Innovations Required for Retail Beamed Power Transmission Over Short Range

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Abstract

Retail beamed power has many potential applications. This paper concentrates on the short range (within 100 km), low efficiency (less than 50%) applications of beamed power transfer. Such applications include connecting micro to medium sized electronic devices with distributed energy sources, transmission of power to mobile consumers, and rapid restructuring of conventional wired grid topology for damage mitigation. The innovations required for realizing these applications are discussed.

Keywords: Retail beamed power transfer, Power distribution and delivery, micro renewable energy

1. Introduction

Modern society has come to rely heavily on devices that are powered using electricity. The traditional method of electric power transmission consists of wired power grids that are widely implemented and well understood. Although modern wired power grids are efficient at high capacity, they require a significant, costly and relatively rigid physical infrastructure. This rigidity is not conducive to mobile computing and to distributed power generation. Applications such as power delivery to remote military and scientific outposts, disaster areas, miniature autonomous robots, and distribution on extra-terrestrial bases, are best served by a flexible method of power transmission. Finally, there is a perceived need for rapidly reconfigurable grids for damage mitigation.

Beamed Power Transmission Systems (BPTS) offer the required flexibility for power distribution. First demonstrated by Nikola Tesla in 1897, this method uses electromagnetic radiation. This paper analyzes the feasibility of BPTS for emerging short range (within 100 km), low efficiency (less than 50%) applications. The paper then points out the technological innovations and research directions required to realize these applications. We begin by describing the science of beamed power transfer. We then discuss the required innovations by outlining a spectrum of possible BPTS applications. The feasibility and cost-effectiveness of these applications is then explored.

2. The Science of Beamed Power Transfer

Wired energy transfer has various disadvantages:
1. Large infrastructure for transmission of power, including wires, poles, land mass (for siting poles), and transformers. Significant efforts and resources are required to set up the infrastructure, and once established it is hard to make changes to the grid topology. Hence, this method of power transfer can be considered rigid.
3. Large clear footprint across forests and mountains.
4. Vulnerable to attacks, accidents and natural disasters. Reliance on a rigid infrastructure inhibits restructuring the grid topology to mitigate damage.
6. High maintenance costs including remote locations.
5. Inhibits development of micro-renewable energy resource exploitation.

Beamed (wireless) power transmission uses electromagnetic radiation (microwave or lasers) for power transfer [2], [3], [11]. BPTS do not rely on a rigid infrastructure of wires and hence can bring great flexibility to power transmission. Wireless power transmission was first demonstrated in 1897 by Nikola Tesla using radio frequencies, and using microwaves in 1964 by William Brown [2]. BPTS were extended to tens of kilowatts by NASA in 1975. In the 1980s, beams of up to 1GW were considered under the Strategic Defense Initiative. BPTS have also been explored for bringing power generated using solar energy in space to the earth both in the USA and outside (e.g. [3], [4], [6], [10]), notably in Japan [13]. BPTS however, has not received much attention for mainstream power distribution.

On the other hand, there has been a revolution in the use of wireless information transmission in the past two decades. Satellite television, cellular telephones, and wireless internet connections reach billions of customers. Research to develop efficient low intensity information transfer over large distances has received a major boost with the advent of digital high-frequency transmission and reception, resulting in devices that require very low power for operation. Thus there are billions of low powered devices operating every day, that have the capability to rapidly decode the information contained in electromagnetic waves.

Wireless transfer of power (or BPTS) uses the same basic science as wireless information transfer. As shown in Figure 1, the direct current is converted to power in the microwave or millimeter wave regime, with efficiencies of 70-90% [2]. The process of forming the beam can be done with efficiencies of 70-97%, but transmission and reception efficiencies vary widely. Ref [2] cites efficiencies as low as 5% to as high as 95%. The final stage of converting the power back from microwave to DC current using rectennas has an efficiency range of about 85-92%. Brown [2] cites an overall efficiency of 52% achieved in DC to DC power transmission using microwave beams in laboratories using standard equipment. Brown also claims that this efficiency could be raised to about 76% using specifically designed components. It should be noted that Brown's results are mostly concerned with power transmission in the 2.4 – 2.5 GHz range. The classical relationship between the efficiency of free space to space transmission and an efficiency parameter τ:

$$\tau = \frac{\sqrt{A_t A_r}}{\lambda D} \qquad 1.$$

where A_t, and A_r represent the area of the transmitting and the receiving aperture respectively, λ denotes the wavelength of the signal, and D denotes the separation distance between the two apertures. Thus as the wavelength is decreased, by going to higher frequencies, the aperture areas required for a given efficiency can be brought down. This consideration offers substantial system improvements if conversion between DC and millimeter waves, especially in the atmospheric transmission windows near 140 and 220 GHz, can be made efficient.

