Opportunities and Constraints for Wireless Power Transmission

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Portions of this presentation were adapted from "Specialized Phased Array Antenna Patterns for Wireless Power and Information Transmission ," poster paper by Seth D. Potter, *Space Manufacturing 10 -- Pathways to the High Frontier: Proceedings of the Twelfth SSI-Princeton Conference*, May 4-7, 1995. Used with permission of the Space Studies Institute.

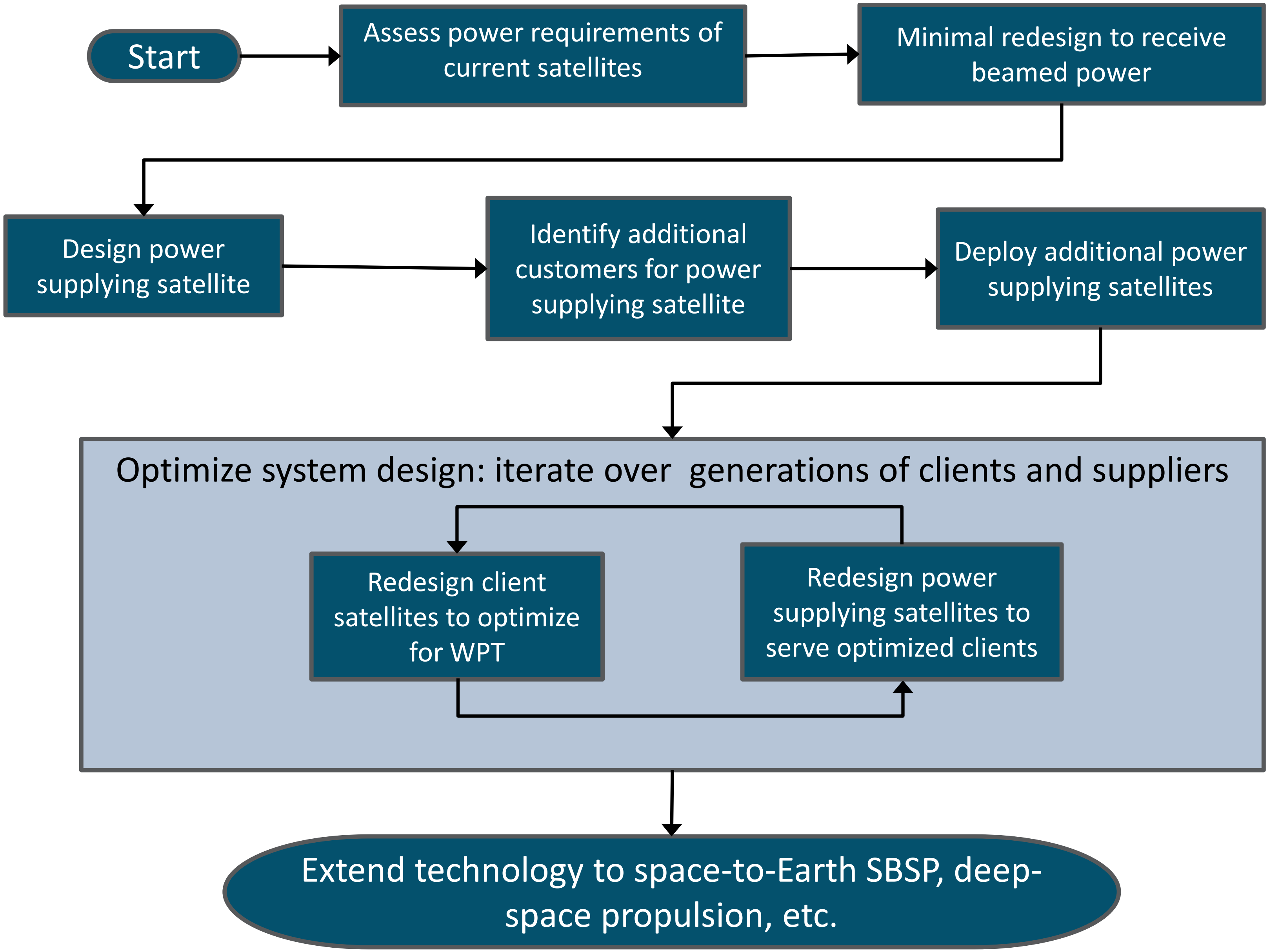
Introduction

- The path to commercial space-based solar power systems may involve addressing early high-value markets where premium prices will be competitive
- Such markets may include satellites whose solar cells become degraded toward the end of their lives
- In addition, satellites in Earth orbits undergo periods of darkness during each orbit in which they are in the Earth's shadow
- This need is currently addressed by sizing the solar arrays and storage batteries on the satellite to collect the extra power needed during these periods and storing it
- If power can be provided by a utility in space during these periods, the solar arrays can be smaller, and the power storage systems can be lighter
- The power utility satellite can then serve other customers while the client satellite is in sunlight

Approach

- Start with an overview of the power requirements for current satellites
- Determine portion of this power that might be served by WPT in the near-term
  - Augment power from degraded solar arrays at the end of their life
  - Lessen the need for energy storage when satellite is in Earth’s shadow
- Set size constraint on satellite-mounted rectenna to be similar to current solar arrays
- Assess electromagnetic and thermal limits on space-based rectennas
- Assess total energy on client satellite (power x duty cycle) feasible from WPT
- Design power supplying satellite to meet this need
- Investigate other clients for same utility
- Build more space-based utilities
- Continue to expand system
- Redesign future client satellites to take full advantage of WPT
- Expand into future markets: space-to-Earth SBSP, WPT for deep space propulsion, etc.

Approach: Flow



Review of WPT Physics

- Phased array antennas consist of planar arrays of dipoles or slotted waveguides
- Used for communications radar; proposed for wireless power transmission
- By varying or tapering the energy distribution across the transmitting antenna aperture, a desired far-field energy distribution (antenna pattern) can be obtained
- Far-field antenna patterns typically have a central peak or main lobe, surrounded by secondary maxima (sidelobes) and minima
- Sidelobes can cause interference to neighboring communications systems, and clutter in radar systems
- Sidelobes can be minimized at the expense of a broader main lobe (i.e., lower gain)
- Transmitter phased-array current distributions of the form $[1 - (\rho/\rho_0)^2]^{n-1}$ will be considered
  - ρ_0 = Phased-array antenna radius
  - ρ = Distance from center of antenna in plane of antenna
  - n = 1, 2, 3, …

Far Field vs. Near Field

- As the terms imply, near field refers to the region near the transmitting antenna; far field refers to the region far from the transmitting antenna
- No hard-and-fast boundary, but it is generally considered to be the Fraunhofer distance d_f:

$$d_f = \frac{2\,D_t^{\,2}}{\lambda}$$

where

D_t = transmitting antenna array diameter

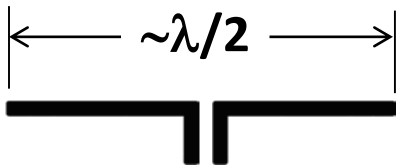
λ = wavelength

- For a classic solar power satellite having a transmitter diameter of 1000 meters and a wavelength of 12.24 cm, d_f = 16,700 km, so for a geostationary SPS at 36,000 km, Earth is in the far field
- Far field wireless power transmission uses electromagnetic waves at radiofrequency, microwave, millimeter wave, infrared, or optical wavelengths

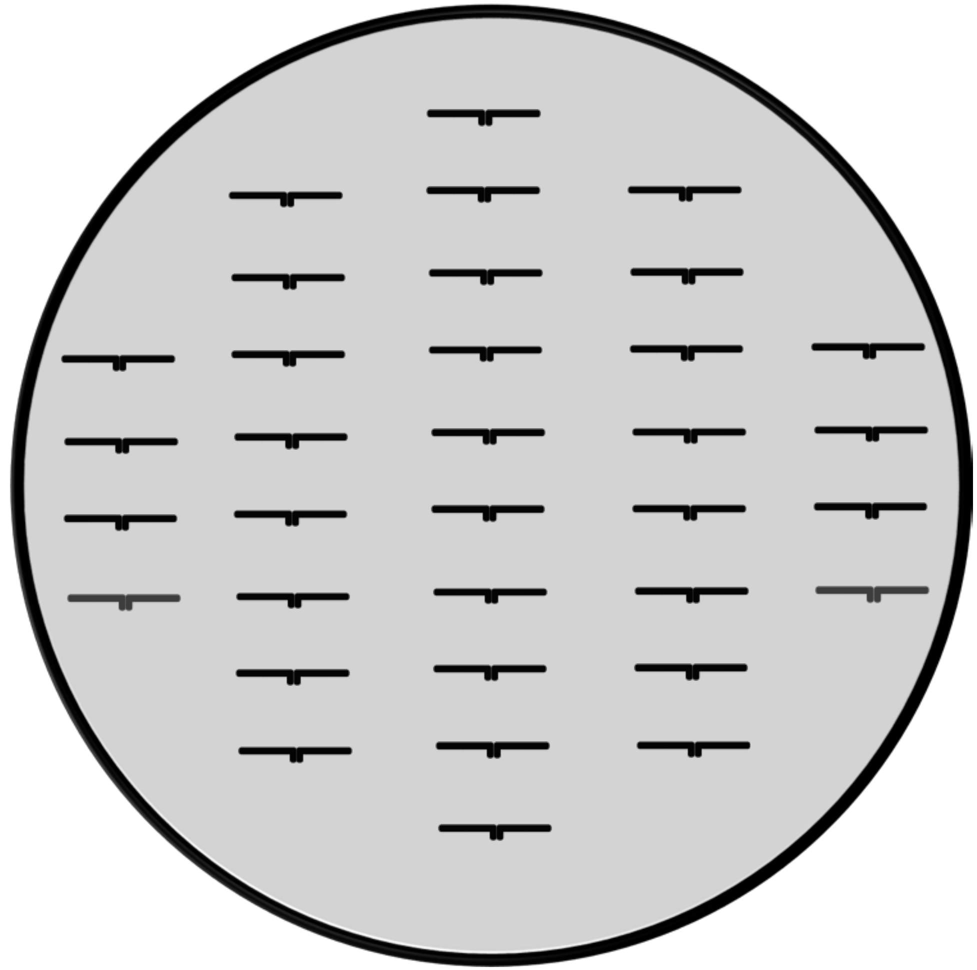
(Very) Near-Field Power Transfer

- Near-field power transfer is already in use for small devices and appliances such as cell phones (reference Jenshan Lin)
- Not amenable to WPT from solar power satellites
- Has been proposed for satellite-to-satellite power transfer
- Can use three different physical principles:
  - Capacitive coupling
    - Uses electric fields
  - Magnetic resonance
    - Uses magnetic fields
  - Inductive coupling
    - Uses magnetic fields

