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WIRELESS POWER TRANSMISSION TECHNOLOGY: BASICS, FREQUENCY CHOICES AND ISSUES

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ABSTRACT

Wireless Power Transmission (WPT) is the Engineering Art of safely and economically transporting energy without wires. Focused electromagnetic radiation issued from Beamers and captured and reconverted by Rectennas at microwave frequencies or band-gap matched photovoltaics (PV) at shorter wavelengths are the currently preferred manifestations of the art.

For high power transfer efficiency, the Beamer must have a particular truncated Gaussian tapered aperture distribution and must be focused on the receiver with the product of the aperture sizes commensurate with the product of the wavelength and the beaming range.

The optimum WPT frequency depends upon the propagation medium and other characteristics of the system. Lasers are preferred for space-to-space links while cm-wavelength microwaves are best for traversing the Earth's atmosphere, due to gaseous absorption and atmospheric meteor scattering of the shorter wavelengths.

and electronics, electromagnetic compatibility, beam right-of-way, cost and affordability. Careful engineering and public outreach are ways to mitigate these issues and bring the benefits of WPT to various beamed power applications for the benefit of society.

INTRODUCTION

Wireless Power Transmission (WPT) uses focused electromagnetic waves to transfer energy from one location to another.[1,2] Generally the input energy to the WPT system is in the form of an electric current, either AC or DC, which must be converted to microwave (on the order of 10 cm wavelength, or 3 GHz frequency) energy or to energy at laser wavelengths (order of 1-micron, 10^{-6} m or less wavelength). This conversion is necessary to permit reasonable sized focused apertures to efficiently beam the energy to the receiving equipment, and for low-loss through the intervening propagation medium.

The receiving equipment is designed to capture a large fraction of the beam and to then convert it to DC current. The DC may be subsequently converted to AC at the local mains frequency (Typically 50 or 60 Hz).

The beamed energy essentially travels in a straight line-of-sight in vacuum, except for the possible uses of reflecting mirrors. There is some slight bending of the rays in the atmosphere however.

A figure of merit of a WPT system is the installed system cost per the product of unit of power and unit of range, for example \$/MW-km.[3,4] For 10's of km ranges and 100's of MW, the current FOM is about two orders of magnitude larger than wired power (open wire lines , cables or waveguides), due to the WPT systems immaturity. However, as stratospheric and space based WPT applications burgeon, WPT technology will mature and costs will drop.

In addition to transporting energy from the sun, energy in the electromagnetic spectrum is used for many services such as radio and TV broadcast, radars, fixed and mobile telecommunications, navigation aids, space communications, Radio Science, etc. WPT has no defined service as such under the International Telecommunications Union (ITU) definitions, but radiating power for commercial purposes is permitted at certain frequencies within designated Industrial, Scientific and Medical (ISM) bands in the US and other countries. Currently laser frequencies or wavelengths are not similarly allocated, but may be in the future.

Beam safety is a primary concern of WPT system engineering in that most beams are invisible to humans and thus at certain power flux density (PFD) levels present a real potential threat to humans and their equipment. Beam interruptions must be tolerated and designed into the WPT systems. Therefore, potential beam intrusion detection and mitigation strategies and techniques are required for personnel and equipment safety.

In the following sections we will discuss WPT technology basics, frequency choices and issues.

BASIC WPT TECHNOLGY

The physical laws of diffraction play a key part in WPT systems. Diffraction manifests itself in the inevitable spreading of a beam of electromagnetic energy as it propagates. In order to efficiently focus and collect a significant fraction of a radiated beam of energy, the diameter of the aperture of the antenna, phased array or telescope must be large when measured in wavelengths. At long ranges and for beams focused at infinity, the beam spread angle is proportional to the wavelength divided by the diameter, (λ/D). Since we are not interested in transmitting energy to infinity, but to a finite range, R, we actually must focus the beam at the receiving target range. A converging spherical phase front beam is desired[5].