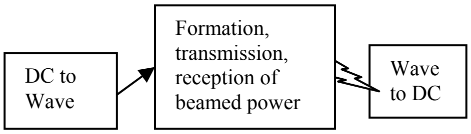

Figure 1: Schematic of a DC to DC beamed power transmission system

3. Feasibility of low range low efficiency BPTS

In the past, researchers have heavily concentrated on the use of BPTS as an enabling technology in Space Solar Power Systems (SPS) (see e.g. [2], [3], [4], [10], [13]). These systems are characterized by low efficiency power transmission from orbital distances (around 400 to 800 Km). With the notable exception of [19], little attention has been given to low intensity, short range (in 100s of Km) power transmission using BPTS for powering devices requiring low to medium range power. This potential area of application of BPTS holds tremendous potential considering the ubiquity of such devices. Power delivery in this context is characterized by low intensity, shorter range, broad coverage, consistency, and efficiency can be traded off for convenience and coverage. We will now use the Friis transmission equation to show that in this context BPTS can produce feasible designs.

Considering ideal conditions for microwave beam transmission, the Friis transmission equation is:

$$P_r = \frac{P_t G_t \, G_r}{(4\Pi R)^2} \lambda^2 \qquad 2.$$

where, P_t is the transmitted Power, P_r is the received power, G_t, G_r are the gains of the transmitting and receiving antenna respectively, and R is the distance over which the power is transferred. Assuming a conservative power efficiency of 20% (i.e. P_r / P_t = 0.2), the variation of the range of the BPTS system with the system frequency is given in Figure 2.

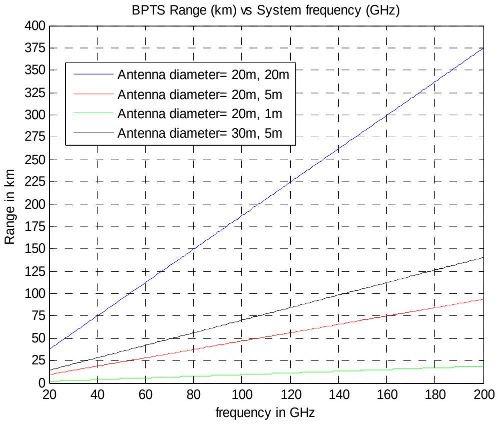

Figure 2 BPTS Range vs. System Frequency with different antenna diameters

The figure shows that for different combinations of antenna diameters the range varies linearly with the transmission frequency.

Figure 3 shows the variation in antenna diameter with different frequency ranges from 2GHz to 200GHz. It can be seen that at lower frequencies (near 2 GHz) larger antennas are required for achieving good transmission ranges. This plot, combined with the fact that the 2 GHz to 2.5 GHz frequency band is heavily used by wireless LAN and other electronic devices, suggests that optimal frequencies for BPTS might lie between 50GHz and 300GHz.

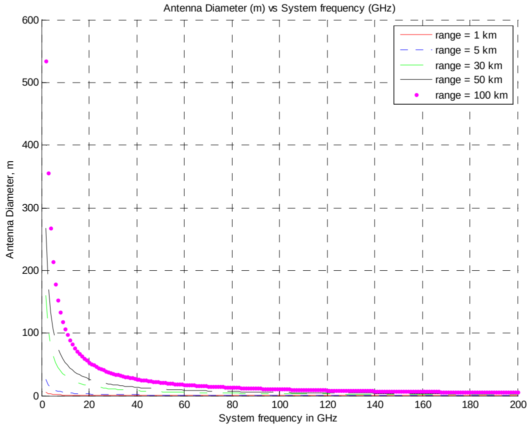

Figure 3 Receiver antenna diameter vs. transmission frequency for different system ranges.

Figure 4 shows the variation in power efficiency as a function of system frequency for a transmitter / receiver antenna combination of 20m and 5m. The plot indicates that higher efficiencies can be achieved at higher transmission frequencies. Hence analysis using the Friis equation strongly suggests use of high transmission frequency for BPTS. However, these results must be studied with caution as they do not account for the effect of atmospheric attenuation. Particularly, it is known that for frequencies greater than 10 GHz the attenuation due to rain is about 10dB/km, while that due to water vapor is greater [1]. Furthermore, in urban environments multi-path effects must also be taken into account. Finally, we note that Ball has raised concerns over the accuracy of atmospheric attenuation values at different frequency ranges [11]. Ball's comments suggest that the values might be excessively conservative, particularly for vertical transmission where the atmospheric density is no longer constant.