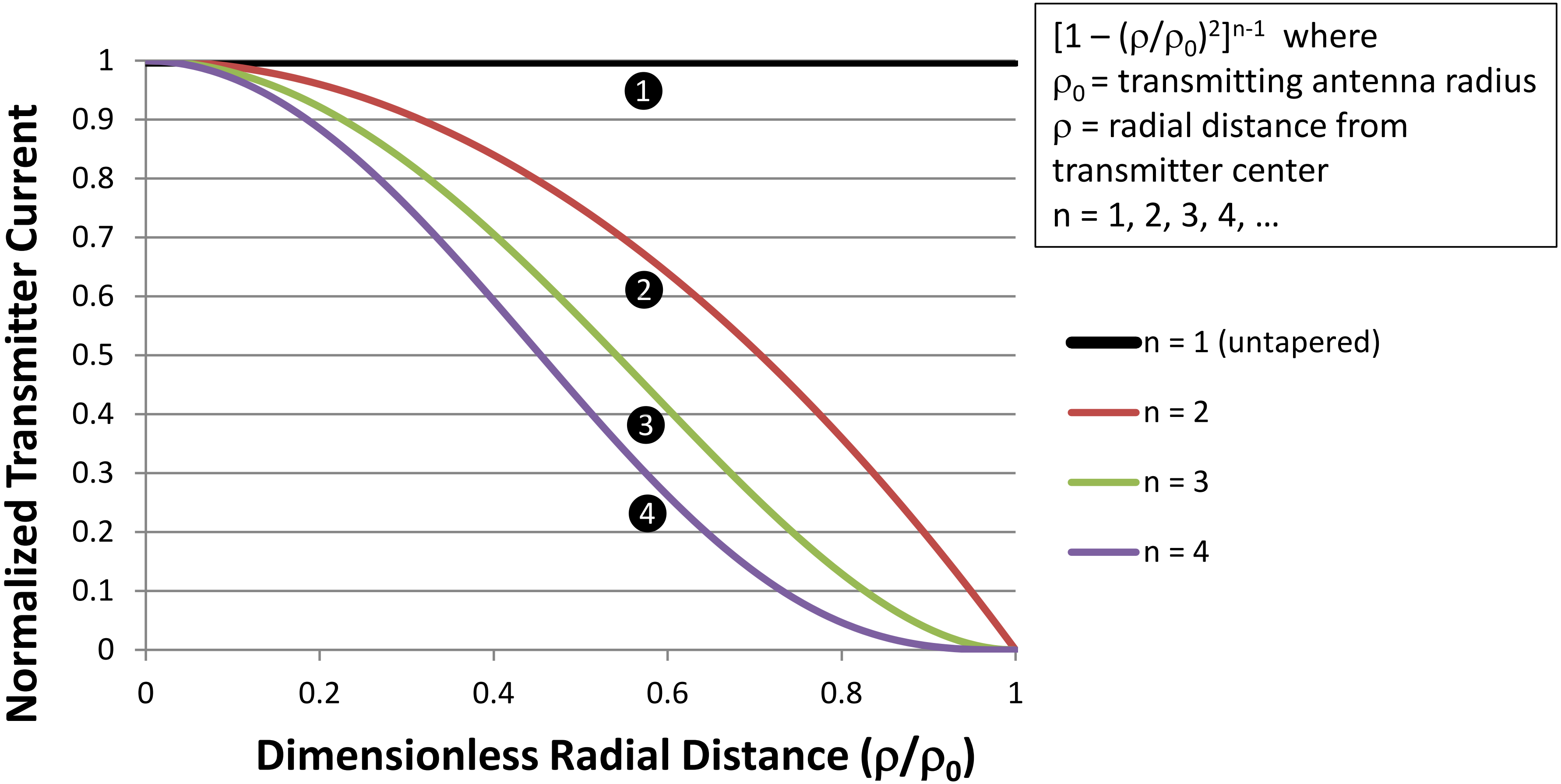
Phased Array Transmitting Antenna: Notional Design



- A phased array transmitting antenna consists of many dipole or slotted waveguide elements, each about a half wavelength long
- By varying the current to the elements, a desired energy distribution at the target can be achieved
- The beam can also be steered by varying the phase of the elements (not covered here)



Current Distribution at Transmitter



Normalized current distribution at transmitter array for n = 1, 2, 3, 4.

Far-Field Received Antenna Patterns

(Linear Polarization)

Electric Field: $$E_n\ (u) = E_n\ (0) \cdot 2^n \cdot n! \cdot \frac{J_n(u)}{u^n}$$

Dimensionless Radial Coordinate: $$u = r \cdot \left\{\frac{\pi D_t}{\lambda x}\right\}$$

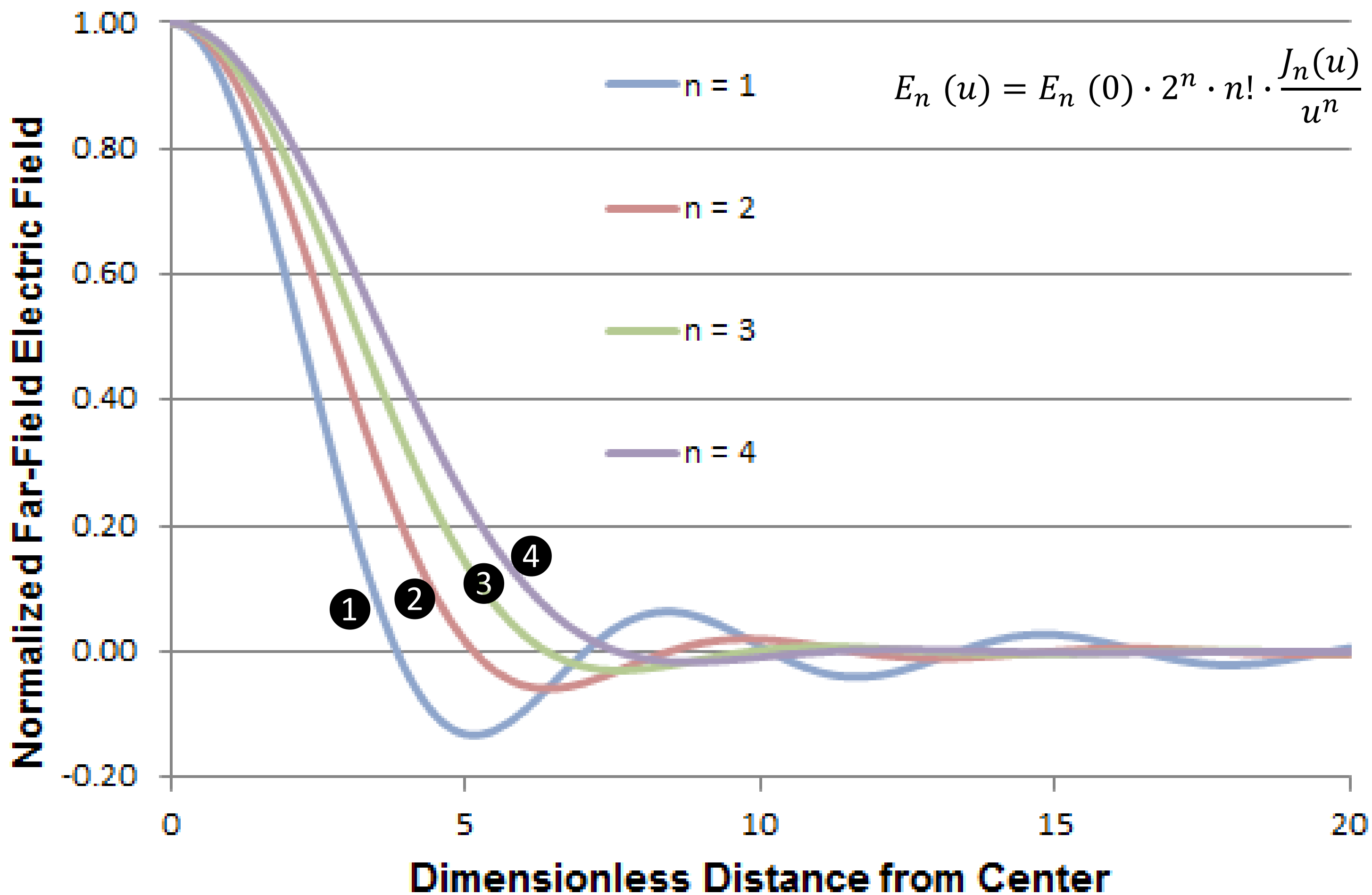
Intensity (power/area): $$I_n\ (u) = I_n\ (0) \cdot [2^n \cdot n!]^2 \cdot \left\{\frac{J_n(u)}{u^n}\right\}^2$$

$$I_n\ (0) = I_1\ (0) \cdot \frac{2n-1}{n^2}$$

$$I_n\ (u) = I_1\ (0) \cdot \frac{2n-1}{n^2} \cdot [2^n \cdot n!]^2 \cdot \left\{\frac{J_n(u)}{u^n}\right\}^2$$

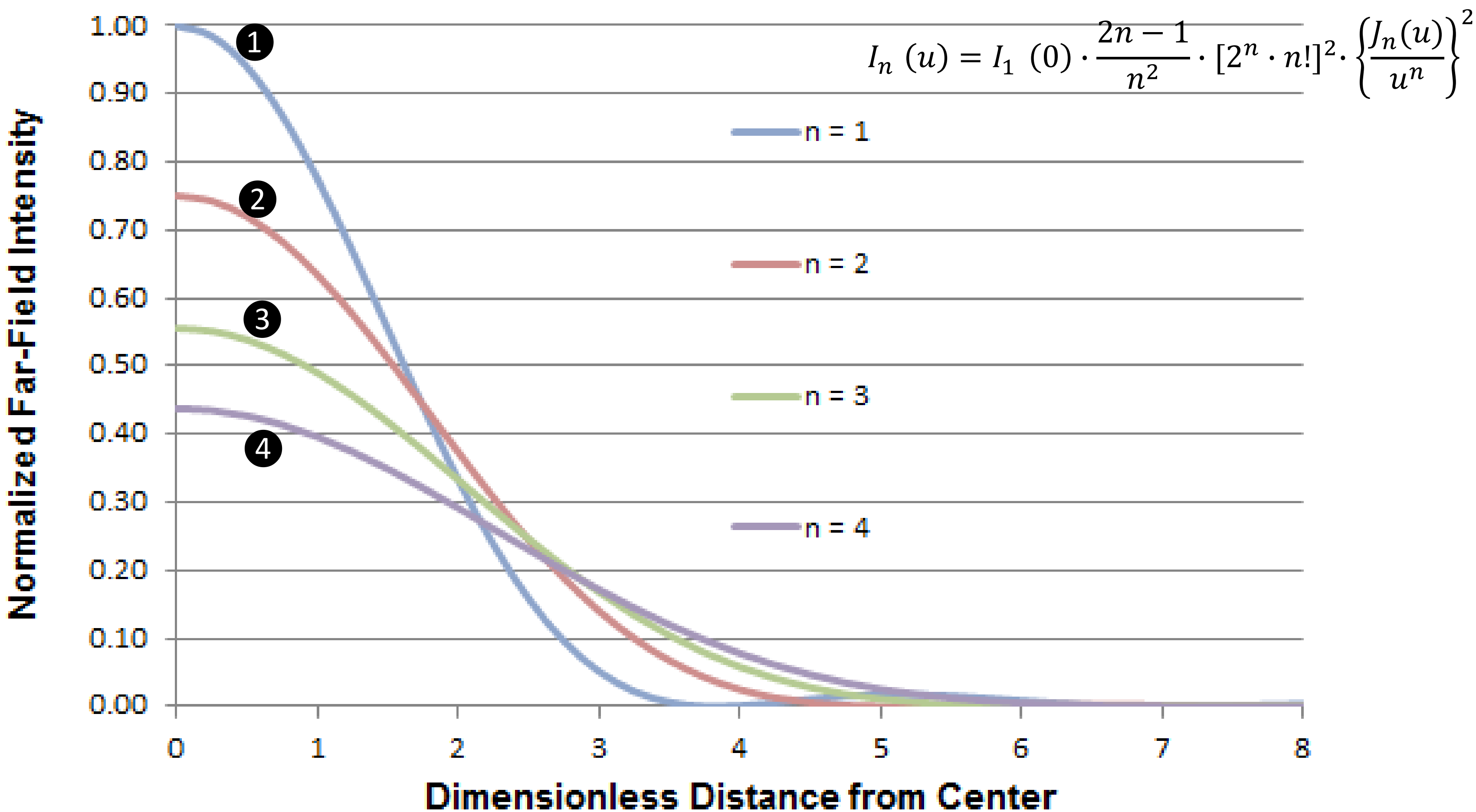
Where $J_n(u)$ is the nth-order Bessel function of the first kind
u = dimensionless distance from center of antenna pattern in plane of receiver
r = distance from center of antenna pattern (with appropriate units)
D_t = transmitting antenna array diameter
λ = wavelength
x = distance from transmitter to receiver

