beaming; and (d) over-moded cavity.

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Near-field WPT is usually implemented with inductive resonant coupling, via a loosely-coupled resonant transformer, one of many examples is given in, e.g. [1]. Some capacitive WPT has also been demonstrated, e.g. [2], and most of near-field powering is done in the 100kHz to a few MHz frequency range. In this paper we point to some advantages of capacitive powering specifically for vehicle charging in the ISM bands. Far-field non-directive low-power far-field harvesting has been advertised for powering IoT sensors, e.g. [3-9], as well as for directive power beaming, as in [10-13].

II. Near-Field High-Power VF WPT

Electric vehicles have a short range (at most 150km) compared to internal-combustion vehicles, resulting in the need for efficient charging, possibly in motion. So far efforts have been made to demonstrate wireless power transfer to electric vehicles using inductive power transfer, e.g. [14], and a few limited cases of capacitive power transfer, e.g. [2]. Capacitive WPT has several advantages over inductive WPT systems: (1) does not require the use of heavy and expensive ferrites for field concentration; (2) benefits from higher frequencies of operation since the capacitive reactance between the vehicle and the road is inversely proportional to frequency; (3) the displacement current corresponding to high power transfer requires a lower electric field at higher frequencies; and (4) sensitivity to misalignment is reduced.

Our goal is to demonstrate >10kW power transfer over a 12-cm gap between the car and road, using an area of less than 1m^2 with an efficiency greater than 90%. Fig.1(a) shows conceptually an array of large air-gap capacitors for powering a vehicle, either stationary or in motion. One of the plates is fed by a transmitter via a matching network is in the road, while the other is in the vehicle and delivers power to an array of rectifiers, which in turn charge the car battery, Fig.2.

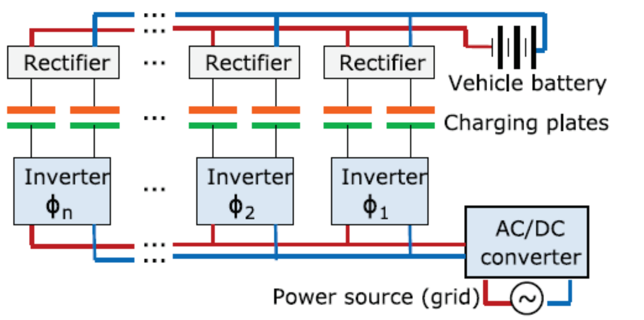


Fig.2. Block diagram of a multi-module capacitive WPT system, with receiving-side capacitor plates shown in orange, and road-side plates shown in green. Phase shifts are applied within the inverters in order to reduce the fringing fields.

Staying within specified safety limits for the electric and magnetic field magnitudes is a challenge [15], given the kW power levels. A distributed near-field phased array is a solution for reducing the field outside of the powering volume, while minimally affecting the desired high power density for WPT, as initially discussed in [16]. Fig.3 shows the setup with a single module consisting of 4 capacitor plates that complete a loop, and an aluminum sheet that represents the ground, while a second sheet that represents the vehicle is not present in the photo for visibility. The plot in Fig.3 shows measured and simulated E-fields for a two- and four-module system (8 and 16 plates) for in-phase and 180° feeding with a 100-W amplifier and the fields measured with an ETS HI6005 probe. Field reductions of 24% with a two-module system and 43% with a four-module system, at distances closer than 25 cm are observed at 6.78MHz. Full-wave EM simulations (HFSS) agree well with measurements and any deviations can be attributed to lack of modeling of the surroundings. Scaling the number of modules and frequency scaling to the 13 and 28-MHz ISM bands are currently under investigation.

