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Antenna Considerations for Retail Beamed Power Delivery in India

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***Abstract*—Past work has shown the relevance of retail electric power delivery in developing areas where the market for micro devices outpaces the power grid infrastructure. Antenna size requirements imply logically that frequencies above 100 GHz must be used for viable power transmission. A power beaming architecture based on near-millimeter waves can enable power exchange at intercontinental, littoral and local levels, enabling participation of micro renewable generators and rural populations. Building on a survey of technological developments, the paper starts the requirements definition for millimeter wave power antenna design. Lighter than air aerostat platforms enable longer horizontal paths to be shifted above the dense, moist lower atmosphere, with vertical transmission between the ground and the aerostat occurring through millimeter waveguides built into tethers. Ground antennae may be integrated with solar photovoltaic panels for multiple uses. The option of transmitting power from local micro generators rather than storing locally, favors the use of technology-intensive mass-produced solid state devices that integrate conversion, transmission, reception and phase variation for beam pointing.**

***Keywords*-millimeter wave; antenna; aerostat; retail power beaming; waveguide**

I. INTRODUCTION

In India, the inability of the terrestrial grid to reach many of the 600,000 villages [1] is a major obstacle to the goal of bringing several hundred million people into the mainstream of economic opportunities. On the other hand, people are clearly willing to pay extremely high marginal costs for the small amounts of power needed to achieve connectivity using mobile (cellular) telephones, even in areas remote from the wired power grid [2]. The usage of cellular telephones in India has generated numerous innovative applications, and these phones are no longer luxuries for people in all walks of life, from financial executives to street vendors and farmers. This creates a strong opportunity to synergize wireless power beaming with the connectivity infrastructure.

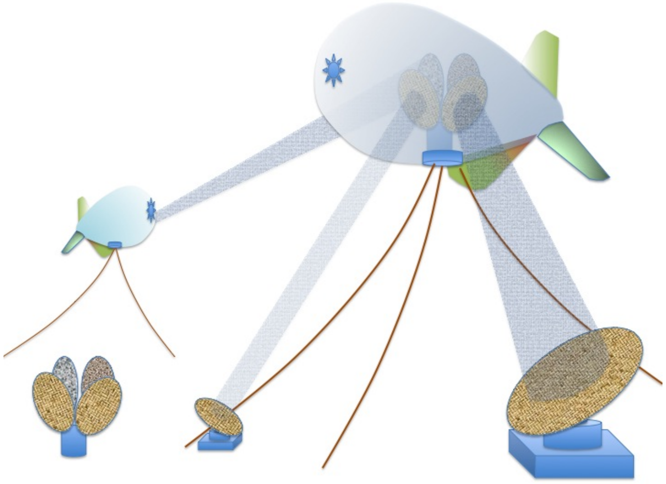

Figure 1. Retail power beaming architecture using waveguide-tethered aerostats. Phased-array antennae inside the aerostats allow millimeter wave beaming between aerostats as well as additional power exchanges with ground antennae. Ground-based converter / antennae may be integrated with solar photovoltaic panels and enable bidirectional beaming including local standalone power generators and local storage.

Reference [3] considered the relevance of millimeter wave power beaming, at high power levels, to the mobile telephone industry. It laid out the general architecture considerations and surveyed the available knowledge base on millimeter wave generation, transmission and beamed power delivery, with a focus on eventual application to bringing electric power to Indian villages. Narrow-band power can be delivered as focused beams to receivers near end-users, from central power plants, rural distribution points, UAVs, tethered aerostats, stratospheric airship platforms, or space satellites. Ref. [4] surveyed technology developments relevant to millimeter wave beaming. The present paper builds on these results, and considers the design requirements for the transmitters, relays and receivers of millimeter wave beamed power for the retail power beaming application. A primary objection to millimeter wave power beaming archi-

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tecture was that absorption at low altitudes due to dense and moist air would pose unacceptable losses. Our realization that highly efficient millimeter waveguides can be built into the dimensions of existing tethers for aerostats anchored at 4000 to 5000 meters altitude, has broken through this obstacle. A companion paper at this conference [5] explores the conceptual design of aerostats and waveguides for this application. In this paper, the implications for antenna design are considered.