Far-Field Electric Field Distributions



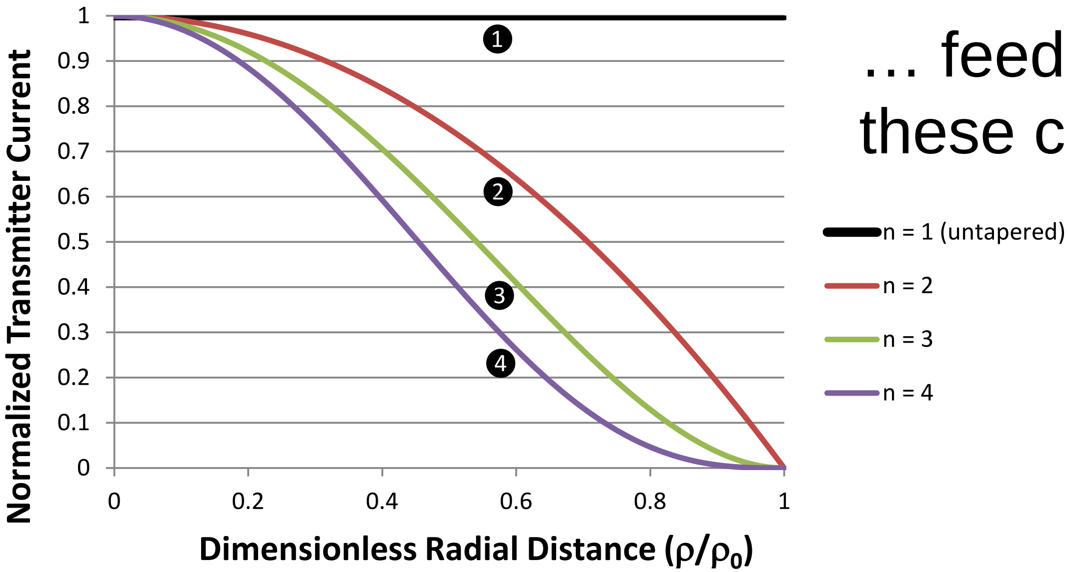
Far field electric field distribution as a function of radial dimensionless distance in plane of receiving antenna. Normalized to the peak intensity of each case.

Far-Field Energy Distributions

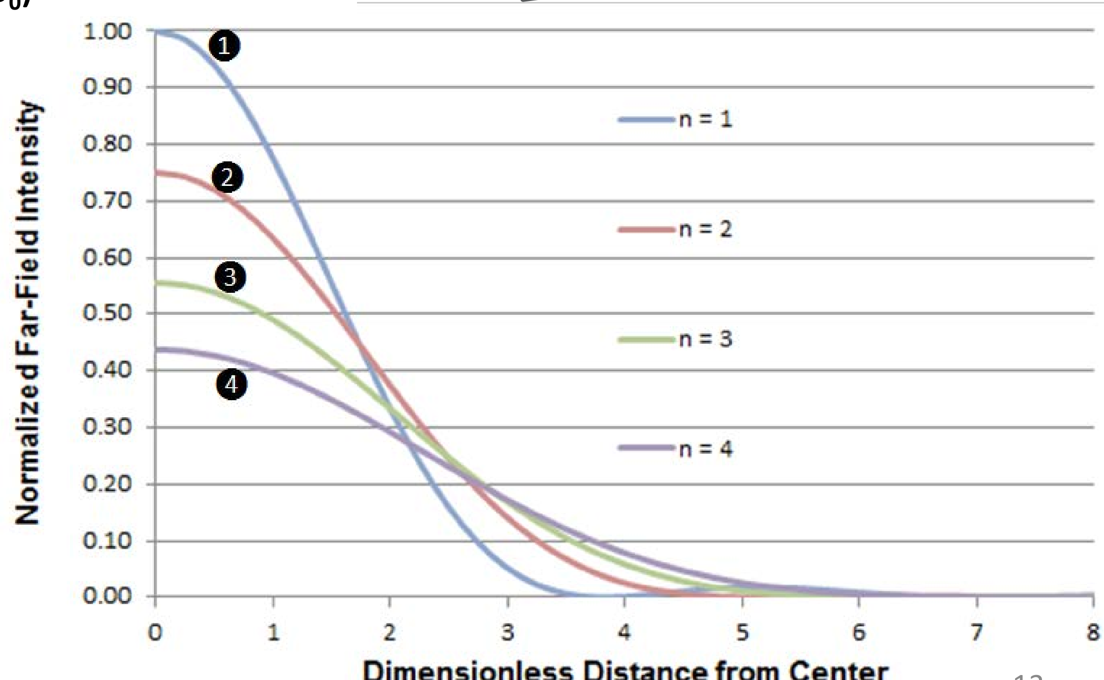


Far field energy distribution as a function of radial dimensionless distance in plane of receiving antenna. Normalized to the peak intensity of the n = 1 case.

In Other Words …

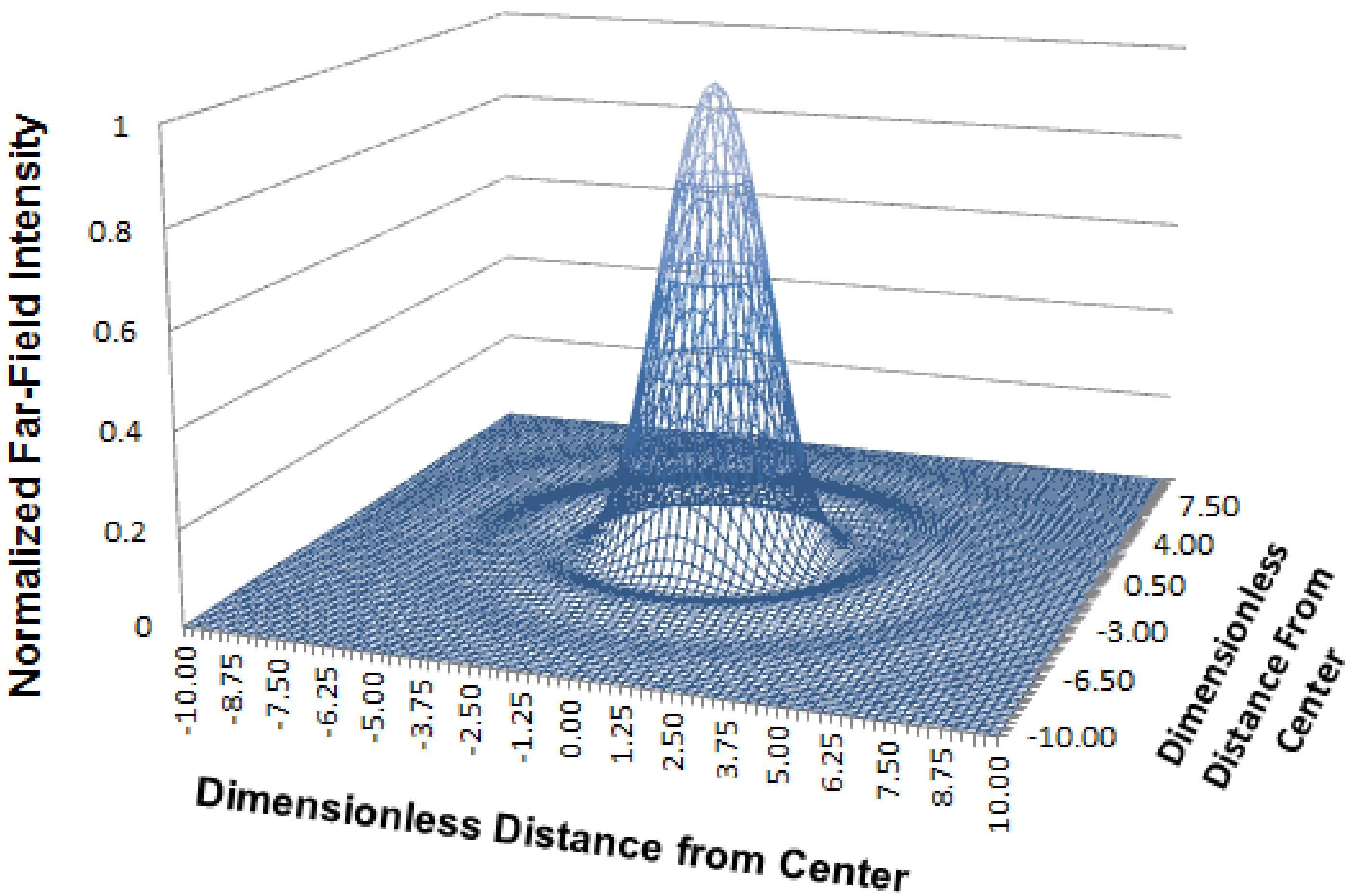


… feed the transmitter these currents …

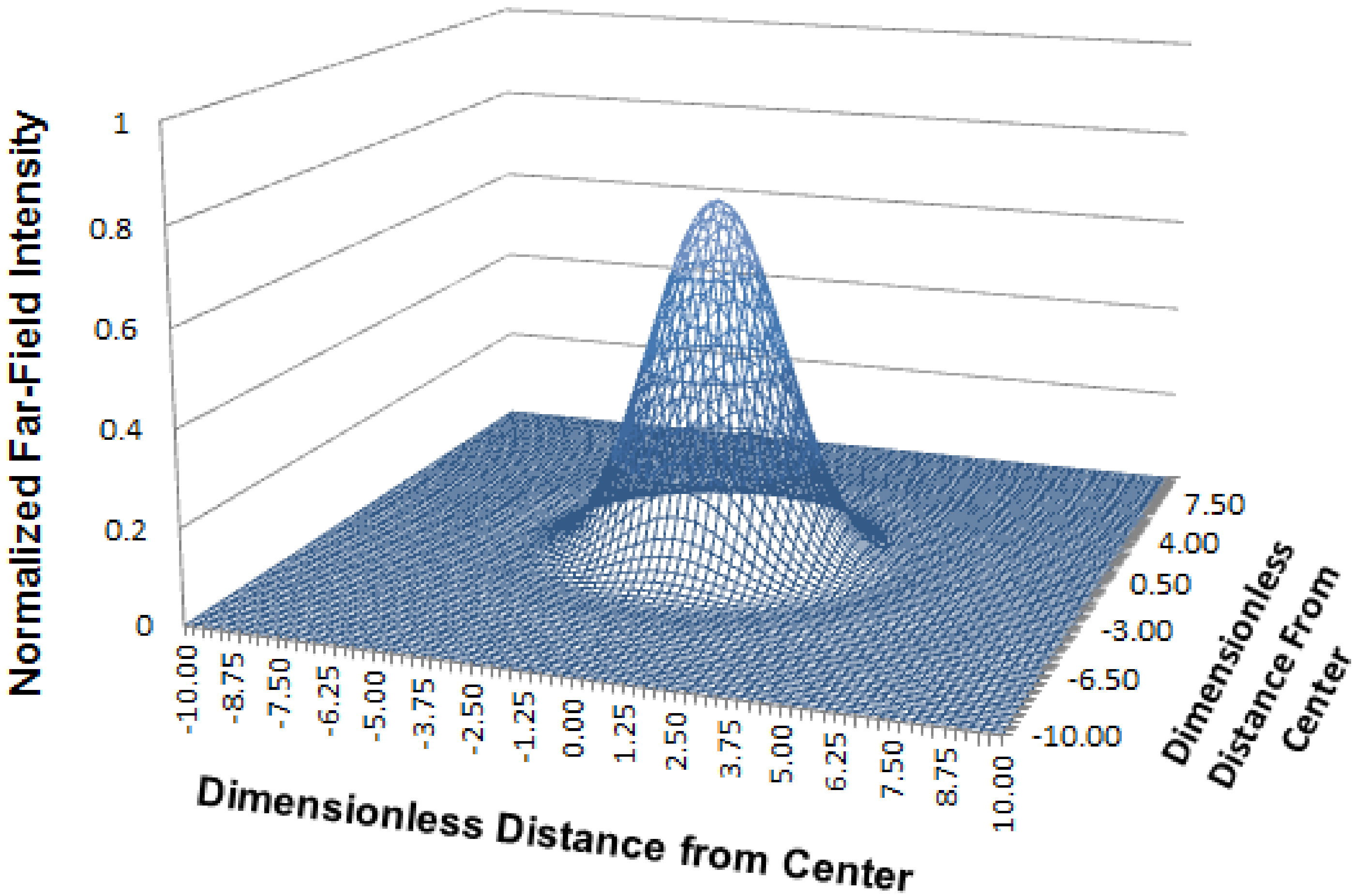


… to get these energy patterns at the receiver.

