MINIATURIZED ULTRA WIDE BAND MULTIPLE INPUT MULTIPLE OUTPUT WEARABLE ANTENNA AS WIRELESS BODY AREA NETWORK FOR BREAST CANCER DETECTION

By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Breast cancer is one most vital and spread diseases among women nowadays. Various techniques and methods have been applied to detect and cure this disease with the most minor side effects on the body, such as Magnetic Resonance Imaging, Chemotherapy, Radiotherapy, and so on. However, each of these methods indicated some drawbacks, like being blocky, having difficulty with mobility, and being present at the clinic for diagnosis. Wearable systems minimize the dimensions of the rigid printed circuit board (PCB) carrying the electronics and feeding the textile antenna for health monitoring applications. In on-body applications, most sensor antennas are bulky (the present antenna systems showed lower performance with larger dimensions), costly, low performance, and send patients' data with the help of personal computers (PC) located in the patients' homes, which is non-wearable. These wearable electronics should interact with the physical environment as smoothly as possible and be protected in hostile environments against mechanical damage and harsh environments. The excellent robustness and flexibility are crucial components that can provide health monitoring systems with the capability of continuously tracking vital signals of the human body with comfort. However, the antenna's performance is degraded in the proximity of the human body. A low-cost, low-profile modified antipodal four terminal Multiple Input Multiple Output (MIMO) Ultra Wide Bnad (UWB) antenna is proposed offering a good radiation performance (miniaturized, high directive gain, and high fidelity). It presents a detachable electrical connection, reduces the risk of infection, and decreases time and costs significantly. It also eliminates the need for a PC to monitor the body locations. The design is fabricated, and the simulation and measured results are matched well, proving the validity of the new concept. It could monitor the human breast in real-time. The wearable UWB MIMO antenna's performance was demonstrated in free space and on body locations at different distances, calculating the reflection coefficient (S_{11}), bandwidth (BW), gain, and efficiency. It is demonstrated that the UWB MIMO antenna provided a good impedance bandwidth ($S_{11} < -10$dB), with high stability in radiation pattern, efficiency, gains, and free space and on-body. Meanwhile, the UWB MIMO has

a Specific Absorption Rate (SAR) under the standard limits for both 1g (<1.6W/Kg) and 10 g tissues (<2W/Kg) in flat and bending situations. Furthermore, the proposed UWB imaging system can detect a tumour with a diameter of less than 5 mm in any location within the breast with the most clutter removal. The concept of detectability of UWB MIMO design offers passive, low-cost, and versatile system reconfigurability, which can benefit wearable applications. In addition, our proposed approach provides a wide range of benefits in various applications when a PC is not always needed. Thus, the solution presented is robust, affordable, flexible, and allows for the extension of the scope of monitoring body locations easily.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMINIATURAN JALUR ULTRA LEBAR ANTENA BERBILANG INPUT BERBILANG OUTPUT BOLEH PAKAI SEBAGAI RANGKAIAN TANPA WAYAR KAWASAN BADAN UNTUK PENGESANAN KANSER PAYUDARA

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Kanser payudara kini merupakan salah satu penyakit paling berbahaya dan berleluasa dikalangan wanita. Pelbagai teknik dan kaedah telah digunakan untuk mengesan dan menyembuhkan penyakit ini dengan kesan sampingan yang minor kepada badan, seperti pengimejan resonans magnet, kemoterapi, radioterapi dan sebagainya. Walau bagaimanapun, setiap kaedah tersebut mempunyai beberapa kelemahan, seperti tersekat, kesukaran untuk bergerak, dan perlu hadir ke klinik untuk diagnosis. Sistem boleh pakai meminimumkan dimensi papan litar tercetak (PCB) tegar dimana ia membawa elektronik dan menyalurkan ke antena tekstil bagi aplikasi pengawasan kesihatan. Dalam aplikasi pada badan, kebanyakan antena penderia adalah besar (sistem antena sedia ada menunjukkan prestasi yang rendah dengan dimensi yang lebih besar), mahal, prestasi yang rendah serta menghantar data pesakit dengan bantuan komputer peribadi (PC) yang terletak di rumah pesakit, yang mana ini adalah tanpa-boleh pakai. Elektronik boleh pakai ini sepatutnya berinteraksi dengan persekitaran fizikal selancar mungkin dan dilindungi ketika persekitaran yang kasar daripada kerosakan mekanikal dan persekitaran yang keras. Keteguhan yang hebat dan fleksibiliti merupakan komponen penting yang boleh menyediakan sistem pengawasan kesihatan dengan keupayaan mengesan isyarat penting pada badan manusia secara berterusan dengan penuh keselesaan. Walau bagaimanapun, prestasi antena merosot apabila berada dalam jarak yang dekat dengan badan manusia. Antena antipodal diubah suai empat terminal berbilang input berbilang output (MIMO) jalur ultra lebar (UWB) yang berkos rendah serta berprofil rendah yang dicadangkan menawarkan prestasi radiasi yang baik (miniatur, gandaan berarah tinggi dan ketepatan tinggi). Ia juga menawarkan sambungan elektrik boleh tanggal, mengurangkan risiko jangkitan dan penyusutan masa dan kos dengan ketara. Ia juga menghapuskan keperluan PC untuk mengawas lokasi badan. Reka bentuk ini difabrikasi, serta dapatan hasil simulasi dan ukuran adalah sangat berpadanan, dan ini membuktikan kesahihan konsep baru ini. Ia juga boleh mengawas payudara manusia dalam masa nyata. Pencapaian antena UWB MIMO boleh pakai didemonstrasi pada

ruang bebas dan lokasi terpakai pada jarak yang berbeza, menggunakan pekali refleksi (S11), jalur lebar (BW), gandaan dan kecekapan. Antena boleh pakai UWB MIMO telah terbukti menghasilkan impedans jalur lebar yang baik (S11< -10dB), dengan kestabilan corak radiasi yang tinggi, kecekapan, gandaan dan dalam ruang bebas dan terpakai. Di samping itu, UMB MIMO mempunyai Kadar Penyerapan Khusus (SAR) dibawah had piawai untuk kedua-dua 1g (<1.6W/Kg) dan10 g tisu (<2 W/Kg) dalam keadaan rata dan lentur. Tambahan pula, sistem pengimejan UWB yang dicadangkan boleh mengesan ketumbuhan yang berdiameter kurang daripada 5 mm pada mana-mana lokasi di dalam payudara dengan penyingkiran serakan tertinggi. Konsep kebolehkesanan reka bentuk UWB MIMO menawarkan aplikasi pasif, kos yang rendah dan sistem rekonfigurasi yang versatil, yang boleh memanfaatkan aplikasi boleh pakai. Di samping itu, pendekatan yang dicadangkan menawarkan manfaat yang luas dalam pelbagai aplikasi dimana PC tidak lagi selalu diperlukan. Oleh itu, penyelesaian yang dibentangkan adalah teguh, berpatutan, fleksibel dan membenarkan skop pengawasan lokasi badan diluaskan dengan sangat mudah.

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LIST OF ABBREVIATIONS

5G	Fifth Generation
ANOVA	Analysis of Variance
Ant 1	Antenna 1
Ant 2	Antenna 2
APES	Amplitude and Phase Estimation
BAN	Body Area Network
BPF	Band Pass Filter
BW	BandWidth
CBTRML	Coherent Beamspace Time Reversal Maximum Likelihood
CFDAS	Coherence Factor Delay and Sum
CMI	Confocal Microwave Imaging
COVID19	Coronavirus 2019
CPW	Coplanar Waveguide
CRDAS	Channel Ranked Delay and Sum
CST	Computer Simulation Technology
CSTMWS	Computer Simulation Technology Microwave Studio
CSTMWSFIT	Computer Simulation Technology Microwave Studio Finite Integration Technique
DA	Data Adaptive
DAS	Delay and Sum
DC	Dielectric Constant
DGS	Defected Ground Structure
DI	Data independent
DMAS	Delay Multiply and Sum

DORT	Decomposition of Time Reversal Operator
DSDMAS	Double Stage Delay Multiply and Sum
EBG	Electromagnetic Band Gap
EFD	Energy Flux Density
EM	Electromagnetic Waves
E	Textiles - Electronic Textiles
FBW	Frequency Band
FCC	Federal Communication Commission
FDAS	Filtered Delay and Sum
FDMAS	Faster Delay Multiply And Sum
FDTD	Finite Difference Time Domain
FF	Fidelity Factor
FH	Higher Frequency
FIR	Finite Impulse Response
FL	Lower Frequency
FL	Lower Frequency
FSS	Frequency Selective Surface
FU	Upper Frequency
GCPW	Ground Coplanar Waveguide
GD	Group Delay
GND	Ground
GPR	Ground Penetrating Radar
HEB	Half Energy Beam
HEBW	Half Energy BeamWidth
HIS	High Impedance Structure

