Thesis Title:

UAV-aided RF Energy Transfer Towards Sustainable IoT Networks

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The internet traffic is growing very rapidly due to exponential growth in the number of Internet of Things (IoT) devices used in different applications. These devices need to operate perpetually for uninterrupted sensing and data gathering in order to report the undesired events. Finite battery capacity of IoT device is the major hurdle towards its perpetual operation in long run, because they consume appreciable amount of energy during sensing, processing, and communication. Further, the installation of wired electricity infrastructure is not possible everywhere due to security, expenditure, or physical constraints. This is a very crucial factor in the next generation wireless network due to increase in number of IoT devices. To this end, this dissertation aims at the energy replenishment solution to ensure perpetual operation of the IoT network. An unmanned aerial vehicle (UAV)-aided energy replenishment framework is proposed in this dissertation, wherein the UAV is considered to travel and hover above the IoT devices and charge them wirelessly through radio frequency energy transfer (RFET). In this dissertation, the theoretical and the experimental avenues of UAV-aided RFET is explored to investigate the limitations and optimization possibilities in practical deployment.

As a first step, a new channel model for UAV-aided RFET is developed. This model plays a key role in RFET-based recharging of wireless IoT devices. Several representative field environments, such as suburban, urban, dense urban, urban high-rise, and rural agriculture deployment scenarios, are considered. The buildup areas are emulated as per the international telecommunication union radio-communication sector (ITU-R) recommendations, whereas time varying dynamics of vegetation growth is considered for rural agriculture. The proposed path loss models for suburban and rural agriculture deployment scenarios are validated by conducting Air-to-Ground (AtG) RF transmission experiments.

The developed path loss model is used to design the charging mechanism for the field deployed IoT devices. The notion of RFET zone is defined; the IoT devices located within it this zone can harvest energy from the UAV-mounted transmitter. Then, the effective power harvested at the IoT devices located at different spatial locations is evaluated by considering the impact of shadowing statistics of path loss and non-linear RF-to-direct current conversion efficiency. With these findings, an optimization problem is formulated with an objective of minimizing the total time in a charging cycle, which is comprised of travel time and charging time. Then, three different charging protocols, namely Voltage-aware Charging Sequence, Operational Time-aware Charging Sequence, and Iterative Charging Sequence, are proposed for performance evaluation in terms of number of healthy sensor nodes in a given deployment area.

To investigate the practical feasibility of AtG RFET, the experimental demonstration is performed by two methods. The transmitter is mounted on a static tripod in the first one, whereas the transmitter is mounted on the bottom of UAV in the second one. The power harvester module is placed below the transmitter, which harvests power from the received RF wave. It is observed that the energy harvested in case of tripod-based AtG RFET set up is comparatively higher than that in case of UAV-based AtG RFET set up. This deviation is caused due to hovering inaccuracy of UAV, which arises due to global positioning system (GPS) error and rotational motion of UAV during mission execution. Based on these experiments, a framework to analyze the hovering inaccuracy of UAV is presented, which comprises of two types of mismatches: Localization mismatch (LM) and Orientation mismatch (OM). Also, the impact of hovering inaccuracy on the performance of UAV-aided RFET is investigated using the data collected from experimental setup.

Using the analysis of hovering inaccuracy, the individual as well as joint impact of mismatches on the received power at ground deployed IoT device is characterized. A generalized radiation pattern of UAV-mounted transmitter antenna is considered for this purpose. A total of four cases arise due to two types of mismatches, i.e., LM and OM. An optimization problem is formulated to find the optimal system parameters: transmit power, hovering altitude, and antenna exponent. To solve this, an algorithm, called Hovering Inaccuracy-aware Optimal Charging System Design, is proposed to find the optimal system parameters. It is observed that the received power at the sensor node reduces significantly in presence of hovering inaccuracy as compared to ideal scenario. Further, the effect of LM is more severe than that of OM.

In the last part, a mitigation strategy to overcome the effect of hovering inaccuracy on UAV-aided RFET is presented. For this purpose, an antenna array is mounted on the bottom of the UAV; this array radiates power over a narrow beam directed towards the sensor node with very high gain. However, the directed beam does not point towards the sensor node due to rotational motion of the UAV, which leads to deviation in the elevation angle. An analytical framework to model this deviation in elevation is presented and its variation is estimated using the data collected through an experimental setup. Then, the optimal system parameters are estimated by formulating an optimization problem. It is observed that the proposed framework significantly mitigates the hovering inaccuracy and the same performance can be achieved with substantially less transmit power level.