II. ARCHITECTURE DESCRIPTION

A schematic illustration of the retail power beaming architecture is shown in Figure 1. Retail beaming by itself is a lossy and technologically intensive option for power transmission. As a long-term means of power transmission it may be less attractive than laying a wired power grid. However, where the power grid does not reach today, wireless power transfer offers an excellent option to start economic development. Power grid infrastructure usually follows roads and railways except where major high-power lines from power plants take more direct routes. Thus, in areas that are poorly served by the transportation infrastructure, power supply also lags. In turn, these areas suffer from economic deprivation and hence there is no incentive for corporations to lay supply infrastructure to such places. When retail beaming is seen as the ”market reach” segment of an abundant source of power, the economic motivation changes drastically. This is part of the motivation for our studies of the retail beaming segment.

A. *Choice of frequency*

As pointed out in Komerath and Chowdhury [3] frequencies below 100GHz are not practical for long-distance beaming, such as that needed to connect to an intercontinental grid through Space. Since the receiver size needed is inversely proportional to frequency, from Figure 2 one can easily see that it will become unacceptably large even for transmission through a high-altitude platform where the transmitting antenna can be large. Several authors have considered beaming using frequencies below 10GHz to assure better transmission through rain and clouds. However, the antenna size in these cases, despite being huge, is still invariably too inadequate to capture more than the primary lobe of the beam, i.e., 84 percent of the power in the beam. Thus the efficiency of transmission through bad weather comes at the cost of an assured loss of 16 percent of the power. For transmission through dry air above 5000m, the 200-223 GHz band offers an attractive transmission efficiency at an extremely small size (and hence mass) of the receiver. One can then afford to capture 98 percent of the power, by going to an antenna diameter of approximately 1.5 times that for the 85 percent capture. This is the approach advocated in [3] for a power beaming architecture. The exception cited was where horizontal beaming is required at low altitudes. In those cases frequencies near 90 to 100 GHz were proposed, as posing less absorption losses than the 200-225 GHz regime. Some frequencies in this range pose health threats to humans, and hence beam safety must be assured.

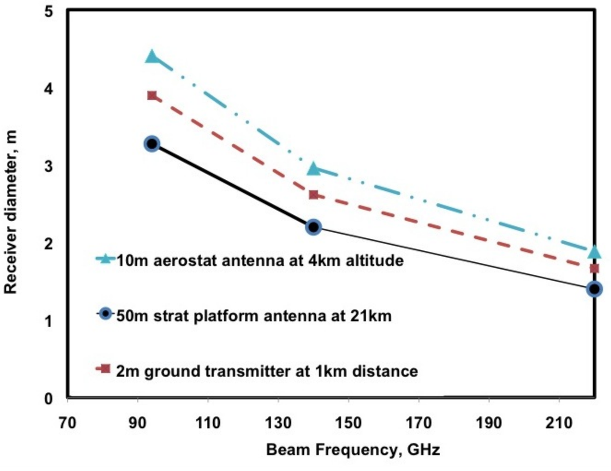

Figure 2. Receiver diameter in meters for 220 GHz beaming from various transmitters

B. *Atmospheric propagation*

One substantial difficulty is that this regime presents very large uncertainties (and opportunities) in the knowledge base on all aspects, particularly on propagation of millimeter waves horizontally and vertically through the atmosphere, and the effects of absorption and scattering by molecules, dust and moisture. Much of the early motivation for obtaining data on atmospheric propagation over the entire spectrum came from the astronomy community, who needed to interpret observations from ground-based telescopes. Thus the data set from the Mauna Kea observatory located at a high altitude in the Hawaiian Islands in the Pacific provide a good basis to assess atmospheric propagation down to about 1700 meters above mean sea level. A widely used source is the 1980s study and model developed for the NATO (AGARD Report 454) by Liebe and Hufford [6], also adopted by the US FCC [7].

Variations are expected in the transmittance data depending on the locations of the data collection sites and the atmospheric conditions [8], [9]. Petty [9] divides the microwave range in the electromagnetic spectrum into five regimes for maximum transmittance at various wavelengths as highlighted in Table I. Regime I spans the range 0-10 GHz in which the maximum transmittance is almost equal to the data for 10 GHz (30 mm wavelength) at the four atmospheric conditions as listed in Table I. Regime II exhibits a single wavelength of 10 mm with maximum transmittance at four different atmospheric