Aperture Energy Distribution

In addition to launching a beam of energy with a spherical phase front, the beamer aperture distribution of energy density must be properly shaped. A truncated Gaussian beam shape is required, with the energy density peaked in the center and decreasing in a controlled fashion toward the edge of the aperture. The ratio of the power density at the aperture edge to the on-axis density is termed the taper (or apodization). Its value is determined by the desired beam-coupling efficiency, the ratio of the energy launched to that captured, as given in the reference cited above.

Tapering the aperture distribution reduces the beam sidelobes and places that energy in the mainbeam, but at the expense of a wider beamwidth. However, this action is necessary in order to promote high beam coupling efficiency.

As a consequence of the tapered aperture transmitting beam, the distribution of energy density across the receiving aperture is also similarly tapered. Achieving the required tapers affects the WPT system efficiency because the effectiveness of energy generation, distribution and collection varies as a function of power density.

A net result of the tapered apertures is that from an engineering economics point of view, there exists an optimum aperture efficiency depending on the WPT system design. That is, at some diameter, the marginal return on making the apertures any larger is not justified. The WPT system design is therefore dependent upon the price of the energy delivered and the areal cost of the transmitting and receiving apertures.

Additional fixed WPT costs are the cost of the beam safety system and the energy storage to permit beam interruptions, depending on the quality of service (QOS) to be provided. The cost for baseload, non-interrupted, high QOS power delivery is high, because of the energy storage necessary for the maximum credible beam safety outage time.

For long range WPT systems, the propagation lag-time for the "power-in-the-pipe" must be considered when a beam interruption is necessary. That is, the slug of power radiated between the time of potential intrusion detection and the time of actual beam shutoff is uncontrollable and will inevitably proceed from the beamer toward the receiver.

A key consideration for purposes of efficient WPT propagation is the frequency of operation of the beamer and receiver.

FREQUENCY CHOICES

The choice of frequency for WPT as dictated by basic physics is dependent upon the propagation medium and the diffraction law. For efficient, low-loss propagation, the wavelength should be large compared to scattering objects therein. Therefore, for beams traversing the Earth's atmosphere, wherein clouds, fog, hail and rain are encountered, the microwave frequencies are first choice, and due to the gaseous absorption bands caused by oxygen and water vapor, the frequencies below about 10 GHz are most desirable as shown the Figure. The lower end of the desired frequencies is set by the increasing size of the Beamer in order to achieve a large diameter in wavelengths.

Similarly, for free space propagation, the desired frequency is as high as the technology will allow efficient energy conversion and the cost effective construction, maintenance and precise pointing of accurate surfaces.

Frequency Allocations

The choice of operating frequency is however, not solely determined by the laws of physics. Existing holders of frequency allocations that are currently agreed upon by international treaties are reluctant to admit new users unless it its to their economic interest.

Thus, in a chicken-and-egg situation, existing spectrum users are reluctant to share or part with their allocation until WPT is shown to be economic, and WPT will have difficulty showing it is economic if it cannot use near optimal frequencies.

In this constraint then WPT experimenters and prototype system builders are using the ISM-band frequencies, which are not prohibited from radiating power for commercial uses[6].

Spectrum Width

How narrow in spectrum bandwidth can a microwave power beam be? If no modulation is purposefully applied, klystrons have been able to yield spectrum widths that are quite narrow[7]. The fundamental frequency, close-in carrier phase noise for a 7.167 GHz 20kW CW klystron, with well regulated power supply and thermal control, was measured at –25dBc/Hz at 0.01 Hz offset from the carrier, -70dBc/Hz at 1 Hz, -90dBc/Hz at 100 Hz and –100dBc/Hz at 10kHz. Thus, a well controlled power beam can be very narrow in spectral width at the fundamental frequency.

Harmonic Frequencies

Another fundamental physics law that applies to WPT is that in order to efficiently convert energy from one form to another, harmonics of the fundamental will be produced. In order to assure electromagnetic compatibility (EMC), the harmonics attendant to WPT operations must be suppressed from radiating at levels that would result in interference to other spectrum users. Thus, filters will be needed at both the beamer transmitters and the rectennas, unless the WPT frequencies could be harmonically related.