HOR	Horizontal
IDAS	Improved Delay and Sum
IDC	Invasive Ductal Carcinoma
ISM	Industrial, Scientific and Medical
L3	Length of the Straight Line
LF	Feed Line
LG	Ground Length
LP	Patch Length
MAMI	Multistatic Adaptive Microwave Imaging
MC	Moisture Content
MDAS	Modified Delay and Sum
Meas	Measures
MIMO	Multiple Input Multiple Output
MIST	Microwave Imaging using Space Time
MMW	Millimeter Wave
MRI	Magnetic Resonance Imaging
MSA	Microstrip Slot Antennas
MTM	Meta Material
MUSIC	Multiple Signal Classification
MVBDMAS	Minimum Variance Adaptive Beamforming Delay Multiply and Sum
MWDAS	Modified Weighted Delay and Sum
MWI	Microwave Imaging
MWT	Microwave Tomography
P	Polarization Vector
PBG	Photonic Band Gap

PCB	Printed Circuit Board
PD	Power Density
PET	Polyethylene Terephthalate
PIN	Input Power
PLA	Polylactic Acid
PRAD	Radiated Power
Q factor	Quality factor
QF	Quality Factor
RCB	Robust Capon Beamformer
RF	Radio Frequency
RTR	Robust Time Reversal
RWCB	Robust Weighted Capon Beamformer
RX	Receiver
SAR	Specific Absorption Rate
SCB	Standard Capon Beamformer
SCD	Surface Current Distribution
SCR	Serum Creatinine
Sim	Simulation
SIW	Substrate Integrated Waveguide
SMA	SubMiniature Version A
SMR	Standardized Mortality Ratios
SNR	Signal to Noise Ratio
SPSS	Statistical Package for the Social Sciences
SSI	Structural Similarity Index
SUT	Sample Under Test

TDE	Time Delay Estimation
TL	transmission line
TOA	Time of Arrival
TR	Time Reversal
TRM	Time Rreversal Imaging
TR- MUSIC	Time Rreversal Multiple Signal Classification
TX	Transmitter
UWB	Ultra Wide band
VER	Vertical
VNA	Vector Network Analyzer
VSWR	Voltage Standing Wave Ratio
WBAN	Wireless Body Area Network
WCB	Weighted Capon Beamformer
WG	Ground Width
WMDAS	Weighted Modified Delay And Sum
WP	Patch Width
WT	Width of the Straight Line
X-ray	Electromagnetic Radiation

CHAPTER 1

INTRODUCTION

The demands for wearable technologies have been raised tremendously. In such wearable technology, wearable antennas are increasingly utilized for wireless body area networks (WBAN) applications. The WBAN application stood out to the researcher because of its advantageous characteristics, such as its low weight, convenience, portability, stretchability, affordability, low energy consumption, and potential military applications. The WBAN applications were vastly utilized to monitor patients' health and transmit the data wirelessly. In expansion, a wearable antenna must be comfortable, adaptable, and work with the slightest corruption close to the body.

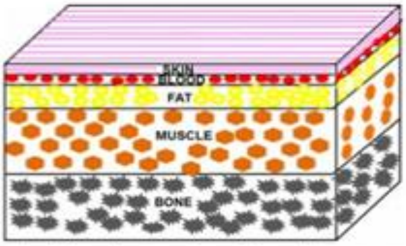
1.1 Introduction

One of the most dangerous diseases for women is breast cancer. This illness causes death each year among women. Several techniques were introduced to challenge this problem and help it get cured. Microwave imaging as a promising method was introduced in the last decades. Microwave imaging uses antennas, especially UWB antennas. They could find and detect the targets as tumours in the imaging area. They could accomplish this task with less cost and time, more comfort, fewer side effects.

A WBAN is a network of low-power, tiny, invasive/non-invasive, lightweight, wireless sensor nodes that keep tabs on the physical body and its environment. When managing health and illness, one of the most important aspects is keeping tabs on people's data. One significant use of WBAN in the health care sector is keeping track of people's physiological activities, such as their health condition.

Flexible wearable antennas are durable, lightweight antennas that can resist a certain amount of mechanical stress. Modern communication systems utilize Flexible/Printed antennas due to their low profile, light, and simplicity of manufacture. Additionally, they can be incorporated into other circuitry systems.

In addition to being relatively average in size, the human body is also renowned for its distinctive asymmetry. There are several strata with varying conductivities and permittivities. As a result, it can readily impair the performance of a wearable antenna. All of these wearable antennas interact closely with the human body and function in the high dielectric medium of the body, which affects the radiation properties of the design. Various body models, such as the 3-layer, homogeneous, and complicated 3D body models, have been explored in the literature (Velan et al., 2014). In addition, numerous levels of the human body were shown in (Haupt, 2016), as presented in Figure 1.1. The proposed antenna was stretched on constructed tissues with typical thicknesses of 2, 4, and 10 mm (Al-Sehemi et al., 2017; Christodoulou et al., 2012; Shakhirul et al., 2018).



Tissues	Permittivity εr	Conductivity (S/m)	Loss Tangent	Density (Kg/m^3)
Skin	31.29	5.0138	0.2835	1100
Fat	5.28	0.1	0.19382	1100
Muscle	52.79	1.705	0.24191	1060
Bone	12.661	3.8591	0.25244	1850

Figure 1.1 : Layered model of human tissue (Haupt, 2016)

One of the most intrusive health issues confronting women, the death count from breast cancer continues to rise. Several methods and strategies were developed to lower the mortality rate. The efficiency of breast self-examination decreased the death rate among women. There is a 14.4 % lifetime chance of acquiring breast cancer. However, the absolute hazard of increasing breast cancer between the years of 40 and 50 is 1.8 %, between the ages of 50 and 60 is 3.2 %, and between the ages of 60 and 70 is 4%.

According to U.S. and European standards, wearable designs must have the lowest SAR on human skin. Intense thermal radiation causes skin and tissue injuries and serious illnesses. Therefore, several planar structures, MTM structures, ferrite sheets, soft surfaces, frequency selective surface (FSS), and giant ground planes were used in the application of body area network (BAN) in order to shield the human body from dangerous electromagnetic radiation (Chen et al., 2018; Kang & Jung, 2015; Kumar et al., 2018; Yan & Vandenbosch, 2016).

Wearable antenna directions can alter applications' performance when bent or stretched. It impacts the wearable antenna's radiation properties and resonance frequency, mainly when necessary circular polarization (CP). Therefore, it is crucial to preserve the antennas hidden and low-profile in wearable applications so they can be easily integrated into regular clothes (Saghati et al., 2015). Reports of wearable antennas crumpling and bending under various situations were given in (Anwar et al., 2017; Saeed et al., 2017; Tong et al., 2018; Wang et al., 2018), making it challenging to keep them flat while worn.

To fulfill the constantly growing need for wireless data traffic, the fifth generation (5G) must offer a broad range of data, up to multiple gigabits per second, and ensure tens of megabits per second with very high availability and dependability. Therefore, many bands have been established and used for 5G applications. In other studies, frequencies greater than 50 GHz were used, including 60 GHz, E-band at (71 – 76) GHz and (81 –

86) GHz, and W-band at (92 – 95) GHz. Another study used the frequency range of (20 – 35) GHz, mainly (23) GHz, (25) GHz, (28) GHz and (32) GHz. Other papers utilized frequency ranges of (15.4 – 36.8) GHz (Ali & Sebak, 2016), as well as lesser bands like (3.5 – 5.1) GHz (Li et al., 2016) and two ranges of (10.125 – 10.225) GHz and (10.475 – 10.575) GHz (Honari et al., 2016).

Wearable antennas should be designed to understand the substrates utilized for the various antenna types. Substrates for wearable antennas can be made from a variety of materials. Because of the electrical and mechanical characteristics of the materials, they must be carefully examined when designing any wearable antenna.

Despite the ability of UWB technology to deliver broad bandwidth communications at low energy costs and high data rates, it is susceptible to interference, particularly in multipath fading, in the face of antenna design issues for 5G micro wireless access points. In the face of significant multipath fading, the system's capacity is severely constrained. UWB technology can therefore be used with MIMO technology to mitigate the impacts of multipath fading. Furthermore, to achieve large system capacity and high communication reliability, antenna systems integrating UWB and MIMO technology can give diversity and multiplexing gain (Li et al., 2017).

1.2 Problem Statement

When tumours are found, many lives can be saved, and the probability of recovery increases. Due to the complexity, unavailability, and immobility of most monitoring devices, many patients find it annoying to perform routine check-ups. In addition, microstrip antennas are practical and flexible for imaging, diagnostic, and therapy applications in the medical field. In the first phases of breast cancer, removing tumours is much simpler and more confident. Instead of Magnetic Resonance Imaging (MRI), the UWB technique can be a new screening method with great potential for detecting breast cancer. In addition, developing a high-performance UWB imaging system is a challenging task in and of itself. As a result of the benefits listed above, the concept of wearable devices and systems has emerged. The current challenges were discussed in the introduction section; however, they can be listed briefly as:

i. The Current non-transparent substrates are too lossy with high loss tangent. Hence, flexible materials should be chosen carefully to have a low tangent loss and lower dielectric constant (Klemm & Troester, 2006). In addition, the flexible antennas should be robust towards bending. Therefore, the proposed antenna should be designed to not change its characteristics dramatically by bending (Affendi et al., 2014; Wang et al., 2016).

ii. The current imaging systems are required more printing areas. Thus, the wearable transceivers should be in low profile. Besides, when the antenna dimension is small can be more robust and less effective in the bending situation and not get degraded in harsh environments (Cai et al., 2015; Saeidi et al., 2019).

iii. The adverse mutual effects of the body on antennas and vice versa produce more side lobes and end–fire radiations, which are not desirable in antenna designing, especially in the on-body situation. Besides, the Specific Absorption Rate (SAR) should be low based on the standards not to affect the body and lose too much power. Most of the current wearable antennas used truncated ground which affected the antenna performances and enhanced the SAR. Therefore, using full-ground and meta surface improves it (Al-Ghamdi et al., 2017).