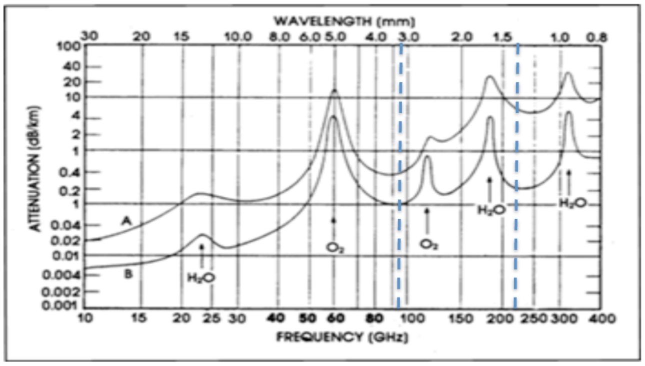

Figure 3. Transmission percentage vs. Frequency for Varying altitudes. From Liebe et al [6]

conditions, while regime III consists of three different wavelengths each exhibiting maximum transmittance for a specific atmospheric condition. Three-millimeter waves corresponding to 100 GHz have maximum transmittance of 0.97 and 0.93 at the dry and polar atmospheric conditions, respectively. Data from Long waves, however, would require large receivers as can be extrapolated from Figure 2 . Shorter waves of wavelengths 2.14mm (140GHz) and 1.43 mm (210GHz), respectively, have very high transmittance at the dry and polar conditions. So 140 and 210 GHz would be of interest for power beaming applications and 210 GHz would be preferable because it will lead to smaller receiver size. These data predict less transmittance at 220GHz compared to 210, but that appears to be at variance with the choice made in several military systems, where 220GHz and 223GHz have been reported as being selected.

Even on a dry day, horizontal propagation of millimeter waves is costly at low altitudes. This is illustrated in Figure 3. However, the same data show that horizontal propagation is much better at 4000 to 5000 meters density altitude. Data from several researchers show that beyond minimal traces of water vapor, losses in passing through the atmosphere (data shown are for 45 degrees inclination) are unacceptable. However, this is true even at 90 to 100 GHz, and in fact at most frequencies above the 10GHz resonance of water molecules. These data suggest that power beaming should occur at frequencies below 10GHz. However, this is a false conclusion even if the antenna size requirement were practical. Experience shows that satellite TV signals are lost during heavy rain or snow. In addition, the scattering or degradation of power beams by density differences and other effects are greater if the beam width is greater. From the above, one might conclude that power beaming is grossly inefficient at any frequency. However, we explore below, several techniques to improve this efficiency very substantially. Compactness of the equipment suits these techniques better to millimeter waves.

Table I
MAXIMUM TRANSMITTANCE AT VARIOUS FREQUENCIES IN GHZ FOR DIFFERENT ATMOSPHERIC CONDITIONS WITH VERTICALLY INTEGRATED WATER VAPOR CONTENT IN KG/M2 GIVEN IN PARENTHESES.

Frequency	Dry(0)	Polar (3.1)	(21.3)	Tropical(53.6)
10	0.98	0.98	0.97	0.97
30	0.97	0.96	0.94	0.89
78	0.85	0.85	0.78	0.63
87	0.94	0.91	0.80	0.61
100	0.97	0.93	0.76	0.52
129	0.92	0.87	0.63	0.33
140	0.98	0.90	0.59	0.25
210	0.98	0.80	0.26	0.04

III. ANTENNA REQUIREMENTS FOR RETAIL POWER BEAMING INFRASTRUCTURE

A. Antenna Size and Material Assumptions

In this section we attempt to lay out a logical process for sizing the retail beamed power infrastructure. We start with assumptions on acceptable antenna size. Transmitters from large power stations are assumed to be up to 150 m in effective diameter. Village-level receivers are limited to 5m in effective diameter. Antennae mounted on aerostats for beaming between aerostats are limited to 10m diameter, and those on high-altitude platforms to 50 meters. Antenna mass per unit area for the antennae mounted on aerial platforms is assumed to be no higher than 0.2 kg per square meter, while those on the ground can reach 0.5 kg per square meter. Millimeter waveguides are assumed to be built with metal walls, of density 7800 kg/ cubic meter. There is evidence of millimeter waves being successfully generated with good efficiency at high power levels. Verhoeven et al. [10] used a MASER powered by an electron beam to generate over 750 kW with over 50 % overall efficiency, with frequency continuously variable over the near-millimeter wave regime. This setup demonstrated the use of milimeter waveguides.

