論文 / 著書情報
Article / Book Information

題目(和文)	ミリ波帯中継器向けデータ電力同時伝送型送受信機の研究
Title(English)	A Study on Transceivers with Simultaneous Wireless Information and Power Transfer for Millimeter-Wave Relay
著者(和文)	井出倫滉
Author(English)	Michihiro Ide
出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第12857号, 授与年月日:2024年9月20日, 学位の種別:課程博士, 審査員:白根 篤史,岡田 健一,廣川 二郎,德田 崇,伊藤 浩之,三友 敏也
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第12857号, Conferred date:2024/9/20, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

A Study on Transceivers with Simultaneous Wireless Information and Power Transfer for Millimeter-Wave Relay

by

Michihiro Ide

A Ph. D. dissertation submitted in partial satisfaction of the requirements for the degree of

Electrical and Electronic Engineering

in the

School of Engineering

of

Tokyo Institute of Technology

Supervised by

Prof. Atsushi Shirane

Summer 2024

Thesis Summary

In this paper, we focus on the simultaneous wireless information and power transfer (SWIPT) technology and propose a wirelessly powered relay for millimeter-wave communication. As long as it can receive wireless power, it can be deployed anywhere. Combined with conventional relay methods, relay networks can be constructed more flexibly. We believe that this will contribute to the future expansion of the 5G communication coverage area and the spread of next-generation D-band communication. This paper is organized with six chapters as follows.

Chapter 1 describes the research background, objectives, and positioning of the research achievements. In recent years, the amount of network traffic has dramatically increased, resulting in a growing demand for high-speed wireless communication in the millimeter-wave band to support high-capacity networks. However, compared with conventional frequency bands, millimeter-wave bands have high directivity and high transmission loss due to obstacles. Therefore, coverage holes can easily occur due to obstacles on the link. Large-scale deployment of base stations to expand the communication area is not realistic in terms of cost, site limitation and CO_2 emissions. Therefore, a combination of large-scale relays and base stations is being considered, and relays that can be flexibly deployed anywhere are needed. This study focuses on SWIPT and proposes a wirelessly powered relay that does not require a power connection. To confirm the feasibility of the relay system, a beamformer IC including an RF/IF circuit section is designed, and level diagrams are estimated based on measurement results. In addition, we consider achieving higher communication speeds and higher power generation to pursue SWIPT technologies, and we also evaluate prototype relays for D-band, which enables faster communication speeds with wider bandwidth, and discrete semiconductor relays, which can generate higher power by using GaAs diodes.

In Chapter 2, we introduce the operating principle of phased arrays and the calculation method of level diagrams as the basis for millimeter-wave wireless communications. As for the fundamentals of millimeter-wave WPT, the conversion efficiency of rectifiers and the calculation methods of FSTE and DC-DC transfer efficiency of WPT are also introduced.

In Chapter 3, we first introduce four conventional relay methods: metasurface, RIS, lens, and conventional transceivers, and discuss their advantages and disadvantages in terms of beam steering and power cable connection. Then, an overview of the operation of the wirelessly powered relay is

given, and the communication distance, relay signal transmission method, frequency selection for communication and WPT, and WPT distance are discussed, and the objectives of the relay are summarized. A comparison between relay methods is also made, and it is shown that the wirelessly powered relay has three advantages: easy deployment, fast beam steering function, and compact device size.

Next, we describes the basic operation of rectifiers and backscatterers as the necessary technologies to realize a wirelessly powered relay. Conventional rectifiers require high input power to achieve maximum efficiency, and power combiners, which reduce the input power, fix the beam direction. On the other hand, conventional backscatter can only support lower modulation scheme and can transmit low data rate signal. IF backscatter can support n-QAM modulation scheme, but has no phase shifting capability. To address these technical issues, we propose four technologies: a phased-array rectifier, a GaAs diode-type stub-loaded rectifier, an LPF-loaded rectifier, and a vector summing backscatter. Each of the proposed technologies is responsible for improvements such as input power reduction, higher efficiency, higher communication speed, and simultaneous realization of phase shift and high data rate transmission, and their positioning compared to conventional technologies is clarified.

