마이크로파 에너지 응용을 위한 AI/ML

한국전자파학회 2023 하계종합학술대회

Workshop #4 - RF/Microwave 에너지 응용

2023. 08. 23

김병관

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REMI LAB
Radar & Electromagnetic Intelligence

충남대학교
CHUNGNAM NATIONAL UNIVERSITY

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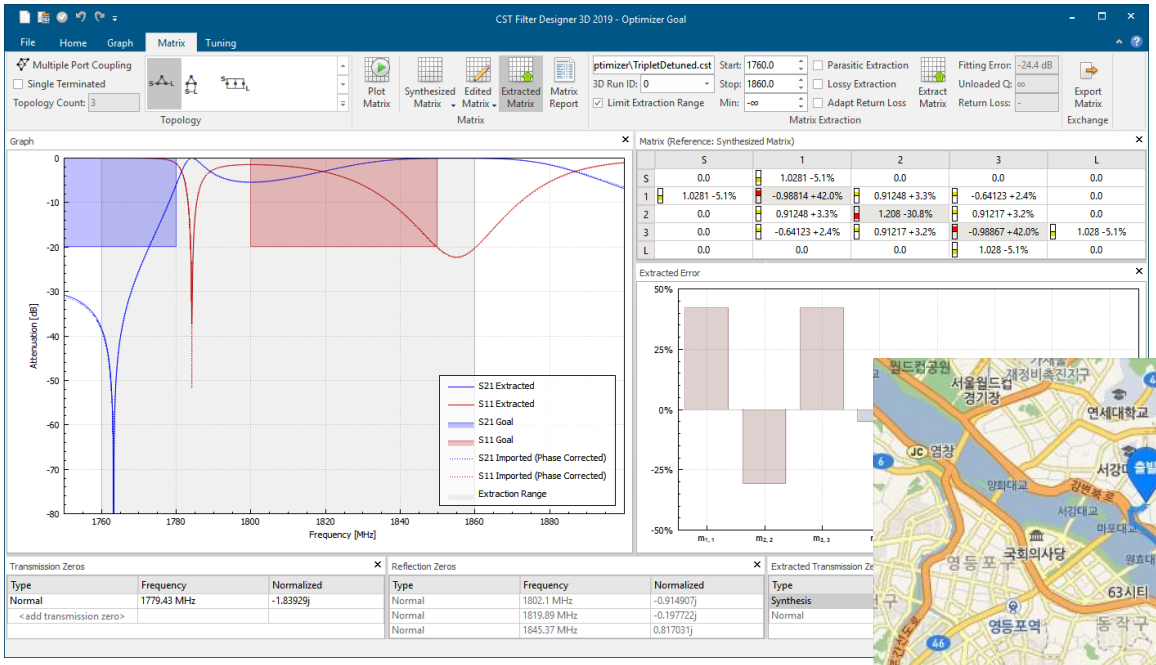
Introduction

- Optimization Algorithm
  - 다양한 곳에서 등장하는 최적화 기법



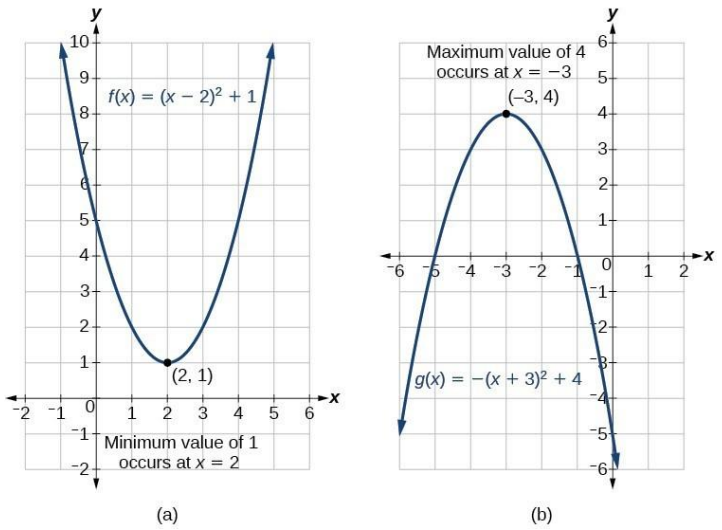
[CST Optimizer for Filter Design]

[지도의 최단/최적 경로 산출 알고리즘]

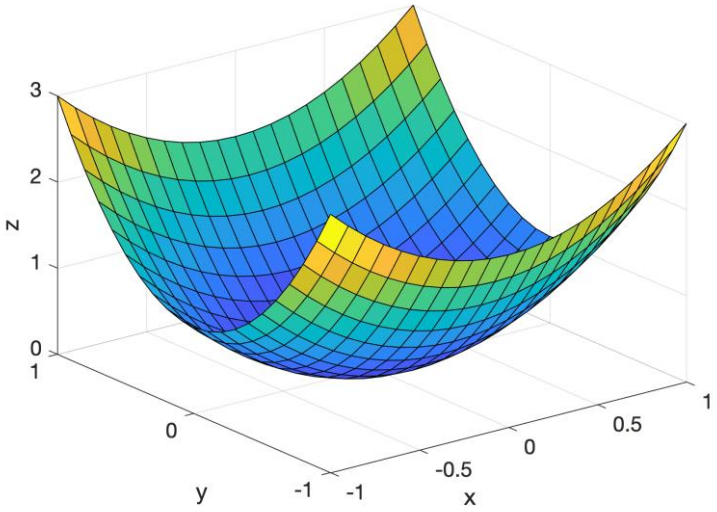
Introduction

- Optimization
  - The problem of finding a set of inputs
  - To an objective function that returns a max or min value.

➔ Derivatives of Multivariate Function



[2차 함수(Convex, Concave) 의 최대값, 최소값]



[3차 함수 g=f(x,y,z) 의 Visualization]

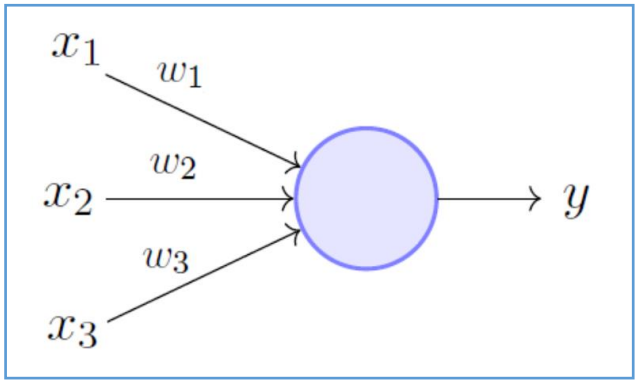
Introduction

- 최적화, Machine Learning 과 AI
  - Machine Learning : **계산**으로 **규칙, 기준**을 **정량적**으로 획득
  - 가장 간단한 1차 함수로 규칙을 표현 한다면?

$$y = w_1x_1 + w_2x_2 + w_3x_3$$

  - y 값이 정해진 기준보다 크면 → Pass
  - y, w, x, b는 숫자 **혹은 행렬**

➔ Derivatives of Multivariate Function (including vectors)



[Perceptron Model (Minsky-Papert, 1969)]

$$\mathbf{y} = \mathbf{W}\mathbf{x} + \mathbf{b}$$

w_1: weights
b_1: bias

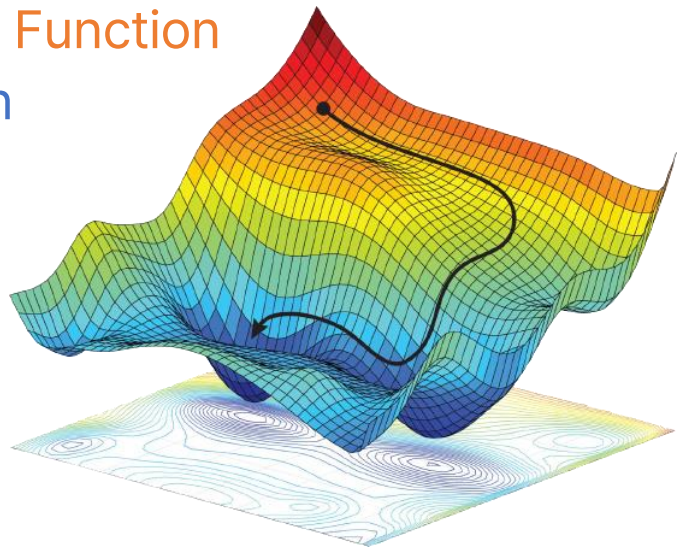
Introduction

- 최적화, Machine Learning 과 AI
  - Machine Learning : **계산**으로 **규칙, 기준**을 **정량적**으로 획득
  - 가장 간단한 1차 함수로 규칙을 표현 한다면?