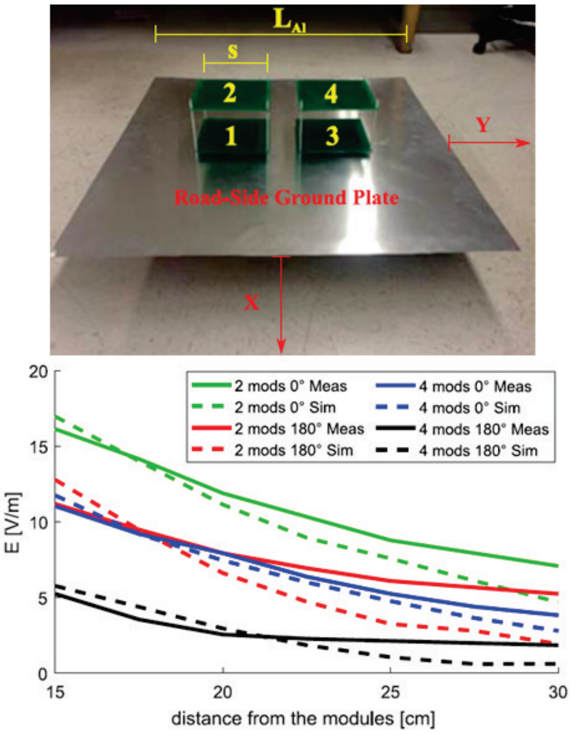
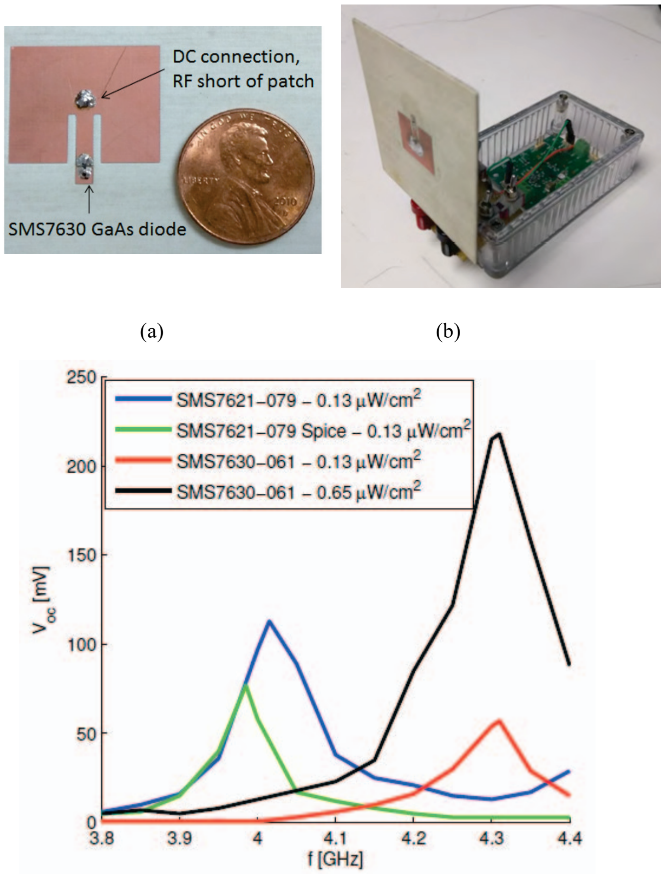


Fig.3. E-field measurement (solid) and simulations (dashed) at 7MHz as a function of distance along x axis for two modules (green and red), four modules (blue and black), and different phases.

III. Low-Power Density Microwave Harvesting

Wireless power harvesting is successfully applied to powering of low-power low duty cycle wireless sensors which are in places where other forms of energy are not available, such as inside walls, in pipes, in bodies, etc. [6]. The challenge in this case is to design an efficient compact rectifier-antenna (rectenna), since the incident power levels are in the μW/cm^2 range and insufficient to turn on a Schottky diode. An additional challenge is efficient power management in a variable-power multipath environment. Some harvesters target specific transmitters, such as cell-phone base stations or FM radio transmitters, e.g. [7.8]. Another application is harvesting power in the antenna sidelobes of a radar altimeter, since aircraft require external very low-power structural health sensors, and battery replacement is inconvenient. The altimeter transmitter operates in a narrow band around 4.2-4.4 GHz with 0.5 W. Measured radiation patterns show a reduction of power by -13 dB at 90° compared to 0°. This results in an estimated 2.2μW/cm^2 power density for a flush-mounted antenna in the proximity of the altimeter [17].

A 4.3GHz rectenna is shown in Fig.4(a), and is integrated with a power management circuit. The open-circuited voltage for different diodes is shown in Fig.4(c), and is boosted from ~200mV to 3V by an efficient TI BQ25504 ultra-low power boost converter in about 9 minutes. The harvester charges a 300-μF capacitor to 1.3mJ in this time, which is sufficient to operate dedicated sensors. The prototype in Fig.4(b) can charge either a 100 or 300μF capacitor, or provide power to a blinking LED to visually show when there is sufficient energy stored.



(a) (b)

(c)

Fig.4. Photo of rectenna at 4.3GHz (a) and the complete harvesting unit with power management (b). Measured open-circuited voltage for two diodes used in the rectifier at power densities <1μW/cm^2.

