MULTIBEAM SATELLITE RESOURCE ALLOCATION FOR SIMULTANEOUS TRANSFER OF INFORMATION AND POWER

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Abstract

The wireless power transfer technology has recently drawn attention of communications and energy experts since it can alleviate the power shortage problem of communication nodes and devices. Its practical application, however, is limited to a very short range communication (less than 1m) only and academic research has been focused on energy harvesting in cellular network scenarios. In this paper, we address a problem of simultaneous transfer of information and power from an advanced multibeam satellite equipped with phased array antenna. First, we discuss the common and different features between information and power transfer from a satellite when they are mathematically modeled and practically implemented in terms of free-space loss, multipath channel, bandwidth allocation, power signal level, etc. Next, we formulate a resource allocation problem for the utility maximization of power transfer and information transmission, and show that the optimal solution is based on channel conditions, user demand for information (and quality of service requirements if added), safety requirement for received power amount, and interference among spotbeams that is primarily determined by geographical distribution of rectennas and receivers. The formulation and analysis developed in this paper can be an initial step towards realizing solar power transmission from multibeam satellites to the Earth in the near future.

1. Introduction

Wireless power transfer is considered as a game-changing solution for recyclable energy and advanced communication technology. However, due to technical difficulties, it is currently limited to a short-range (less than 1m) resonance induction and energy harvesting in a beginning step for cellular networks. Academic research has been focused on terrestrial cellular network scenarios in the name of simultaneous wireless information and power transfer (SWIPT) [1, 2] or information-theoretic approach [3, 4]. The space-based solar power transmission [5, 6] from satellites has been a long-term project and is finally expected to be realized in a few decades [7]. In addition to the traditional application for information transmission, the simultaneous transmission of information and power from satellites can allow uninterrupted connectivity to isolated areas. The space-terrestrial heterogeneous network [8, 9], which consists of satellites and terrestrial subnets, can feed solar power from the space to large rectennas (rectifying antennas) located in unpopulated areas, and then distribute to each user through terrestrial power line or wireless links. Fig. 1 illustrates a scheme of emergency networks with simultaneous transmission of information and power, which can be realized in the space-terrestrial heterogeneous network.