$$y = w_1 x_1 + w_2 x_2 + w_3 x_3$$

  - 현재 이 규칙이 얼마나 정확한가? ➔ Loss Function
  - 최적의 규칙을 찾는 과정 ➔ Optimization

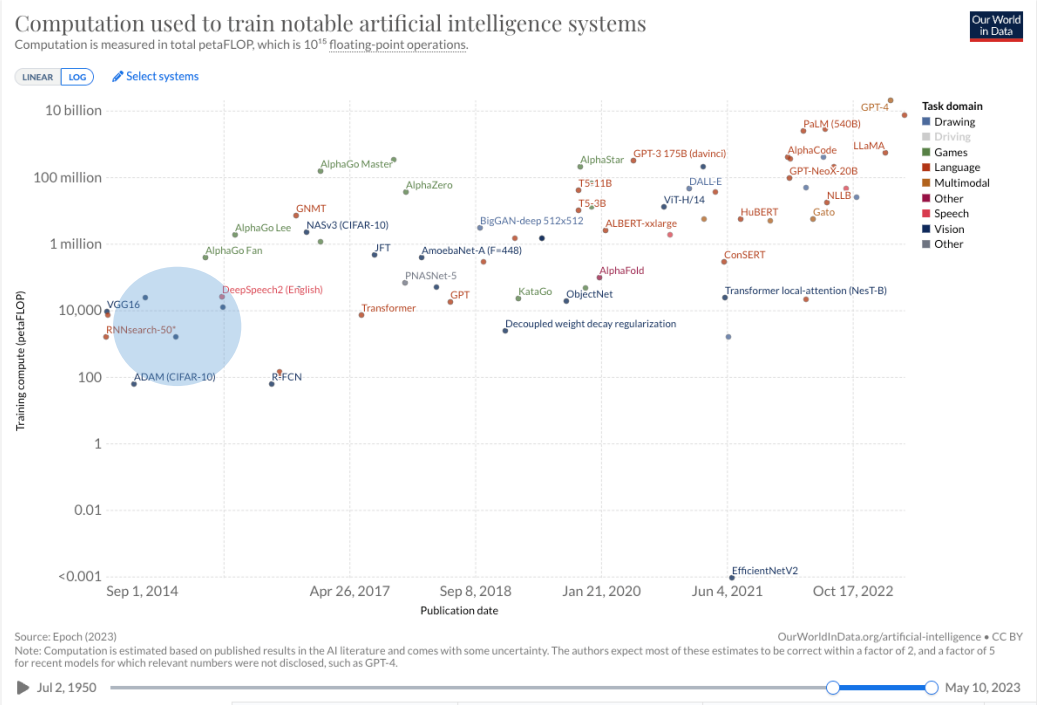
$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$$



[Optimization 과정의 개념도]

Introduction

- 최적화, Machine Learning 과 AI
  - Machine Learning : **계산**으로 **규칙, 기준**을 **정량적**으로 획득
  - Artificial Intelligence (인공 지능) 이 되려면?



[머신러닝 및 인공지능 훈련에 들어가는 연산 수]

https://ourworldindata.org/grapher/artificial-intelligence-training-computation

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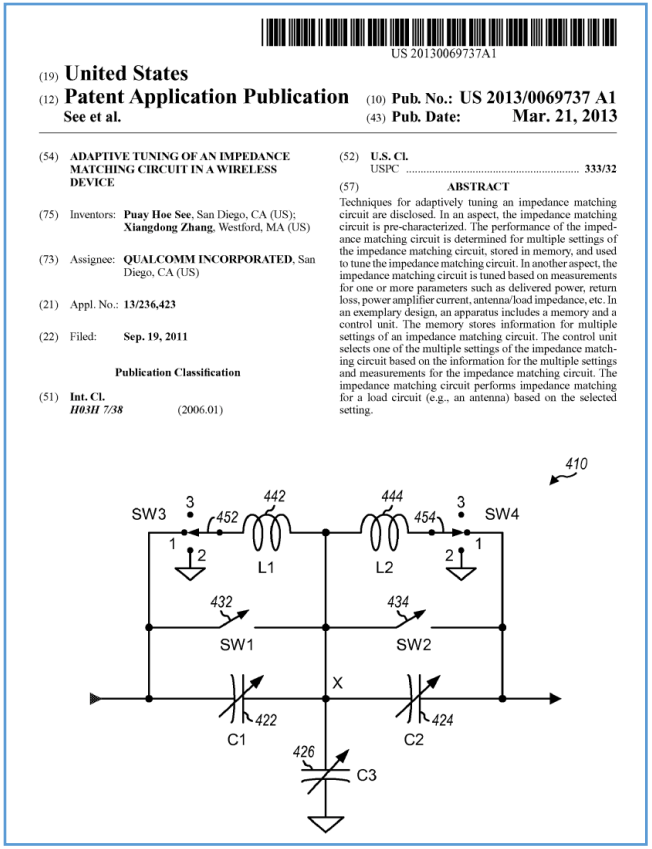
마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - iPhone 4
    - If you ever experience this on your iPhone 4, avoid gripping it in the lower left corner in a way that covers both sides of the black strip in the metal band, or simply use one of many available cases.

[iPhone 4 의 안테나 성능 문제로 인한 속도 저하 현상]

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - Patent – Qualcomm, 2013



US 20130069737A1

(19) **United States**

(12) **Patent Application Publication**
See et al.

(10) **Pub. No.: US 2013/0069737 A1**

(43) **Pub. Date: Mar. 21, 2013**

(54) **ADAPTIVE TUNING OF AN IMPEDANCE MATCHING CIRCUIT IN A WIRELESS DEVICE**

(75) Inventors: **Puay Hoe See**, San Diego, CA (US); **Xiangdong Zhang**, Westford, MA (US)

(73) Assignee: **QUALCOMM INCORPORATED**, San Diego, CA (US)

(21) Appl. No.: **13/236,423**

(22) Filed: **Sep. 19, 2011**

Publication Classification

(51) **Int. Cl.**
H03H 7/38 (2006.01)

(52) **U.S. Cl.**
USPC **333/32**

(57) **ABSTRACT**

Techniques for adaptively tuning an impedance matching circuit are disclosed. In an aspect, the impedance matching circuit is pre-characterized. The performance of the impedance matching circuit is determined for multiple settings of the impedance matching circuit, stored in memory, and used to tune the impedance matching circuit. In another aspect, the impedance matching circuit is tuned based on measurements for one or more parameters such as delivered power, return loss, power amplifier current, antenna/load impedance, etc. In an exemplary design, an apparatus includes a memory and a control unit. The memory stores information for multiple settings of an impedance matching circuit. The control unit selects one of the multiple settings of the impedance matching circuit based on the information for the multiple settings and measurements for the impedance matching circuit. The impedance matching circuit performs impedance matching for a load circuit (e.g., an antenna) based on the selected setting.

Patent Citations (14)

Publication number	Priority date	Publication date	Assignee	Title
Family To Family Citations				
JPH04368022A *	1991-06-14	1992-12-21	Kokusai Electric Co Ltd	Antenna matching circuit and antenna matching method employing the same
JPH08195684A *	1995-01-18	1996-07-30	Anritsu Corp	空中線自動整合装置
JP4140098B2 *	1998-10-20	2008-08-27	ソニー株式会社	アンテナ装置および無線通信機
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JP2008011341A	2006-06-30	2008-01-17	Matsushita Electric Ind Co Ltd	携帯無線端末
KR100726260B1 *	2006-08-07	2007-06-08	삼성전자주식회사	통신 장치의 정합 제어 장치 및 방법
JP2008061116A *	2006-09-01	2008-03-13	Toyota Industries Corp	無線受信機とアンテナ整合方法
US8072285B2	2008-09-24	2011-12-06	Paratek Microwave, Inc.	Methods for tuning an adaptive impedance matching network with a look-up table
JP4894836B2	2008-09-30	2012-03-14	株式会社ＪｖｃケンウッＤ	アンテナ整合装置及びその制御方法
US8072272B2	2009-08-19	2011-12-06	Qualcomm, Incorporated	Digital tunable inter-stage matching circuit
JP2011130372A *	2009-12-21	2011-06-30	Hitachi Kokusai Electric Inc	整合器
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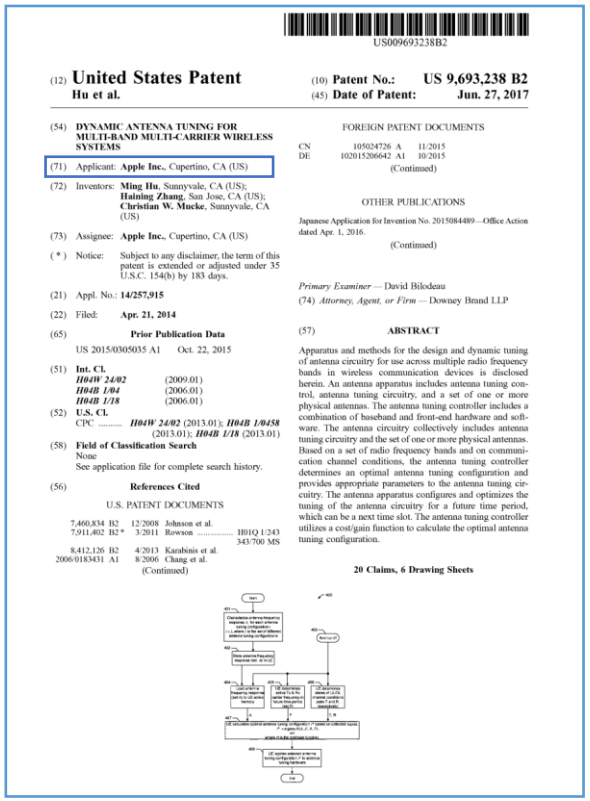
JP5672098B2	2011-03-18	2015-02-18	富士通株式会社	無線端末装置

* Cited by examiner, † Cited by third party

See, P. H., & Zhang, X. (2015). *U.S. Patent No. 9,054,756*. Washington, DC: U.S. Patent and Trademark Office.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - Patent – Apple, 2017



US009693238B2

(12) **United States Patent**
Hu et al.