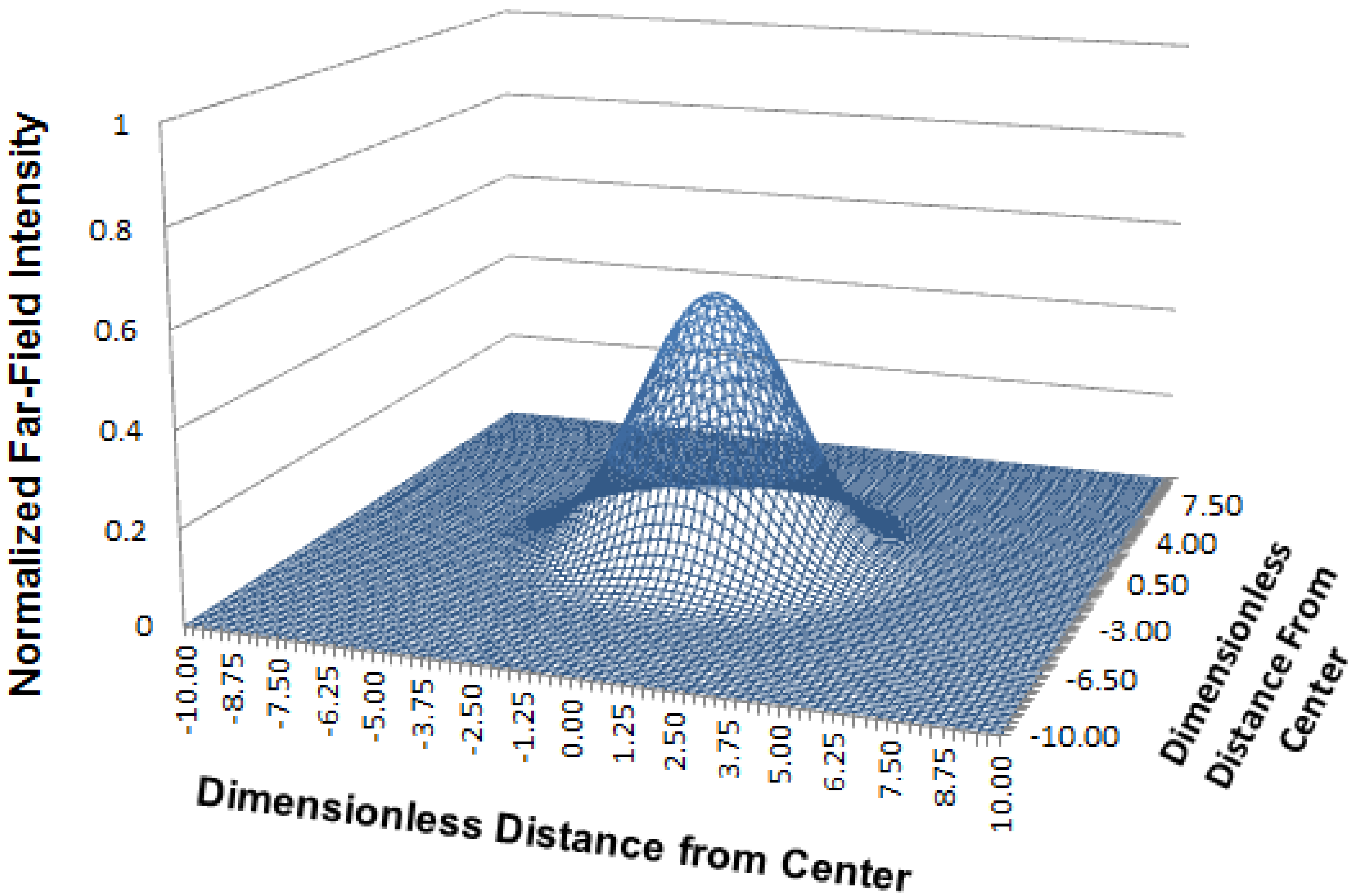
Energy Distribution – Case 1 (3D)



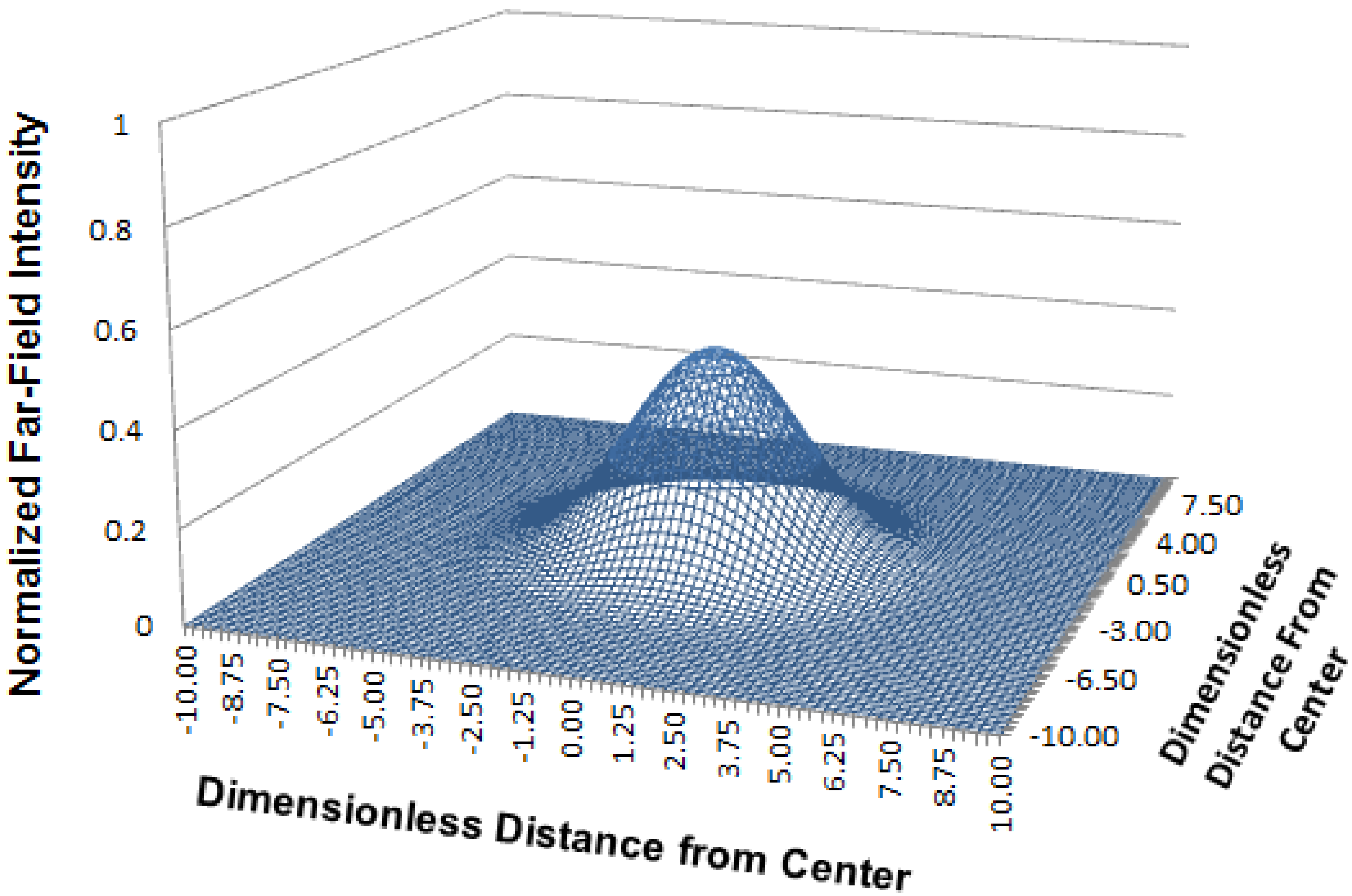
Energy Distribution – Case 2 (3D)



Energy Distribution – Case 3 (3D)

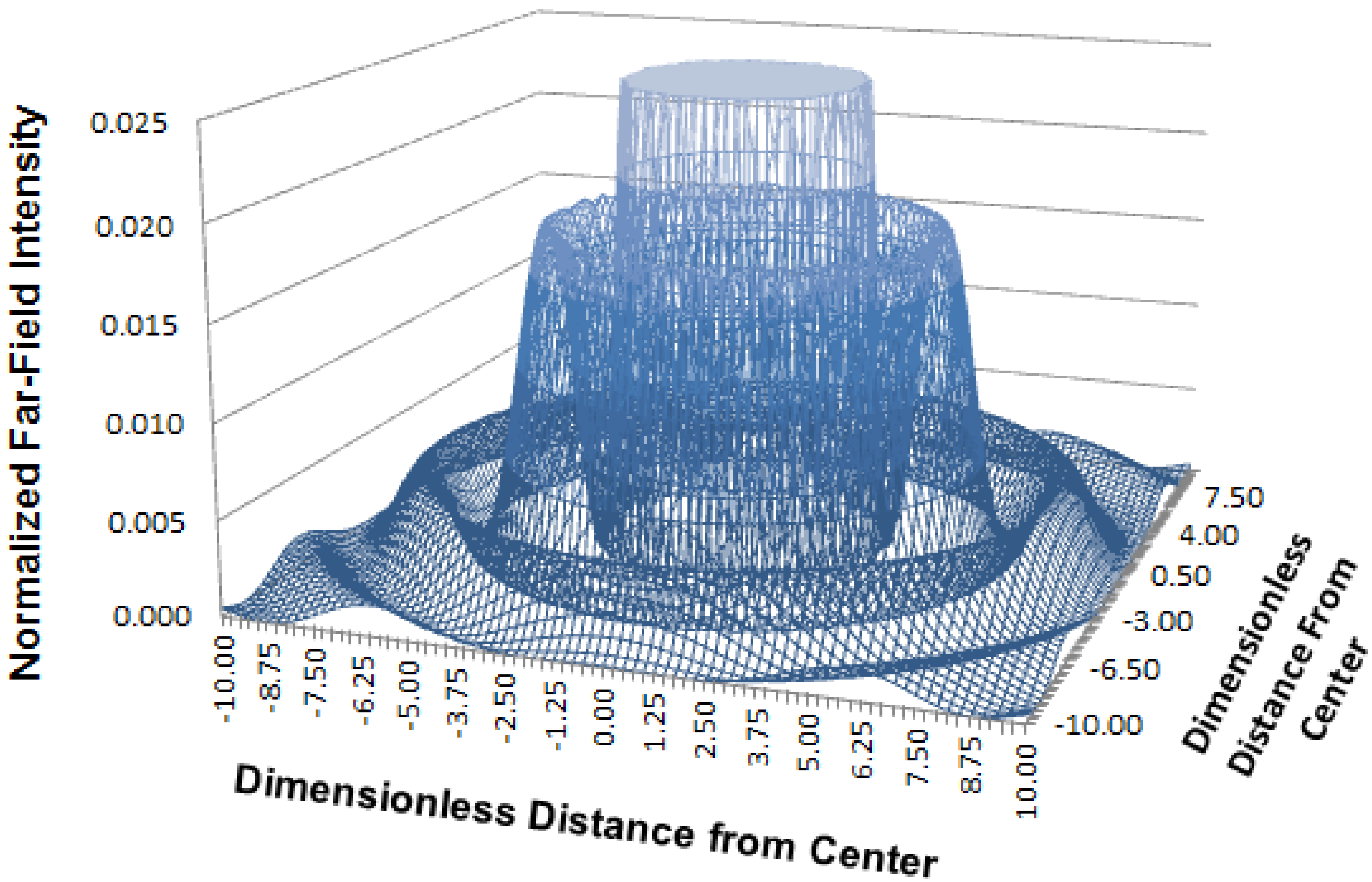


Energy Distribution – Case 4 (3D)