In the absence of such a desirable state of affairs, the decision of the exact frequency for a particular WPT application should also involve where, in the spectrum, the harmonics would lie, in order to minimize interference. For example, the primary emissions from microwave ovens in the S-Band ISM Band of 2.4 GHz to 2.5 GHz lie in the band from 2.42 to 2.48 GHz. If we select these frequencies as the range within which we desire to put an SSP for example, the harmonic frequencies would lie in the following spectrum allocations in the USA. The data is derived from the admittedly out-of-date cited reference, but useful as an example of the consideration attendant to a WPT frequency selection[8]. Only the first ten harmonics will be discussed for both the S- and C-ISM-Bands in this example.

Constrained S-Band ISM Example

The second harmonics from 4.84 to 4.96 GHz would encompass the Primary US Government Fixed and Mobile band of 4.8-4.99 GHz, which has Non-government use for Radio Astronomy, in particular, the 4.82966 GHz Formaldehyde line in interstellar clouds, would be adjacent. A footnote, US74 states among other considerations, that in the Receive Only band 4.99-5.0 GHz (also adjacent to our SSP 2nd harmonic in this example) ..."the radio astronomy service shall be protected from extraband radiation only to the extent that such radiation exceeds the level which would be present if the offending station were operating in compliance with the technical standards or criteria applicable to the service in which it operates."

The third harmonics of frequencies from 7.26 to 7.44 GHz could impact a portion of the Defense Satellite Communications System (DSCS) downlink frequencies at 7.25-7.75 GHz, in these Federal Fixed and Space bands.

The fourth harmonics at 9.68 to 9.92 GHz would lie in bands for space radars and military aircraft, including the Space Station 9.5-9.8 GHz radar assignment.

The fifth harmonics at 12.1 to 12.4 GHz lie in Ku-Band fixed satellite downlink bands, in particular the popular DirectTV and PrimrStar.

The sixth harmonics at 14.52 to 14.88 GHz encompass part of a military, NASA data relay and aviation band. 14.59 to 15.25 is TDRSS uplink, and the shuttle communicates with TDRSS in the 14.7145 to 15.1365 band of frequencies.

The seventh harmonics at 16.94 to 17.36 GHz lie in bands that are for NASA and military radars and active microwave sensors, and uplink feeders for the Direct Broadcast Satellite (DBS) service.

The eighth harmonics at 19.36 to 19.84, lie in bands for multi-purpose satellite downlinks.

The ninth harmonics at 21.7 to 22.32 GHz fall into the21.2-23.6 GHz general-purpose band for private, public and government uses. Uses are phone bypass, aviation links, broadcast operations and satellite water vapor measurements at the 22.235 GHz line.

The tenth harmonics at 24.2 to 24.8 GHz lie in bands for Government and amateur radiolocation , active Earth exploration satellite uses, airport surface detection equipment (ASDE) radars, and intersatellite links, among other uses.

In some cases, a monochromatic spectrum line could probably be tolerated, in others, perhaps not. An individual service by service study with detailed equipment susceptibility knowledge would be required to answer the potential interference questions accurately.

<u>C-Band ISM Harmonics Example</u>

Switching to the C-Band ISM band of 5.725-5.875 GHz, the second harmonics at 11.45-11.75 GHz fall in fixed satellite space to Earth links, broadcast studio-transmitter links and PrimeStar downlinks, for example.

The third harmonics at 17.175-17.625 lie in military radar and Government radiolocation bands also used for active Earth exploration-satellite and DBS feeder links.

The fourth harmonics at 22.9 to 23.5 GHz fall into the 21.2-23.4 GHz general-purpose fixed band that includes fixed mobile and intersatellite links.

The fifth harmonics at 28.625 to 29.375 lie in what was proposed in the cited reference, at that time to be the 27.5-29.5 GHz local multipoint distribution service (LMDS).

The sixth harmonics at 34.35 to 35.25 GHz lie in the 33.4 to 36 GHz government radiolocation band which is also used by police radars, satellite cloud and snow sensors and a Deep Space Uplink for NASA at 34.2-34.7 GHz.

