博士論文（要約）

Research on Low Power RF Circuits and Highly Efficient Wireless Power Transmission for IoT Nodes

(IoT ノード向け低消費電力無線通信回路と
高効率無線給電の研究)

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Abstract

Internet of things (IoT) applications are a prospective technology driver for a low power design in a very large scale integration (VLSI) system. A low power operation for a large number of IoT nodes is a fundamental requirement because the energy cost is the most significant concern to realize the IoT application. In IoT applications, “things” are sensing the information relating to a human activity and environment as data. The IoT nodes send the sensed data to high performance computers through an internet. Using the data, the system improves our productivity and quality of life after some transactions at the computer. For this application, the cost of the IoT nodes limits the performance of the whole of the system because the quality of available data depends on the number of IoT nodes. To enhance the system performance, inexpensive sensing and communication techniques are required. In accordance with these backgrounds, a low power circuit design is a key technology to reduce a cost because the cost corresponds to the power consumption in IoT nodes. Specifically, the power consumption in a wireless communication and power management circuit needs to be reduced because the power of these blocks dominates the large portion of the total power in IoT nodes. A purpose of this dissertation is to reduce the cost of IoT nodes by reducing the power consumption in wireless communication and power management circuits.

This dissertation is organized with five chapters. The first chapter describes an introduction for IoT applications and target of this dissertation. A wireless transceiver is a fundamental circuit block to connect “things” through an internet. The power consumption to communicate with other devices is a dominant source for a total power in IoT nodes. To reduce the power consumption for the wireless communication, low-

power crystal oscillators and wireless transmitter are developed in the chapter 2 and 3, respectively. Additionally, a highly efficient wireless power transmission circuit is developed to reduce the wiring cost for IoT nodes in chapter 4. The misalignment tolerant wireless power transmission circuit realizes an inexpensive and robust wireless power charging for IoT nodes. A summary of this dissertation is given in chapter 5. New findings and discussions introduced in this dissertation are summarized in the chapter. Finally, several discussion for upcoming IoT applications is given for future works.

In the Chapter 2, three energy efficient crystal oscillators are developed to reduce the power consumption during the start-up and steady state in IoT nodes. At first, a quick start-up crystal oscillator reduces the start-up time of IoT nodes by introducing a new variation-torelant chirp injector and negative resistance booster. The developed crystal oscillator reduces the start-up time by 92 % from 2.1 ms to 158 μs at a temperature of 25 °C and supply voltage of 1.5 V. The variation-tolerant quick start-up technique reduces the power consumption in the whole system because the short start-up time in a crystal oscillator significantly reduces a wasted power loss in other active circuits (e.g., low noise amplifier and power amplifier) for RF communications. This is the first report to achieve the variation-tolerant quick start-up in a crystal oscillator design. Next, a dual mode crystal oscillator with a new snooze mode is developed for an intermittent operation in IoT nodes. The new crystal oscillator varies the operation mode depending on the state in IoT nodes. A new snooze mode with a proposed automatic self-power gating (ASPG) and multistage CMOS inverter reduces the power consumption by 93 % from a conventional Pierce crystal oscillator with a single-stage CMOS inverter. The crystal oscillator achieves a low power operation at the oscillation frequency of 39.25 MHz with the power consumption of 69 μW in an active mode and 9.2 μW in a snooze mode. Finally, a stacked-amplifier crystal oscillator is developed for an ultra-low power operation in the steady state. A 3.3 V, 39.25 MHz stacked-amplifier crystal oscillator fabricated in a 65 nm CMOS consumes 19 μW and achieves the phase noise of -139 dBc/Hz at 1 kHz offset frequency. The corresponding figure of merit (FoM) of -248 dBc/Hz is the lowest in published crystal oscillators. The low-power and low-noise crystal oscillator enhances the performance (e.g., minimum sensitivity and power consumption) of wireless transceivers in IoT nodes.

In the Chapter 3, a new highly energy-efficient wireless transmitter is developed to achieve the low-energy wireless communication for IoT applications. To develop a highly efficient power amplifier for IoT nodes, a new design method of a dual supply voltage scheme is introduced in this chapter. A wireless transmitter fabricated in a 40 nm CMOS process achieves the highest drain efficiency of 42 % and the highest global efficiency of 28 % at a output power of -20 dBm, thereby achieving the lowest energy of 36 pJ/bit among the reported wireless transmitters.

In the Chapter 4, a misalignment tolerant magnetically resonant wireless power transmission is introduced to achieve a low cost and robust power charging for a large number of IoT nodes. The wireless power transmission system with a new control algorism of zero-phase-difference capacitance control (ZPDCC) achieves an adaptive capacitance control to maximize the transmission efficiency depending on the transmission distance. The measured total efficiency is increased by 1.7 times from 16 % to 27 % at a transmission distance of 2.5 mm by introducing the new ZPDCC fabricated in a 180 nm CMOS process.

Chapter 5 gives a summary about the developments shown in this dissertation. Short summaries corresponding to each chapter are given in this chapter. The technical progresses for developing IoT nodes are briefly described. Finally, a discussion for future works is given in this chapter.