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Shiban Kishen Koul · Richa Bharadwaj

Wearable Antennas and Body Centric Communication

Present and Future

Springer

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We would like to dedicate our efforts to our families who inspired and supported us through everything.

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Preface

Wireless body area network (WBAN) technology is providing attractive new possibilities in wearable communication considering increase in demand of connectivity, information-centric users and the ever-evolving wireless world. From applications in day-to-day activities and general well-being to specific domains such as healthcare, telemedicine, defence, sports, entertainment, search, and rescue emergency operations, WBANs form an integral part in enhancing quality of life. The rising popularity of commercial wearable gadgets, such as fitness trackers and smart watches which provide real-time information regarding various health stats, enhanced detection, and sensing capabilities, has paved way for several research advancements in the domain of wearable sensing technologies. The upcoming era of Internet of Things (IoT) is revolutionizing the way gadgets connect with wearable devices being the key focus, operating in variable and dynamic environments over short and long range. The future generation of wearable devices will be compact, low cost, lightweight, efficient, low power, portable, and accessible, provide flexibility of integration, and work with high data rates and high-quality wireless connectivity.

Antenna is one of the key components of the WBAN which is integrated with wearable gadgets and clothing to provide robust wireless connectivity between the wearable devices suitable for a wide range of applications. Research and development in the field of antennas and propagation for body-centric communication is an upcoming area due to the miniaturization of devices, new fabrication technologies, advancement in material science, and availability of wide range of the electromagnetic spectrum for operation of the wearable devices. They must efficiently support various channels ranging from on-body communications to off-body/body-to-body and even in-body implantable communications.

Antennas and radio wave propagation constitute the basic elements of the wireless channel which determine the quality and the reliability of the wireless link and hence have a great impact on the quality of service offered by a whole system. Ultra-wideband (UWB) (3.6–10 GHz) and 60 GHz millimeter-wave (mmWave) (57–64) GHz frequency bands are considered as attractive solutions for future WBANs due to the high data rates, compact devices, and availability of

wide bandwidth. Many research activities have been focused on the design and development of wearable antennas and characterization of the body-centric propagation channel which need to consider various challenges of working in proximity with the human body, dynamic scenarios, and variable environments.

This book highlights the recent progress and state-of-the-art techniques in the field of antennas for body-centric communication at UWB and 60 GHz mmWaves frequencies. Work related to current trends, research aspects in wearable antenna design, optimization of antenna parameters, and characterization and modelling of the channel are reported for various types of body-centric links. Various applications have also been discussed such as localization and tracking of the human subject, monitoring of physical activities using wearable technology. Radar-based applications such as monitoring of vital sign parameters, tracking of human subject, and medical imaging have also been reported. Finally, IoT applications and machine learning approach have been described which aim to enhance the overall performance in various domains such as healthcare systems, smart home, and smart cities. This book will serve as a comprehensive resource for graduate students, researchers, and professionals in academia as well as industry in the field of antennas and propagation, microwave engineering, and wireless communication.

Chapter 1 introduces the wireless body area networks and gives an overview of the applications, current and future technologies, and an outline of the antenna and propagation aspects for wireless body-centric communication. The scope of the book is also provided with a summary of the content of the chapters.

Chapter 2 describes various aspects of the on-body propagation from antenna design to channel modelling in the UWB and mmWave frequency range. Key features related to on-body antenna design and requirements, simulation and phantom-based study, and body-centric channel characterization for static and dynamic scenarios are reported.

Chapter 3 focuses on modelling and characterization of the off-body and body-to-body propagation channels for UWB and mmWave frequency range. Theoretical, numerical, simulation-based, and experimental investigations are reported to understand the channel behaviour in the presence of the human subject.

Chapter 4 presents latest trends in wearable flexible antenna design covering aspects such as fabrication techniques, substrate material selection, and novel designs suitable for UWB and mmWave communication. Electromagnetic and mechanical properties of such antennas are discussed for free space and on-body scenarios.

Chapter 5 gives an overview of in-body and on-body antenna design and channel characteristics of implantable UWB communication systems suitable for several medical applications such as capsule endoscopy and vital body parameter monitoring.

Chapter 6 gives an insight on the factors affecting the localization accuracy while tracking a human subject in an indoor environment using simple and effective techniques based on channel information and time of arrival localization techniques.

Chapter 7 presents work related to monitoring and assessment of physical activities using channel information, gait movement, and joint angle estimation during flexion/extension of limbs using wearable UWB technology.

Chapter 8 presents recent advances and state-of-the-art techniques related to IR-UWB and mmWave radar system design, vital sign monitoring, detection, daily activity monitoring, fall detection, sleep monitoring, gait analysis, and gesture recognition.