The seventh harmonics at 40.075 to 41.125 GHz lie in government military satellite space to Earth service and non-government direct satellite broadcasting and terrestrial broadcasting.

The eighth harmonics from 45.8 to 47.0 GHz fall into a government mobile satellite to Earth band of 45.5-47.0 GHz.

The ninth harmonics at 51.525 to 52.875 GHz fall totally into a passive Earth exploration satellite receive-only band containing an oxygen line, the 51.4 to 54.25 GHz band where no transmissions are permitted.

The tenth harmonics at 57.25 to 58.75 GHz fall into the 54.25-58.2 GHz band for passive satellite atmospheric temperature sensors and the 58.2-59.0 GHz receive only band

Adequately dealing with the receive-only bands will require clever engineering indeed. Purposely controlled, active nullifying of selected harmonics may be required in the power converters.. Assuring adequate control of all of the potential propagating modes will be difficult.

WPT ISSUES

There are four fundamental issues in WPT. They are beam safety, frequency allocation, affordability and beam right-of-way.

WPT Beam Safety

High-power in any form is potentially dangerous to personnel and equipment, and since power beams can be invisible, the WPT systems must be designed to protect such. A fail-safe approach is to only maintain the beam if the continued test of a structured beam intrusion detection system renders the desired proper operating response. That is, the absence of a detection signal is insufficient to maintain the beam.

WPT Frequency Allocation

The frequency allocation issue may only be satisfactorily resolved with international cooperation and enlightened economic sharing, in addition to the previously discussed clever engineering for adequate filtering. Realigning the lower frequency ISM-Bands so as to be harmonically related, as the upper bands are, would be a welcome step.

WPT Affordability

The current cost of WPT systems is large, due to immaturity and the fact that large quantities of capital must be committed with no revenue return until the entire system is completed and is operating. The laws of diffraction mean a spread beam with low PFD, until the aperture is filled. Another cost factor is that currently, WPT systems use different forms of power converter at the two ends of a link, thus requiring twice the equipment investment and resulting in non bi-directional power flow capability. Most DC-RF converters are capable of inverse operation, but have not been specifically designed to be efficient when operated in either the generator or inverter mode of operation. Similarly, solid state lasers and photodiodes are not totally incompatible for inverse operation. The economies of scale for production of a single converter device, capable of use as either a generator or inverter would be nice.