1.3 Research Objectives

This project aims to suggest and develop a miniaturized UWB wearable antenna for WBAN application to detect and grade breast cancer in each stage of tumour growth in a low-cost, fast, and high-resolution image. The proposed antenna should give high performance in terms of simplicity, broad BW (which offers the high resolution), and fewer side effects on the body since the SAR is low.

1. To determine if the flexile substrates and conductive materials can provide adequate interaction between the antenna and the breast sample under test. Afterward, to design a wearable, flexible multi-wideband antenna with miniaturized size.
2. To develop an antenna with improved radiation efficiency, gain, bandwidth, and resolution (96%, 5.72 dBi, 25.2 GHz, and 95%) while keeping a small form factor (24 × 24) mm.
3. To evaluate the performance of the antenna design and flexibility in detecting various tumour sizes experimentally.

1.4 Scope of Research

Studies have utilized several techniques to detect a tumour in BREASTs. However, only Microwave Imaging (MWI) is chosen for its advantages, such as being non-invasive, faster, and small in size. For imaging, a variety of UWB antennas are employed. Among all the patch shapes, the bowtie and Vivaldi antennae are used for the antenna sensor design. Other forms of the patch, such as elliptical, wide slot, and stack antennas, were not used. Because the bowtie and Vivaldi patch shape showed better outcomes, more straightforward structure than other types, and can work at the lower band with smaller dimensions than others. Then, the antenna is loaded simply using stubs, slots, and shorting pins. At the same time, it did not use complicated loading like using electronic elements and shorting posts.

After the simulation of the antennas in free space, they are investigated in a breast environment. The breast samples are 3D printed using a material with the dielectric constant of the breast. The measurement is carried out in a lab environment. Image reconstruction was initiated once it was shown that the antenna provided high-quality breast imaging. The current imaging methods presented in the literature have several drawbacks and limitations. As a result, an image reconstruction algorithm is developed. Other algorithms such as Modified Delay and Sum (MDAS), Faster Delay Multiply And Sum (FDMAS), Weighted Modified Delay And Sum (WMDAS), Standard Capon Beamformer (SCB), and other DA and DI were not used. They showed some limitations on resolution and correct localization of the target, and still, some clutter exists in the detected images. It is based on three standard algorithms: delay and sum (DAS), delay multiply and sum (DMAS), and time reversal (TR). An array of 4 and 9 are evaluated for assessment and review. Additionally, breast samples are restricted to a maximum and minimum size of $(30)\ cm$ and $(10)\ cm$, and tumour diameters are decreased to $(8)\ mm$ and $(4)\ mm$, respectively (see Figure 1.2).

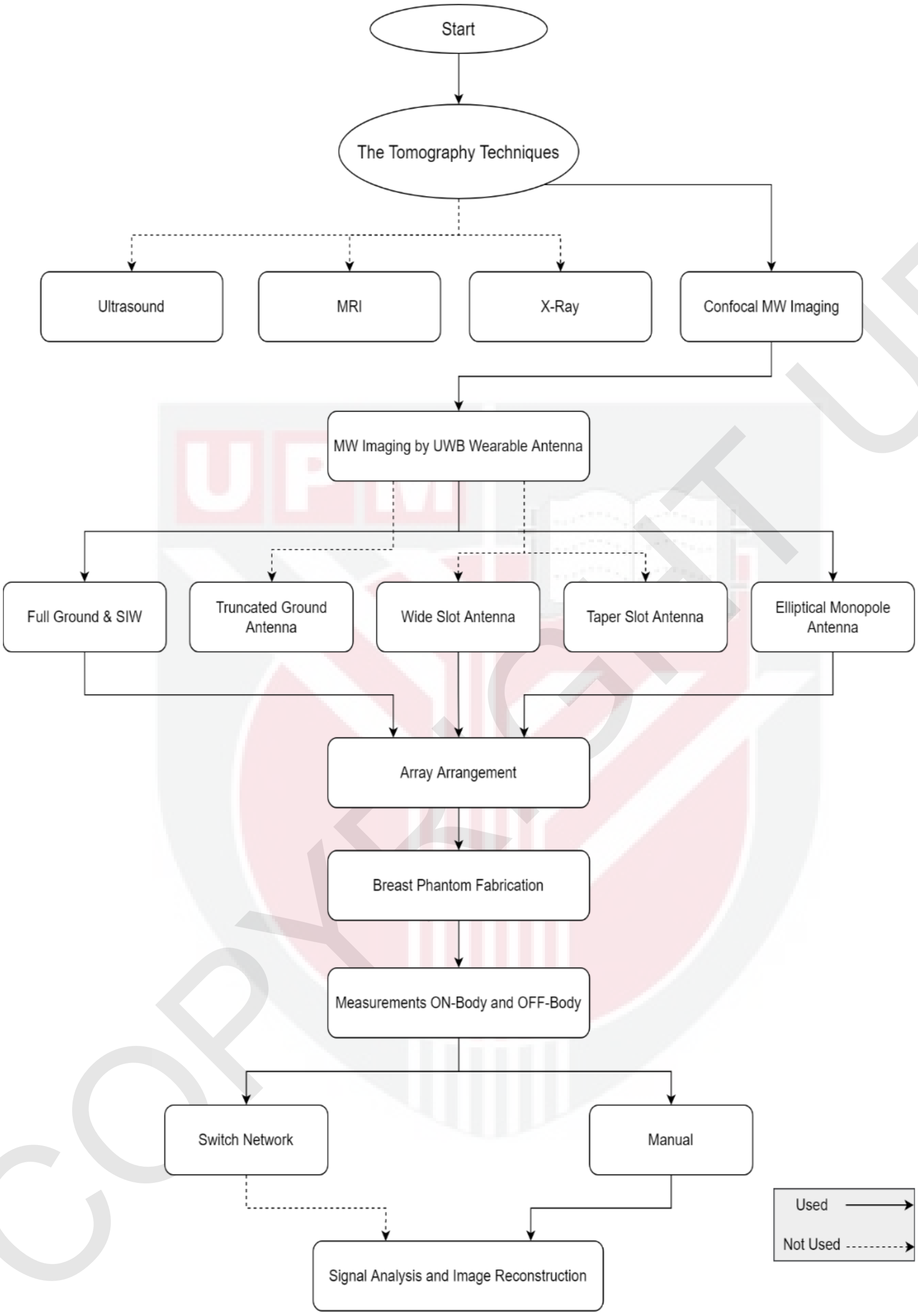


Figure 1.2 : The scope of study

1.5 Configuration of the Thesis

This section summarizes the structure of the thesis. Chapter 2 discusses the background of the BREAST, the difficulties, the many ways for tomography of the BREAST sample, and MWI as an early detection approach for breast tumours. Then, an explanation of UWB antenna sensor requirements for MWI is provided. Chapter 3 details the measurement of BREAST's dielectric properties, the strategy for building UWB antenna sensors for MWI, the suggested algorithm, current image reconstruction techniques, and the construction of the imaging device. Chapter 4 then examines the results of the manufactured antenna sensors, their size reduction techniques, and an analysis of the image reconstruction capabilities of the antenna sensor array. The thesis is concluded with a brief discussion of future research in Chapter 5, which reviews the findings and their comparisons.

REFERENCES

Adam, A. A., Rahim, S. K. A., Tan, K. G., & Reza, A. W. (2013). Design of 3.1–12 GHz printed elliptical disc monopole antenna with half circular modified ground plane for UWB application. *Wireless Personal Communications*, *69*(2), 535-549.

Addepalli, T., & Anitha, V. (2020). A very compact and closely spaced circular shaped UWB MIMO antenna with improved isolation. *AEU-International Journal of Electronics and Communications*, *114*, 153016.

Affendi, N., Alias, N., Razali, N., Awang, Z., & Samsuri, A. (2014). Flexible antennas using a new material. *In 2014 Asia-Pacific Microwave Conference* (pp. 1420-1422). IEEE. Sendai, Japan.

Ahadi, M., Isa, M., Saripan, M. I., & Hasan, W. (2015). Three dimensions localization of tumors in confocal microwave imaging for breast cancer detection. *Microwave and Optical Technology Letters*, *57*(12), 2917-2929.

Ahamed, M. M., Bhowmik, K., & Al Suman, A. (2012). Analysis and design of rectangular microstrip patch antenna on different resonant frequencies for pervasive wireless communication. *International journal of scientific & technology research*, 1(5), 2010-2013.

Ahamed, M. M., Bhowmik, K., Shahidulla, M., Islam, M. S., & Rahman, M. A. (2012). Rectangular micro strip patch antenna at 2ghz on different dielectric constant for pervasive wireless communication. *International Journal of Electrical and Computer Engineering*, *2*(3), 417.

Ahmed, M., Ahmed, M., & Shaalan, A. (2017). A novel UWB double layer lotus wearable antenna for integration on astronauts spacesuit. *In 2017 Japan-Africa Conference on Electronics, Communications and Computers (JAC-ECC)* (pp. 144-147). IEEE. Alexandria, Egypt.