In summary, even with a low 20% efficiency the Friis equation indicates that a feasible BPTS system with reasonable antenna dimensions can be designed that can enable wireless power transmission over short ranges.

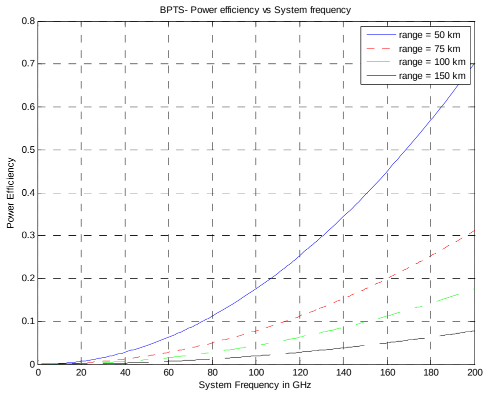

Figure 4 BPTS power efficiency vs. transmission frequency for a different system ranges, assuming transmitting antenna diameter of 20m and receiving antenna diameter of 5m.

This analysis supports the feasibility of BPTS intended to deliver small amounts of power to micro-to-medium sized devices for performing valuable functions over short ranges. In the simplest architecture, power will be spread over a significant area, inside which all devices can accept whatever power falls on their collectors, the rest being wasted. This will result in a significant loss of efficiency, however, if the energy used is sourced from micro-renewable sources, this becomes less of a concern.

Such BPTS can augment the established wired grid to satisfy requirements that are currently ill satisfied:

1. Rapidly provide power to remote consumers without having to setup expensive wired architecture or without having to carry power generation capabilities.
2. Manage seamlessly distributed power generation and consumption. This includes connecting mobile or distributed power sources with the main grid and connecting mobile power consumers with distributed sources without requiring elaborate wire infrastructure.
3. Rapidly restructure grid topology to enable fast and efficient mitigation of partial grid failures.

4. Potential Applications

In this section we discuss some potential applications of BPTS. This discussion serves to give perspective on what is required in terms of technical breakthroughs and pinpoint technical innovations required.

1. **Broad area low intensity power distribution**: Small scaled BPTS can be used in a mall or a café type environment to allow enabled devices to charge automatically. Due to the proximity of the power source, and low power requirements of modern portable electronics, the intensity of the transmitted power need not be high.
2. **Rapid power delivery to remote military or scientific outposts:** BPTS can be used to deliver targeted power to military outposts or scientific outposts operating in remote regions.
3. **High endurance miniature robots**: Battery power is one of the limiting factors in the design of miniature robotic vehicles such as Miniature Unmanned Aerial Systems (M-UAS). These vehicles are unable to carry significant amount of onboard power. Power delivery using trailing wires has been previously attempted [14]; however this method can prove impractical and limiting due to the infrastructure required. BPTS have the potential to revolutionize the capabilities afforded by M-UAS by using beamed power transmission to increasing their endurance. This capability can enable exciting new applications, including indoor arena exploration with a team of networked M-UAS operating in the vicinity of a mother-ship that harvests energy locally and transmits power wirelessly to recipient M-UAS.
4. **Distributed energy generation**: There is a strong drive in the market towards using smaller self sufficient units that generate sufficient electricity for local purposes. This paradigm is termed as distributed energy generation. It is postulated that distributed energy generation will not only be able to support our ever growing energy needs, but it has the potential to be extremely cost effective and sustainable since it is primarily based on exploiting renewable resources [14]. The power distribution systems that support distributed energy generation must remain flexible and highly adaptable. BPTS based distribution systems can provide this flexibility as they are not tied to a rigid ground based infrastructure.
5. **Remote area exploration**: Beamed power can be used to increase the distance a single unit can cover while exploring remote areas through targeted power delivery. On extraterrestrial bases such as the moon, beamed power is an extremely attractive option since the cost of transporting wires and other grid related components can be formidable. Furthermore, where there is no atmosphere, (such as the Moon) ideal efficiencies can be achieved. These benefits make the use of beamed power on lunar bases an extremely attractive option. Reference [16] suggests the use of mobile lunar surface power generation plants to ensure continued solar energy

supply throughout the lunar night and day. BPTS systems have a clear advantage over conventional wired power transmission systems in this case.