Chapter 4 describes the working principles of the proposed circuit architectures and details the measurement results for three CMOS-integrated prototype transceivers: phased array for 5G, retroreflective array for 5G, and reflective array for D-band. The phased array for 5G is composed of a phased array rectifier, which achieves long-range and beam-steerable WPT, and a vector summing backscatter, which achieves high-speed communication and phase shifting. The prototype phased array module is capable of generating more than 3mW of power in the range of ±30° with beam-steerable WPT, and achieves beamforming transmission of 5G NR signals with low power consumption of 0.03mW/path. On the other hand, the 5G retroreflective array is capable of beam-steering WPT in 2D direction, and the retroreflective operation is realized by bidirectional LC loaded rectifier. The rotationally symmetric antenna pair provides wide-angle coverage in the 2-D direction, and a range of ±60° can be covered by combining with a 90° phase shifter, while a 16:1 power combiner enables WPT over longer distances. The phase-shifter array, power combiner, and LC-loaded rectifier configuration enables bi-directional communication, and the retroreflective beam is automatically formed simply by optimizing the phase-shifter array based on WPT power generation. This is a completely passive operation that requires no biasing, allowing relay operation with lower power consumption. Finally, the D-band reflective array consists of an LPF-loaded rectifier that supports high-speed transmission and reception with a bandwidth above 8 GHz, which is not possible due to the narrow bandwidth characteristics of conventional LC-loaded rectifiers. The 64-element power combiner network has no phase shifter, so it can transmit the communication signal in the reflected direction relative to the incident direction of the WPT signal. The 8 GHz wideband communication can support higher data rates than 5G transceivers, and 48 Gbps is achieved in the probe measurement.

Chapter 5 describes the operation principle and detailed circuit architecture of the bidirectional phased-array transceiver for 5G using only discrete semiconductors. For the relay system, the SNR within the relay and the transmit EIRP are important elements for the communication to be established, and the transmit EIRP is especially dominant in the wirelessly powered type. The power generation is limited to 500mW in CMOS integrated relay system, but GaAs diodes can rectify more high power and higher power generation can improve the EIRP. The bidirectional phased array consists of a stub-load rectifier with GaAs diodes and a 180° phase shifter, and achieves a conversion efficiency of 54%, which is higher than that of CMOS rectifiers. The 256-element 180° shifters can control the direction of the transmit and receive beams independently of the receive direction of the WPT signal. The main advantage of the discrete semiconductor is the high efficiency and power generation during WPT, and the generous power budget allows the use of high gain and high power IF amplifiers, effectively extending the relay distance.

Finally, Chater 6 summarizes challenges and solutions of wirelessly powered relays and describes future technological developments of SWIPT. By further improving power generation and communication speed, it is expected that these technologies will enable the deployment of critical infrastructure such as power and networks anywhere in the world, and also make it possible to realize alternative communication and power lines during disasters and HAPS (High Altitude Platform Station). We believe that SWIPT technology will contribute to a society where people can connect to the network anywhere and do not have to worry about the battery life of their devices.

Acknowledgment

This paper describes research conducted under the kind guidance and encouraging support of Professor Kenichi Okada and Associate Professor Atsushi Shirane in the Graduate School of Electrical and Electronic Engineering doctoral course at the Tokyo Institute of Technology. This paper summarizes six years of research on simultaneous wireless information and power transfer, starting from the fourth year of undergraduate study. I would like to thank all those who provided valuable advice and helpful support throughout this research.

First of all, I would like to express my gratitude to Associate Professor Atsushi Shirane for his research guidance from the beginning of my affiliation with the laboratory and for his invaluable assistance in advancing my research theme of wireless power transfer. Despite my limited knowledge and experience at the time, I was fortunate to have the opportunity to engage in tape-outs and measurements from an early stage, which proved invaluable in my personal and professional development. The research theme of wireless power transfer, which was initially modest in scope, has now become a group supported by several junior members. The group is a dynamic and engaging place to conduct research activities with like-minded colleagues. I am fortunate to have the opportunity to lead such a fulfilling research life thanks to the enthusiastic guidance of Assistant Professor Shirane. I am deeply grateful for his support.