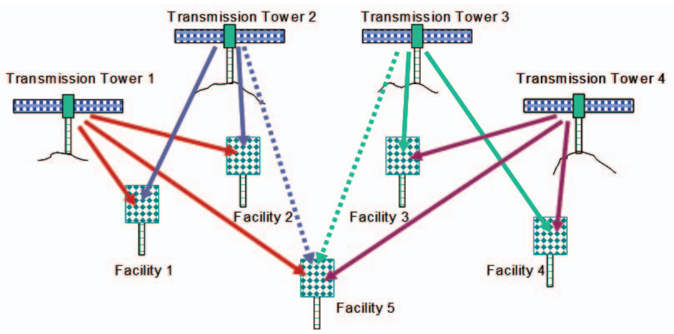
IV. Far-Field Microwave Beaming

Recently there has been a desire to establish a manned science base on the Earth’s moon. The main problem is the lack of water, although there is evidence that a crater on the

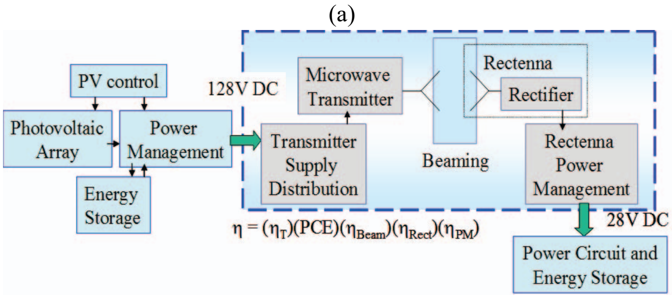
South Pole contains water in the lunar regolith. Water ice can survive in cold, permanently shadowed craters at the Moon's poles. For in-situ resources, it is desired to use lunar materials to produce oxygen and extract water with a robotic mission. In 2009, NASA LCROSS space probe detected a significant amount of hydroxyl group in the material thrown up from a south polar crater by an impactor. In 2010, ISRO's Chandrayaan-1 discovered more than 40 permanently darkened craters near the North Pole which are hypothesized to contain an estimated 600 million tons of water ice.

The process of water extraction requires electrical power. Since the ice can only survive in the shade, photovoltaics are not feasible in the crater; however there is continuous sunlight at the crater edge. NASA has developed a variety of light-weight PVs, including flexible Fresnel lens arrays [18] that are expected to scale to power levels greater than 1000 W/kg. Load stations are planned to be 0.5 to 2km away from mountain-tops where photovoltaic generation stations can be placed. Each site is expected to require 10kW of power, and if carried by cables, they would have a total mass of around 7,500kg, which very expensive to transport from Earth to the Moon. Additional drawbacks of cables include sensitivity to temperature, safety hazard for lunar operations, susceptible to solar flare induced transient effects, difficult to manage due to residual cable stresses, difficult to move in the event that a different facility needs to be powered.

Directive wireless power beaming becomes an alternative. The Moon has a radius that is 0.273 of the Earth's (R= 1738.14 km), resulting in a short line of sight and towers needed for the RF transmitters. Since there is no wind and the gravity is low, tall masts for increasing line of sight are feasible, as shown in the illustration in Fig.4(a).



(a)



(b)

Fig.5. (a) Configuration of power transmission towers and facilities receiving beamed power. (b) Functional diagram of the wireless power link. Each arrow represents a directional microwave beam. The length of the arrow is an indicator of the aperture size of that particular transmit antenna.

Directed WPT was first proposed by Nickola Tesla (U.S. patent No. 685,954, Nov. 1901) [19]. In 1961, Bill Brown published an article on WPT using microwaves, and in 1964 demonstrated the capability by powering a tethered subscale helicopter for 10 hours [20]. Fig.5b shows a high-level block diagram of a wireless power beaming system for one of the links. The DC power from the PV arrays is converted to microwave power by oscillators and an amplifier chain. Referring to Fig.5a, each transmitter needs to provide 12.5kW for the five 10-kW stations. This number will be increased by the reciprocal of the total system efficiency

$$\eta = \eta_T \cdot PCE \cdot \eta_{Beam} \cdot \eta_{\mathrm{Rect}} \cdot \eta_{PM} = \frac{P_{DC,in}}{P_{DC,out}}$$

where the efficiency definitions are given in the table below, with some references for state-of-the-art efficiencies:

