DARPA/MTO & OASD(R&E) Roundtable Report

Department of Defense Power Beaming Roundtable

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EXECUTIVE SUMMARY

Wireless power transfer has progressed well beyond the pursuits of Marconi and Tesla and witnesses growing commercial interest, including the profusion of RFID and burgeoning market for mid-field coupling. In the early 1980s, the National Academies' Committee on Satellite Power Systems concluded that space-to-ground power transfer would be viable at certain cost targets, several of which have been reached. However, high-power wireless energy transfer over long distances lacks an immediate driver in the commercial marketplace. Recently the Japan Aerospace Exploration Agency (JAXA) announced an ambitious 25-year program to deploy a 1 GW, geosynchronous solar power plant. In March 2015, a JAXA ground test, in partnership with Mitsubishi, demonstrated 10 kW received over 500 m at microwave frequencies [1]. Although this falls short of the 1975 NASA JPL Goldstone demonstration (up to 34 kW over 1.5 km at 82% efficiency) [2][3], it demonstrates revived international interest.

Reflecting this renewed interest, DARPA/MTO organized a DoD Power Beaming Roundtable on August 21, 2015, as a forum for government personnel to discuss technological and mission-enabling opportunities, recent S&T advances, and the perceived scientific and/or engineering challenges to practical power beaming. The attendees at this Roundtable are listed in Appendix A and the Agenda for the Roundtable is shown in Appendix B.

Key findings from the Roundtable discussion are summarized below in three major categories: the current state of technology, potential applications, and current investments:

State of Technology:

- In the 1970s, power beaming concepts were focused on large, monolithic transmitter and receiver structures. In the 1990s, this moved towards partially modular structures that still contained a common backbone, and today the focus is on completely modular structures that result in low cost and high customizability.
- Technologies for long-range, directed transmission have advanced significantly in the past decade and are available at millimeter wave (mm-wave) and optical frequencies, as well as at the traditional S-band. This represents a major change from the 1970s, when NASA first examined space-based solar power (SSP) in-depth, and substantially reduces the anticipated cost of an intermediate demonstration vehicle and an eventual utility-scale power plant.
- Significant discussion focused on the benefits and comparison of power beaming at mm-wave frequencies and optical frequencies. Current and historical DoD investment to develop high power lasers for directed energy weapons and to develop active denial systems at RF frequencies could be leveraged for wireless power beaming using optical or RF wavelengths, respectively.
- As related to RF power beaming, frequencies studied now include 5.8 GHz, 35 GHz and 94 GHz, in addition to 2.45 GHz, characteristic of prior work. Nevertheless, the majority of ongoing power beaming work remains focused on 2.45 GHz, due to the availability of low cost components and low atmospheric attenuation.
    - Higher frequencies have the advantage of smaller apertures and are less restricted, as lower frequency bands allocated for industrial, scientific and medical (ISM) use are overrun by commercial products including low-power consumer WiFi. However, atmospheric absorption is greater at higher frequencies and component efficiencies decline.
    - Power beaming using mm-wave also has the benefits of eye safety and lack of deep turbulence effects and can leverage the thorough understanding of power density safety limits from extensive data on human and animal effects from the mm-wave active denial program.
    - The Active Denial System (ADS) has demonstrated between 2 and 100 W/cm^2 on target, depending on scale and range, and could be leveraged for higher mm-wave power densities with the use of new materials and architectures in suitable rectennas.

    - Rectenna technology, which converts high power density microwave energy to DC power, unlike transmitter technologies, has not seen significant advances in the past decades. The efficiency record of 91.4% at 2.45GHz is still the state of the art 38 years after it was first published by Bill Brown [4]. Demonstrated rectenna efficiency at mm-wave remains significantly lower, e.g., 35% at 95 GHz with 10–100 mW/cm^2, leaving significant room for improvement.
- Lasers offer a smaller aperture than RF transmitters, and may be particularly well suited for compact applications (such as UAVs). For comparable transmit aperture size, the spreading angle of the optical beam is approximately 3000x smaller than a 95 GHz mm-wave beam and 100,000x smaller than a 3 GHz microwave beam. Optical radiation can be used to form narrow beams with relatively small transmit/receive apertures, and narrow beams may help prevent detection by an adversary.
    - Adaptive optics can be used for intelligent beam forming and mitigation of beam steering and scintillation effects due to atmospheric turbulence close to the ground (mainly during the day). It should be noted that atmospheric turbulence over the surface of the water is much less than solid ground and shows no diurnal variation.
    - Losses for optical beams due to aerosol scattering are largest in the lowest 2 km of the atmosphere, which limits the horizontal propagation distance of optical beams. Clouds and precipitation also limit transmission of optical beams.
    - Recent advances in high power fiber lasers and fiber-array technologies, driven by investment in directed energy systems, open new opportunities for power beaming applications. High efficiency laser power converters (photovoltaics or PVs) at low incident power levels have become commercially available, with room for improvement remaining, especially at increased power levels, as the technology matures.