I would like to thank Professor Kenichi Okada, who has been my advisor since my time as an undergraduate student. In Okada's laboratory, I was fortunate to have many opportunities for tape-outs, convenient access to a variety of measurement equipment, and the opportunity to pursue my research without any inconvenience. He provided me with a cutting-edge and fulfilling research environment, as well as helpful advice on a number of occasions regarding the direction of my research, presentation methods, writing papers, and other related matters. He also taught me not only technical skills but also how to navigate the academic world, which has broadened my perspectives. I am deeply appreciative of his guidance and support.

I would like to thank Professor Takashi Tokuda, Professor Jiro Hirokawa, Associate Professor Hiroyuki Ito, and Mr. Mitomo of Toshiba Corporation for taking the time to serve as reviewers for this paper. Their valuable comments and advice during the review process helped us to improve the overall quality of this paper.

I am grateful to the members of the WPT group, Mr. Keito Yuasa, Mr. Sena Kato, Mr. Osamu Date, Mr. Ruoxin Tao, and Mr. Masayuki Kikuchi, for their daily exchange of useful information and discussions, and for their various kinds of help in advancing this research. They have been a great help to me in a number of ways, including assisting with measurements, writing papers, scheduling overseas business trips, and setting up measurement and design environments. I would like to express my sincere gratitude to them and wish them all the best in their future endeavors.

I would also like to thank the other members, Jian Pang, Zheng Li, Ibrahim Abdo, Carrel da Gomez, Wang Yun, Dongwon You, Xi Fu, Ashbir Aviat Fadila, Hans Herdian, Zhang Yuncheng, Qiu Junjun, Huang Hongye, Wang Chun, Chenxin Liu, Xiaolin Wang, Carolyn Jill Mayeda, and Yudai Yamazaki for their technical support and discussion.

I am grateful to Mr. Hiroyuki Sakai and Mr. Kazuaki Kunihiro for their assistance in managing the measurement schedule and ordering measurement equipment.

I would also like to express my gratitude to Yoshino Kasuga, Makiko Tsunashima, and Tomoko Iwahiro for their invaluable assistance with administrative procedures, which greatly facilitated the progress of my research.

Finally, I would like to express my deepest gratitude to my parents and family. They provided invaluable support, not only financially while I was pursuing my bachelor course, but also in navigating the challenges of balancing academic pursuits with the demands of daily life. Their understanding and assistance were instrumental in enabling me to successfully complete the doctoral program.

In closing, I would like to extend my best wishes for continued success and growth to the Okada and Shirane laboratories.

Research Achievements Related to This Paper

Journal Paper

[J1] M. Ide, A. Shirane, K. Yanagisawa, D. You, J. Pang and K. Okada, "A 28-GHz Phased-Array Relay Transceiver for 5G Network Using Vector-Summing Backscatter With 24-GHz Wireless Power and LO Transfer," in IEEE Journal of Solid-State Circuits, vol. 57, no. 4, pp. 1211-1223, April 2022.

[J2] M. Ide, K. Yuasa, S. Kato, T. Tomura, K. Okada and A. Shirane, "A 256-Element Phased-Array Relay Transceiver for 5G Network Using 24-GHz Wireless Power Transfer With Discrete ICs," in IEEE Microwave and Wireless Technology Letters (Early Access), pp. 1-4, May 2024.

International Conferences

[I1] M. Ide, A. Shirane, K. Yanagisawa, D. You, J. Pang and K. Okada, "A 28-GHz Phased-Array Relay Transceiver for 5G Network Using Vector-Summing Backscatter with 24-GHz Wireless Power and LO Transfer," IEEE Symposium on VLSI Circuits, Kyoto, Japan, pp. 1-2, June 2021.

[I2] M. Ide, A. Shirane, D. You, Z. Li, J. Pang, K. Yanagisawa and K. Okada, "A 28-GHz Phased-Array Relay Transceiver for 5G Network Using Vector-Summing Backscatter with 24-GHz Wireless Power and LO Transfer," IEEE International Solid-State Circuits Conference Student Research Preview (ISSCC SRP), San Francisco, CA, USA, Feb. 2021.

[I3] M. Ide et al., "A 28-GHz Fully-Passive Retro-Reflective Phased-Array Backscattering Transceiver for 5G Network with 24-GHz Beam-Steered Wireless Power Transfer," IEEE Symposium on VLSI Circuits, Honolulu, HI, USA, pp. 96-97, June 2022.