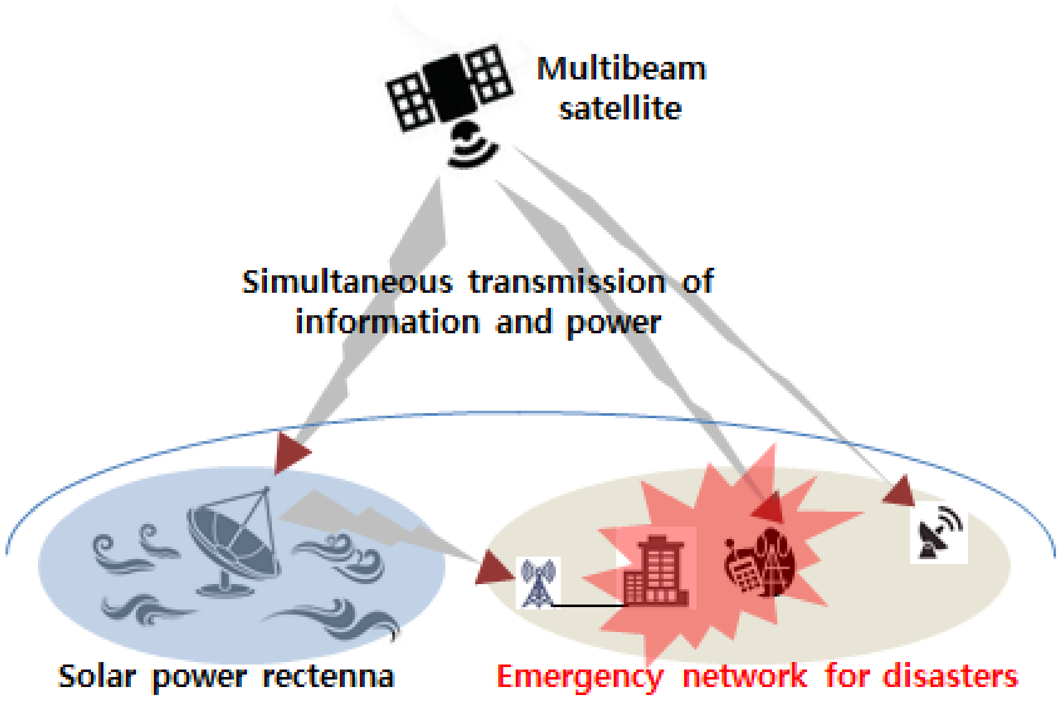

Fig. 1. An emergency network with simultaneous transmission of information and power.

Realizing solar power transmission still requires a lot of technical advancement, such as deployment of very wide solar panels with high-efficiency power amplifiers, satellite body structure to sustain a high volume of antennas and amplifiers, and a large scale of rectennas on the ground. Even if the focus of the research and development for solar power transmission has been on the aforementioned mechanical and physical technologies, the development of the high-layer architecture and protocol, which is optimized for power transfer as well as information transmission, should be accompanied. This paper attempts to shed light on the mathematical modeling and analysis for high-layer structure of solar power satellites in the perspective of communication network layers by comparing with the traditional communication satellites for information transmission. We investigate the technology for simultaneous transmissions of information and power that can distribute the solar energy from an advanced multibeam satellite equipped with phased array antenna [10].

The rest of the paper is organized as follows: In section 2, we compare the common and distinct features of power and information transfer. In section 3, an example of a resource allocation problem is provided with its mathematical solution under the constraints of simultaneous information and power transfer. Section 4 concludes the paper.

2. Comparison of Power Transfer to Information Transmission

In this section, we compare the common and different features between information and power transfer from a satellite in terms of free-space loss, power attenuation, bandwidth allocation, and signal power level. These features can be useful for mathematical modeling and analysis of simultaneous information and power transfer.

Signal attenuation due to free-space loss is governed by the Friis transmission equation [11] with the received signal power inversely proportional to the square of the propagating distance in the same way as for information. Let us suppose a geostationary (GEO) satellite at the altitude of 36,000 km that transmits power at the Ka band (around 30 GHz). The power attenuation of more than 200 dB by free-space loss only is obtained by the Friis equation as follows:

$$\text{Power loss} = -20 \log_{10} (\text{wavelength}/4\pi/\text{distance}) = -20 \log_{10} (0.01\text{m}/4\pi/36{,}000\text{km}) = 213 \text{ dB}$$

Assuming the receiver gain up to 130 dB with a wide diameter of 3 km, the receiver gain is as follows:

$$\text{Receiver gain} = 20 \log_{10} (2\pi \text{ diameter}/\text{wavelength}) = 20 \log_{10} (2\pi * 3\text{km}/0.01\text{m}) = 126 \text{ dB}.$$

Based on these numbers, the beamforming gain of near 90 dB at the transmitter with a diameter of the order of 10m to 100m would be preferred to compensate for free space only. This implies that transmission beamforming should be able to generate very narrow agile spotbeams in a very large scale.

Since the solar power rectennas are currently planned to be installed in unpopulated areas such as deserts and oceans due to safety reasons, the multipath effects are not considered to be a major concern. With a large scale of stationary rectennas in the beginning blueprint, the issue of mobility in the receiver side will be suppressed as well. Rain and moisture at the atmosphere are still big causes for power attenuation, in particular, making it hard to utilize high frequency bands for power transmission. Channel prediction and system adaptation techniques should be more aggressive for power transmission through the atmosphere. Nevertheless, a simple method of shutting down power transmission to an area with a bad channel condition can still improve power transmission efficiency.