Chapter 9 discusses various research studies based on UWB radar imaging for medical and through-wall detection applications. Several antenna designs, development of image reconstruction algorithms, and providing set-up details of the complete microwave imaging systems are reported.

Chapter 10 presents an overview of the Internet of Things (IoT) and explores the role of machine learning in enhancing overall performance with the focus on healthcare applications. Various technologies and state-of-the-art techniques related to compact antenna design for body-centric communication for IoT applications are discussed in this chapter.

New Delhi, India

Shiban Kishen Koul
Richa Bharadwaj

Contents

1 Introduction to Body Centric Wireless Communication 1
1.1 Body Centric Wireless Communication 1
1.2 The Wireless Body Area Networks 3
1.2.1 Applications 6
1.3 State-of-the-Art Technologies 9
1.3.1 Wireless Medical Telemetry System (WMTS) and Medical Implant Communications Service (MICS) Bands 9
1.3.2 Industrial, Scientific, and Medical (ISM) Band 9
1.3.3 Ultra-Wideband Technology (UWB) 10
1.3.4 mmWave 60 GHz Technology 11
1.3.5 THz Technology 12
1.4 Wearable Antenna and Body-Centric Propagation Aspects 12
1.5 Scope of the Book 14
References 16

2 On-Body Radio Propagation: UWB and mmW Technologies 19
2.1 Introduction 19
2.2 Wearable Antenna Requirements 20
2.2.1 Design Strategy 20
2.2.2 Simulation Based Approach: Performance Analysis . . . 21
2.2.3 UWB Antennas Design for On-Body Communication 22
2.2.4 60 GHz On-Body Antenna Design and Analysis 23
2.2.5 Effect of Feeding Structures 25
2.3 Influence of Wearable Antenna Location on the Radiation Pattern 28
2.3.1 Variation of Antenna Radiation Pattern with Body Location and Limb Movements 28
2.3.2 60 GHz Antenna Array for Wearable Smart Glasses . . . 34

2.4 Statistical On-Body Measurement Results 35
2.4.1 Electromagnetic Simulation Based Channel Modeling 36
2.4.2 Tissue Mimicking Phantoms 36
2.4.3 On-Body Propagation Analysis for UWB Communication 40
2.4.4 On-Body Propagation Analysis at 60 GHz 43
2.5 UWB Dynamic On-Body Communication Channels 45
2.5.1 Classification and Statistical Analysis of the On-Body Channel During Physical Exercises 46
2.5.2 On-Body Links Channel Classification 46
2.5.3 Upper Limbs Activity 47
2.5.4 Lower Limbs Activity 50
2.5.5 Path Loss and Rms Delay Spread Statistical Analysis . . . 52
2.5.6 On-Body Channel Links Analysis During Daily Physical Activities 54
2.6 Dynamic 60 GHz On-Body Propagation Channels 55
2.7 Conclusion 57
References 57

3 Indoor Off-Body and Body-to-Body Communication: UWB and mmW Technologies 61
3.1 Introduction 61
3.2 The Indoor Propagation Environment 62
3.2.1 Path Loss Model 62
3.2.2 Multipath Model 63
3.2.3 UWB Multipath Channel 64
3.2.4 Human Body Influence on Body-Centric Propagation Channels 64
3.3 UWB Channel Modelling and Characterization 65
3.3.1 Off-Body Link 65
3.3.2 Body-to-Body Link 67
3.3.3 Angular Body-Centric Channel Characterization at UWB Frequencies 67
3.3.4 Body-to-Body and Off-Body Links: Experimental Investigation 69
3.3.5 Spatial Variation of Path Loss for Off-Body Links: Application Specific 81
3.4 mmWave: 60 GHz 87
3.4.1 Off-Body Communication 87
3.4.2 Body-to-Body Communication at 60 GHz 90
3.4.3 Near-Body Shadowing at 60 GHz 94
3.5 Conclusion 95
References 96

4 Flexible and Textile Antennas for Body-Centric Applications 99
4.1 Introduction 99
4.2 Flexible Antenna Requirements 101
4.3 State-of-the-Art Fabrication and Printing Techniques 102
4.4 Flexible Substrates Based UWB Antennas 103
4.4.1 Kapton 103
4.4.2 LCP 105
4.4.3 PDMS 106
4.4.4 Paper 108
4.4.5 Innovative Substrate Materials 108
4.5 UWB Textile Antennas 112
4.5.1 Cotton Cloth 112
4.5.2 Felt 113
4.5.3 (PDMS)-Embedded Conductive-Fabric 115
4.5.4 Denim Jean 116
4.5.5 Novel Textile Materials 116
4.6 60 GHz Flexible and Textile Antennas 118
4.7 Conclusion 121
References 122