(10) **Patent No.: US 9,693,238 B2**
(45) **Date of Patent: Jun. 27, 2017**

(54) **DYNAMIC ANTENNA TUNING FOR MULTI-BAND MULTI-CARRIER WIRELESS SYSTEMS**

(71) Applicant: **Apple Inc.**, Cupertino, CA (US)

(72) Inventors: **Ming Hu**, Sunnyvale, CA (US); **Haining Zhang**, San Jose, CA (US); **Christian W. Mucke**, Sunnyvale, CA (US)

(73) Assignee: **Apple Inc.**, Cupertino, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 183 days.

(21) Appl. No.: **14/257,915**

(22) Filed: **Apr. 21, 2014**

(65) **Prior Publication Data**

US 2015/0305035 A1 Oct. 22, 2015

(51) **Int. Cl.**
H04W 24/02 (2009.01)
H04B 1/04 (2006.01)
H04B 1/18 (2006.01)

(52) **U.S. Cl.**
CPC ***H04W 24/02*** (2013.01); ***H04B 1/0458*** (2013.01); ***H04B 1/18*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

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(Continued)

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(Continued)

Primary Examiner — David Bilodeau
(74) *Attorney, Agent, or Firm* — Downey Brand LLP

(57) **ABSTRACT**

Apparatus and methods for the design and dynamic tuning of antenna circuitry for use across multiple radio frequency bands in wireless communication devices is disclosed herein. An antenna apparatus includes antenna tuning control, antenna tuning circuitry, and a set of one or more physical antennas. The antenna tuning controller includes a combination of baseband and front-end hardware and software. The antenna circuitry collectively includes antenna tuning circuitry and the set of one or more physical antennas. Based on a set of radio frequency bands and on communication channel conditions, the antenna tuning controller determines an optimal antenna tuning configuration and provides appropriate parameters to the antenna tuning circuitry. The antenna apparatus configures and optimizes the tuning of the antenna circuitry for a future time period, which can be a next time slot. The antenna tuning controller utilizes a cost/gain function to calculate the optimal antenna tuning configuration.

20 Claims, 6 Drawing Sheets

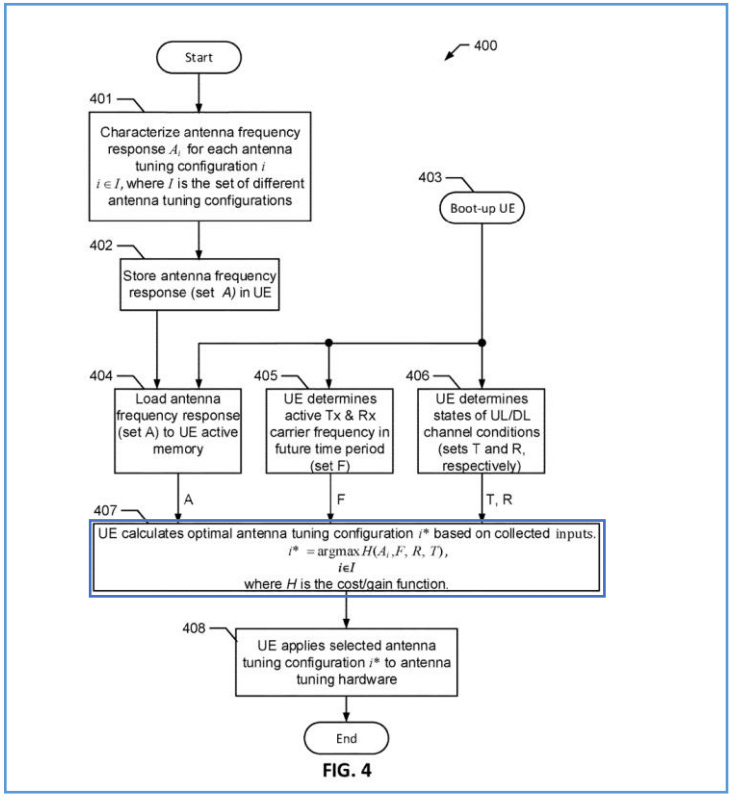
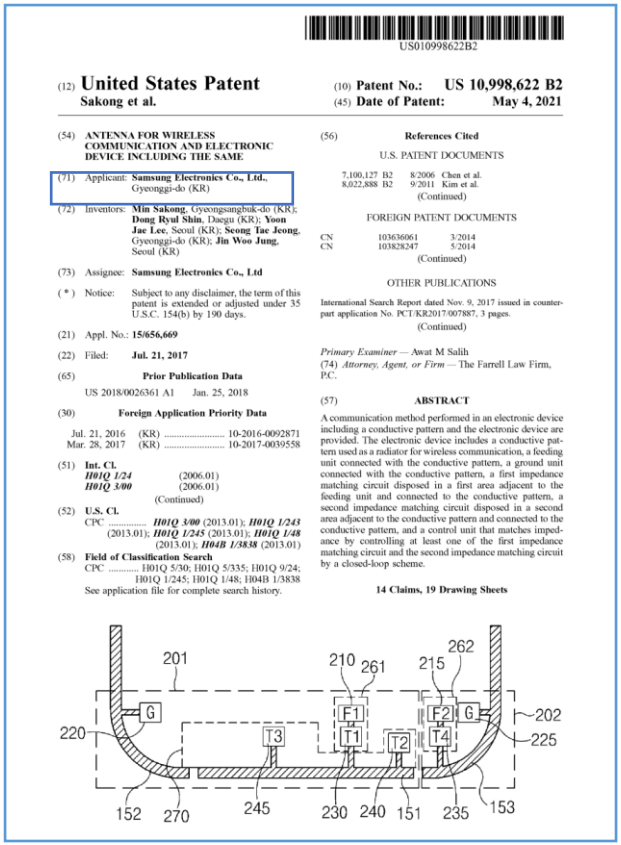


FIG. 4

Hu, M., Zhang, H., & Mucke, C. W. (2017). *U.S. Patent No. 9,693,238*. Washington, DC: U.S. Patent and Trademark Office.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - Patent – Samsung, 2021



US010998622B2

(12) **United States Patent**
Sakong et al.

(10) **Patent No.: US 10,998,622 B2**
(45) **Date of Patent: May 4, 2021**

(54) **ANTENNA FOR WIRELESS COMMUNICATION AND ELECTRONIC DEVICE INCLUDING THE SAME**

(71) Applicant: **Samsung Electronics Co., Ltd.**, Gyeonggi-do (KR)

(72) Inventors: **Min Sakong**, Gyeongsangbuk-do (KR); **Dong Ryul Shin**, Daegu (KR); **Yoon Jae Lee**, Seoul (KR); **Seong Tae Jeong**, Gyeonggi-do (KR); **Jin Woo Jung**, Seoul (KR)

(73) Assignee: **Samsung Electronics Co., Ltd**

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 190 days.

(21) Appl. No.: **15/656,669**

(22) Filed: **Jul. 21, 2017**

(65) **Prior Publication Data**

US 2018/0026361 A1 Jan. 25, 2018

(30) **Foreign Application Priority Data**

Jul. 21, 2016 (KR) 10-2016-0092871
Mar. 28, 2017 (KR) 10-2017-0039558

(51) **Int. Cl.**
H01Q 1/24 (2006.01)
H01Q 3/00 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***H01Q 3/00*** (2013.01); ***H01Q 1/243*** (2013.01); ***H01Q 1/245*** (2013.01); ***H01Q 1/48*** (2013.01); ***H04B 1/3838*** (2013.01)

(58) **Field of Classification Search**
CPC H01Q 5/30; H01Q 5/335; H01Q 9/24; H01Q 1/245; H01Q 1/48; H04B 1/3838
See application file for complete search history.

(56) **References Cited**

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(Continued)

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CN 103828247 5/2014
(Continued)

OTHER PUBLICATIONS

International Search Report dated Nov. 9, 2017 issued in counterpart application No. PCT/KR2017/007887, 3 pages.
(Continued)

Primary Examiner — Awat M Salih
(74) *Attorney, Agent, or Firm* — The Farrell Law Firm, P.C.

(57) **ABSTRACT**

A communication method performed in an electronic device including a conductive pattern and the electronic device are provided. The electronic device includes a conductive pattern used as a radiator for wireless communication, a feeding unit connected with the conductive pattern, a ground unit connected with the conductive pattern, a first impedance matching circuit disposed in a first area adjacent to the feeding unit and connected to the conductive pattern, a second impedance matching circuit disposed in a second area adjacent to the conductive pattern and connected to the conductive pattern, and a control unit that matches impedance by controlling at least one of the first impedance matching circuit and the second impedance matching circuit by a closed-loop scheme.