B. Unique Aspects of Beamed Power Systems

Several aspects that must be noted about systems for beaming power.

1) Single frequency and point-to-point power delivery, imply very high boresight gain and narrow beams.
2) Spillover is wasted power.
3) Resonant elements will achieving very high coupling efficiencies and minimize heat dissipation.

Feed horns and waveguides of various types are expected to be used heavily. Cavity-backed slotted antenna elements may be used to achieve sharp S11 parameter values of -30dB or lower. With millimeter beams, it is generally possible to design for minimal spillover (small end taper) and narrow beam size without compromising aperture efficiency, sizing antenna at 1.5 times the diameter required to capture only the primary lobe [11]. Antennae may be built as large arrays of mass-produced microchips integrating several functions. Thus it is assumed that phase array beam steering and adaptive control of the beam to compensate for path and receiver distortions, will be incorporated. Berland [12] summarizes the concept of smart antennas that can achieve excellent beam pointing using digital signal processing. Active cancellation of side lobes and near-real-time tracking enable mobile phone systems to minimize cross-talk between signals to different customers. The cost-effectiveness and safety features of active pointing have to be evaluated. Active pointing may be used on some initial systems to minimize the number of transmitter and receivers in remote areas. As the system is refined, simpler passive systems may be preferred for the majority of customer sites.

IV. TETHERED AEROSTATS AND WAVEGUIDES FOR POWER BEAMING

We now turn to a solution approach that may be particularly suitable for the Indian rural market. Experience is growing around the world with both tethered and free-flying Lighter Than Air (LTA) platforms, which include balloons, aerostats, rigid inflatable airships and stratospheric platforms. Applications include aerial imaging [13], remote sensing [14], radar [15] visual and infrared monitoring of international borders [16], [17], airspace and movement on the ground , traffic monitoring and control [18], synthetic aperture astronomical telescopes [19]–[21], relaying electromagnetic signals, wind power [22], [23] from the jet stream, and solar power collection.

As discussed in [5], the optimal altitude above India for a free-flying, powered LTA platform to minimize wind effects, is around 21,000 m, which is well into the stratosphere. Oodo et al [24] described a digital beam-forming antenna for the 25-30 GHz range, for operation on stratospheric platforms. This is clearly too high to consider a waveguide tether. However, at 4000 to 5000 m, an aerostat is already well above most of the precipitation and low-altitude gusts. Tethers going up to such altitudes are already commonplace. These tethers are used not only to provide the tension needed to hold the aerostat in position, but also as conduits for electrical power to on-board devices including rudimentary propulsion, communications, command and control. Accordingly, present-day tethers are on the order of 50 mm in diameter, with a Kevlar core for strength and with other cables wrapped around the core.

Millimeter waveguides for 220 GHz are small enough in cross-section to allow several such waveguides to be placed inside each tether. In [5], we present initial calculations showing that an aerostat parked at 5500 m altitude, and conveying 5 MW of power at 220 GHz to the ground, is quite feasible. Power levels of 2 to 3 times that amount should be possible to handle using evacuated tethers, since the 5 MW calculation was based on a factor of safety of 2 beyond the breakdown power level for atmospheric air [25]. A single village cannot be expected to afford such an aerostat, so a tradeoff has to be done between the area served, the altitude, the aerostat size and the power transmission capacity. A bundle of millimeter waveguides could be envisaged, to be integrated with future tether designs. Over southern and central India, even in the monsoons, 4000 meters is considered to be high enough to get above most of the clouds and precipitation. In temperate zones where convective thunderstorms can occur, and over mountain ranges where there may be substantial updrafts, the optimal altitude may be much higher, or the aerostat may have to be moved to safety. In this architecture, the power is conveyed up to and down from the aerostat as millimeter waves, with all conversion to and from millimeter waves being done on the ground. This eliminates much of the mass needed for conversion, from the aerostat payload.