Akki, R. S., & Arunachalam, K. (2014). Breast tissue phantoms to assist compression study for cancer detection using microwave radiometry. *In 2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (pp. 1119-1122). IEEE. Chicago, IL, USA.

Al-Ghamdi, A. A., Al-Hartomy, O. A., Al-Solamy, F. R., Dishovsky, N. T., Atanasov, N. T., & Atanasova, G. L. (2017). Enhancing antenna performance and SAR reduction by a conductive composite loaded with carbon-silica hybrid filler. *AEU-International Journal of Electronics and Communications*, *72*, 184-191.

Al-Sehemi, A. G., Al-Ghamdi, A. A., Dishovsky, N. T., Atanasov, N. T., & Atanasova, G. L. (2017). Flexible and small wearable antenna for wireless body area network applications. *Journal of Electromagnetic waves and Applications*, *31*(11-12), 1063-1082.

Alhawari, A. R., Almawgani, A., Hindi, A. T., Alghamdi, H., & Saeidi, T. (2021). Metamaterial-based wearable flexible elliptical UWB antenna for WBAN and breast imaging applications. *AIP Advances, 11*(1), 015128.

Ali, M. M. M., & Sebak, A.-R. (2016). Compact UWB high gain fermi taper slot antenna for future 5G communication systems. *In 2016 17th International Symposium on Antenna Technology and Applied Electromagnetics (ANTEM)* (pp. 1-2). IEEE. Montréal, QC, Canada.

Altaf, A., Iqbal, A., Smida, A., Smida, J., Althuwayb, A. A., Hassan Kiani, S., . . . Limiti, E. (2020). Isolation improvement in UWB-MIMO antenna system using slotted stub. *Electronics, 9*(10), 1582.

Amineh, R. K., Ravan, M., Trehan, A., & Nikolova, N. K. (2010). Near-field microwave imaging based on aperture raster scanning with TEM horn antennas. *IEEE Transactions on Antennas and Propagation, 59*(3), 928-940.

Andersen, J., & Rasmussen, H. (1976). Decoupling and descattering networks for antennas. *IEEE Transactions on Antennas and Propagation, 24*(6), 841-846.

Anwar, M. S., & Bangert, A. (2017). 3D printed microfluidics-based reconfigurable antenna. *In 2017 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP)* (pp. 1-3). IEEE. Pavia, Italy.

Arezoomand, A. S., Sadeghzadeh, R.-A., & Naser-Moghadasi, M. (2016). Novel techniques in tapered slot antenna for linearity phase center and gain enhancement. *IEEE antennas and wireless propagation letters, 16*, 270-273.

Azeez, H. I., Yang, H.-C., & Chen, W.-S. (2019). Wearable triband E-shaped dipole antenna with low SAR for IoT applications. *Electronics, 8*(6), 665.

Badhan, K., & Singh, J. (2017). Analysis of Different Performance Parameters of Bodywearable Antenna-A Review. *Adv. Wirel. Mob. Commun, 10*, 735-745.

Balanis, C. A. (2015). *Antenna Theory Analysis and Design*, 3rd edition, 1- 1136: JohnWiley& Sons. *Inc., Publication.*

Bhartia, P., Bahl, I., Garg, R., & Ittipiboon, A. (2000). *Microstrip Antenna Design Handbook, 1- 875*: Artech House Antennas and Propagation Library.

Bilal, M., Yin, W., Abdullah, M., Armitage, D., & Peyton, A. (2007). Ultra Wide Band Tomography-Experimental Hardware and Image Reconstruction. *In Proceedings of the 5th World Congress on Industrial Process Tomography*. Leeds, UK.

Bocquet, B., Van de Velde, J., Mamouni, A., Leroy, Y., Giaux, G., Delannoy, J., & Delvalee, D. (1990). Microwave radiometric imaging at 3GHz for the exploration of breast tumors. *IEEE Transactions on Microwave Theory and techniques, 38*(6), 791-793.

Boero, F., Fedeli, A., Lanini, M., Maffongelli, M., Monleone, R., Pastorino, M., . . . Sansalone, A. (2018). Microwave tomography for the inspection of wood materials: Imaging system and experimental results. *IEEE Transactions on Microwave Theory and techniques, 66*(7), 3497-3510.

Canadian Cancer Society, (2017). from http://www.cancer.ca/en/cancer-information/cancer-types/breast/what-is-breast-cancer (accessed 15 Jun. 2020).

Britannica, (2021). from https://www.britannica.com/science/cancer-disease (accessed 6 May. 2021).

Cai, Y., Qian, Z., Cao, W., & Zhang, Y. (2015). Research on the half complementary split-ring resonator and its application for designing miniaturized patch antenna. *Microwave and Optical Technology Letters, 57*(11), 2601-2604.

Caldeira, J. M., Rodrigues, J. J., & Lorenz, P. (2012). Toward ubiquitous mobility solutions for body sensor networks on healthcare. *IEEE Communications Magazine, 50*(5), 108-115.

Breast Cancer, B, (2015). from https://en.wikipedia.org/wiki/Breast_cancer (accessed 6 Dec. 2019).

Breast Cancer Early Detection and Diagnosis, (2015). from http://www.cancer.org/cancer/breastcancer/detailedguide/breast-cancer-detection (accessed 7 Dec. 2019).

Cancer, S. o. B. (2013). from http://www.breastcancer.org/ (accessed 14 Dec. 2019).

Carver, K. R., & Coffey, E. L. (1979). *Theoretical Investigation of the Microstrip Antenna.* New Mexico State Univ Las Cruces Physical Science Lab.

Chen, C.-C., Higgins, M. B., O'Neill, K., & Detsch, R. (2001). Ultrawide-bandwidth fully-polarimetric ground penetrating radar classification of subsurface unexploded ordnance. *IEEE Transactions on Geoscience and Remote Sensing*. 39(6), 1221-1230. IEEE. Piscataway, USA.

Chen, L., Lei, Z., Yang, R., Fan, J., & Shi, X. (2014). A broadband artificial material for gain enhancement of antipodal tapered slot antenna. *IEEE Transactions on Antennas and Propagation, 63*(1), 395-400.

Chen, S. J., Ranasinghe, D. C., & Fumeaux, C. (2018). A robust snap-on button solution for reconfigurable wearable textile antennas. *IEEE Transactions on Antennas and Propagation, 66*(9), 4541-4551.

Chen, X., Zhang, S., & Li, Q. (2018). A review of mutual coupling in MIMO systems. *IEEE Access, 6*, 24706-24719.

Chen, Y., Gunawan, E., Low, K. S., Wang, S.-c., Kim, Y., & Soh, C. B. (2007). Pulse design for time reversal method as applied to ultrawideband microwave breast cancer detection: A two-dimensional analysis. *IEEE Transactions on Antennas and Propagation, 55*(1), 194-204.

Chien, J.-T. (2018). *Source separation and machine learning, 1-384*: Academic Press.

Christodoulou, C. G., Tawk, Y., Lane, S. A., & Erwin, S. R. (2012). Reconfigurable antennas for wireless and space applications. *Proceedings of the IEEE, 100*(7), 2250-2261.

Daniel, O. T. Z., Yuanjin, Z., & Zhiping, L. (2010). Design and experimental investigation of UWB microwave imaging via MIMO beamforming. *In 2010 IEEE International Conference on Ultra-Wideband*. (Vol. 2, pp. 1-4). IEEE. Nanjing, China.

Davis, S. K., Van Veen, B. D., Hagness, S. C., & Kelcz, F. (2007). Breast tumor characterization based on ultrawideband microwave backscatter. *IEEE transactions on biomedical engineering, 55*(1), 237-246.

Deschamps, G. A. (1953). Microstrip microwave antennas. *In Proceedings of the Third Symposium on the USAF Antenna Research and Development Program, Oct*. (pp. 18-22).

Dey, A. B., Pattanayak, S. S., Mitra, D., & Arif, W. (2021). Investigation and design of enhanced decoupled UWB MIMO antenna for wearable applications. *Microwave and Optical Technology Letters, 63*(3), 845-861.

Zhang, H. (2015). Microwave imaging for ultra-wideband antenna based cancer detection. PhD Thesis, The University of Edinburgh, Scotland.

El Gharbi, M., Martinez-Estrada, M., Fernández-García, R., Ahyoud, S., & Gil, I. (2021). A novel ultra-wide band wearable antenna under different bending conditions for electronic-textile applications. *The Journal of The Textile Institute, 112*(3), 437-443.

El Mashade, M. B. (2020). Binary integration performance analysis of CA family of CFAR strategies in homogeneous Weibull clutter. *Radioelectronics and Communications Systems, 63*(1), 24-41.

Elahi, M. A. (2018). Confocal microwave imaging and artifact removal algorithms for the early detection of breast cancer. PhD Thesis, National University of Ireland Galway, Ireland.

Elahi, M. A., Glavin, M., Jones, E., & O'Halloran, M. (2013). Artifact removal algorithms for microwave imaging of the breast. *Progress In Electromagnetics Research, 141*, 185-200.

Elahi, M. A., O'Loughlin, D., Lavoie, B. R., Glavin, M., Jones, E., Fear, E. C., & O'Halloran, M. (2018). Evaluation of image reconstruction algorithms for confocal microwave imaging: Application to patient data. *Sensors, 18*(6), 1678.

