論 文 の 内 容 の 要 旨

論文題目　　Design of Multitone Waveforms for RF Energy Harvesting Systems
（RFエネルギーハーベスティングシステムを実現するマルチトーン波形の設計）

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The achievements made through the development of science and technology have been changing our lifestyles more conveniently. The integrated circuits introduced in almost every electronic device nowadays enable such devices more portable, more convenient, and more energy-efficient. Recently, the Internet of Things (IoT) has been widely known to people around the globe; collecting a considerable amount of information will become a new paradigm for humans to yield better quality of life, efficient operations in factories, and so forth. In making this paradigm, low power operations of sensor devices become one of the keys as the power supply becomes cumbersome when all these devices need to be connected through the cable or embed batteries that require periodic recharge frequently. An extreme version of low power operated sensors is the devices that work without batteries, which can be seen in daily life as a radio frequency identifier (RFID) tags, transportation cards, and as such. These devices cannot operate computationally intense tasks; however, simple sensing tasks can be substituted by these devices. Recent progress has made it possible to add software-programmable functions by users to such devices known as wireless identification sensing platforms (WISPs), which will expand the wide use of battery-less devices.

Battery-less devices require an external power source for operations. Radio frequency (RF) wireless power transfer (WPT) technology is receiving a lot of attention as a means of power supply to support the spread use of these battery-less devices. Recently the opportunities to exchange information through wireless transmission have been increasing, which results in flowing enormous amount of electromagnetic (EM) waves around us. In addition, the technologies to extract power from the EM waves have made it possible to extract sufficient power to drive simple sensors; conveniently harvest from the environment becomes one of the reasons for gaining the attention for the battery-less devices as a primary source of energy. However, the integration of power consumption from the clock, peripheral modules results in requiring mW of power even for battery-less devices to operate, which is beyond the limit that the ambient energy harvesting can supply. Therefore, relying on ambient energy from the environment still has a leap for supplying such devices; dedicated RF power sources are necessary to power these devices.

The origins of RF WPT date back to more than 100 years. In the past, researches on wireless power to devices such as helicopters and to the ground from space were prevalent applications for the RF WPT. Beamforming techniques were applied to such applications to deliver high power. Although such techniques are very promising for powering the battery-less devices, the required knowledge of channel state information (CSI) burdens the devices to calculate and deliver the information, which is cost-full operations for such devices. Recently, there is a growing expectation for WPT using multitone waveforms, where multiple tones are added to form beat-tones waveforms so that it generates a high peak to average power ratio. This nature results in having better efficiency without increasing the transmit power due to the nonlinear behaviors at the receiver side. In addition, naive multitone waveforms require very simple feedback techniques, if any, as opposed to beamforming, which is attractive for computationally limited devices. Thus, these techniques become necessary for operating battery-less devices.

Based on these issues, this paper proposes the following for RF WPT using multitone waveforms.

- Waveform design method for improving power conversion efficiency (PCE) performances based on the receivers' parameter characterizations are proposed. Prior to that, the PCE performances depending on the configurations of rectifiers are characterized based on rigorous experiments at UHF, including wire and wireless transmissions as well as noise conditions. The experiments show that there exist specific points (saturation points) for frequency spacing that multitone waveforms have to assign to improve the PCEs, and the saturation points can be controlled or strongly affected by the value of storage capacitance at the receiver. These investigations result in introducing the design instructions for multitone waveforms depending on the receiver circuits.
- Waveform design methods of increasing the sensitivities or peak voltage acquisitions are proposed. The performance of sensitivity or peak voltage

acquisitions has also been characterized prior to this. Similar to the previous case, the saturation points can be controlled or strongly affected by the value of storage capacitance at the receiver. However, based on the results, the frequency spacing of the multitone waveforms needs to be smaller than the saturation point of the peak voltage acquisition, which is one of the unique findings in contrast to the case for the PCE cases. In addition, the relation between the saturation point of PCEs and peak voltage acquisitions have been revealed. Based on the sensitivity analysis using practical devices, it has been revealed that the characterizations of the sensitivities of receiver devices depend on the types of DC-DC converters.

- Waveform design method for transmitting both information and power simultaneously has been proposed using multitone waveforms. The design waveform utilizes the nature of nonlinear devices, thereby generating varieties of output by shifting the tone configurations of the waveforms. Based on the analysis by simulations and experiments, it is possible to categorize the nonlinear outputs based on the arrangements of the intermodulation products (IM2s). It is also tested by the manufactured SWIPT circuits and verify that design waveforms can transmit information while transmitting power, which results in suppressing the voltage drop that occurred when transmitting information by utilizing frequency-shifted multitone waveforms.