14 Claims, 19 Drawing Sheets

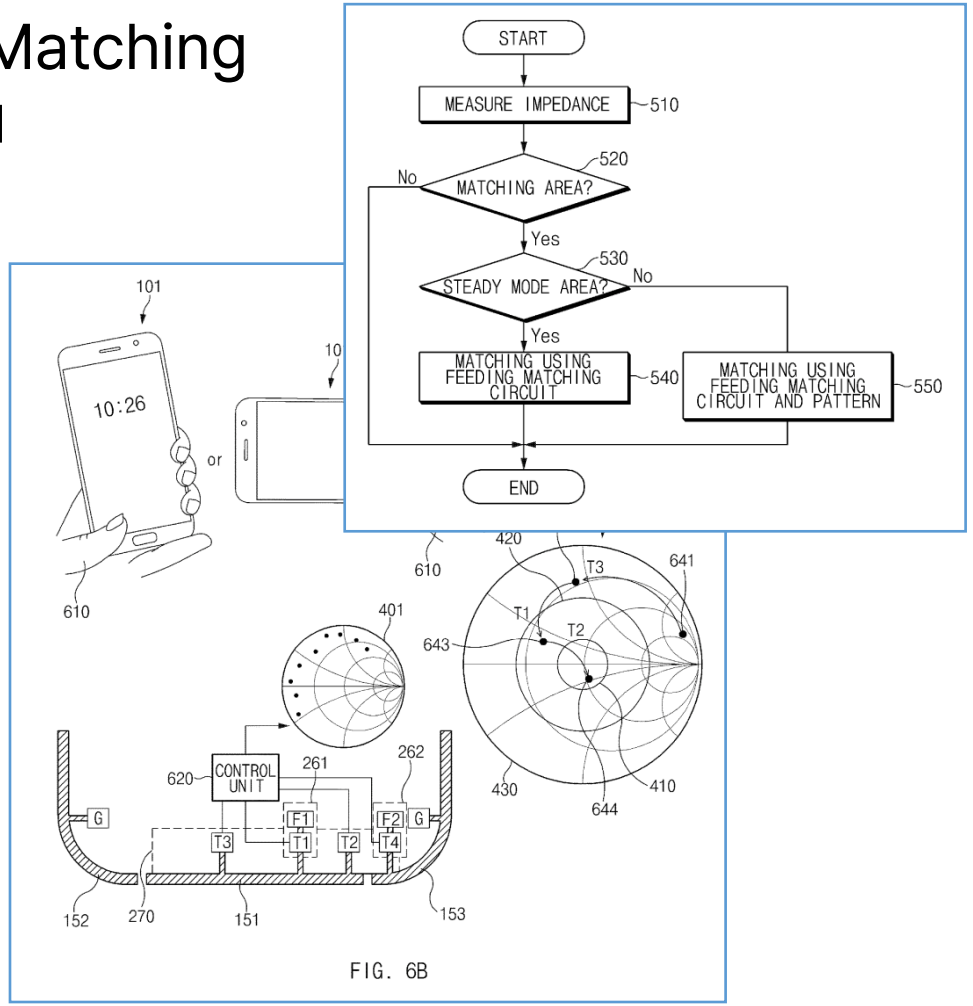


FIG. 6B

Sakong, M., Shin, D. R., Lee, Y. J., Jeong, S. T., & Jung, J. W. (2021). *U.S. Patent No. 10,998,622*. Washington, DC: U.S. Patent and Trademark Office.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - LUT (Look Up Table) : 개발은 어렵지만, 효율적임

700

Circuit Setting	Freq	Config	Switch Settings	Control Settings	Band/ Mode
1	F1	Config a	SW1 ...	C1 ...	B1
2	F2	Config b	SW1 ...	C1 ...	B2
⋮	⋮	⋮	⋮	⋮	⋮
K	FK	Config b	SW1 ...	C1 ...	BK

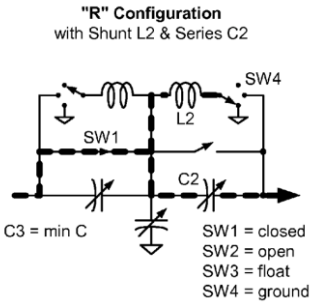


FIG. 5E

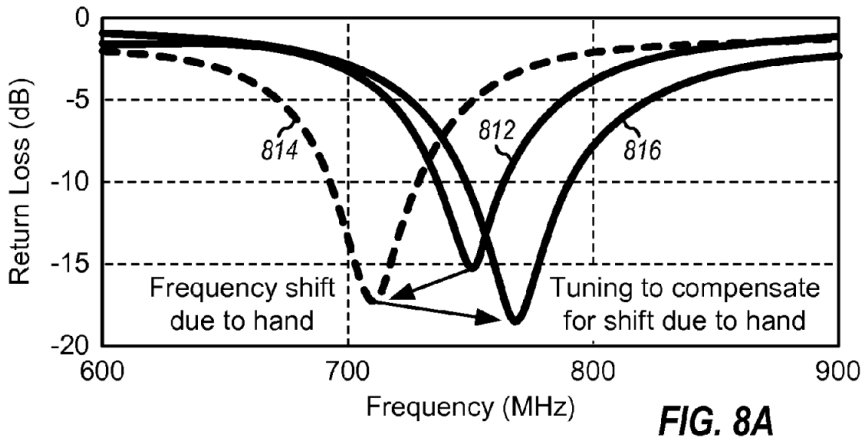


FIG. 8A

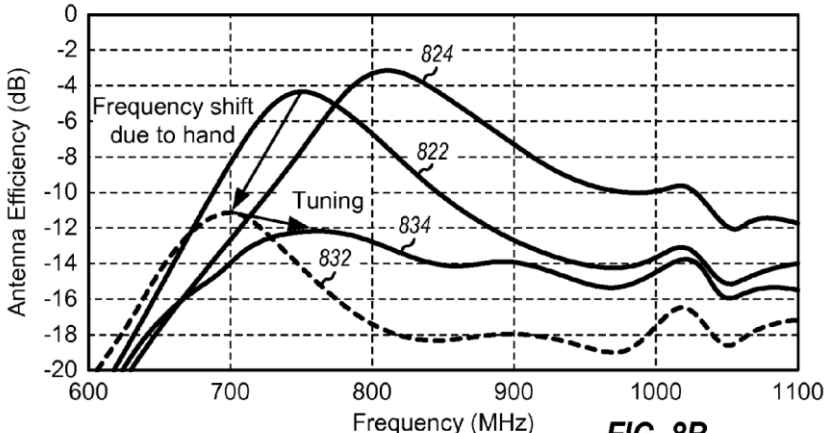
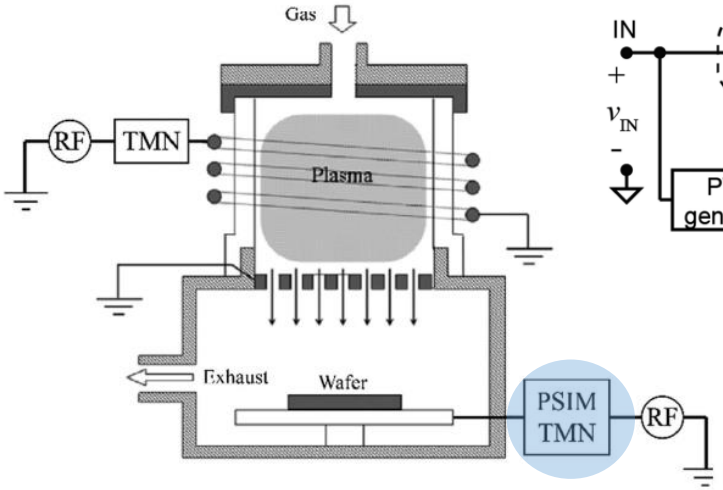


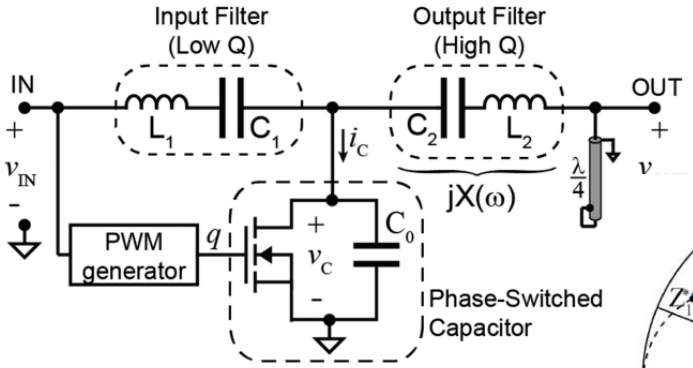
FIG. 8B

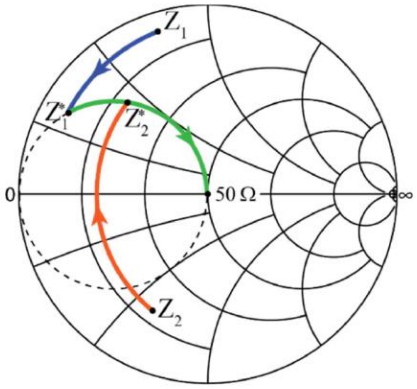
See, P. H., & Zhang, X. (2015). *U.S. Patent No. 9,054,756*. Washington, DC: U.S. Patent and Trademark Office.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - Speed & Accuracy required for high-power system
  - Problem: How to design circuit & control elements
  - Both requires high-level domain knowledge



