Georgia Institute of Technology

Department of Electrical and Computer Engineering

ECE 6390 - Satellite Communication and Navigation Systems

Title: Pilot signal to coordinate a distributed wireless power transfer aperture in space

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Team 1:
Jaxon Topel
Jason Fornek
Alexander Blair
William Trimble
Mohamed Zaher

Professor:
Gregory D. Durgin

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Motivation

The motivation behind our team choosing topic 3 is mainly backed by our individual interests and what fits our team's expertise best. We were all interested in a project that was more technically engaging in areas such as signal processing and RF engineering. We all came to our initial meeting drawn to topics that would challenge us to apply real-world communication system principles to modern space technology, and the pilot beam system stood out as a perfect intersection meeting all our goals and interests.

We believe this topic will provide us with an opportunity to explore system design and technical completion of an RF/Signal Processing system, which is a concept that will leverage key knowledge learned in class, specifically in areas such as link analysis, modulation theory, RF front-end design, and more. We will be challenged with designing an architecture that will include precise signal design for synchronization, RF link budgeting, and strategies to become resilient against jamming and other interference.

Beyond technical appeal, we were also motivated by choosing a project where we could gain further expertise and knowledge in the key areas of interest previously stated. By choosing this topic, our team will gain experience with advanced communication system design but also be able to contribute to the growing field of spaced based energy.

Expected Outcome

By the end of this project, our team will deliver a complete design, architecture, and analysis of a pilot beam coordination system for a geostationary (GEO) space-based power transfer aperture. The following outcomes detail the expected technical deliverables and discuss the results we currently intend to produce. The expected outcome for our project will consist of one earth antenna transmitting towards multiple satellites to coordinate a distributed wireless power transfer aperture in space. The following sections below will be the main deliverables of the IEEE two column journal we will be submitting.

Pilot Signal Design:

The pilot signal will serve as the core method behind synchronizing phase and frequency alignment across satellites in the distributed wireless power transfer aperture. Our design will focus on developing a reliable pilot signal transmitted from a single earth-based antenna to multiple satellites in geostationary orbit. This pilot will serve as a shared timing and phase reference that will allow each satellite to lock onto the same carrier frequency and maintain coherent beamforming toward the ground receiver. Various high-SNR modulation schemes will be investigated, and the best performing combination of signal characteristics will be used for our system design. Each satellite will continuously receive the pilot beam, extract phase and frequency offset information through a phase-locked loop (PLL) and adjust phase accordingly.

Through maintaining synchronization, the satellite system will operate as a coherent transmitting array which will maximize power transfer efficiency and minimize interference at the receiver. This strategy ultimately provides the framework for phase-aligned transmission across a GEO network, contributing to the realization of space-based power systems capable of highly efficient energy delivery.

RF Link Analysis:

The main goal of this analysis is to ensure that there is a sufficient amount of received power and signal-to-noise ratio for a reliable phase lock and hence alignment between the microwave power beam and the pilot signal.

The first part of designing the RF link is to understand the medium we are operating in and determine a frequency band that will be successful in transmitting and receiving at our desired targets. Considering this is a GEO based communication link, C, X, Ku, and Ka band are most common for this distance depending on the application. Having careful and narrow beam steering will also be important in order to transmit and receive signals at this distance, hence why many satellites operate in Ku and Ka band where there is a wider bandwidth available. Also, it’s necessary to consider the gains of each antenna (and relays) because it is estimated that there is roughly 200dB of path loss between earth and GEO.

We propose using an uplink signal from ground to GEO array elements. The center frequency and bandwidth will be further studied during the project phase. However, we are targeting a pilot frequency of around 5.8 GHz, and the bandwidth will be a few MHz (will be more determined by the chosen modulation scheme). The chosen frequency and the bandwidth will certainly affect the free-space propagation loss (FSPL), which is an integral part of the link budget analysis especially since we are dealing with a large distance from earth to GEO of around 36,000 km.

Another important part that needs to be addressed carefully is the earth's TX EIRP and GEO satellite's Rx antenna gains. Not only the antenna gains, but we also have to design for a proper beamwidth to get a desired pointing accuracy. The perturbations that can affect the antenna positioning on both sides will have a significant impact on the antenna gains. Hence, we need to evaluate how much tolerance we could handle in the antenna positioning accuracy before the antenna gain drop below the threshold level dictated by the receiver's sensitivity.