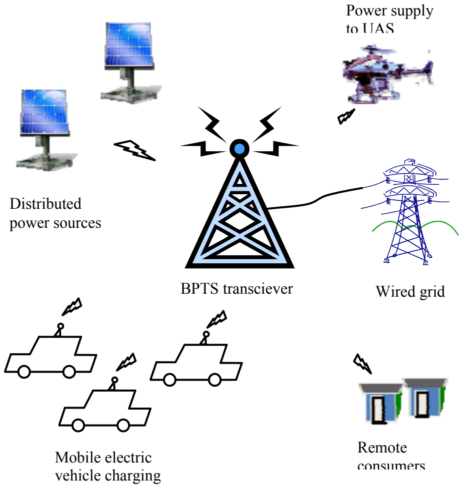

Figure 5: Possible applications of BPTS over short ranges (tens of kilometers)

6. **Increasing the range of electrically powered vehicles**: Current electrically powered vehicles are limited in range by battery weight and volume. Enabling metered power delivery on highways or in parking lots can aid greatly in increasing the range of electric cars and can provide new sources of revenue. By shielding the vehicles, or by delivering the power only when the vehicle is parked and unoccupied, safety concerns can be eliminated.
7. **Rapid restructuring of grid topology for damage mitigation**: Augmenting the wired power grid with BPTS transceivers can mitigate partial damage in conventional wired grids by enabling rapid rerouting of power to avoid areas of the grid that are damaged and incapable of transmission.

Figure 5 shows a schematic of the possible flexibility in applications afforded by BPTS. The figure visualizes the distribution of power generated from distributed energy sources and the conventional wired grid to remote consumers, flying vehicles, and electric vehicles.

5. Cost-effectiveness of BPTS for Potential Applications

The current cost per kilometer for wired power transmission is around USD 1 million (2010) (see for example [20],[21] for cost per mile). This cost includes material, siting (land cost), and environmental costs. It is traditionally computed by dividing the total cost of the project by the number of kilometers of wires used. Since traditional transmission projects range over hundreds (if not thousands) of kilometers, adjustments must be made for savings realized due to large scale production and operation. Due to this reason, this cost could be misleading over short distances. Therefore, we propose the following model for capturing the effective cost ϵ_w of wired power transmission:

$$\epsilon_w = \alpha R + e^{-\beta R}. \qquad 3.$$

In the above equation, R denotes the distance over which power is to be transmitted, the constant α captures the cost per kilometer, and the exponential term accounts for the effect of savings realized over large distances. Clearly, for a given β, if R is large, the effect of the exponential term is negligible.

On the other hand, the infrastructure cost for BPTS over short distances is significantly lower than wired transmission systems as siting and material costs are significantly reduced. Assuming that a BPTS implementation over 1 km is equivalent to a wired implementation with 10 poles, one way to approximate the cost of BPTS per kilometer is to divide the cost per kilometer of wired transmission by 10. With this assumption, the cost of BPTS can be approximated to be about USD 100,000 per km. However, this cost does not account for the reduced efficiency of power transmission over large distances. The power transmission efficiency (P_r/P_t), as modeled by the Friis equation (equation 2), is inversely proportional to the distance. The following model can be used to capture the effective cost ϵ_b of BPTS systems:

$$\epsilon_b = 0.1\alpha R + \frac{\gamma}{\frac{P_r}{P_t}}. \qquad 4.$$

In the above equation, for a scaling constant γ the last term captures the losses resulting from loss of efficiency over long distances. Figure 6 show the effective cost of wired and beamed power transmission for various frequencies. In that plot the receiving and transmitting antenna diameters are set to $D_r = 4\ m, D_t = 5\,m$, the antenna gains are approximated using the equation $G_r = \eta\left(\frac{\pi D_r}{\lambda}\right)^2$, where $\lambda = \frac{c}{\omega}$ is the wavelength and $\eta = 0.8$ is a transmission efficiency factor. From Figure 5 it can be seen that over a distance of 1 Km BPTS are competitive with wired power systems. The figure also shows that the cost of BPTS increases significantly over that of wired transmission with increasing transmission distance, and that the cost is inversely proportional to the transmission frequency. Particularly with a transmission frequency of around 20 GHz, BPTS can compete with wired transmission for distances up to 6 Km. The numerical values will depend heavily on the actual design of the BPTS, nonetheless, the trends should still remain the same.