The trade-off between power and information transfer in terms of bandwidth allocation, which is shown in the short-range resonant coupling [3], is also applied to the long-range transmission. The wider the bandwidth is, the bigger the information capacity is, but the less efficient the power transfer is. High-efficiency wideband antennas for power transmission and reception can be made of gallium nitride (GaN) solid-state power amplifiers (SSPA), which is one of the major research areas for solar power transmission. As the solar power transmission level is aimed at as high as 1GW, it is practically infeasible to integrate a large number of travelling wave tube amplifiers (TWTAs). While some other technologies such as klystron and magnetron are explored, cost-efficient and stable integration of SSPA will be a key to the success of the solar power transmission project [5].

Table 1 summarizes the differences between information and power transmission, which can be used for mathematical modeling and analysis.

	Information transmission	Power transmission
Free space loss	Proportional to the squared distance	
Transmitted power level	~ 1kW	Up to 1GW
Satellite Tx antenna size	< 10 m	~ 100 m
Ground station Rx antenna size	~ 10 m	~ 3 km
Mobility support	Yes	No
Power attenuation	Rain, atmospheric moistures, multipath, shadowing, blocking, Doppler shifts	Rain and atmospheric moistures
Power amplifiers	TWTA, SSPA	Klystron, magnetron, SSPA (made of GaN)

Table 1. Comparison of information and power transmission.

3. Resource Allocation for Simultaneous Transfer of Power and Information

As described in Section 1, previous research on solar power transmission has been focused on the physical layer implementation. The high-layer protocol and cross-layer architecture optimized for simultaneous transfer of power and information cannot be ignored since they have big impact on the overall system performance. In an attempt to illustrate an exemplary work on high-layer design, in this section, we set up a resource allocation problem for maximum utility that is a function of transferred power and data transmission rate. We note that similar problems in the terrestrial energy harvesting scenario can be found in [12-14].

3.1. Formulation

Let us suppose a satellite that can transmit power and information simultaneously to I (≥1) solar power rectennas and J (≥1) information receivers. It is currently known that the state-of-the-art receiver architecture cannot receive power and decode information from the same signal at the same time [1]. Therefore, we assume that the solar power rectenna and the information receiver are independent of each other, and separate power should be allocated for respective purpose.

The objective is to maximize the system utility U, which is a function of power transfer and data transmission rate, under some constraints. Let P_i denote the amount of on-board satellite power transferred to solar power rectenna i ($1 \le i \le I$) and R_j the data transmission rate with on-board satellite power Q_j assigned to information receiver j ($1 \le j \le J$). We assume that the signal power attenuation denoted by α_i^2 (or α_j^2) over the link to rectenna i (or receiver j) is due to weather effects that only change quasi-statically. The power loss incurred by deploying the zero-forcing transmission strategy is represented by H_i (or H_j) and is given by a function of the beamwidth and the distance between active rectennas and receivers. We assume that interbeam interference occurs when active rectennas/receivers are located within one spotbeam width, which is defined as the mainlobe width of the narrowest sportbeam. The problem is formulated as follows:

$$\text{Maximize } U(\alpha_i^2 H_i P_i, R_j)$$

Subject to

$$\alpha_i^2 H_i P_i \le P^{max},\ 1 \le i \le I$$
$$R_j \ge R_j^{min},\ 1 \le j \le J \quad \text{and}$$
$$\sum P_i + \sum Q_j \le P^{total},$$

where P^{max} denotes the maximum power limit that a rectenna receive, R_j^{min} the minimum data rate that receiver j requires, and P^{total} the total on-board power available for the satellite, respectively. One difference between power and information transmission is reflected in the first constraint, such that the power transmission problem has maximum power constraints for power transmission spotbeams, which are not imposed for information transmission beam if SSPAs are used instead of TWTAs. Due to health safety and environmental protection, the amount of received power should be controlled under an allowable threshold, for example, $10W/m^2$ as the typical maximum number allowable for human exposure [7]. The second constraint represents that each information receiver requires receiving the minimum data rate to satisfy traffic demand and QoS requirement. Note that additional QoS constraints can be imposed in a similar manner. The last constraint is on the total on-board power limitation to be used for simultaneous power and information transmission.