Eshtiaghi, R., Nourinia, J., & Ghobadi, C. (2010). Electromagnetically coupled band-notched elliptical monopole antenna for UWB applications. *IEEE Transactions on Antennas and Propagation, 58*(4), 1397-1402.

Ethaib, S., Omar, R., Kamal, S. M. M., Awang Biak, D. R., & Zubaidi, S. L. (2020). Microwave-assisted pyrolysis of biomass waste: a mini review. *Processes, 8*(9), 1190.

Fear, E. C., Li, X., Hagness, S. C., & Stuchly, M. A. (2002). Confocal microwave imaging for breast cancer detection: Localization of tumors in three dimensions. *IEEE transactions on biomedical engineering,* 49(8), 812-822.

Fung, C. (2011). *Basic antenna theory and application*. Worcester Polytechnic Institute, 18, United States.

Garg, R., Bhartia, P., Bahl, I. J., & Ittipiboon, A. (2001). *Microstrip antenna design handbook*: Artech house.

Golnabi, A. H., Meaney, P. M., Geimer, S., Zhou, T., & Paulsen, K. D. (2011). Microwave tomography for bone imaging. *In 2011 IEEE international symposium on Biomedical imaging: from nano to macro*. (pp. 956-959). IEEE. Chicago, IL, USA.

Guo, J.-y., Liu, F., Jing, G.-d., Zhao, L.-y., Yin, Y.-z., & Huang, G.-l. (2020). Mutual coupling reduction of multiple antenna systems. *Frontiers of Information Technology & Electronic Engineering,* 21(3), 366-376.

Gupta, B. K., & Mishra, S. (2014). Analysis of Circular Disc Antenna Using Defective Ground Plane. *International Journal of Research in Engineering and Technology (IJRET),* 2319-2321.

Gurjar, R., Upadhyay, D. K., Kanaujia, B. K., & Kumar, A. (2020). A compact modified sierpinski carpet fractal UWB MIMO antenna with square-shaped funnel-like ground stub. *AEU-International Journal of Electronics and Communications,* 117, 153126.

Breast Ultrasound, (2020). from http://www.webmd.com/breast-cancer/breast-ultrasound (accessed 15 Aug. 2020).

Habib Ullah, M., Islam, M., Ahsan, M., Mandeep, J., & Misran, N. (2014). A dual band slotted patch antenna on dielectric material substrate. *International Journal of Antennas and Propagation,* 2014.

Hammouch, N., Ammor, H., & Himdi, M. (2021). A Compact Flexible UWB Antenna for Biomedical Applications: Especially for Breast Cancer Detection. *In WITS 2020* (pp. 1061-1072). Springer, Singapore.

Hamzah, N., Tokimatsu, K., & Yoshikawa, K. (2019). Solid fuel from oil palm biomass residues and municipal solid waste by hydrothermal treatment for electrical power generation in Malaysia: A review. *Sustainability,* 11(4), 1060.

Hamzah, N. N., Bakar, E. S., Ashaari, Z., & Hua, L. S. (2017). Assessment of oil palm wood quality improvement through integrated treatment process as function of sawing pattern and slab thickness. *Journal of Oil Palm Research*, 29(3), 366-372.

Hansson, L., Lundgren, N., Antti, A., & Hagman, O. (2005). Microwave penetration in wood using imaging sensor. *Measurement,* 38(1), 15-20.

Hao, Y., Zou, N., & Liang, G. (2019). Robust capon beamforming against steering vector error dominated by large direction-of-arrival mismatch for passive sonar. *Journal of Marine Science and Engineering,* 7(3), 80.

Henriksson, T., Klemm, M., Gibbins, D., Leendertz, J., Horseman, T., Preece, A., . . . Craddock, I. (2011). Clinical trials of a multistatic UWB radar for breast imaging. *In 2011 Loughborough Antennas & Propagation Conference*. (pp. 1-4). IEEE. Loughborough, UK.

Hernández-Gómez, E., Olvera-Cervantes, J., Corona-Chávez, A., & Sosa-Morales, M. (2014). Development of a low cost dielectric permittivity sensor for organic and inorganic materials in the microwave frequency range. *In 2014 IEEE 9th IberoAmerican Congress on Sensors.* (pp. 1-4). IEEE. Bogota, Colombia.

Hilger, I., Geyer, C., Rimkus, G., Helbig, M., Sachs, J., Schwarz, U., . . . Kaiser, W. (2010). Could we use UWB sensing for breast cancer detection?. *In Proceedings of the Fourth European Conference on Antennas and Propagation*. (pp. 1-4). IEEE. Barcelona, Spain.

Honari, M. M., Mirzavand, R., Melzer, J., & Mousavi, P. (2016). A new aperture antenna using substrate integrated waveguide corrugated structures for 5G applications. *IEEE antennas and wireless propagation letters,* 16, 254-257.

Hossain, M. D., & Mohan, A. S. (2015). Coherent time-reversal microwave imaging for the detection and localization of breast tissue malignancies. *Radio Science,* 50(2), 87-98.

Hossain, M. D., & Mohan, A. S. (2017). Cancer detection in highly dense breasts using coherently focused time-reversal microwave imaging. *IEEE Transactions on Computational Imaging,* 3(4), 928-939.

Howell, J. (1975). Microstrip antennas. *IEEE Transactions on Antennas and Propagation,* 23(1), 90-93.

Hu, Z. H. S. (2012). Antennas with frequency domain control for future communication systems. PhD Thesis, University of Birmingham, England.

National Cancer Institute, (2018). from https://www.cancer.gov/about-cancer/understanding (accessed 10 Dec. 2019).

Jafari, H. M., Deen, M. J., Hranilovic, S., & Nikolova, N. K. (2007). A study of ultrawideband antennas for near-field imaging. *IEEE Transactions on Antennas and Propagation*, 55(4), 1184-1188.

Jang, T., Zhang, C., Youn, H., Zhou, J., & Guo, L. J. (2016). Semitransparent and flexible mechanically reconfigurable electrically small antennas based on tortuous metallic micromesh. *IEEE Transactions on Antennas and Propagation,* 65(1), 150-158.

Ji, S., Yu, T. N., Gao, Y. J., Han, J. K., Liu, C., Chung, K. L., & Zong, W. H. (2018, August). A novel flexible UWB antenna. *In 2018 IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM)* (pp. 1-2). IEEE. Nagoya, Japan.

Jouadé, A., Ferro-Famil, L., Méric, S., Lafond, O., & Le Coq, L. (2017). High resolution radar focusing using spectral estimation methods in wide-band and near-field configurations: Application to millimeter-wave near-range imaging. *Progress In Electromagnetics Research B,* 79, 45-64.

Kaatze, U. (2010). Techniques for measuring the microwave dielectric properties of materials. *Metrologia,* 47(2), S91.

Kakhki, M. B., & Rezaei, P. (2017). Reconfigurable microstrip slot antenna with DGS for UWB applications. *International Journal of Microwave and Wireless Technologies,* 9(7), 1517-1522.

Kang, S., & Jung, C. W. (2015). Wearable fabric reconfigurable beam steering antenna for on/off-body communication system. *In 2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*. (pp. 1211-1212). IEEE. Vancouver, BC, Canada.

Khor, W. C., Bialkowski, M. E., Abbosh, A., Seman, N., & Crozier, S. (2007). An ultra wideband microwave imaging system for breast cancer detection. *IEICE Transactions on Communications,* 90(9), 2376-2381.

Kikuta, K., & Hirose, A. (2015). Compact folded-fin tapered slot antenna for UWB applications. *IEEE antennas and wireless propagation letters,* 14, 1192-1195.

Kim, S.-W., & Choi, D.-Y. (2016). Implementation of rectangular slit-inserted ultra-wideband tapered slot antenna. *SpringerPlus,* 5(1), 1-11.

Kim, S., Kim, G., Noh, S., & Choi, D. (2015). Design and implementation of an IR-ultra wide band tapered slot antenna with a rectangular slot structure. *In International conference on green and human information technology* (pp. 321-324). Bangkok, Thailand.

Kirtania, S. G., Elger, A. W., Hasan, M., Wisniewska, A., Sekhar, K., Karacolak, T., & Sekhar, P. K. (2020). Flexible antennas: a review. *Micromachines,* 11(9), 847.

Kirtania, S. G., Younes, B. A., Hossain, A. R., Karacolak, T., & Sekhar, P. K. (2021). CPW-fed flexible ultra-wideband antenna for IoT applications. *Micromachines,* 12(4), 453.

Klemm, M., Craddock, I., Leendertz, J., Preece, A., & Benjamin, R. (2008). Improved delay-and-sum beamforming algorithm for breast cancer detection. *International Journal of Antennas and Propagation,* 2008.

Klemm, M., Gibbins, D., Leendertz, J., Horseman, T., Preece, A., Benjamin, R., & Craddock, I. (2011). Development and testing of a 60-element UWB conformal array for breast cancer imaging. *In Proceedings of the 5th European Conference on Antennas and Propagation (EUCAP)* (pp. 3077-3079). IEEE. Rome, Italy.

Klemm, M., & Troester, G. (2006). EM energy absorption in the human body tissues due to UWB antennas. *Progress In Electromagnetics Research,* 62, 261-280.