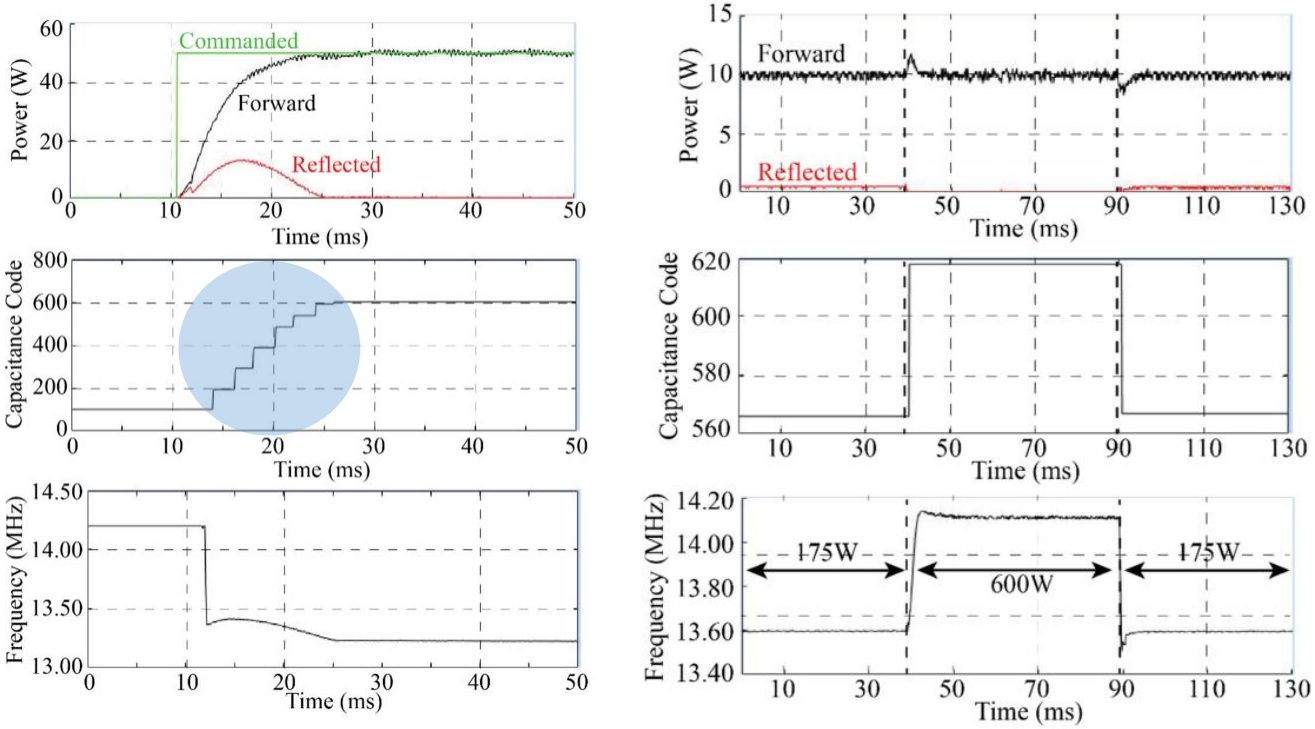




Jurkov, A. S., Radomski, A., & Perreault, D. J. (2020). Tunable matching networks based on phase-switched impedance modulation. *IEEE Transactions on Power Electronics*, *35*(10), 10150-10167.
Jurkov, A. S., Radomski, A., & Perreault, D. J. (2017, October). Tunable impedance matching networks based on phase-switched impedance modulation. In *2017 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 947-954). IEEE.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - Impedance can be matched only when after measuring I-V.
  - What if we know total process and estimate it?

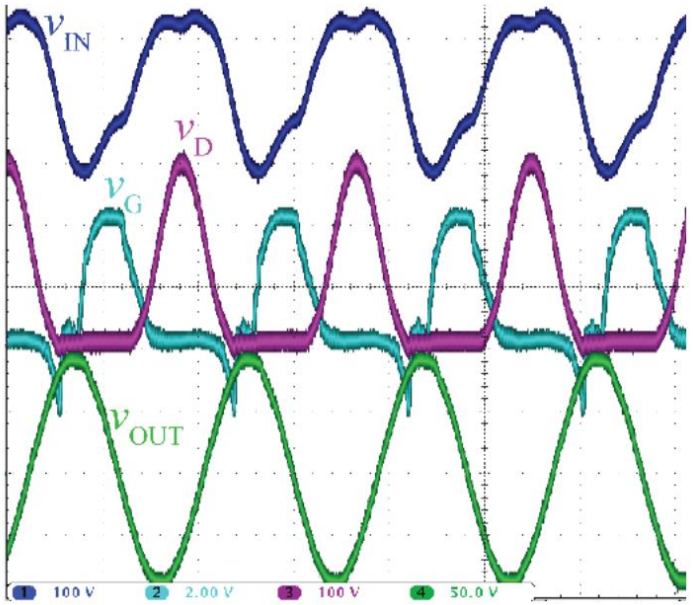


Jurkov, A. S., Radomski, A., & Perreault, D. J. (2020). Tunable matching networks based on phase-switched impedance modulation. *IEEE Transactions on Power Electronics*, *35*(10), 10150-10167.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - What kind of data do we need?
    - Is the measured data optimal solution? or local max/min?
    - Requires quantization (up to few bits)
    - Phase ambiguity

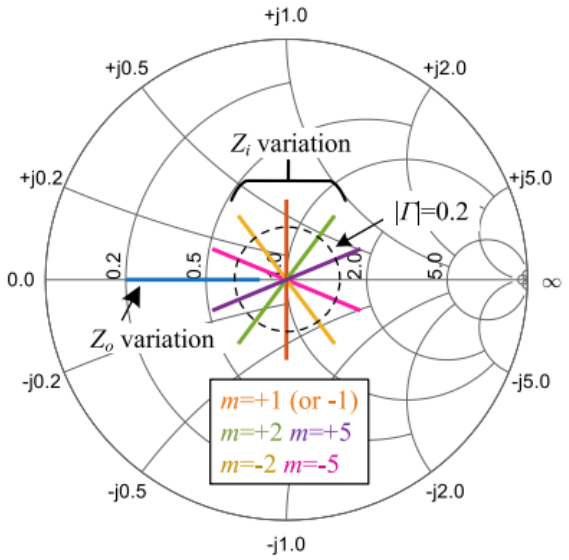
Test Case	Load (Ω)	Conduction Angle (°)	Frequency (MHz)
A	19.1 + j32.3	0	13.18
B	20.3 + j1.62	0	13.99
C	17.9 – j13.6	144.8	14.37
D	9.91 + j24.7	182.8	13.36
E	9.61 – j1.10	195.1	13.97
F	10.0 – j16.3	194.6	14.38
G	5.40 + j31.6	210.6	13.06
H	3.97 + j0.98	218.8	13.81
K	5.33 – j11.8	206.2	14.18

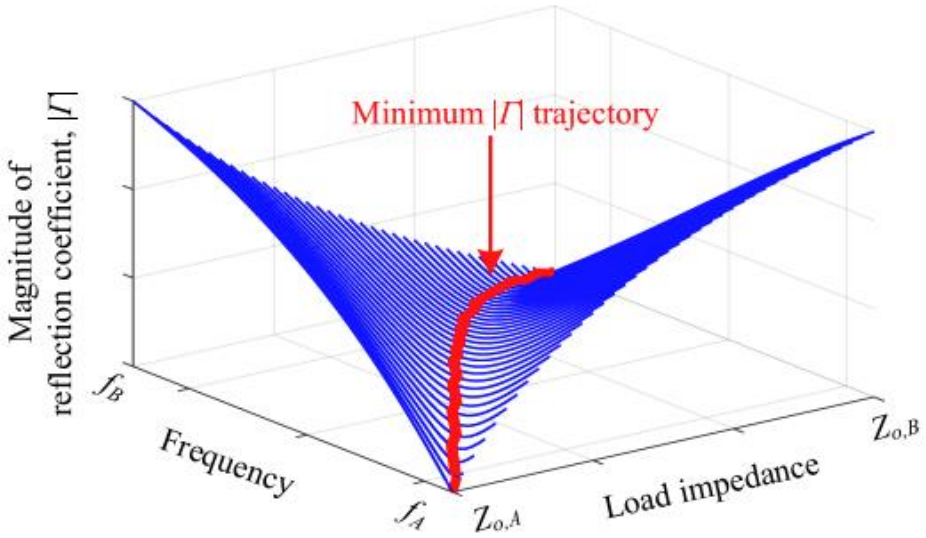


Jurkov, A. S., Radomski, A., & Perreault, D. J. (2017, October). Tunable impedance matching networks based on phase-switched impedance modulation. In *2017 IEEE Energy Conversion Congress and Exposition (ECCE)* (pp. 947-954). IEEE.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - Impedance Compressing Matching Network (ICMN)
    - Two frequency, Two-port network approach
    - We want to find lowest reflection, from possible frequency range