To ensure a proper reception of the pilot signal at GEO, we need to account in our budget for all sources of noise in the system as well as for the interferers. Both the noise and the interferers lower the SNDR of the system, which increases the BER at the RX side. Interferers can cause gain desensitization at the RX's LNA, reducing the SNR significantly and hence the sensitivity. Phase noise of the pilot signal can also degrade the SNR and hence the phase lock accuracy, so we need to study how to account for that in our link budget analysis.

One vital relationship that we need to investigate in this project is how to choose a specific Rx sensitivity (or SNR) to meet a specific phase-error target and ensure the phase alignment to the degree that we want. For example, if our microwave beam should be within a phase error of 1 deg at the earth's rectenna, then how can we determine and ensure RX's sensitivity to the pilot signal to achieve that.

In addition, we need to account for other possible distortion sources in our link budgeting like rain attenuation and atmospheric absorption. Moreover, in case of using relay satellites in other orbits then we may need to account for the doppler shift as well since these satellites are moving with respect to the earth and the GEO satellite.

Placement of Transmitters/Relays:

An important aspect of the system's design is the placement and number of pilot signal transmitters and relays. These considerations will impact the design choices of the pilot signal itself, as well as its efficacy in coordinating the aperture. Estimations of link budget and orientation of satellites in the aperture will further influence these choices.

We will also determine specifics in how the transmitters will contact each satellite, whether that is best done through a highly directional antenna that must be steered (such as a phased array or mechanically steered antenna), or whether a wider beam that can reach multiple satellites at once is feasible.

Determination of the number of relays, and if any are strictly necessary, will take potential visibility and blackout periods into account. Furthermore, fail safes and backup transmitters and relays will also be considered to ensure continuous power transmission. In the case that several relays are utilized, considerations such as phase synchronization and higher precision formation position will factor into the design of antenna geometry and beam steering method. Additionally, the altitude of the relays in relation to the main satellite will be studied to weigh advantages in LEO orbit such as reduced path loss and lower transmission requirements vs disadvantages such as higher complexity in alignment and shorter orbital lifetime due to drag.

Finally, we will investigate the best ways to estimate the current position and orientation of each satellite to best account for orbital perturbations that accumulate over time.

Resistance to Noise, Interference, & Jamming:

For our pilot signal design, we must take into account scenarios where our signal could be interrupted due to noise, interference, and jamming. For a ground-to-satellite communication link, there can be poor atmospheric conditions, orbital perturbations, rain attenuation, and passive and active jamming. These effects will be further investigated and related back to how the medium is disrupted. The key measurement needed to be successful in transmitting and receiving our pilot signal is SNR and Signal-to-Jammer-plus-Noise-Ratio (SJNR). One key aspect that shall be understood is the difference between interference and jamming in earth's atmosphere versus in a vacuum like space. This is necessary to understand because signals are disturbed differently in each medium, subsequently leading to challenges when transmitting from a ground station, through LEO, and receiving in GEO. In addition, one paper suggests that satellite-to-satellite jamming is an emerging threat due to the proximity and wave propagation characteristics in free space allows for more directed and dense attacks. [12] This may be a topic beyond the scope of this project, however, it may be worth investigating since we plan on transmitting the pilot signal to multiple paddle satellites.

Milestones Chart & Work Distribution Plan

Date	Task	Assignee
10/292025	Initial Meeting	Team 1
11/3/2025	Meeting #2, Work Distribution	Team 1
11/4/2025	Project Proposal	Team 1
11/12/2025	Solidify Technical Approach for all aspects of the project.	Team 1
12/3/2025	Complete Pilot Signal Analysis & write up	Jaxon Topel & Mohamed Zaher
12/3/2025	Complete Noise, Interference, & Jamming analysis	Jason Fornek & Jaxon Topel
12/3/2025	Complete Placement of Transmitters & Relays analysis	Alexander Blair & William Trimble
12/3/2025	Complete RF Link Analysis	Mohamed Zaher & Jason Fornek
12/3/2025	Complete All Technical Analysis & Report Write up	Team 1
12/5/2025	Project Due Date	Team 1
12/11/2025	Peer Evaluations	Team 1
12/11/2025	Team Member Evaluations	Team 1

Figure 1: Comprehensive Milestone Chart and Work Distribution Planning.