Efficiency	Description	Max Demonstrated
$\eta_T = \frac{P_{RF,antenna}}{P_{DC,in}}$	TX DC-RF conversion efficiency	70-80% at 2-5GHz, GaN PAs
PCE	TX power-combining efficiency	80-90% [21]
$\eta_{Beam} = \frac{P_{RF,Trans}}{P_{RF,\mathrm{Rec}}}$	TX to RX beaming efficiency	About 80% for far-field [22]
$\eta_{\mathrm{Rect}} = \frac{P_{DC,\mathrm{Rectified}}}{P_{RF,\mathrm{Rec}}}$	Rectification efficiency	80% [23]
$\eta_{PM} = \frac{P_{DC,out}}{P_{DC,\mathrm{Rectified}}}$	Rectenna power management efficiency required to produce Vout	85-90% depends on power

For a given aperture size A_i assuming a beaming frequency f at which the free-space wavelength is λ, the required beam size d for a power beaming range *Rij* can be determined using the antenna theorem $A_i / D_i = \lambda^2 / 4\pi$, where *Ai* is the effective area of the antenna of transmitter i and *Di* the directivity. Assuming a 100% aperture efficiency, the half-power beamwidth of a symmetrical-beam antenna can be calculated approximately to be, in degrees from $Di=32{,}000/\theta^2$. For different power beaming ranges, the aperture size can now be estimated using

$$\tan\theta_{-3dB} = di / R_{ij} \Rightarrow 2di = aperture.$$

The following simple estimate can be used for beaming efficiency and determining the required aperture size. If the transmit and receive antennas are in each other's far field, one can define (from the Friis formula) a beaming efficiency as $\eta_{ij} = \frac{P_{Rj}}{P_i} = \frac{A_i A_j}{\lambda^2 R_{ij}^2}$, where the effective areas of the antennas are assumed to be equal to their geometric areas for this estimate. The distance *Rij* needs to be in the far field, and can be measured in terms of the free-space wavelength, which results in the following expression for the required aperture sizes as a function of desired beaming efficiency:

$$A_i A_j = \kappa_{ij}^2 \lambda^4 \eta_{ij}.$$

A more general beaming efficiency can be derived for the scenario in Fig.5a to be:

$$\eta_{ij} = \frac{P_{Rj}}{\sum_{i=1}^{4} P_{Ti} / \kappa_{ij}^2} = \frac{A_i A_j}{\lambda^4},$$

where the transmitted power is scaled by a unit-less number which describes the range measured in electrical distance (number of wavelengths). In the lunar surface beaming scenario, P_{Rj}=10kW, and Rij is constrained between 0.5km and 2km. The other parameters are allowed to vary and the results are plotted in Fig.6. In these two sample figures, the rectenna efficiency is fixed to 50% and 70%, respectively. The best reported rectenna efficiencies are around 80%. A study can now be performed to determine the best operation frequency in terms of array size and far-field distance, aperture efficiency, transmitter and receiver efficiency and cost. This study shows that frequencies between 2 and 5GHz have the best tradeoffs.

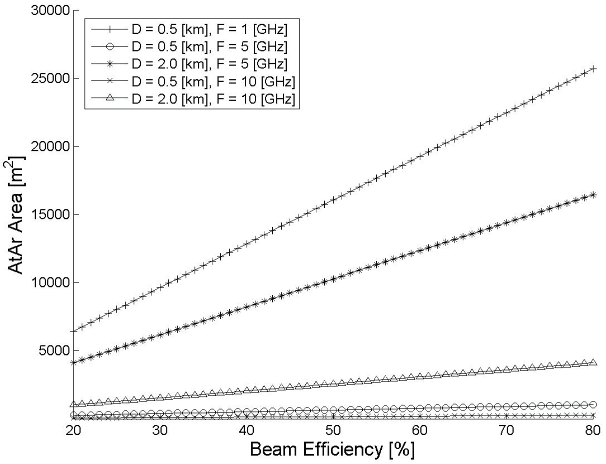


Fig.6. Example plot of product of transmit and receive apertures, in square meters, for 3 frequencies and 2 ranges (R=D=0.5 and 2km). The graph shows how the size varies as a function of beaming efficiency.

V. Summary and Conclusions

In summary, this paper presents an overview of techniques for near-field high-power capacitive WPT with field focusing, ultra-low power density harvesting WPT and high-power distributed beaming for space applications. It is found that in all of these diverse application cases, wireless power transfer has unique advantages and can be done efficiently and at a comparatively low cost.

Acknowledgment

This work was funded in part by Hudson Moore Jr. and Lockheed Martin Endowed Chairs and by Boeing, ARPA-E and the National Science Foundation. The author acknowledges contributions of her graduate students Dr. Joe Hagerty, Jose Estrada, Sean Korhummel and Prof. Khurram Afridi, all at the University of Colorado, Boulder.

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