[I4] M. Ide, K. Yuasa, S. Kato, A. Shirane and K. Okada, "28-GHz Fully-Passive Retro-Reflective Phased-Array Backscattering Transceiver for 5G Network with 24-GHz Beam-Steered Wireless power Transfer," IEEE International Solid-State Circuits Conference Student Research Preview (ISSCC SRP), San Francisco, CA, USA, Feb. 2022.

[I5] M. Ide, K. Yuasa, S. Kato, A. Shirane and K. Okada, “A 256-Elements Phased-Array Relay Transceiver for 5G Network Using 24GHz Wireless Power Transfer with Discrete ICs,” IEEE/MTT-S International Microwave Symposium (IMS), Washington, D.C., USA, June 2024.

Domestic Conferences

[D1] M. Ide, et al., “電力合成器を用いたミリ波無線電力伝送向け RF-DC 変換器”, IEICE General Conference, Mar. 2020.

[D2] M. Ide, et al., “ミリ波帯 5G 中継機向けビーム制御型バックスキャッタ”, The Institute of Electronics, Information and Communication Engineers (IEICE) Society, Sept. 2021.

[D3] M. Ide, et al., “ミリ波帯 5G 中継機向け再帰反射型バックスキャッタ”, The Institute of Electronics, Information and Communication Engineers (IEICE) Society, Sept. 2022.

[D4] M. Ide, et al., “無線給電型 5G 向けリレー送受信機”, 電子情報通信学会 LSI とシステムのワークショップ, May 2022.

[D5] M. Ide, et al., “A 28-GHz Fully-Passive Retro-Reflective Phased-Array Backscattering Transceiver for 5G Network with 24-GHz Beam-Steered Wireless Power Transfer,” IEEE SSCS Japan Chapter VLSI Circuits 報告会, July 2022.

Co-Author Journal Papers

[JC1] D. You, F. Xi, H. Herdian, X. Wang, Y. Narukiyo, A. Fadila, H. Lee, M. Ide et al., "A Ka-Band 64-Element Deployable Active Phased-Array TX on a Flexible Hetero Segmented Liquid Crystal Polymer for Small Satellites," in IEEE Microwave and Wireless Technology Letters, vol. 33, no. 6, pp. 903-906, June 2023.

[JC2] X. Fu, D. You, X. Wang, Y. Wang, C. J. Mayeda, Y. Gao, M. Ide et al., "A Low-Power 256-Element Ka-Band CMOS Phased-Array Receiver With On-Chip Distributed Radiation Sensors for Small Satellite Constellations," in IEEE Journal of Solid-State Circuits, vol. 58, no. 12, pp. 3380-3395, Dec. 2023.

[JC3] D. You, X. Wang, H. Herdian, X. Fu, H. Lee, M. Ide et al., "A Ka-Band Deployable Active Phased Array Transmitter Fabricated on 4-Layer Liquid Crystal Polymer Substrate for Small-Satellite Mount," in IEEE Access, vol. 11, pp. 69522-69535, July 2023.

[JC4] K. Yuasa, M. Ide, S. Kato, K. Okada and A. Shirane, "Millimeter-Wave Transceiver Utilizing On-Chip Butler Matrix for Simultaneous 5G Relay Communication and Wireless Power Transfer," in IEICE Transactions on Electronics, vol. E106-C, no. 7, pp. 1-8, July 2024.

Co-Author International Conferences

[IC1] D. You, Y. Wang, X. Fu, H. Herdian, X. Wang, A. Fadila, H. Lee, M. Ide et al., "A Ka- Band Dual Circularly Polarized CMOS Transmitter with Adaptive Scan Impedance Tuner and Active XPD Calibration Technique for Satellite Terminal," IEEE Radio Frequency Integrated Circuits Symposium (RFIC), Denver, CO, USA, pp. 15-18, June 2022.

[IC2] S. Kato, K. Yuasa, M. Ide, A. Shirane and K. Okada, "A CMOS Full-Wave Switching Rectifier with Frequency Up-Down Conversion for 5G NR Wirelessly-Powered Relay Transceivers," IEEE 48th European Solid State Circuits Conference (ESSCIRC), Milan, Italy, pp. 345-348, Sept. 2022.