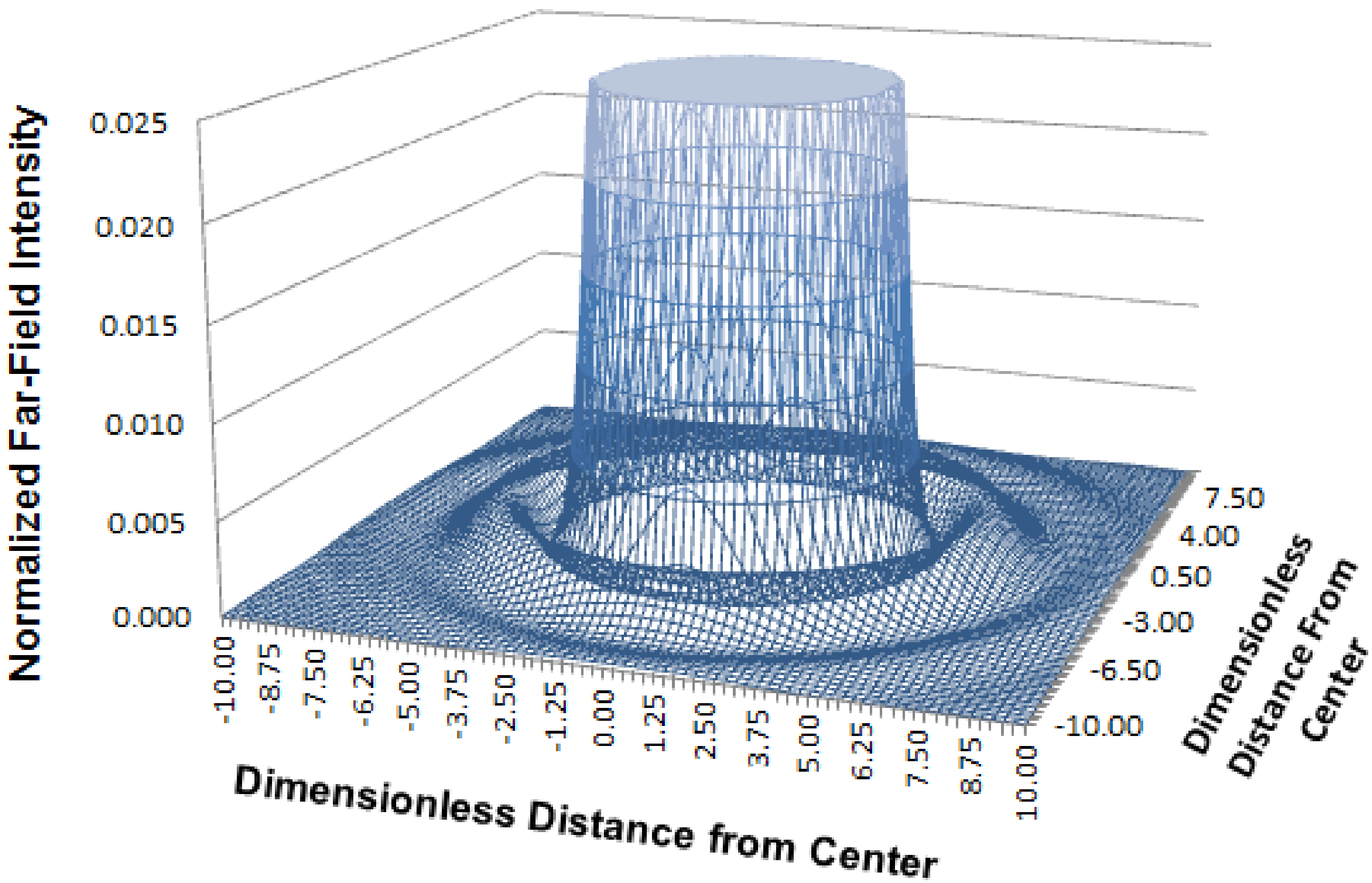
Energy Distribution – Case 1 (3D)

(Vertical scale expanded to show sidelobes)



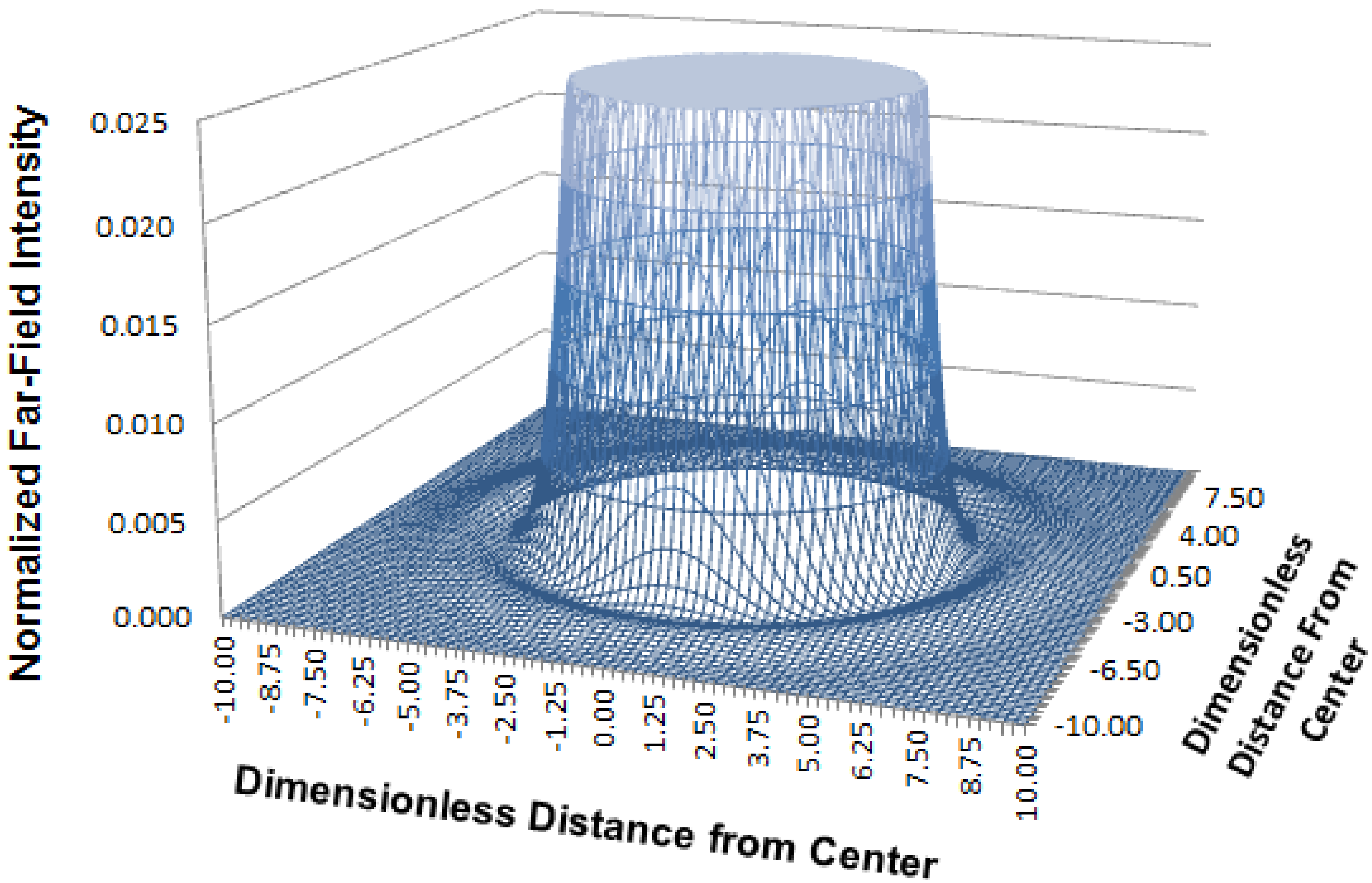
Energy Distribution – Case 2 (3D)

(Vertical scale expanded to show sidelobes)



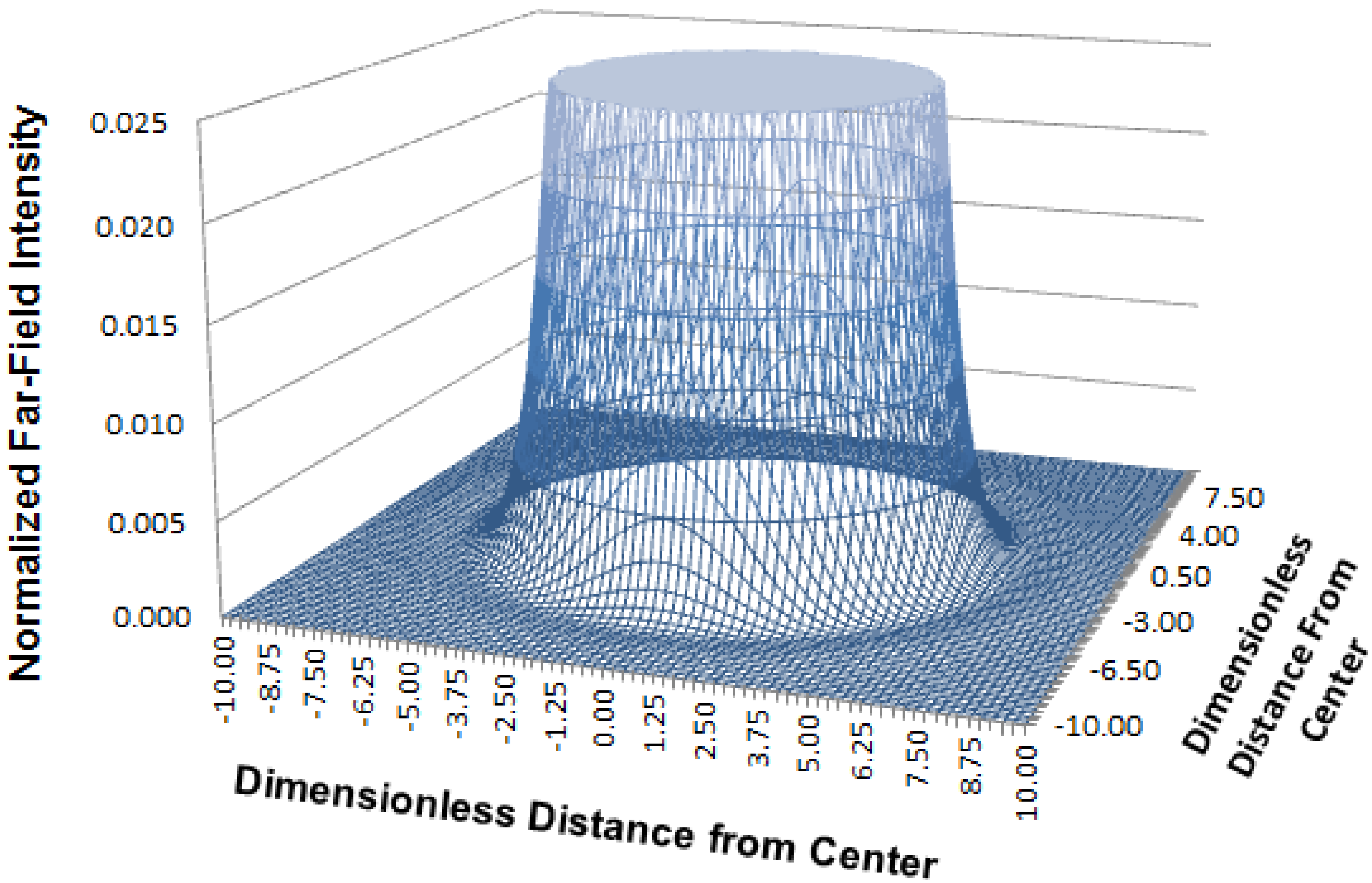
Energy Distribution – Case 3 (3D)