5 Implantable Antennas for WBANs 125
5.1 Introduction 125
5.2 UWB Implantable Antennas 126
5.2.1 Antenna Design Considerations 126
5.2.2 Antenna Design Examples for Various Applications . . . 126
5.3 UWB Phantoms for Implantable Communication 133
5.4 Channel Characterization for Implantable Communication 135
5.4.1 Phantom-Based Channel Characterization 135
5.4.2 Channel Modeling and Communication Link Analysis 140
5.4.3 Simulation, in Vivo and Phantom Based Comparison . . . 140
5.4.4 Diversity Experimental Results 143
5.5 Conclusion 146
References 146

6 Body Centric Localization and Tracking Using Compact Wearable Antennas 149
6.1 Introduction 149
6.1.1 State-of-the-Art Localization Techniques 151
6.2 Body Worn Antenna Localization 153
6.2.1 Body-Worn Antenna Localization Techniques 154
6.2.2 Limbs Channel Classification: 160
6.2.3 Human Body Localization 163
6.2.4 Localization Results for Various Activities 165

6.3 Random Base Station Placement 167
6.3.1 Random Base Station Configurations 168
6.3.2 Localization Accuracy Analysis 170
6.4 L-shape Base Station Configuration Measurements 171
6.4.1 L-shape Localization 172
6.4.2 Channel Classification and Localization Accuracy 174
6.5 Realistic and Cluttered Indoor Environment 174
6.5.1 UWB Body Centric Localization in Cluttered Environments 174
6.5.2 UWB Body Centric Localization Using Hybrid Antenna Configuration 176
6.6 Machine Learning and UWB Body-Centric Localization 180
6.6.1 Measurement Set Up 181
6.6.2 Algorithm and Localization Results 182
6.7 Conclusion 185
References 185

7 Wearable Technology for Human Activity Monitoring and Recognition 191
7.1 Introduction 191
7.1.1 State-of-the-Art-Technologies 193
7.2 Assessment of the Physical Activities 195
7.2.1 Measurement Set Up 196
7.2.2 Activity Assessment Results 199
7.2.3 Activity Monitoring Performance 203
7.3 Daily Physical Activity Recognition 204
7.4 Joint Angle Estimation Using UWB Wearable Technology 207
7.5 Gait Activity Assessment 209
7.5.1 Gait Activity Analysis 211
7.5.2 Step Length Estimation of Human Gait 211
7.5.3 Foot Clearance Analysis During Walking 213
7.5.4 Gait Activity Identification 214
7.6 Conclusion 215
References 215

8 UWB and 60 GHz Radar Technology for Vital Sign Monitoring, Activity Classification and Detection 219
8.1 Introduction 219
8.2 Vital Sign Monitoring 220
8.2.1 Mathematical Model 221
8.2.2 Algorithms and Techniques for Vital Sign Monitoring 223

8.3 Activity Recognition and Classification 232
8.3.1 Activity Recognition 232
8.3.2 Through Wall Radar Activity Recognition 233
8.3.3 Gesture Recognition 236
8.3.4 Gait Analysis 236
8.3.5 Sleep Monitoring 237
8.3.6 Daily Activity Monitoring 238
8.3.7 Fall Detection 238
8.3.8 Detection and Localization 239
8.4 60 GHz Vital Sign Monitoring 239
8.5 60 GHz Activity Monitoring 246
8.6 Conclusion 248
References 249

9 UWB Radar Technology for Imaging Applications 253
9.1 Introduction 253
9.2 UWB Radar for Medical Imaging Applications 255
9.2.1 Antenna Design Requirements 256
9.2.2 Breast Cancer Detection: State of the Art Techniques and Algorithms 257
9.2.3 Brain Imaging 270
9.2.4 Time-Lapse Imaging of Human Heart Motion 273
9.3 Through Wall Imaging 274
9.3.1 UWB Though Wall System Design Aspects and Imaging Techniques 276
9.3.2 Through Wall Human Sensing and Building Layout Reconstruction Using UWB-MIMO 278
9.3.3 Through-The-Wall Detection of Multiple Stationary Humans 280
9.3.4 Current State-Of-The-Art Techniques for UWB TWI 280
9.4 Conclusion 282
References 283

10 Emerging Technologies and Future Aspects 287
10.1 Introduction 287
10.2 IoT Applications 289
10.2.1 Smart Cities 290
10.2.2 Smart Home 290
10.2.3 Smart Vehicles 291
10.2.4 Smart Industry 292
10.2.5 IoT for Healthcare 292