Tasks to be done:

1- System architecture for the whole transmitter-relay-ground rectenna
2- Link budget analysis --> calculate free-space propagation loss, antenna gains, receiver sensitivity, noise, SNR, BER, ...
3- Pilot signal design: determine the type of pilot signal, frequency, power, modulation scheme, ...
4- Interference & jamming investigation: develop understanding of the surrounding environment and the possible jammers and how to make out system more robust.
5- Orbital geometry: calculate the deterministic look angles between the GEO and ground rectenna station, study the effect of the orbital and environment perturbations on the calculated look angles in the case with and without pilot tone used.
6- Integration between all different investigations and designs and summarizing into a well-documented report.

References

[1] W. C. Brown, "The History of Power Transmission by Radio Waves," in IEEE Transactions on Microwave Theory and Techniques, vol. 32, no. 9, pp. 1230-1242, September 1984, doi: 10.1109/TMTT.1984.1132833.

[2] C. T. Rodenbeck, Ming-yi Li and Kai Chang, "A phased-array architecture for retrodirective microwave power transmission from the space solar power satellite," 2004 IEEE MTT-S International Microwave Symposium Digest (IEEE Cat. No.04CH37535), Fort Worth, TX, USA, 2004, pp. 1679-1682 Vol.3, doi: 10.1109/MWSYM.2004.1338912.

[3] T. Takahashi, T. Mizuno, M. Sawa, T. Sasaki, T. Takahashi and N. Shinohara, "Development of phased array for high accurate microwave power transmission," 2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, Kyoto, Japan, 2011, pp. 157-160, doi: 10.1109/IMWS.2011.5877112.

[4] Y. Homma et al., "New phased array and rectenna array systems for microwave power transmission research," 2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, Kyoto, Japan, 2011, pp. 59-62, doi: 10.1109/IMWS.2011.5877091.

[5] S. Sasaki, K. Tanaka and K. -i. Maki, "Microwave Power Transmission Technologies for Solar Power Satellites," in Proceedings of the IEEE, vol. 101, no. 6, pp. 1438-1447, June 2013, doi: 10.1109/JPROC.2013.2246851.

[6] A. Massa, G. Oliveri, F. Viani and P. Rocca, "Array Designs for Long-Distance Wireless Power Transmission: State-of-the-Art and Innovative Solutions," in Proceedings of the IEEE, vol. 101, no. 6, pp. 1464-1481, June 2013, doi: 10.1109/JPROC.2013.2245491.

[7] C. R. Valenta and G. D. Durgin, "Harvesting Wireless Power: Survey of Energy-Harvester Conversion Efficiency in Far-Field, Wireless Power Transfer Systems," in IEEE Microwave Magazine, vol. 15, no. 4, pp. 108-120, June 2014, doi: 10.1109/MMM.2014.2309499.

[8] W. Jiang and W. M. D. Wright, "Full-Duplex Airborne Ultrasonic Data Communication Using a Pilot-Aided QAM-OFDM Modulation Scheme," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 63, no. 8, pp. 1177-1185, Aug. 2016, doi: 10.1109/TUFFC.2016.2570434.

[9] Q. Gao, J. Lv and G. -x. Li, "Performance Analysis of Orthogonal Coded Modulation Based on 6PSK and BPSK in Alerting Channel for GEO Mobile Satellite System," 2010 International Conference on Signal Acquisition and Processing, Bangalore, India, 2010, pp. 322-326, doi: 10.1109/ICSAP.2010.52.

[10] B. Qiang, B. Jiang and X. Gao, "Pilot sequence design for GEO multi-beam MIMO satellite communication system," 2014 Sixth International Conference on Wireless Communications and Signal Processing (WCSP), Hefei, China, 2014, pp. 1-5, doi: 10.1109/WCSP.2014.6992056.

[11] D. M. Kovalev and A. B. Sergienko, "Optimization of Pilot Signal Power in OFDM-Based OTFS System," 2025 27th International Conference on Digital Signal Processing and its Applications (DSPA), Moscow, Russian Federation, 2025, pp. 1-5, doi: 10.1109/DSPA64310.2025.10977871.

[12] A. Boumeftah, O. Ben Yahia, J. -F. Frigon, G. Falco and G. K. Kurt, "Adaptive Detection of On-Orbit Jamming for Securing GEO Satellite Links," 2025 12th Advanced Satellite Multimedia Systems Conference and the 18th Signal Processing for Space Communications Workshop (ASMS/SPSC), Sitges, Spain, 2025, pp. 1-8, doi: 10.1109/ASMS/SPSC64465.2025.10946028.