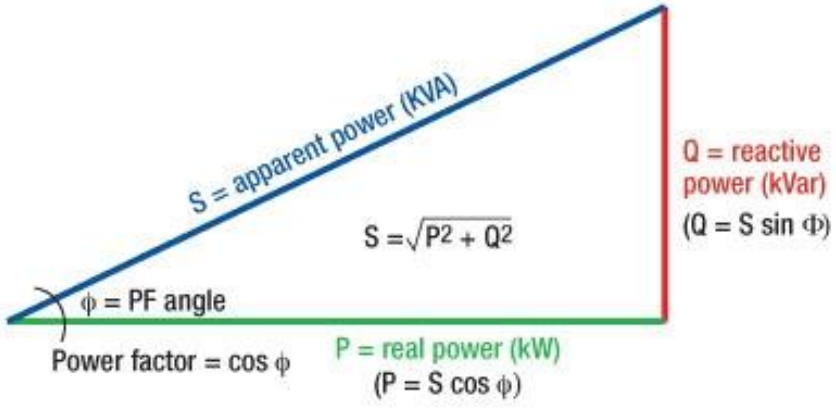


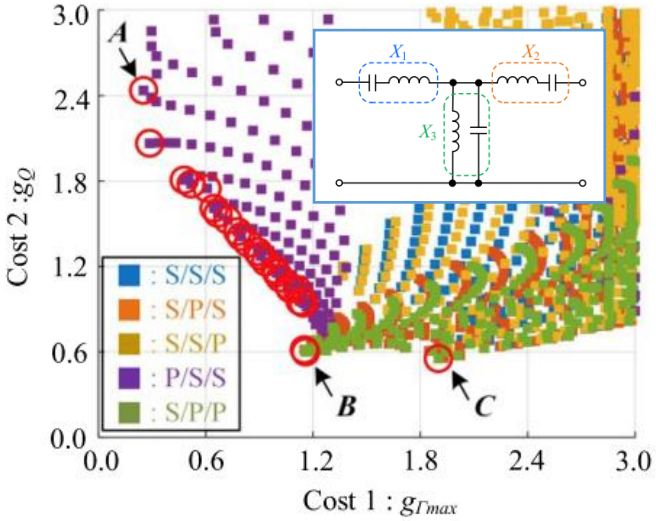


Chung, E., Ha, J. I., Al Bastami, A., & Perreault, D. J. (2021). Impedance compressing matching network based on two-port network analysis for wireless power transfer system. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, *3*(3), 432-442.

마이크로파 에너지 응용을 위한 ML

- Automatic Impedance Matching
  - Impedance Compressing Matching Network (ICMN)
    - Evaluation : two cost function
      - Maximum reflection coefficient
      - The sum of maximum stored energy per unit power (kVA/kW, Power Factor)
    - How to get optimal solution, when we have two different objectives?

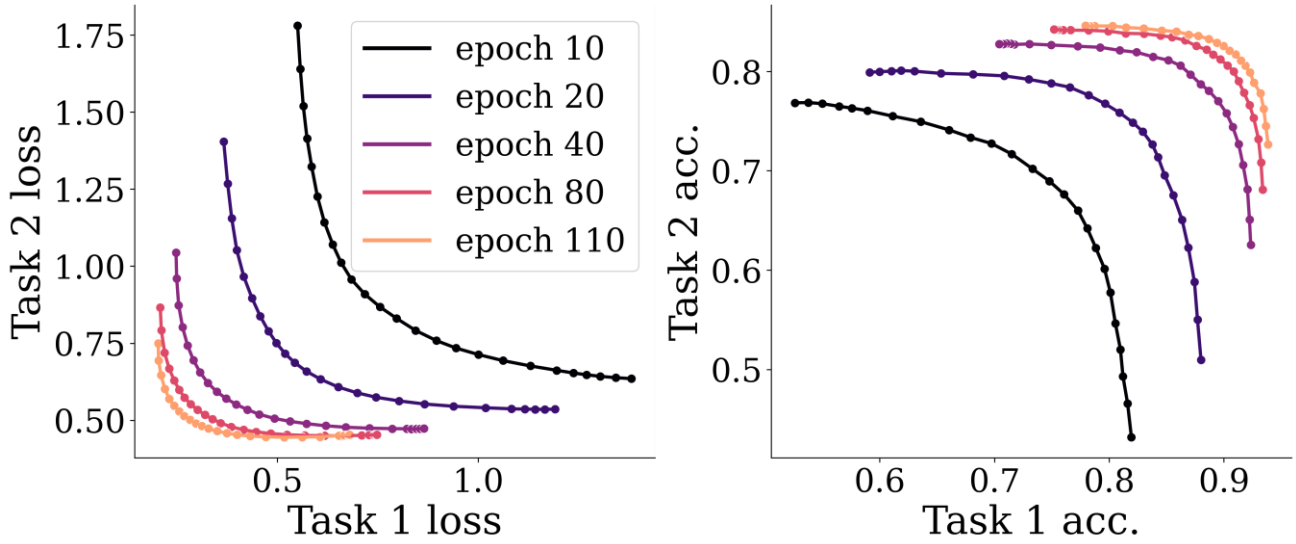




Chung, E., Ha, J. I., Al Bastami, A., & Perreault, D. J. (2021). Impedance compressing matching network based on two-port network analysis for wireless power transfer system. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, *3*(3), 432-442.

마이크로파 에너지 응용을 위한 ML

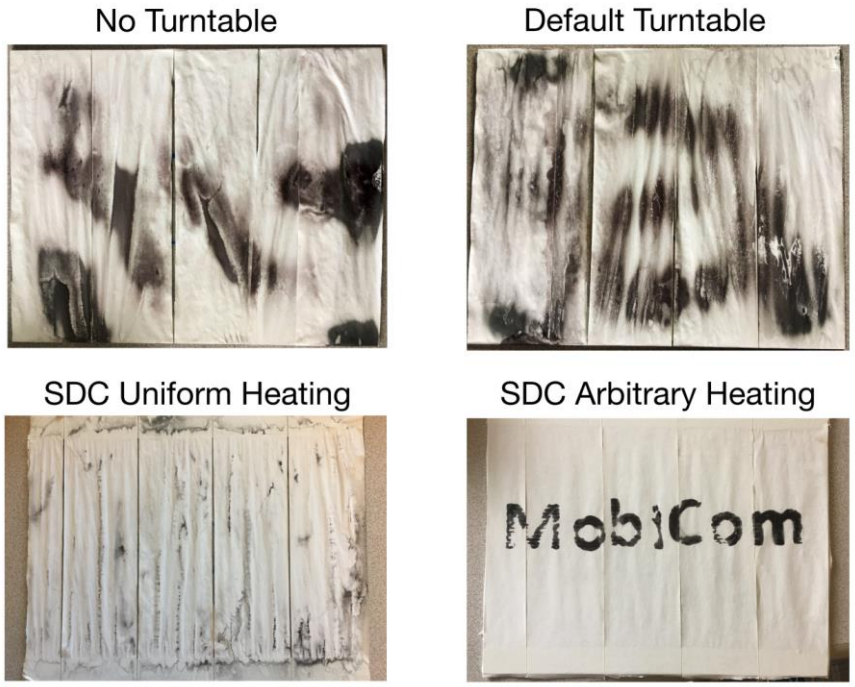
- Automatic Impedance Matching
  - Pareto Optimal – Multi-objective Optimization
    - How to find pareto front? (a **set** of optimal solutions)
  - Genetic algorithms are most popular solution.
  - If scales are getting large, GA fails to converge.

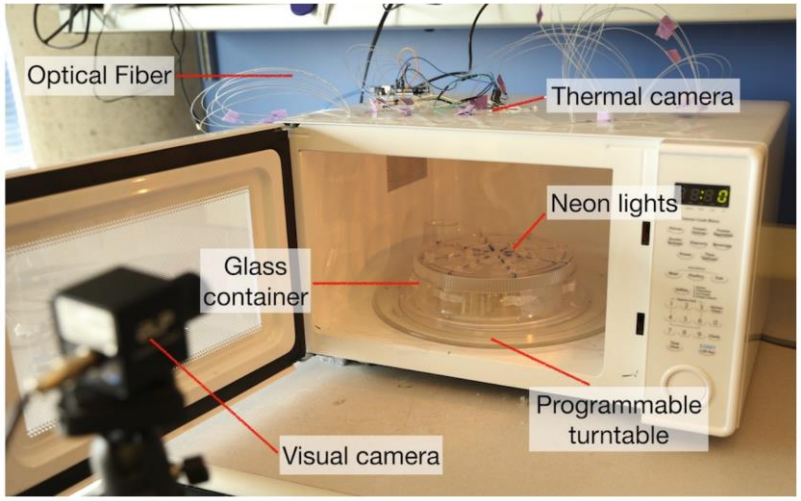


Navon, A., Shamsian, A., Chechik, G., & Fetaya, E. (2020). Learning the pareto front with hypernetworks. *arXiv preprint arXiv:2010.04104*.

마이크로파 에너지 응용을 위한 ML

- Multi-modal Data & Learning
  - Optimization is **to find an input for an objective function.**
  - An input data may not be in form of microwave : Turntable!