Potential Applications:

Potential modalities for power beaming include all combinations between ground, sea, air, and space platforms. Generation and delivery of SSP can exploit the unobstructed line of sight from space to a ground station and operate nearly 24/7 from a geosynchronous orbit (GEO). A key challenge to SSP, which is dominated by launch and space assembly costs, is achieving cost ($/W) comparable to terrestrial energy sources. However, it should be remembered that the cost of conventionally delivered energy varies by country, region, and application.

- The low launch costs targeted by the SpaceX and competing programs help make the cost targets more feasible. The use of ultra-light, modular structures, along with advances in space robotics will reduce space assembly costs and provide additional reductions in launch costs. It is expected that GaN RF components will decrease in cost in the future, benefitting from economies of scale driven by the GaN-based LED and power electronics markets. Development of ultra-light-weight, low cost PV will also reduce the cost of SSP. With the combination of a modular approach and a SpaceX launch vehicle, achieving a $0.5/kW-hr levelized cost of energy is considered realistic. This makes the cost of SSP comparable to the cost of wind and solar PV power, when they were first introduced as a renewable energy source. Government-provided incentives and high volume production reduced the cost of wind and solar PV to within the average US retail price and similar principles could be applied to SSP.
- World-wide SSP coverage could be achieved with only three GEO satellites.
- Applications discussed include power for remote sites with minimal infrastructure, powering of UAVs and lighter-than-air platforms for persistent surveillance, SSP to power the grid, and power beaming for humanitarian assistance and disaster relief (HADR) missions. The initial driver for SSP will likely be power delivery for HADR, remote regions undergoing initial electrification, forward operating bases for exploration and security, or remote platforms for telecommunication, all of which presently have relatively high energy costs.
- Near-term mm-wave and laser power beaming for defense applications include beaming to a small robot or remote sentinel; beaming to recharge the batteries of a squad; beaming up to an aerostat or

unmanned aircraft systems for a high power function, such as jamming; and inter-satellite power beaming.

- Use of SSP and/or terrestrial power beaming for covert DoD applications will be complicated by the difficulties in concealing directional transmission from a sophisticated adversary. However, current approaches – that include energy supply deliveries – may likewise reveal the position of the receiving unit/individual, while power beaming receivers may be obscured or masked by using materials that are transparent at RF (for example, a boulder shaped cover).
- Beamed energy launch propulsion capabilities, in which beamed energy is used to assist in rocket-propelled launch, can drastically reduce launch cost by reducing both the amount of fuel needed and number of stages needed in a launch vehicle. This technology could enable dedicated launch capabilities for small satellites and is relevant to both commercial and DoD interests. Similarly, in-space propulsion would be accelerated by power beaming. The significant benefits are beginning to garner commercial interest, with companies such as Parkin Research and Escape Dynamics developing rocket propulsion systems powered by beamed microwaves. Any amount of investment towards this development would support future DoD needs.

Current and Future Investment:

- The commercial market is presently competing for low-power, short-range wireless power, focused specifically on inductive or resonant coupling, for applications including smartphone and laptop battery charging. Development of high-power, long-range power beaming will likely require government investment.
- In addition to Japan, the United Arab Emirates is considering investing $18B for development of power beaming [5]. The investment within China and EU is difficult to accurately ascertain, but it is clear that there is international interest.
- Development of a utility-scale, GW-level (km-scale) SSP system may represent a larger investment than the DoD is willing to make in the near-term. Near-term defense applications would likely involve megawatts, rather than gigawatts, making the PV arrays, radiators, and rectennas all on the order of tens of meters in scale, rather than several kilometers in scale. This brings the SSP hardware close to the scale of the International Space Station and allows technology demonstrations to leverage known best practices for launch, construction, operation, and maintenance.
- On-going effort within DARPA/TTO to develop space robotics technologies could be highly relevant for the in-space assembly necessary for SSP. Close engagement between government agencies and perhaps international partners to support activities associated with development of SSP is important.
- A push for improvement in end-to-end efficiencies across a range of different frequencies could be enabling. At 2.45 GHz and 5.8 GHz, demonstrated transmission efficiencies may be adequate but development of flexible rectennas would be beneficial. At higher frequencies, including 50 GHz, 95 GHz and laser wavelengths, it would be beneficial to develop receivers and deployable antennas that are capable of being embedded in aircraft.
- The roll-out of the GPS network, which began with a limited system for DoD users and eventually gained widespread commercial adoption following a directive by the Reagan administration [6], may be an appropriate model to follow for development and roll-out of this technology.