Kocbek, E., Garcia, H. A., Hooijmans, C. M., Mijatović, I., Lah, B., & Brdjanovic, D. (2020). Microwave treatment of municipal sewage sludge: Evaluation of the drying performance and energy demand of a pilot-scale microwave drying system. *Science of the Total Environment,* 742, 140541.

Kraszewski, A. W., & Nelson, S. (1995). Application of microwave techniques in agricultural research. *In Proceedings of 1995 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference* (Vol. 1, pp. 117-126). IEEE. Rio de Janeiro, Brazil.

Kruger, R. A., Kopecky, K. K., Aisen, A. M., Reinecke, D. R., Kruger, G. A., & Kiser Jr, W. L. (1999). Thermoacoustic CT with radio waves: A medical imaging paradigm. *Radiology,* 211(1), 275-278.

Kumar, J., Basu, B., Talukdar, F. A., & Nandi, A. (2018). Graphene-based multimode inspired frequency reconfigurable user terminal antenna for satellite communication. *Iet Communications,* 12(1), 67-74.

Kumar, S., Lee, G. H., Kim, D. H., Mohyuddin, W., Choi, H. C., & Kim, K. W. (2020). A compact four-port UWB MIMO antenna with connected ground and wide axial ratio bandwidth. *International Journal of Microwave and Wireless Technologies,* 12(1), 75-85.

Lan, X., & Liu, W. (2017). A Fully Quaternion-Valued Capon Beamformer Based on Crossed-Dipole Arrays. *arXiv preprint arXiv:*1707.08207.

Lazebnik, M., Madsen, E. L., Frank, G. R., & Hagness, S. C. (2005). Tissue-mimicking phantom materials for narrowband and ultrawideband microwave applications. *Physics in Medicine & Biology, 50*(18), 4245.

Lee, K. F., Luk, K. M., & Lai, H. W. (2017). *Microstrip patch antennas*: World Scientific.

Lerosey, G., De Rosny, J., Tourin, A., Derode, A., Montaldo, G., & Fink, M. (2004). Time reversal of electromagnetic waves. *Physical review letters,* 92(19), 193904.

Li, Q., Xiao, X., Wang, L., Song, H., Kono, H., Liu, P., . . . Kikkawa, T. (2015). Direct extraction of tumor response based on ensemble empirical mode decomposition for image reconstruction of early breast cancer detection by UWB. *IEEE transactions on biomedical circuits and systems*, 9(5), 710-724.

Li, X., & Hagness, S. C. (2001). A confocal microwave imaging algorithm for breast cancer detection. *IEEE microwave and wireless components letters*, 11(3), 130-132.

Li, Y., Wang, C., Yuan, H., Liu, N., Zhao, H., & Li, X. (2016). A 5G MIMO antenna manufactured by 3-D printing method. *IEEE antennas and wireless propagation letters*, 16, 657-660.

Li, Y., Yu, B., Shen, H., Zhu, L., & Yang, G. (2017). An 8-port planar UWB MIMO antenna for future 5G micro wireless access point applications. *In 2017 International Applied Computational Electromagnetics Society Symposium (ACES)* (pp. 1-2). IEEE. Suzhou, China.

Lian, Q., Zhang, J., Gan, L., Ma, Q., Zong, Z., & Wang, Y. (2017). The biocontrol efficacy of Streptomyces pratensis LMM15 on Botrytis cinerea in tomato. *BioMed Research International*, 2017.

Lin, M.-S., Huang, C.-H., & Hsu, C.-I. G. (2012). Performance study of electromagnetic protective sheets for wireless communication systems. *In 2012 Asia-Pacific Symposium on Electromagnetic Compatibility* (pp. 725-728). IEEE. Singapore.

Lin, M.-S., Huang, Y.-H., & Hsu, C.-I. G. (2014). Design a dual-band high-impedance surface structure for electromagnetic protection in WLAN applications. *In 2014 International Symposium on Electromagnetic Compatibility, Tokyo* (pp. 525-528). IEEE. Tokyo, Japan.

Liu, J., Zhong, S., & Esselle, K. P. (2010). A printed elliptical monopole antenna with modified feeding structure for bandwidth enhancement. *IEEE Transactions on Antennas and Propagation*, 59(2), 667-670.

Liu, Y.-T., & Su, C.-W. (2008). Wideband omnidirectional operation monopole antenna. *Progress in Electromagnetics Research Letters*, 1, 255-261.

Liu, Y. Q., Liang, J. G., & Wang, Y. W. (2017). Gain-improved double-slot TSA with Y-shaped corrugated edges. *Electronics Letters*, 53(12), 759-760.

Lund, A. a. L., M. (2018). Two-way ANOVA in SPSS Statistics. from https://statistics.laerd.com/spss-tutorials/two-way-anova-using-spss-statistics (accessed 4 Jan. 2021).

Mahmood, S. N., Ishak, A. J., Saeidi, T., Soh, A. C., Jalal, A., Imran, M. A., & Abbasi, Q. H. (2021). Full ground ultra-wideband wearable textile antenna for breast cancer and wireless body area network applications. *Micromachines*, 12(3), 322.

Malekpoor, H., & Jam, S. (2013). Miniaturised asymmetric E-shaped microstrip patch antenna with folded-patch feed. *IET Microwaves, Antennas & Propagation*, 7(2), 85-91.

Mamiński, M., Kozakiewicz, P., Jaskółowski, W., Chin, K. L., H'ng, P. S., & Toczyłowska-Mamińska, R. (2016). Enhancement of technical value of oil palm (Elaeis guineensis Jacq.) waste trunk through modification with 1, 3-dimethylol-4, 5-dihydroxyethyleneurea (DMDHEU). *European Journal of Wood and Wood Products,* 74(6), 837-844.

Mars, R., Reju, V. G., Khong, A. W., Hioka, Y., & Niwa, K. (2018). Beamforming techniques using microphone arrays *Academic Press Library in Signal Processing, Volume 7* (pp. 585-612): Elsevier.

Masson, Y., Cupillard, P., Capdeville, Y., & Romanowicz, B. (2014). On the numerical implementation of time-reversal mirrors for tomographic imaging. *Geophysical Journal International,* 196(3), 1580-1599.

Matrone, G., Savoia, A. S., Caliano, G., & Magenes, G. (2014). The delay multiply and sum beamforming algorithm in ultrasound B-mode medical imaging. *IEEE transactions on medical imaging,* 34(4), 940-949.

Medica, H, (2017). from https://www.medicalnewstoday.com/articles/37136#symptoms (accessed 2 Jan. 2019).

Monleone, R., Pastorino, M., Poretti, S., Randazzo, A., Massimini, A., & Salvade, A. (2012). *Nondestructive evaluations by using a prototype of a microwave tomograph.* Microwave Materials Characterization: IntechOpen.

Moosazadeh, M., & Kharkovsky, S. (2015). A compact high-gain and front-to-back ratio elliptically tapered antipodal Vivaldi antenna with trapezoid-shaped dielectric lens. *IEEE antennas and wireless propagation letters*, 15, 552-555.

Mozaffarzadeh, M., Mahloojifar, A., Orooji, M., Kratkiewicz, K., Adabi, S., & Nasiriavanaki, M. (2018). Linear-array photoacoustic imaging using minimum variance-based delay multiply and sum adaptive beamforming algorithm. *Journal of biomedical optics,* 23(2), 026002.

Mozaffarzadeh, M., Sadeghi, M., Mahloojifar, A., & Orooji, M. (2018). Double-stage delay multiply and sum beamforming algorithm applied to ultrasound medical imaging. *Ultrasound in medicine & biology,* 44(3), 677-686.

Mukherjee, S., Tamburrino, A., Haq, M., Udpa, S., & Udpa, L. (2018). Far field microwave NDE of composite structures using time reversal mirror. *NDT & E International,* 93, 7-17.

Mukherjee, S., Udpa, L., Udpa, S., Rothwell, E. J., & Deng, Y. (2019a). Microwave time-reversal mirror for imaging and hyperthermia treatment of breast tumors. *Progress In Electromagnetics Research M,* 77, 1-16.

Mukherjee, S., Udpa, L., Udpa, S., Rothwell, E. J., & Deng, Y. (2019b). A time reversal-based microwave imaging system for detection of breast tumors. *IEEE Transactions on Microwave Theory and techniques,* 67(5), 2062-2075.

Nadakuduti, J., Chen, G., & Zoughi, R. (2006). Semiempirical electromagnetic modeling of crack detection and sizing in cement-based materials using near-field microwave methods. *IEEE Transactions on Instrumentation and Measurement,* 55(2), 588-597.

National Center for Biotechnology Information, U. S. N. L. o. M, (2007). from https://www.ncbi.nlm.nih.gov/books/NBK20362/ (accessed 10 Dec. 2019).

Negi, D., Khanna, R., & Kaur, J. (2019). Design and performance analysis of a conformal CPW fed wideband antenna with Mu-Negative metamaterial for wearable applications. *International Journal of Microwave and Wireless Technologies*, 11(8), 806-820.

Norouzzadeh, E., Chamaani, S., & Moll, J. (2019). Parametric study of time-reversal imaging for the detection of tumors in MRI-derived breast phantoms. *In 2019 12th German Microwave Conference (GeMiC)* (pp. 206-209). IEEE. Stuttgart, Germany.