WPT Beam Right-of-Way

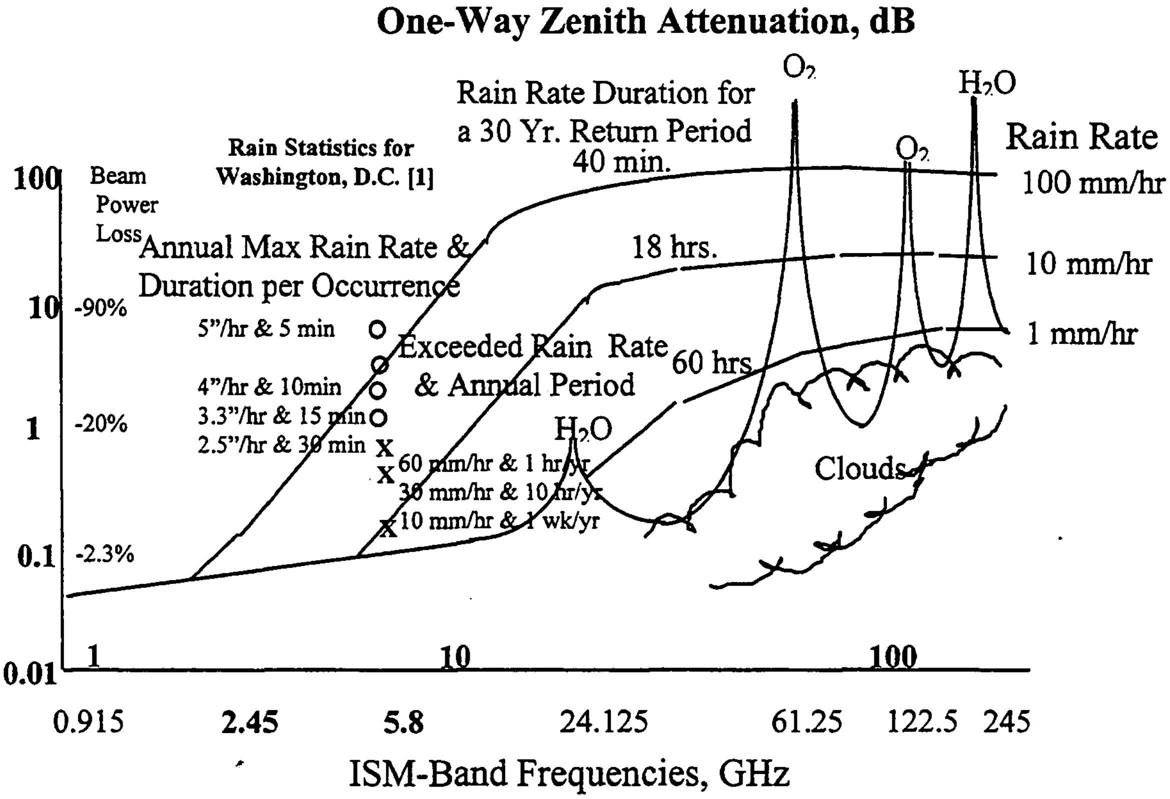
Beam right-of-way (ROW) is a concept that is new to the WPT form of energy transmission, although its wired form has dealt with this issue for over a century. Utilities employing open wire lines and cables and high-pressure gas lines have engendered the constructs of easements, warning signs and barriers, for example, along with public education such as no flying of kites with conducting strings such as copper wire, or call-before-digging. Unless WPT beams ROWs are somehow marked and the populace trained in the proper response, then the WPT systems must inherently assure beam safety.

Visible power beams such as auto headlamps, laser pointers, flashlights, spotlights and sun glints have been interactions of humans with visible WPT, although generally of low PFD. Because of sun glints, we have developed the blink and eye aversion to protect our personal receivers. However, commercial energy transport beams must be of higher PFD to be economical, and ROW is an issue[9].

REFERENCES

1. Brown, W., "The History of Power Transmission by Radio Waves," IEEE Transactions on Microwave Theory and Techniques, Special Centennial Historical Issue, Vol. MTT-32, No. 9, Sept. 1984.
2. Dickinson, R. and Grey, G., "Lasers That Beam Power to Earth," Aerospace America, pp. 50-54, July 1999.
3. Dickinson, R. and Maynard, O., "Ground Based Wireless and Wired Power Transmission Cost Comparison," 34th IECEC, Vancouver, BC, July 1999.
4. Dickinson, R. and Mankins, J., "Comparison of Intercontinental Wireless and Wired Power Transmission, IAF '99 Conference, Amsterdam, Oct. 4-8, 1999.
5. Goubau, G. and Schwering, F., "Free Space Beam Transmission," Sect. 3.5, Microwave Power Engineering, Vol. 1, pp. 241-255, Academic Press, 1968.
6. Allen, E. and Garlan, H,. "Evolution of Regulatory Standards of Interference," Proceedings of the IRE, Section 24-Radio Frequency Interference, pp. 1306-1311, May 1962.
7. Conroy, B. and Le, D., "Measurement of Allan Variance and Phase Noise at Fractions of a Millihertz, "Rev. Sci. Instrum. 61, (6), pp. 1720-1723, American Institute of Physics, June 1990.

8. Kobb, B., Spectrum Guide, New Signals Press, Falls Church, VA, 1995.
9. Dickinson, R., "Safety Issues in SPS Wireless Power Transmission," Space Policy 16 (2000) 117-122.



[1] Propagation Effects Handbook for Satellite Systems Design, Louis J. Ippolito, NASA Ref. Publication 1082(04), Feb. 1989.