REFERENCES

[1] Mitsubishi in partnership with JAXA, “MHI Successfully Completes Ground Demonstration Testing of Wireless Power Transmission Technology for SSPS,” *Mitsubishi Heavy Industries, LTD Press Release,* March 2015.

[2] R. M. Dickinson, ”Evaluation of a Microwave High-Power Receiption-Conversion Array for Wireless Power Transmission,” *Jet Propulsion Laboratory Technical Memorandum*, 33-741, September 1975.

[3] W. C. Brown, “The History of Power Transmission by Radio Waves,” *IEEE Transactions on Microwave Theory and Techniques*, Vol. 32, No. 9, September 1984.

[4] W. C. Brown, “Electronic and mechanical improvement of the receiving terminal of a free-space microwave power transmission system,” *Raytheon Company, Wayland, MA,* Tech. Report PT-4964, NASA Report No. CR-135194, NASA Contract No. NAS 3-19722, pp. 51-52, 66, August 1977.

[5] Off-World Industrialization Consortium, Invitation to Expo 2020 Dubai, June 2015.

[6] C. Alexandrow, “50 Years of Bridging the Gap: The Story of GPS,” DARPA, 2008.

Appendices

Appendix A: Attendee List

Power Beaming Attendees

August 21st 2015

DARPA 06-300

First Name	Last Name	Institution
Abed	Eyad	NSF
Atwater	Harry	Caltech
Bar-Cohen	Avram	DARPA
Comer	Philip	DMEA
Dawidowicz	Edward	CERDEC
Duncan	Kate	CERDEC
Felbinger	Jonathan	OSD
Fischer	Richard	NRL
Garretson	Peter	AFRL
Hajimiri	Ali	Caltech
Hodiak	Justin	Raytheon
Hoff	Brad	AFRL
Jaffe	Paul	NRL
Kazemi	Hooman	Raytheon
Leete	Steve	NASA
Lewis	Jay	DARPA
Liu	Jony	ARL
Livanos	Alexis	Caltech
Madonna	Rich	NGC
Mankins	John	Artemis
Matin	Kaiser	SPC
McSpadden	James	Raytheon
Plaks	Kenneth	PM/MTO
Roach	Pat	AFOSR
Roesler	Gordon	PM/TTO
Shaver	Dave	PM/STO
Sivananthan	Abi	BAH
Smith	Teresa	NGC
Strogen	Bret	OSD
Ting	Tony	NRL
Vorontsov	Mikhail	Optonicus
Wardlaw	Mike	ONR
Zheng	Yan	BAH

Appendix B: Agenda

DOD Power Beaming Roundtable

21 August 2015

DARPA 06-300, 675 N Randolph St, Arlington, VA 22201

Agenda

Start	End	Topic	Presenter	Attendees
8:30	8:45	**Welcome**	Avram Bar-Cohen & Jonathan Felbinger	All
8:45	9:00	**Introductions**	All	All
9:00	9:30	**Plenary**	John Mankins	All
9:30	9:50	**NASA**	Steven Leete	All
9:50	10:20	**Raytheon SAS**	James McSpadden Justin Hodiak	Government only
10:20	10:35	*Break*		
10:35	11:20	**NGES–Caltech**	Teresa Smith Richard Madonna Harry Atwater Alexis Livanos	Government only
11:20	12:00	**Raytheon Missile Systems**	Hooman Kazemi	Government only
12:00	12:20	**Optonicus**	Mikhail Vorontsov	Government only
12:20	13:30	*Lunch*		
13:30	13:45	**Recapitulation**	Avram Bar-Cohen	Government only
13:45	14:45	**Roundtable discussion I**		Government only
14:45	15:00	*Break*		
15:00	16:00	**Roundtable discussion II**		Government only
16:00	16:15	**Take-aways & next steps**	Avram Bar-Cohen	Government only