Nugroho, A., & Wu, Z. (1999). Microwave imaging of 3d lossy dielectric objects using algebraic reconstruction techniques. *Industrial Process Tomography, Buxton, Greater Manchester, UK* (pp. 201-205). Manchester, UK.

Nyfors, E. (2000). Industrial microwave sensors—A review. *Subsurface Sensing Technologies and Applications,* 1(1), 23-43.

Omar, R., Idris, A., Yunus, R., Khalid, K., & Isma, M. A. (2011). Characterization of empty fruit bunch for microwave-assisted pyrolysis. *Fuel,* 90(4), 1536-1544.

Oni, M. A. I., & Ali, M. T. (2014). Design of a compact, low-profile, elliptical patch UWB antenna and performance analysis in vicinity of human layered tissue model for wireless body area network (WBAN) applications. *International Journal of Innovation and Applied Studies,* 8(4), 1770.

Osman, M. A., Rahim, M., Samsuri, N., Elbasheer, M., & Ali, M. (2012). Textile UWB antenna bending and wet performances. *International Journal of Antennas and Propagation,* 2012.

Ostadrahimi, M., Mojabi, P., Noghanian, S., Shafai, L., Pistorius, S., & LoVetri, J. (2011). A novel microwave tomography system based on the scattering probe technique. *IEEE Transactions on Instrumentation and Measurement,* 61(2), 379-390.

Ostadrahimi, M., Noghanian, S., Shafai, L., Zakaria, A., Kaye, C., & LoVetri, J. (2010). Investigating a double layer Vivaldi antenna design for fixed array field measurement. *International Journal of Ultra Wideband Communications and Systems,* 1(4), 282-290.

Pack, J.-K., Kim, T.-H., Jeon, S.-I., Lee, J.-M., & Kim, K.-C. (2010). Breast cancer detector using microwave tomography image technology. *In 2010 Asia-Pacific*

International Symposium on Electromagnetic Compatibility (pp. 362-365). IEEE. Beijing, China.

Park, J., Park, C., Lee, K., Cho, Y.-H., & Park, Y. (2017). Time-reversing a monochromatic subwavelength optical focus by optical phase conjugation of multiply-scattered light. *Scientific reports*, 7(1), 1-6.

Pastorino, M., Salvadè, A., Monleone, R., Bartesaghi, T., Bozza, G., & Randazzo, A. (2007). Detection of defects in wood slabs by using a microwave imaging technique. *In 2007 IEEE Instrumentation & Measurement Technology Conference IMTC 2007* (pp. 1-6). IEEE. Warsaw, Poland.

Pawar, D. K. N. a. S. S. (2014). Analysis of elliptical planar metal plate monopole antenna with different feeding strip length for UWB application. *International Journal of Advanced Technology in Engineering and Science*, 2, 532-536.

Pozar, D. (1983). Considerations for millimeter wave printed antennas. *IEEE Transactions on Antennas and Propagation*, 31(5), 740-747.

Pozar, D. M. (2011). *Microwave engineering*: John wiley & sons.

R. L. Haupt, Y. T., and C. G. Christodoulou. (2016). *Reconfigurable antennas (Vol. 3)*. Handb. Antenna Technol.

Radiography, (2010). from https://en.wikipedia.org/wiki/Radiography (accessed 6 Dec. 2019).

Rattanadecho, P. (2006). The simulation of microwave heating of wood using a rectangular wave guide: Influence of frequency and sample size. *Chemical Engineering Science*, 61(14), 4798-4811.

Riaz, L. (2011). Design of Ultra Wideband Antenna Array for Microwave Tomography. MSc Thesis, University of Gävle.

Rodrigues, D. B., Maccarini, P. F., Salahi, S., Oliveira, T. R., Pereira, P. J., Limão-Vieira, P., . . . Stauffer, P. R. (2014). Design and optimization of an ultra wideband and compact microwave antenna for radiometric monitoring of brain temperature. *IEEE transactions on biomedical engineering*, 61(7), 2154-2160.

Roggenbuck, M., Catenacci, J., Walker, R., Hanson, E., Hsieh, J., & Patch, S. (2014). Thermoacoustic imaging with VHF signal generation: A new contrast mechanism for cancer imaging over large fields of view *Abdomen and thoracic imaging* (pp. 523-557): Springer.

Rothwell, E. J., & Cloud, M. J. (2018). *Electromagnetics*: CRC press.

Saeed, S. M., Balanis, C. A., & Birtcher, C. R. (2017). A wearable and reconfigurable folded slot antenna for body-worn devices. *In 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting* (pp. 575-576). IEEE. San Diego, CA, USA.

Saeidi, T., Ismail, I., Alhawari, A. R., & Wen, W. P. (2019). Near-field and far-field investigation of miniaturized UWB antenna for imaging of wood. *AIP Advances*, 9(3), 035232.

Saeidi, T., Ismail, I., Noghanian, S., Alhawari, A. R., Abbasi, Q. H., Imran, M. A., . . . Ali, S. M. (2021). High Gain Triple-Band Metamaterial-Based Antipodal Vivaldi MIMO Antenna for 5G Communications. *Micromachines*, 12(3), 250.

Saeidi, T., Ismail, I., Wen, W. P., & Alhawari, A. R. (2019). Dielectric properties of complete oil palm trunk sample (healthy and unhealthy). *AIP Advances*, 9(7), 075314.

Saeidi, T., Ismail, I., Wen, W. P., Alhawari, A. R., & Mohammadi, A. (2019). Ultra-wideband antennas for wireless communication applications. *International Journal of Antennas and Propagation*, 2019.

Saghati, A. P., Batra, J. S., Kameoka, J., & Entesari, K. (2015). Miniature and reconfigurable CPW folded slot antennas employing liquid-metal capacitive loading. *IEEE Transactions on Antennas and Propagation*, 63(9), 3798-3807.

Saha, T. K., Knaus, T. N., Khosla, A., & Sekhar, P. K. (2018). A CPW-fed flexible UWB antenna for IoT applications. *Microsystem Technologies*, 1-7.

Saidaiah, B., Sudhakar, A., & Raju, K. P. (2012). Circular disk monopole antenna for broadband applications. *International Journal of Scientific and Research Publications*, 2(6), 1-4.

Salvadè, A., Pastorino, M., Monleone, R., Bartesaghi, T., Bozza, G., & Randazzo, A. (2008). Microwave detection of dielectric structures by using a tomographic approach. *In 2008 IEEE Instrumentation and Measurement Technology Conference* (pp. 1300-1305). IEEE. Victoria, BC, Canada.

Sampath, R., & Selvan, K. T. (2020). Compact hybrid Sierpinski Koch fractal UWB MIMO antenna with pattern diversity. *International Journal of RF and Microwave Computer-Aided Engineering*, 30(1), e22017.

Samsuzzaman, M., Islam, M., Mandeep, J., & Misran, N. (2014). Printed wide-slot antenna design with bandwidth and gain enhancement on low-cost substrate. *The Scientific World Journal*, 2014.

Schajer, G. S., & Orhan, F. B. (2005). Microwave non-destructive testing of wood and similar orthotropic materials. *Subsurface Sensing Technologies and Applications*, 6(4), 293-313.

Scheeler, R., Kuester, E. F., & Popović, Z. (2013). Sensing depth of microwave radiation for internal body temperature measurement. *IEEE Transactions on Antennas and Propagation*, 62(3), 1293-1303.

Screening, (2019). from http://www.cancer.gov/cancertopics/pdq/screening/breast/Patient/page3 (accessed 4 Dec. 2019).

Shakhirul, M., Jusoh, M., Lee, Y., & Husna, C. N. (2018). A review of reconfigurable frequency switching technique on micostrip antenna. *In Journal of Physics: Conference Series* (Vol. 1019, No. 1, p. 012042). IOP Publishing.

Shakib, M. N., Moghavvemi, M., & Mahadi, W. N. (2015). A low-profile patch antenna for ultrawideband application. *IEEE antennas and wireless propagation letters,* 14, 1790-1793.

Shao, W., Zhou, B., & Wang, G. (2005). Early breast tumor imaging via UWB microwave method: study on multi-target detection. *In 2005 IEEE Antennas and Propagation Society International Symposium* (Vol. 3, pp. 835-838). IEEE. Washington, DC, USA.

Sharma, V., Saxena, V., Sharma, K., & Bhatnagar, D. (2011). Radiation performance of an elliptical patch antenna with three orthogonal sector slots. *Romanian Journal of Information Science and Technology*, 14(2), 123-130.

Sharony, J. (2006). Introduction to wireless MIMO–theory and applications. *CEWIT—Center of Excellence in Wireless and Informational Technology, Stony Brook University, IEEE LI.*

Shoaib, N., Shoaib, S., Khattak, R. Y., Shoaib, I., Chen, X., & Perwaiz, A. (2018). MIMO antennas for smart 5G devices. *IEEE Access,* 6, 77014-77021.

Sim, C. Y. D., Tseng, C. W., & Leu, H. J. (2012). Embroidered wearable antenna for ultrawideband applications. *Microwave and Optical Technology Letters,* 54(11), 2597-2600.

Simorangkir, R. B., Kiourti, A., & Esselle, K. P. (2018). UWB wearable antenna with a full ground plane based on PDMS-embedded conductive fabric. *IEEE antennas and wireless propagation letters,* 17(3), 493-496.