[IC3] D. You, X. Fu, X. Wang, Y. Gao, W. Wang, J. Sakamaki, H. Herdian, S. Kato, M. Ide et al., "19.4 A Small-Satellite-Mounted 256-Element Ka-Band CMOS Phased-Array Transmitter Achieving 63.8dBm EIRP Under 26.6W Power Consumption Using Single/Dual Circular Polarization Active Coupler," IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, USA, pp. 298-300, Feb. 2023.

[IC4] X. Fu, D. You, X. Wang, M. Ide et al., "A 2.95mW/element Ka-band CMOS Phased-Array Receiver Utilizing On-Chip Distributed Radiation Sensors in Low-Earth-Orbit Small Satellite Constellation," IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, USA, pp. 18-20, Feb. 2023.

[IC5] Dongwon You, Xi Fu, Hans Herdian, Xiaolin Wang, Yasto Narukiyo, Ashbir Aviat Fadila, Hojun Lee, Michihiro Ide, Sena Kato, Zheng Li, Yun Wang, Daisuke Awaji, Jian Pang, Hiraku Sakamoto, Kenichi Okada, and Atsushi Shirane, "A Ka-Band 64-element Deployable Active Phased Array Transmitter on a Flexible Hetero Segmented Liquid Crystal Polymer for Small Satellites," IEEE/MTT-S International Microwave Symposium (IMS), San Diego, CA, June 2023.

[IC6] K. Yuasa, M. Ide, S. Kato, K. Okada and A. Shirane, "Beam Control Free 28GHz 5G Relay Transceiver and 24GHz Wireless Power Receiver Using On-Chip Butler Matrix," IEEE/MTT-S International Microwave Symposium (IMS), San Diego, CA, USA, pp. 199-202, June 2023.

[IC7] Sena Kato, Shu Date, Tao Ruoxin, Yasuto Narukiyo, Hiroki Hayashi, Keito Yuasa, Michihiro Ide, Takashi Tomura, Kenichi Okada, and Atsushi Shirane, “A 28GHz 5G NR Wirelessly Powered Relay Transceiver Using Rectifier-Type 4th-Order Sub-Harmonic Mixer,” IEEE Symposium on VLSI Circuits, Honolulu, HI, USA, June 2024.

Co-Author Domestic Conferences

[DC1] S. Kato, M. Ide, A. Shirane and K. Okada, “ミリ波帯 5G バッテリーレス中継機向け 24GHz 整流器の高効率化,” The Institute of Electronics, Information and Communication Engineers (IEICE) Society, Sept. 2021.

[DC2] K. Yuasa, M. Ide, A. Shirane and K. Okada, “フェーズドアレイ整流器によるミリ波帯 5G バッテリーレス受信機,” The Institute of Electronics, Information and Communication Engineers (IEICE) Society, Sept. 2021.

[DC3] K. Masayuki, S. Kato, M. Ide, K. Yuasa, S. Date, K. Okada and A. Shirane, “ミリ波帯無線電力伝送受信器に用いる低損失 32 対 1 電力合成器,” IEICE General Conference, Mar. 2024.

[DC4] S. Kato, K. Yuasa, M. Ide, K. Okada and A. Shirane, “ミリ波帯 5G 無線電力伝送デバイスに向けた 24GHz 整流器型ミキサー回路,” IEICE General Conference, Mar. 2024.

[DC5] S. Date, M. Ide, K. Yuasa, S. Kato, K. Okada and A. Shirane, “無線電力伝送を用いたミリ波帯 5G 中継器用再帰反射型送信機,” IEICE General Conference, Mar. 2024.

[DC6] K. Yuasa, M. Ide, S. Kato, K. Okada and A. Shirane, “ビーム制御不要 28GHz 中継機および 24GHz 無線電力伝送,” IEICE General Conference, Mar. 2024.

Prize

- Outstanding Master's Paper Award for 2021,
  URL: https://educ.titech.ac.jp/ee/news/2022_04/062280.html, Apr. 2022.
- IEEE SSCS Japan Chapter Academic Research Award, May 2022.