(Vertical scale expanded to show sidelobes)

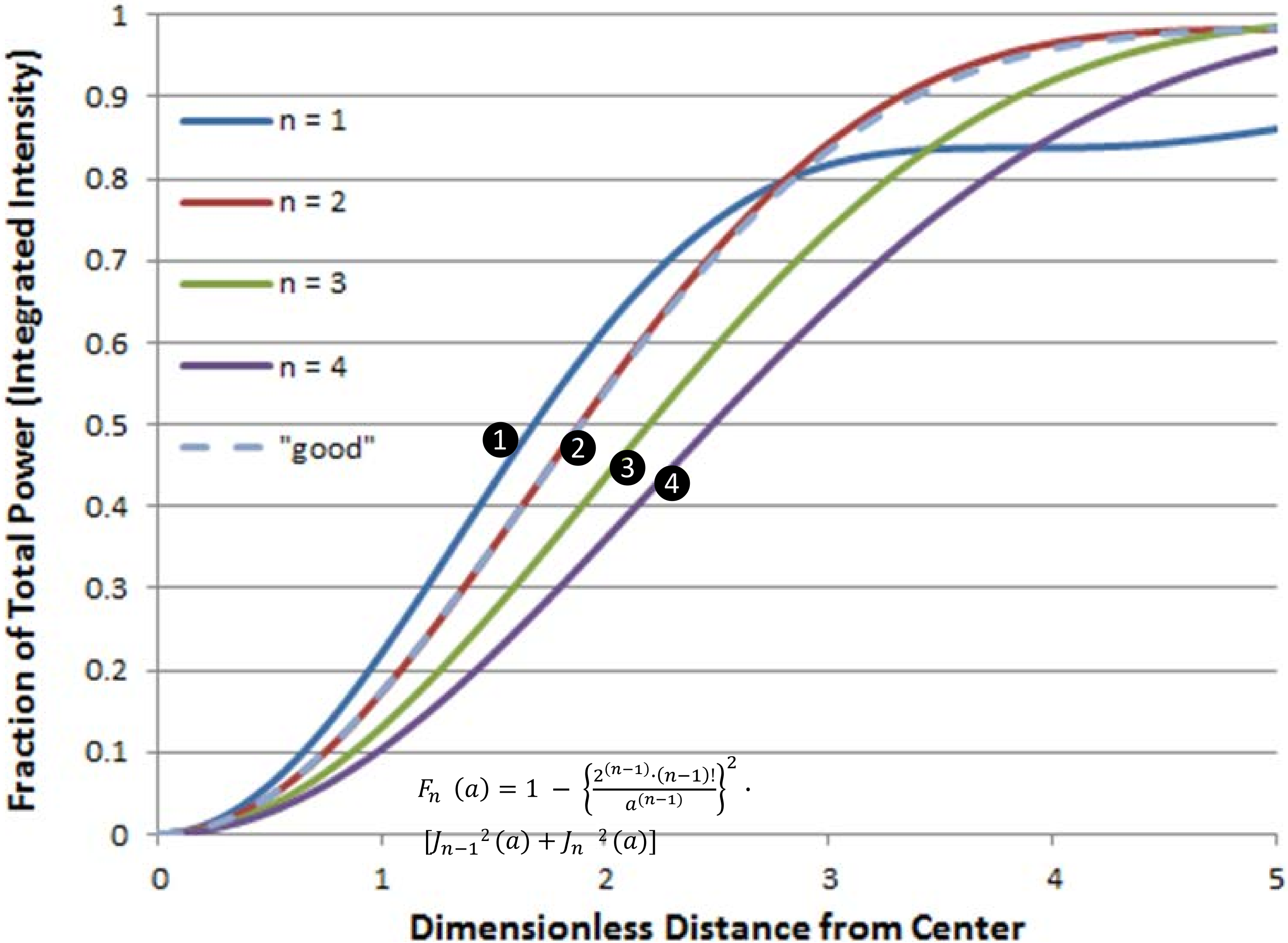


Energy Distribution – Case 4 (3D)

(Vertical scale expanded to show sidelobes)

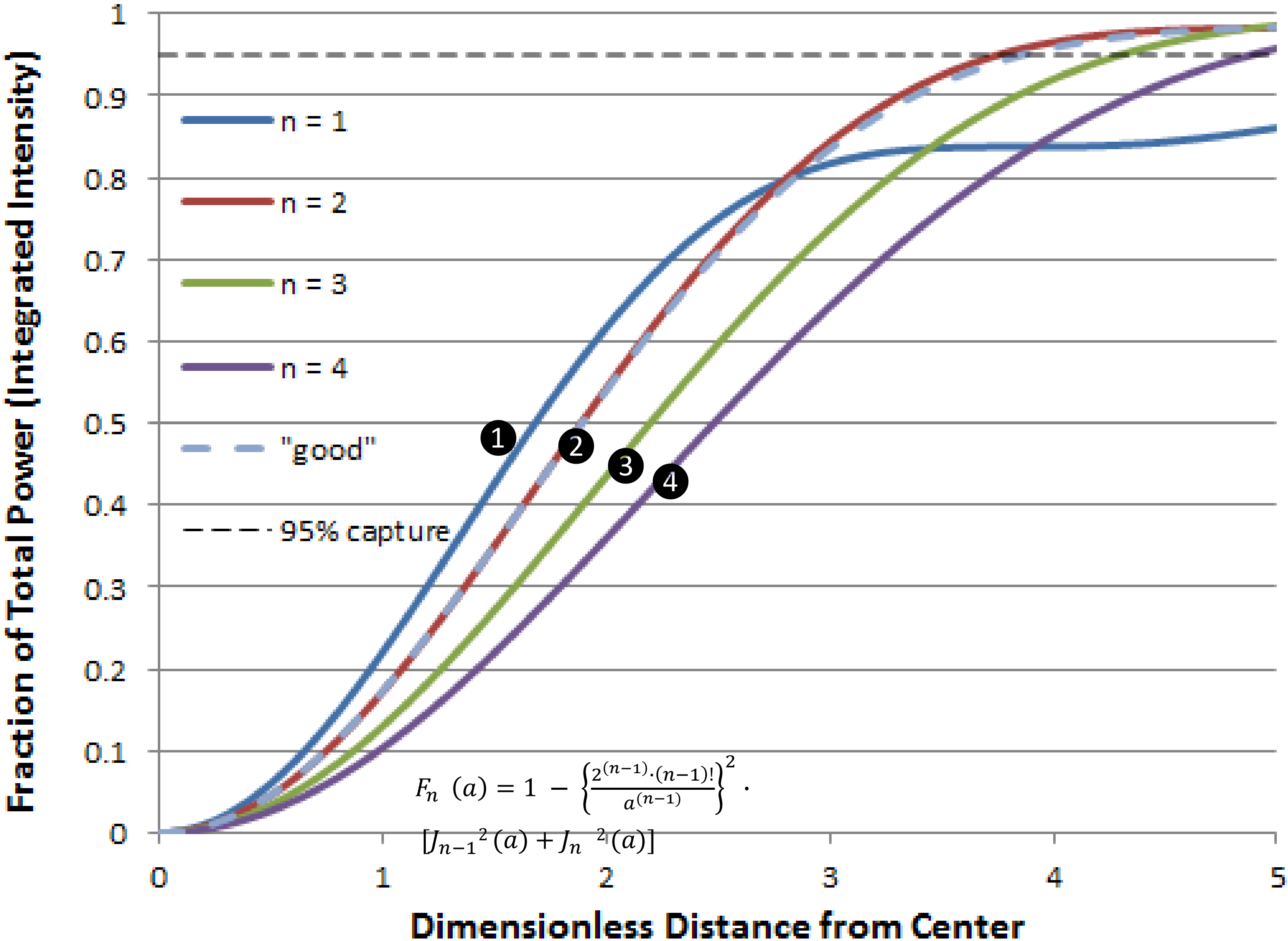


Rectifying Antenna (Rectenna) Sizing

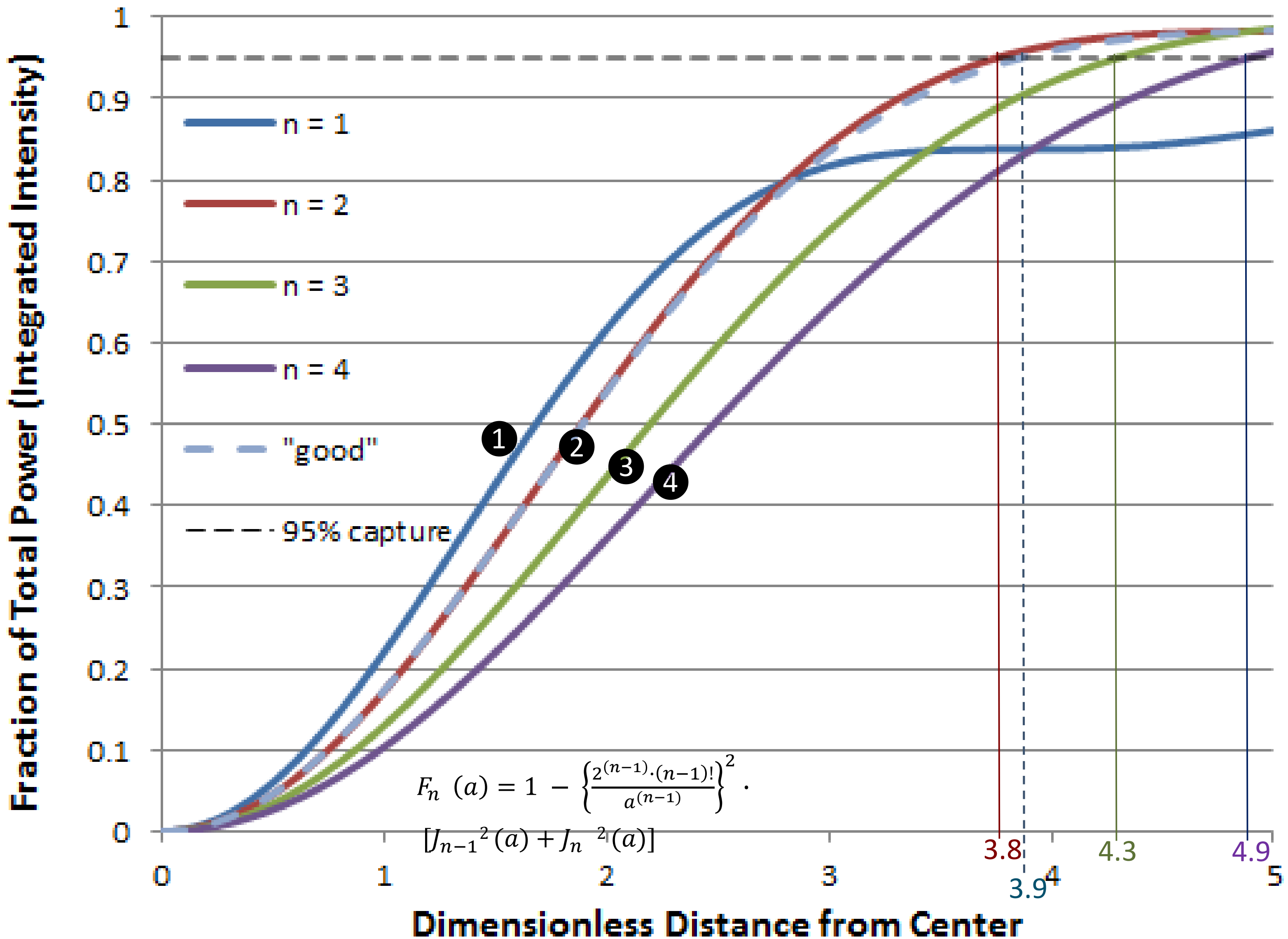


$$F_n(a) = 1 - \left\{\frac{2^{(n-1)}\cdot(n-1)!}{a^{(n-1)}}\right\}^2 \cdot [J_{n-1}^2(a) + J_n^2(a)]$$