3.2. Analysis

We assume that the utility U is a concave function of P_i and R_j. The data rate R_j is modeled as Shannon capacity of the assigned power Q_j:

$$R_j = W \log(1+ \alpha_j^2 H_j Q_j / WN_0),$$

where W is the bandwidth used and N_0 is the additive white Gaussian noise power density. Thus, the utility is also a concave function of Q_j. The satellite is assumed to have K active beams to transmit power and information at the same time. With $K \ll I+J$ in practice, the satellite should decide which rectennas and/or receivers will be served at each time slot.

By solving the Lagrangian function that is constructed from the utility maximization problem and applying the Kuhn-Tucker condition in the similar way as previous work [8, 9], we derive the following equations:

$$\partial U/\partial P_i - \omega_i \alpha_i^2 H_i = \lambda \text{ and}$$
$$\partial U/\partial Q_j + \kappa_j \partial R_j/\partial Q_j = \lambda,$$

where ω_i, κ_j, and λ are the Lagrangian multipliers for $\alpha_i^2 H_i P_i \leq P^{max}$, $R_j \geq R_j^{min}$, and $\sum P_i + \sum Q_j \leq P^{total}$, respectively. The multiplier has a non-zero positive value only when the equality of the corresponding constraint holds (i.e., the constraint is active [15]), and is equal to zero when the inequality holds but the equality does not (i.e., the constraint is inactive [15]). According to the derived equations, the optimum scheduling for the satellite can be summarized as follows:

- When the constraints of $\alpha_i^2 H_i P_i \leq P^{max}$ and $R_j \geq R_j^{min}$ are inactive, the rectenna(s) or receiver(s) that give the highest marginal return of the utility with respect to the allocated power should be served.
- As the power is multiplied with channel condition α_i^2 (or α_j^2) and potential interbeam interference loss H_i (or H_j), $\partial U/\partial P_i$ and $\partial U/\partial Q_j$ have $\alpha_i^2 H_i$ and $\alpha_j^2 H_j$ multiplied respectively. Thus, the rectenna(s) and receiver(s) that have better channel conditions and less interbeam interference are preferred.
- The amount of power allocation is decided in the similar way as the water-filling algorithm [16].
- When the constraint of $R_j \geq R_j^{min}$ is active, the amount of power allocated to the receiver should be sufficient to satisfy the minimum data rate requirement.
- When the constraint of $\alpha_i^2 H_i P_i \leq P^{max}$ is active, the amount of power allocated to the rectenna should be upper-bounded.

In summary, the result indicates that the optimal solution for simultaneous information and power transmission should be based on channel conditions, user demand for information (and quality of service requirements if added), safety requirement for received power amount, and interbeam interference among spotbeams.

4. Conclusion

Microwave power transfer and radio frequency (RF) energy harvesting have recently drawn attention as they can be a future solution for convergence of communications and energy technologies. However, the focus has been on the implementation of physical devices and analysis of the terrestrial case. In this paper, we considered a problem of simultaneous transfer of information and power from an advanced multibeam satellite equipped with phased array antenna from the perspective of power transfer networks. First, we discussed the common and different features between information and power transfer from a satellite in terms of free-space loss, multipath channel, bandwidth allocation, power signal level, etc. when they are mathematically modeled and practically implemented. Next, we provided an exemplary resource allocation problem for the maximum utility with respect to power transfer and information transmission. The constraints taken into account are to guarantee the minimum information transmission and to keep the received power under the maximum threshold for safety. From mathematical analysis, we showed that the optimal solution is based on channel conditions, user demand for information, power safety requirements, and potential interbeam interference.

Future work may include more detailed performance analysis of the resource allocation algorithm for simultaneous power and information transfer from satellites, development of control and feedback signals from ground to satellite, and ultimate interconnection between solar power satellites and terrestrial smart grids.

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