A. *Conformal Antenna Carriage*

The horizontal transmission and reception between aerostats is conducted using antennae built into the aerostat, giving transmission efficiencies nearly as good as for beaming through vacuum. NASA concepts for inflatable parabolic antennae [26] have been aimed to achieve large aperture with low mass. A 14-meter version was demonstrated on the Space Shuttle Mission STS-77 in 1996. An inflatable tube supported a thin-membrane parabolic surface, with three struts to support a feed. The deployed surface quality was unsatisfactory. A 3.3m x 1m inflatable L-band SAR array was deployed by the Jet Propulsion Laboratory and Dover ILC. These had aereal mass values of roughly 3.3kg per square meter. Inflation could be used to support the antenna structure in tension, and to form the gas envelope shape at altitude. Demonstrations to date imply that the aerostat shape can be conformed to provide the needed buoyancy and structural support for the antenna. However, this may pose a difficult optimization problem, as well as placing heavy concentrated loads far from the center of buoyancy of the aerostat. A more attractive option may be to place optimized antennae inside the envelope itself, near the center of buoyancy, as shown in Figure 1. The envelope must then be very close to 100 percent transparent at 220 GHz. Since a receiving antenna for 220 GHz is likely to be much lighter than a tether bundle required to convey the same power to the operating height of an aerostat, it is likely that beaming requirements far in excess of the usual level, will be best met using wireless beaming from the ground, despite the higher transmission loss.

V. GROUND ANTENNA

The receiver antenna on the ground is likely to become a mass-produced consumer item. Provided that the tether waveguide approach works, power delivery to the ground through tethers is likely to become the preferred delivery mode to villages. The number of aerostats will likely be less than the number of villages, and a terrestrial sub-grid connecting villages will be many years away. In the interim, there is a strong need for power beaming near ground level, and from aerostats or towers. The distances are likely to be on the order of one kilometer except for the aerostat application where it may be upto a 45 degree visibility cone from an aerostat parked at 4000 m.

From Figure 2 we see that the required antenna size is on the same order as the practical size of solar photovoltaic (PV) panels that villagers may use. Solar photovoltaic panels have been shown to pick up radio frequency and millimeter waves efficiently [27]–[30]. Thus it makes sense to integrate a millimeter wave antenna and converter with a solar panel. The power transmission from this panel could be sized at a level comparable to the peak power rating of the solar panel, since the main use of the millimeter wave delivery will be in the absence of solar power. A millimeter wave antenna, being much more closely-spaced than a PV panel's metal grid, may require innovative solutions such as lenses for the PV cells, that refract sunlight but are transparent to millimeter waves. Tracking dish receivers are probably not viable, and instead, phase array signal processing will be built into the millimeter wave receivers. Reception over a wide cone of visibility will thus be a requirement. These aspects are illustrated in Figure 1.

The phase array requirement and the need to integrate with PV panels, may provide the argument favoring designs that use distributed multifunctional (MMIC) solid-state arrays over dedicated antenna grids. These arrays will have large numbers of mass-produced solid-state chips integrating the reception, conversion and possible transmission functions. No doubt this is a large leap in technology even compared to solar PV arrays but once accepted in the marketplace it can be expected to become as commonplace as TV sets. The acceptance of TV and mobile telephones in India provides supportive evidence.

A strong additional advantage of the MMIC approach suggested above, is that it is compatible with beaming of locally-generated excess power from micro-renewable generators. It is hard at present to imagine a situation where Indian villagers will have much excess electric power to sell, but if the infrastructure is present, villagers may very well choose to use their land to place such generators and sell power rather than attempt to store it locally. The relevant tradeoff then is between the costs (including losses) in local storage versus beamed transmission and reception.

VI. CONCLUSION

In this draft paper, some preliminary considerations and requirements are laid out for the design of retail power beaming systems. An overall architecture is defined.

1) The logic is laid out on why millimeter wave power beaming is required.
2) The large uncertainties in the propagation efficiency of millimeter waves pose uncertainties in choosing the best frequency for beaming.
3) The destructive effect of precipitated moisture on millimeter waves is a dominant issue.
4) Tethered aerostats at 4000 to 5000m altitude enable efficient horizontal beaming with short vertical atmospheric traverses.
5) Waveguides offer the possibility to transit the moist, dense lower troposphere with minimal losses.
6) Preliminary sizing relates tether size to beamed power wattage, and suggests achievable system parameters.
7) Upper bounds for waveguide attenuation are shown, and these suggest that evacuated or gas-filled waveguides should offer the same propagation efficiency as the dry upper atmosphere, or better.
8) Examples of inflatable shapes used to support antennae in space suggest that aerostat shapes may be configured to support required antenna shapes.
9) Smart antenna technology including active beam modification and multiple-element arrays conformed using feedback, may be adapted from the beam weapon and mobile telephony fields for the retail power beaming application.

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