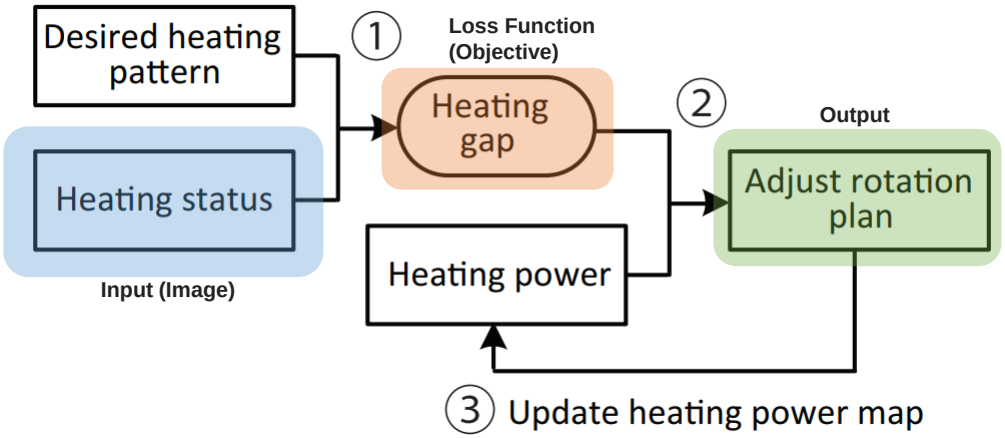


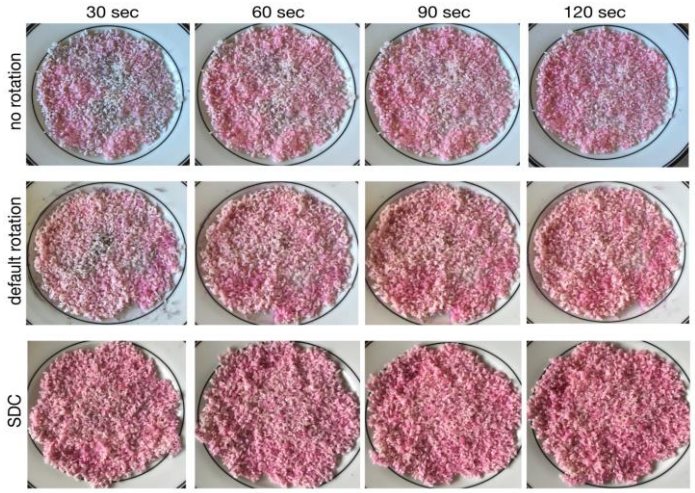


Jin, H., Wang, J., Kumar, S., & Hong, J. (2019, October). Software-defined cooking using a microwave oven. In *The 25th Annual International Conference on Mobile Computing and Networking* (pp. 1-16).

마이크로파 에너지 응용을 위한 ML

- Multi-modal Data & Learning
  - Thermal camera provides a feature to the algorithm.
  - Objective : uniform heating to sample space
  - Limitation: single material (rice / bacon)
    + Detection, Classification, Segmentation ?

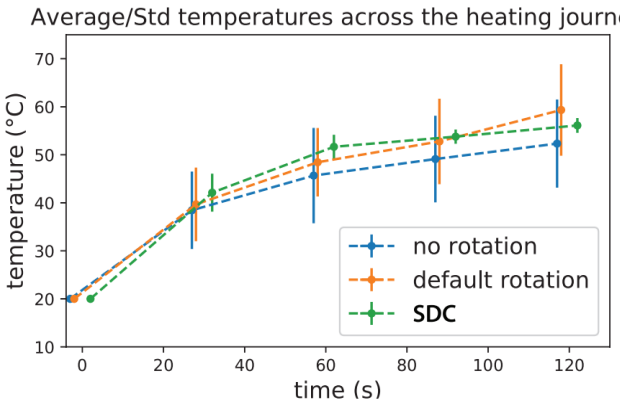


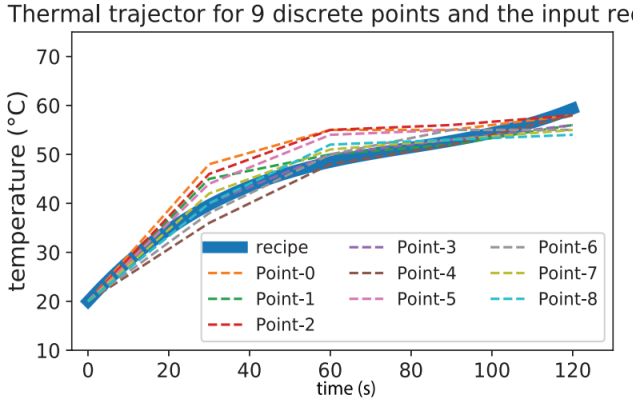


Jin, H., Wang, J., Kumar, S., & Hong, J. (2019, October). Software-defined cooking using a microwave oven. In *The 25th Annual International Conference on Mobile Computing and Networking* (pp. 1-16).

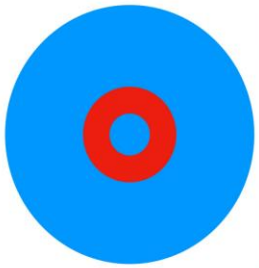
마이크로파 에너지 응용을 위한 ML

- Multi-modal Data & Learning
  - Performance Metric : stability & linearity

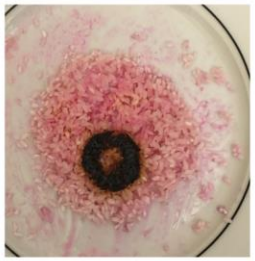




  - Recipe (Objective function) can be defined by user


Recipe geometry

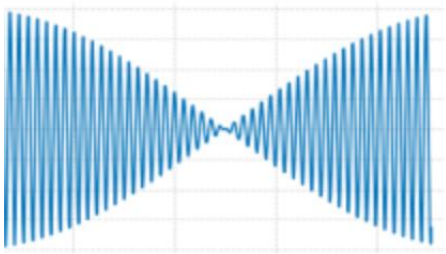

SDC without accessories

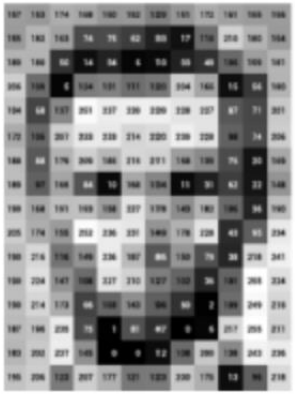

SDC with accessories

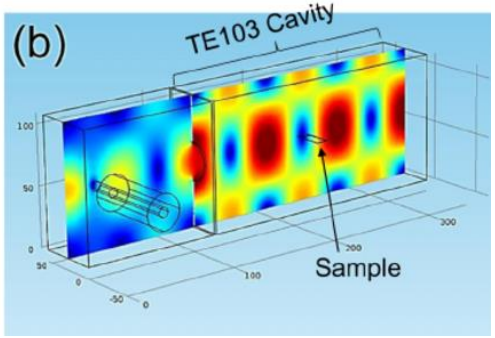
Jin, H., Wang, J., Kumar, S., & Hong, J. (2019, October). Software-defined cooking using a microwave oven. In *The 25th Annual International Conference on Mobile Computing and Networking* (pp. 1-16).

마이크로파 에너지 응용을 위한 ML

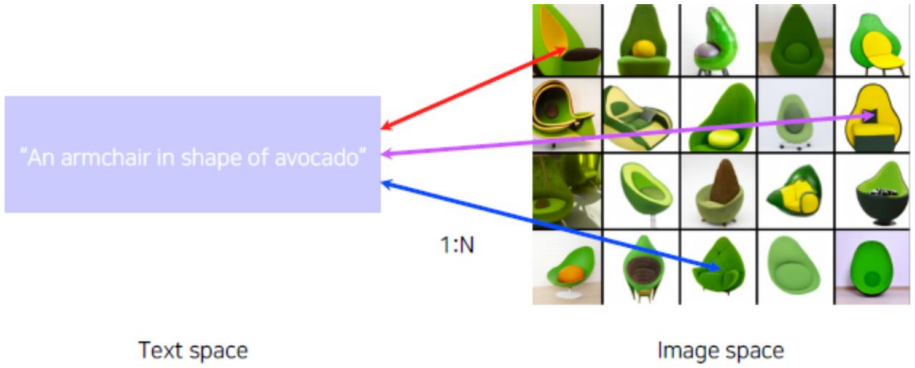
- Multi-modal Data & Learning
  - Data modality is various.





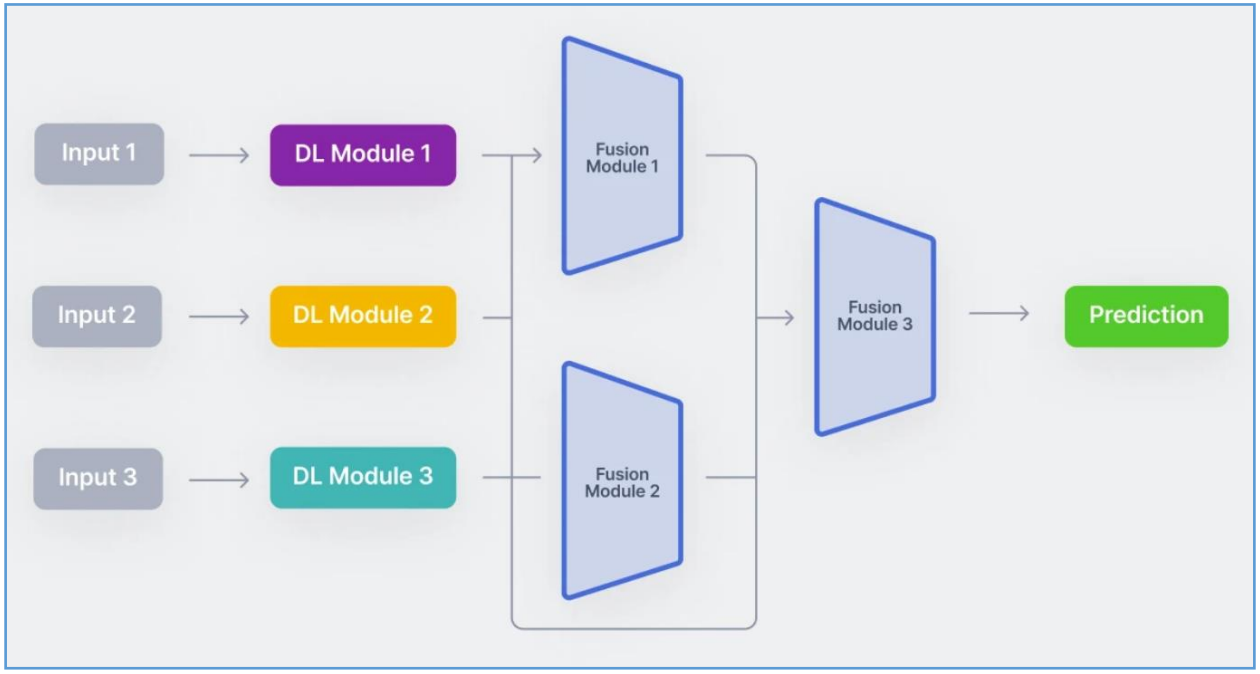


  - Unbalanced feature space



마이크로파 에너지 응용을 위한 ML

- Multi-modal Data & Learning
  - **Network should be designed by the characteristic of data.**
  - Pre-training for each modality required.
  - Concatenation of latent feature vectors