Rectifying Antenna (Rectenna) Sizing



Rectifying Antenna (Rectenna) Sizing



Satellite Specifications

Satellite	Typical Mission	Typical Orbit	Mass at Launch (kg)	First Customer	Power Level (kW)	Reference
Boeing 702 HP	Communications	GEO	5400-5900	PanAmSat Corp.	>12	http://www.boeing.com/space/boeing-satellite-family/
Boeing 702 MP	Communications	GEO	5800-6100	Intelsat	6 to 12	http://www.boeing.com/space/boeing-satellite-family/
Boeing 702 SP	Communications	GEO	1500-2000	Asia Broadcast Satellite	3 to 8	http://www.boeing.com/space/boeing-satellite-family/
Boeing 702 HP GEM	Communications	GEO	1500-2000	MEXSAT	8 to 10	http://www.boeing.com/space/boeing-satellite-family/
Boeing 502			1000		1.5	http://www.boeing.com/space/boeing-satellite-family/
Lockheed Martin AEHF	Military Communications					http://m.lockheedmartin.com/us/products/advanced-extremely-high-frequency--aehf-.html
International Space Station	Research	LEO	419,725		84 -120	https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays.html
Hubble Space Telescope	Research	LEO	11,110		~2.1 average	http://hubble.stsci.edu/the_telescope/hubble_essentials/quick_facts.php

Client Satellite Orbits

Altitude (km)	Orbital Period (hours)	Shadow Duty Cycle (fraction)	Time in Shadow (hours)	Comments
200	1.47	0.421	0.621	
350	1.53	0.397	0.605	ISS
540	1.59	0.373	0.594	Hubble
1,000	1.75	0.332	0.582	
1,500	1.93	0.300	0.581	
2,000	2.12	0.275	0.584	
5,000	3.36	0.189	0.636	
20,200	11.98	0.077	0.924	GPS
35,786	23.93	0.048	1.157	GEO at equinoxes

- Maximum fraction of time in shadow varies greatly, but is a fairly consistent half hour to hour, typically ~36 minutes
  - For non-equatorial orbits, time may be shorter if line of nodes of orbit not aligned with sun vector
- To be investigated: can a common power supplying satellite, operating in collect-store-transmit mode be designed for multiple orbits, with individual units deployed in particular orbits

Power Transmission Modes

Order-of-Magnitude Distance	Power Transmission Mode / Wavelength	Pros	Cons
Contact	Conduction	Most efficient	Requires rendezvous & docking w/each client; hence, extensive redesign of client
Meters	Inductive or magnetic coupling	Highly efficient	Requires rendezvous w/each client; possible EMI
10's - 100's of meters	Full spectrum lamp	Little or no redesign of client; minimal EMI	Less efficient; requires rendezvous
Up to 10's of km	Microwaves	Highly efficient; extensible to full-scale SSP	Requires some redesign of client; ΔV required to serve multiple clients; possible EMI
Up to 100's of km	Millimeter waves	Efficient; extensible to full-scale SSP	Requires some redesign of client; ΔV required to serve multiple clients; possible EMI
Up to tens of 1000's of km	Lasers (IR or optical)	Can serve multiple clients without changing orbits, modest redesign of client, depending on choice of wavelengths; minimal EMI	May be less efficient, unless laser matched to solar array bandgap; treaty/legal/weaponization issues

Electromagnetic Environmental Effects

(from MIL-STD-464C)

- Current standards for space systems vary greatly by frequency

TABLE 3. Maximum external EME for space and launch vehicle systems.

Frequency Range (MHz)		Electric Field (V/m – rms)	
		Peak	Average
0.01	2	1	1
2	30	73	73
30	150	17	17
150	225	4	1
225	400	*	*
400	700	47	6
700	790	1	1
790	1000	7	7
1000	2000	63	63
2000	2700	187	187
2700	3600	23	8
3600	4000	2	2
4000	5400	3	3
5400	5900	164	164
5900	6000	164	164
6000	7900	6	6
7900	8000	3	1
8000	8400	1	1
8400	8500	3	1
8500	11000	140	116
11000	14000	114	114
14000	18000	16	9
18000	50000	23	23

NOTE: *denotes no emitters in that frequency range.

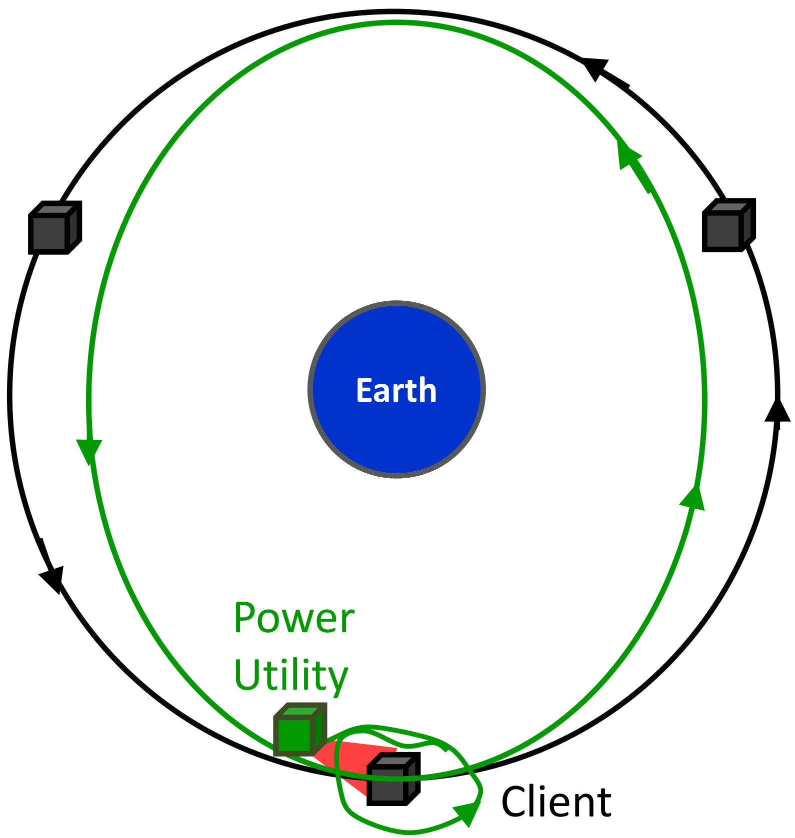
Maximum Beaming Distances

Transmit-ter Diameter (m)	Receiver Diameter (m)	Frequency (GHz)	Wavelength	Approx. Near Field Boundary (m)	Diffraction-Limited Distance (km)	Max Distance (km) for 50% Capture (Case 2)
20	20	2.45	12.24 cm	6.5	1.3	2.7
20	20	5.8	5.17 cm	15	3.2	6.4
20	20	35	8.57 mm	93	19	39
20	20	60	5.00 mm	160	33	67
20	20	94	3.19 mm	251	51	104
20	20	245	1.22 mm	654	134	272
3	20	3.0.E+05	1.00 μm	18,000	24,590	49,959

- Lasers at optical or IR wavelengths can beam to clients in different orbits without changing orbit
- Microwaves and millimeter waves will require orbital transfer to serve multiple client satellites

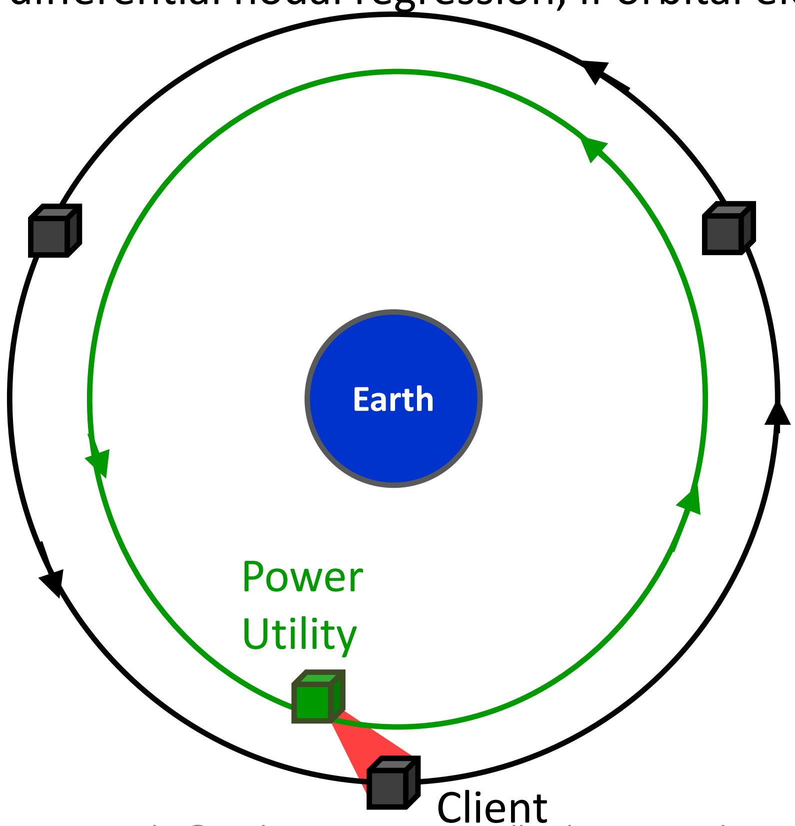
Scenario A: Proximity

- Dock for direct conductive connection
- Close rendezvous for inductive coupling
- Co-orbit in a "halo" of no more than a few km for microwave WPT or a few 10's of km for mm wave WPT
- Service client, then move on to next client in same orbital plane