The above preliminary analysis indicates that for applications requiring power transmission over short distances (within 100 km) BPTS can compete with wired power transmission in terms of cost effectiveness. There are a number of applications that fall into this category, including the ones mentioned in the previous section. On the other hand, when efficiency over long distances is considered, BPTS are ineffective. Transmission at higher frequencies, improved antenna design, and better understanding of health effects of high frequency transmission are required to make a case for BPTS over larger distances.

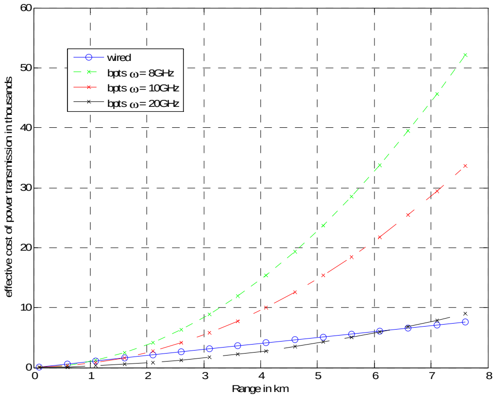

Figure 6 effective cost of wired and beamed power transmission for various frequencies.

6. Required Technological Innovations

In this section we provide a high level overview of the required technological innovations to realize some of the potential applications discussed in the previous section.

a) **Efficient Frequency Conversion:** One major hurdle in implementing BPTS is the inefficiency in converting microwave frequencies to the typical 50-60 Hz operating frequency voltages, and vice-versa. Advancements in Optical Rectennas which couple and rectify optical frequencies to DC provide encouraging news for beamed power. This direction of research needs to be further pursued.
b) **Advancements in Antennas:** Antennas operating efficiently at higher frequencies are very important for beamed power. Development of low cost antennas capable of transmitting at higher frequencies (20 to 200 GHz) with narrow frequency bands will be required. These antennas should be designed in the form of phased arrays, to allow real-time control for changing the direction of beam at high frequencies without physical actuation.
c) **Advancement in Electronics:** Passive and active electronic circuits operating at frequencies of the order of 90 and 250 GHz will require significant advancements in nano-scale fabrication technologies and RF engineering.
d) **Direct Conversion of Broadband Sunlight to Narrowband wave:** The implications of solving this breakthrough technological concept are enormous from a Retail Beamed Power perspective. The need to convert sunlight to DC is eliminated by this technology and hence the efficiency improves significantly not only for Space Solar Power (SPS, an application of BPTS that has been studied widely, see e.g. [3], [4], [10], [13]), but in general for Beamed Power.
e) **Innovations in sub 200GHz radiation monitoring**
f) Brown in [2] mentions that studies conducted by DOE/NASA have found no major issues that would hinder the deployment of BPTS, including environmental and biological considerations (Brown is referring to [18]). Similar studies are yet to be reported on the 200 GHz regime.

g) **Decentralized grid management through networked control:** A major capability brought about by the use of beamed power is the flexibility in the grid and the ability to support distributed power generation. Advances in decentralized management of grid structures are required. This includes thinking of each transceiver as an autonomous agent that must use locally available information to function synergistically with other networked transceivers to meet globally defined needs. The emerging field of decentralized control of networked systems (see for example [17]) promises the development of tools that will be essential for guaranteeing this. Some areas where technological advances are needed are: 1. Real time decentralized fault detection in grids 2. Efficient real time restructuring of grid topology to ensure uninterrupted delivery of power by bypassing nonfunctional units. 3. Decentralized grid voltage regulation.
h) **Graph based models of decentralized grids**: A power distribution system consists of independent power generation and consumption nodes that are connected through some kind of a network. Such systems are very well represented through the framework of Graph theory. Graph theory has excellent tools that can be used to model power distribution systems. For example, the notion of strong connectivity of a graph can be used to determine whether a network can distribute power over all its nodes. Research in bringing the tools of graph theory to modeling decentralized grids equipped with BPTS will be invaluable.

7. Conclusions

In this paper we described a number of innovations required for bringing Beamed Power Transmission (BPTS) from concept to reality. We noted that BPTS is an established concept that can bring immense flexibility to power distribution and generation. We pointed out several possible applications for BPTS that range from power delivery to remote outposts, to power delivery to mobile units. Furthermore, the feasibility of BPTS for these applications and its cost-effectiveness was also analyzed. We conclude that technological innovations needed include improved antenna design, efficient frequency conversion, conversion of broadband sunlight to narrowband wave, innovations in radiation monitoring, and control theoretic approaches in decentralized grid management. This list is by no means exhaustive. We strongly believe that current advances in electronics, control theory, and antenna design are pointing in the right direction to undertake these innovations.

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