Simorangkir, R. B., Yang, Y., Esselle, K. P., & Zeb, B. A. (2017). A method to realize robust flexible electronically tunable antennas using polymer-embedded conductive fabric. *IEEE Transactions on Antennas and Propagation,* 66(1), 50-58.

Singha, R., Vakula, D., & Sarma, N. (2014). Compact concentric ring shaped antenna for ultra wide band applications. *In IOP Conference Series: Materials Science and Engineering* (Vol. 67, No. 1, p. 012004). IOP Publishing.

Smirnov, A., Yanin, D., Galka, A., Kostrov, A., & Strikovskiy, A. (2013). Noninvasive technique of investigating biological tissues based on a method of a resonant near-field microwave tomography. *In 2013 IX Internatioal Conference on Antenna Theory and Techniques* (pp. 529-531). IEEE. Odessa, Ukraine.

Sneha, K., & Sastry, N. (2017). Wide band printed ring circular slot radiator. *In Proceedings of the World Congress on Engineering* (Vol. 1). London, U.K.

Song, J., Zhao, Z., Wang, J., Zhu, X., Wu, J., Nie, Z., & Liu, Q.-H. (2014). Evaluation of contrast enhancement by carbon nanotubes for microwave-induced thermoacoustic tomography. *IEEE transactions on biomedical engineering,* 62(3), 930-938.

National Breast Cancer Foundation, (2009). from http://www.nationalbreastcancer.org/ (accessed 6 Dec. 2019).

Stauffer, P., Snow, B., Rodrigues, D., Salahi, S., Oliveira, T., Reudink, D., & Maccarini, P. (2014). Non-invasive measurement of brain temperature with microwave radiometry: demonstration in a head phantom and clinical case. *The neuroradiology journal*, 27(1), 3-12.

Stauffer, P. R., Rodriques, D. B., Salahi, S., Topsakal, E., Oliveira, T. R., Prakash, A., . . . Maccarini, P. F. (2013). Stable microwave radiometry system for long term monitoring of deep tissue temperature. *In Energy-based Treatment of Tissue and Assessment* VII (Vol. 8584, pp. 227-237). SPIE. San Francisco, California, United States.

Stutzman, W. L., & Thiele, G. A. (2012). *Antenna theory and design*: John Wiley & Sons.

Sugitani, T., Kubota, S., Toya, A., Xiao, X., & Kikkawa, T. (2013). A Compact 4 × 4 Planar UWB Antenna Array for 3-D Breast Cancer Detection. *IEEE antennas and wireless propagation letters,* 12, 733-736.

Sugumaran, B., Balasubramanian, R., & Palaniswamy, S. K. (2021). Reduced specific absorption rate compact flexible monopole antenna system for smart wearable wireless communications. *Engineering Science and Technology, an International Journal,* 24(3), 682-693.

Taflove, A., Hagness, S. C., & Piket-May, M. (2005). *Computational electromagnetics: the finite-difference time-domain method*. The Electrical Engineering Handbook, 3, 629-670.

Tereshchenko, O., Buesink, F. J. K., & Leferink, F. B. J. (2011). An overview of the techniques for measuring the dielectric properties of materials. *In 2011 XXXth URSI General Assembly and Scientific Symposium* (pp. 1-4). IEEE. Istanbul, Turkey.

Thakur, D., Baghel, V., & Talluri, S. R. (2021). Proximal gradient method based robust Capon beamforming against large DOA mismatch. *Frequenz,* 75(7-8), 259-266.

Tong, X., Liu, C., Liu, X., Guo, H., & Yang, X. (2018). Dual-band on-/off-body reconfigurable antenna for wireless body area network (WBAN) applications. *Microwave and Optical Technology Letters,* 60(4), 945-951.

Tu, Z.-h., Li, W.-A., & Chu, Q.-X. (2014). Single-layer differential CPW-fed notch-band tapered-slot UWB antenna. *IEEE antennas and wireless propagation letters*, 13, 1296-1299.

Uthansakul, P., Assanuk, D., & Uthansakul, M. (2011). An optimal design of multiple antenna positions on mobile devices based on mutual coupling analysis. *International Journal of Antennas and Propagation*, 2011.

Velan, S., Sundarsingh, E. F., Kanagasabai, M., Sarma, A. K., Raviteja, C., Sivasamy, R., & Pakkathillam, J. K. (2014). Dual-band EBG integrated monopole antenna deploying fractal geometry for wearable applications. *IEEE antennas and wireless propagation letters,* 14, 249-252.

Wang, C., Yeo, J. C., Chu, H., Lim, C. T., & Guo, Y.-X. (2018). Design of a reconfigurable patch antenna using the movement of liquid metal. *IEEE antennas and wireless propagation letters,* 17(6), 974-977.

Wang, J., Lim, E., Leach, M., Wang, Z., Man, K., & Huang, Y. (2016). Review of wearable antennas for WBAN applications. *IAENG Int. J. Comput. Sci*, 43(4), 474-480.

Wang, K., Li, L., & Eibert, T. F. (2013). Comparison of compact monopole antenna arrays with eigenmode excitation and multiport conjugate matching. *IEEE Transactions on Antennas and Propagation*, 61(8), 4054-4062.

Wang, L., & Huang, B. (2012). Design of ultra-wideband MIMO antenna for breast tumor detection. *International Journal of Antennas and Propagation*, 2012.

Wang, X. (2014). Thermoacoustic applications in breast cancer detection and communications. PhD Thesis, The University of Arizona, Arizona, United States.

Wang, Y.-W., & Yu, Z.-W. (2017). A novel symmetric double-slot structure for antipodal Vivaldi antenna to lower cross-polarization level. *IEEE Transactions on Antennas and Propagation,* 65(10), 5599-5604.

Warbal, P., Pramanik, M., & Saha, R. K. (2019). A robust modified delay-and-sum algorithm for photoacoustic tomography imaging with apodized transducers. *In European Conference on Biomedical Optics* (p. 11077_38). Optical Society of America. Munich, Germany.

William H. Hayt, J., John A. Buck. (2012). *Engineering Electromagnetics, Eighth Edition, 1-614*: McGraw-Hil.

Wu, A., & Guan, B. (2016). Printed slot antennas for various wideband applications using shape blending. *International Journal of RF and Microwave Computer-Aided Engineering,* 26(1), 3-12.

Wu, J., Zhao, Z., Nie, Z., & Liu, Q.-H. (2014). A printed UWB Vivaldi antenna using stepped connection structure between slotline and tapered patches. *IEEE antennas and wireless propagation letters,* 13, 698-701.

Wu, Z., McCann, H., Davis, L., Boughriet, A., & Nugroho, A. (2014). Microwave tomographic imaging of dielectric objects using Newton-Kantorovich algorithms. *In 2nd World Congress on Industrial Process Tomography* (pp. 477-483). Hannover, United Kingdom.

Xin, H., Wang, X., Qin, T., Meng, H., Qin, Y., & Witte, R. S. (2014). Time-efficient contrast-enhanced thermoacoustic imaging modality for 3-D breast cancer detection using compressive sensing. *In 2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS)* (pp. 1-2). IEEE. Beijing, China.

Yadav, A., Kumar Singh, V., Kumar Bhoi, A., Marques, G., Garcia-Zapirain, B., & de la Torre Díez, I. (2020). Wireless body area networks: UWB wearable textile antenna for telemedicine and mobile health systems. *Micromachines,* 11(6), 558.

Yalduz, H., Tabaru, T. E., Kilic, V. T., & Turkmen, M. (2020). Design and analysis of low profile and low SAR full-textile UWB wearable antenna with metamaterial for WBAN applications. *AEU-International Journal of Electronics and Communications,* 126, 153465.

Yan, S., & Vandenbosch, G. A. (2016). Radiation pattern-reconfigurable wearable antenna based on metamaterial structure. *IEEE antennas and wireless propagation letters,* 15, 1715-1718.

Yang, B., Zhuge, X., Yarovoy, A., & Ligthart, L. (2008). UWB MIMO antenna array topology design using PSO for through dress near-field imaging. *In 2008 38th European Microwave Conference* (pp. 1620-1623). IEEE. Amsterdam, Netherlands.

Yeung, L. K., & Wang, Y. E. (2008). Mode-based beamforming arrays for miniaturized platforms. *IEEE Transactions on Microwave Theory and techniques,* 57(1), 45-52.

Yousefnia, M., Ebrahimzadeh, A., Dehmollaian, M., & Madannejad, A. (2018). A time-reversal imaging system for breast screening: Theory and initial phantom results. *IEEE transactions on biomedical engineering,* 65(11), 2542-2551.

Zhang, J., Zhang, X., & Xiao, S. (2017). Antipodal Vivaldi antenna to detect uhf signals that leaked out of the joint of a transformer. *International Journal of Antennas and Propagation,* 2017.

Zhao, L., & Wu, K.-L. (2014). A decoupling technique for four-element symmetric arrays with reactively loaded dummy elements. *IEEE Transactions on Antennas and Propagation,* 62(8), 4416-4421.

Zhao, Y., Shao, W., & Wang, G. (2004). UWB microwave imaging for early breast cancer detection: Effect of two synthetic antenna array configurations. *In 2004 IEEE International Conference on Systems, Man and Cybernetics (IEEE Cat. No. 04CH37583)* (Vol. 5, pp. 4468-4473). IEEE. The Hague, Netherlands.