마이크로파 에너지 응용을 위한 ML

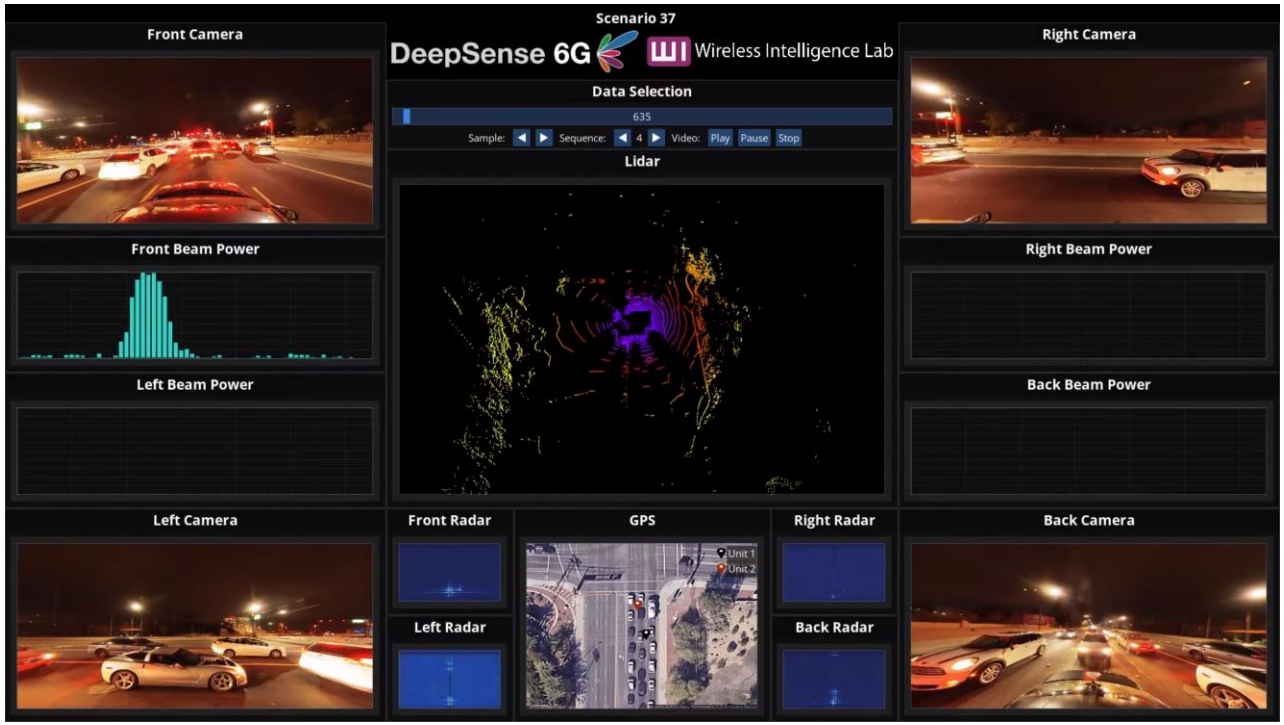
*Digital Surface Model

- Multi-modal Data & Learning
  - Sentinel-1, Sentinel-2, Land Use, RGB, DSM*
  - Benchmark dataset for remote sensing

Hu, J., Liu, R., Hong, D., Camero, A., Yao, J., Schneider, M., ... & Zhu, X. X. (2023). MDAS: a new multimodal benchmark dataset for remote sensing. *Earth System Science Data*, *15*(1), 113-131.

마이크로파 에너지 응용을 위한 ML

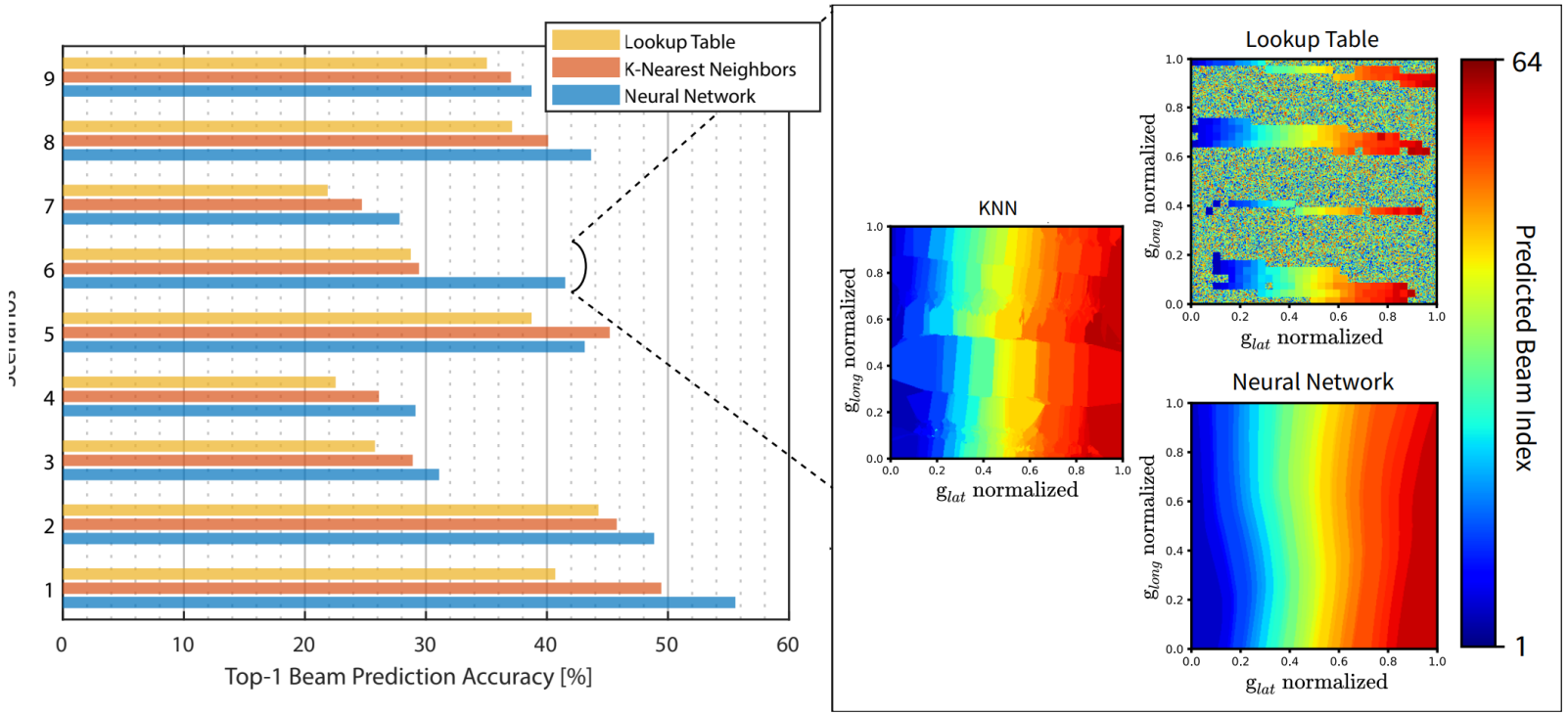
- Multi-modal Data & Learning
  - GPS, Radar, Lidar, RSSI
  - For accurate beam alignment



Alkhateeb, A., Charan, G., Osman, T., Hredzak, A., Morais, J., Demirhan, U., & Srinivas, N. (2023). DeepSense 6G: A large-scale real-world multi-modal sensing and communication dataset. *IEEE Communications Magazine*.

마이크로파 에너지 응용을 위한 ML

- Multi-modal Data & Learning
  - Given UE position, the beam prediction gets more accurate.



(a) Top-1 accuracy comparison on every Scenario.

(b) Scenario 6 prediction maps.

Morais, J., Behboodi, A., Pezeshki, H., & Alkhateeb, A. (2022). Position aided beam prediction in the real world: How useful GPS locations actually are?. *arXiv preprint arXiv:2205.09054*.

마이크로파 에너지 응용을 위한 ML

- Multi-modal Data & Learning
  - Machine learning depends on the **data**.
  - 직접 데이터를 살펴보는 것은 데이터를 획득한 방법에 관계없이 늘 좋은 연습 (공부)가 됨.

http://karpathy.github.io/2014/09/02/what-i-learned-from-competing-against-a-convnet-on-imagenet/

Thank you

Department of Radio & Information Communications Engineering

CHUNGNAM NATIONAL UNIVERSITY