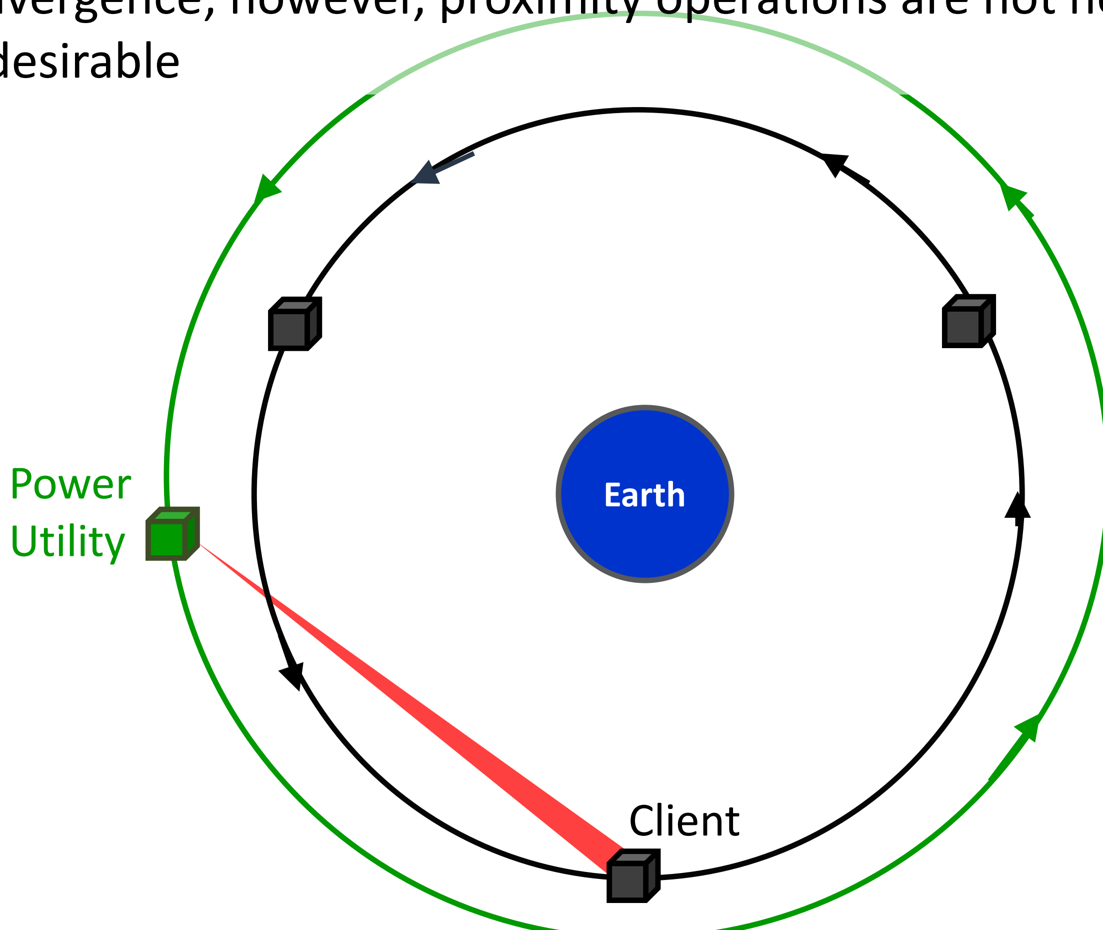
Scenario B: Flyby

- No rendezvous; power utility is in a slightly lower, or slightly higher orbit than client
- Wavelength: mm waves or shorter
- Service client during flyby, then move on to next client
  - Client likely in same plane
  - However, may be able to propagate from one plane to another with similar inclinations by differential nodal regression, if orbital elements are properly chosen



Scenario C: Beam Slewing

- Orbit transfer not needed
- Beaming distance: up to thousands of km
- Service client, and move on to next client, by beam slewing
- Wavelength: infrared or optical
- Can take advantage of orbital motion to extend contact time and minimize beam divergence; however, proximity operations are not needed, and may not be desirable



Conclusions

- A process has been developed to assess the market for a near-term space-based power utility to serve assets in space
- Preliminary application of this process suggests further work is justified
  - Need to determine more specific requirements; assess electrical and thermal limits on space-based WPT; beam contact times, as determined by orbital motion; etc.
- Such a utility can serve as a set of transitional steps toward a large-scale space solar power system to supply energy to Earth

Acknowledgements

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  - John Mankins
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  - Space Studies Institute / Gary Hudson, Lee Valentine
- Perspiration
  - Gary Barnhard
  - John Mankins
  - ISDC 2017 Organizing Committee

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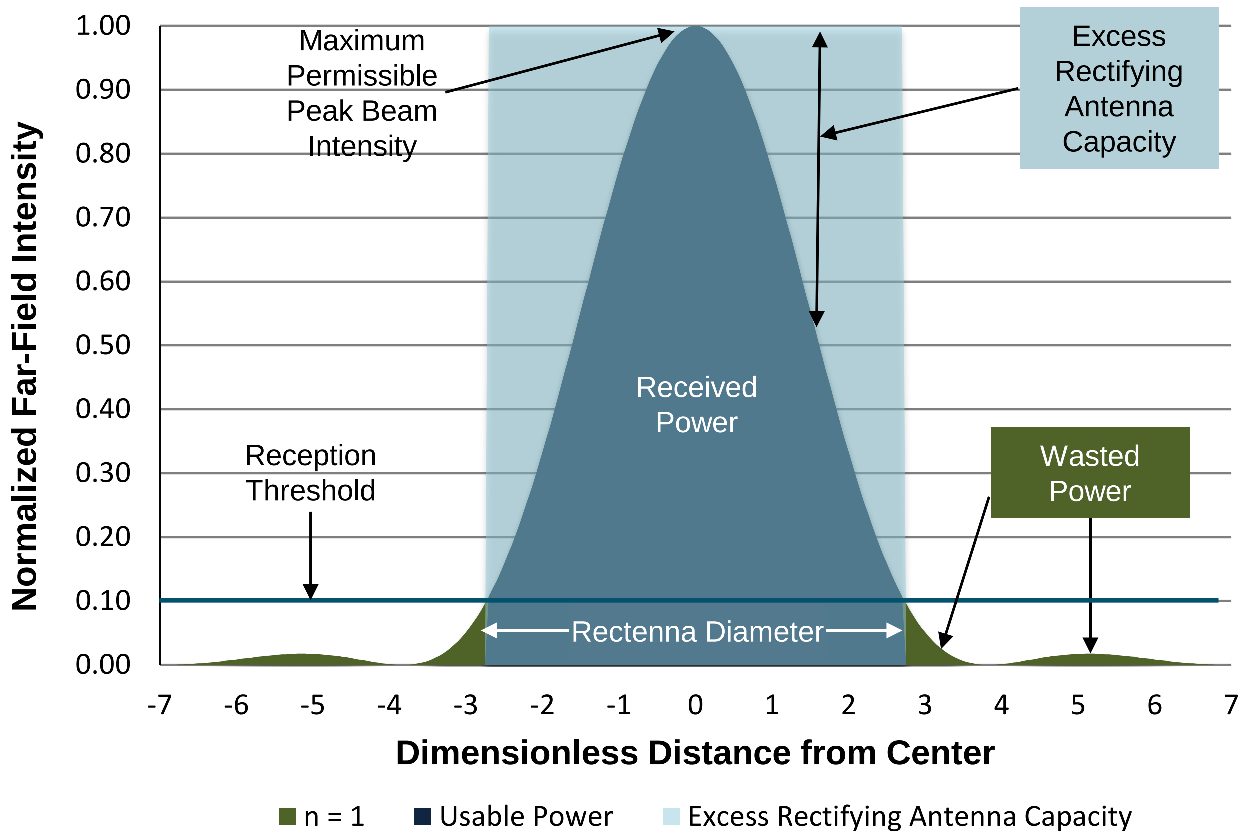
Backups

Relative Rectenna Sizes for Tapered Beams

Beam Taper	Relative Radius of Main Lobe	Relative Radius of 83.8% Capture Area	Relative Radius of 95% Capture Area	Relative Peak Beam Intensity	Fraction of Power in Main Lobe (F_n)	Power in Sidelobes (MW) if P_t = 5 GW
n = 1	1	1	3.21	1	0.8378	811
n = 2	1.34	0.775	0.98	0.75	0.9825	87.5
n = 3	1.67	0.901	1.12	0.556	0.9966	17.2
n = 4	1.98	1.02	1.27	0.438	0.9991	4.35
n = 5	2.29	1.13	1.42	0.36	0.9997	1.27
n = 6	2.59	1.23	1.55	0.306	0.9999	0.41
"good"	1.64	0.786	1.01	0.757	0.9851	74.5

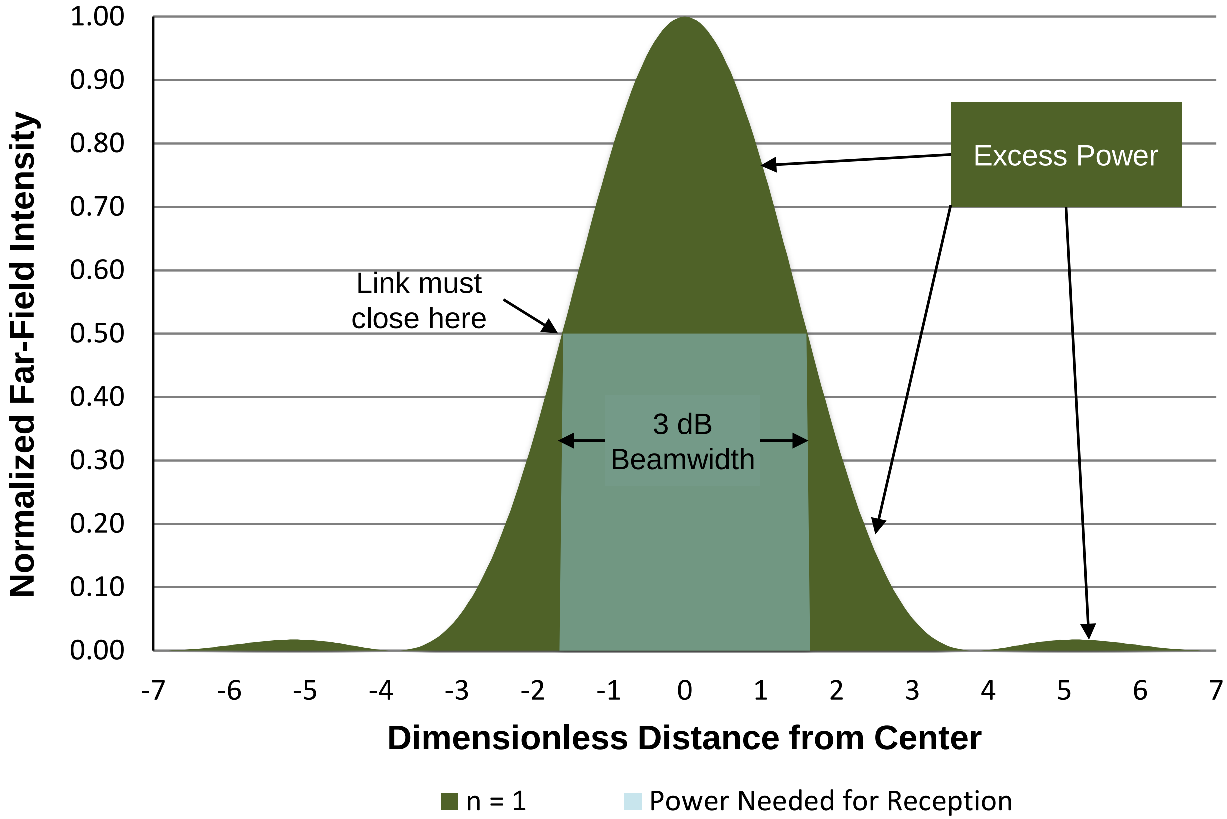
Relative radii are shown normalized to the n = 1 main lobe radius (which captures 83.8% of the power).

Implications for Systems Architecture: Wireless Power Transmission



- Traditional rectifying antenna (rectenna) capture efficiency = 2D integral (volume under curve) in region where intensity is above threshold (dark blue) / total volume under curve (green plus dark blue)
- Proposed figure of merit: capture efficiency x rectenna fill factor
  - Latter given by power incident on rectenna (dark blue) / total rectenna capacity (light blue + dark blue)

Implications for Systems Architecture: Communication



- Communication systems are typically (but not always) designed to close the link at the 3 dB (half-power) beamwidth
- Optimum beam shape may be a “flat top” – a limiting case, not fully achievable in practice
- Proposed figure of merit: power usage efficiency = power needed to close link in coverage area (blue) / total volume under intensity curve (green, including blue)