10.3 Antenna Design Requirements for IoT Body-Centric Communication Applications 295
10.3.1 Band-Notch Antennas 296
10.3.2 Graphene and Nano-Particle Based Antennas 297
10.3.3 3D Printing Based Antennas 298
10.3.4 Novel Electro-Textile and Materials 299
10.3.5 Flexible Antennas 299
10.3.6 Epidermal and Implantable Antennas 300
10.3.7 Meta-Materials and Electromagnetic Band Gap (EBG) Structures 302
10.3.8 MIMO Antennas 304
10.4 Machine Learning for Improved Well-Being and Healthcare Applications 305
10.4.1 Electronic Health Records Maintenance and Data Mining 306
10.4.2 Monitoring and Classification 307
10.4.3 Diagnostics and Prevention 308
10.4.4 Assessment and Prediction 308
10.5 Conclusion 308
References 309

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Abbreviations

1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
5G	Fifth Generation
6G	Sixth Generation
A	Received Signal Amplitude
AAV	Absolute Acceleration Variation
AB_R	Abdomen Right
ABS	Acrylonitrile Butadiene Styrene
AD	Arctangent Demodulation
ADC	Analog-To-Digital Converter
ADL	Activities of Daily Living
AFD	Average Fade Duration
AI	Artificial Intelligence
AM	Additive Manufacture
AN	Ankle
AOA	Angle of Arrival
ATA-FGP	All-Textile Antenna with Full Ground Plane
AVA	Antipodal Vivaldi Antenna
B	Back
BANs	Body Area Networks
BAVA	Balanced Antipodal Vivaldi Antenna
BCNs	Body-Centric Networks
BCWN	Body-Centric Wireless Networks
BCWS	Body-Centric Wireless Sensor
BDT	Boosted Decision Tree
BLE	Bluetooth Low Energy
BMI	Body Mass Index
B-MI	Brain–Machine Interface
BOS	Base of Support

B-P	Back Projection
BP	Blood Pressure
BR	Breath Rate
BSF	Body Shadowing Factor
BSs	Base Stations
CAD	Computer-Aided Design
CDF	Cumulative Distribution Function
CF	Coherence Factor
CFAR	Constant False Alarm Rate
CF-DAS	Coherence Factor Delay and Sum
CFR	Channel Frequency Response
CIR	Channel Impulse Response
CNN	Convolutional Neural Network
CP	Circular Polarization
CPI	Coherent Processing Interval
CPW	Coplanar Waveguide
CS	Compressed Sensing
CSAR	Circular Synthetic Aperture Radar
CSD	Complex Signal Demodulation
CSF	Cerebrospinal Fluid
CT	Computed Tomography
CTBV	Continuous Time Binary Valued
CW	Continuous Wave
CWT	Continuous Wavelet Transform
DAQ	Multifunction Data Acquisition
DAS	Delay And Sum
DCNN	Deep Convolutional Neural Network
DCT	Discrete Cosine Transform
DL	Deep Learning
DMAS	Delay-Multiply-And-Sum
DNNs	Deep Neural Networks
DOP	Dilution of Precision
DRA	Dielectric Resonance Antenna
D-S	Displacement Signal
DS	Doppler Spectrogram
DSN	Noise Threshold
EBG	Electromagnetic Band Gap
ECG	Electrocardiograph
ECTSRLS	Equality Constrained Taylor Series Robust Least Squares
ECU	Electronic Control Unit
EEG	Electroencephalogram
EEMD	Ensemble Empirical Mode Decomposition
EFIR	Extended Finite Impulse Response
EHR	Electronic Health Record
EKF	Extended Kalman Filter

EM	Electromagnetic
EMD	Empirical Mode Decomposition
EMG	Electromyograph
ESD	Ensemble Subspace Discriminant
ETSA	Exponentially Tapered Slot Antenna
F	Face
FA	Frequency Accumulation
FCC	Federal Communications Commission
FDM	Fused Deposition Modelling
FDTD	Finite-Difference Time-Domain
FED	Feature Embedding Dimension
FEM	Finite Element Method
FFF	Fuse Filament Fabrication
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
FIT	Finite Integration Technique
FMCW	Frequency-Modulated Continuous Wave
FN	False Negative
FP	False Positive
FPCB	Flexible Printed Circuit Board
FPGA	Field-Programmable Gate Array
FPS	Frames Per Second
FR	Front
FS	Free Space
FTI	Feature Time Index
FVPIEF	First Valley-Peak of IMF Energy Function
GAF	Graphene-Assembled Film
GBP	Global Back Projection
GDOP	Geometric Dilution of Precision
GI	Gastrointestinal
GO	Geometrical Optics
GPIB	General-Purpose Interface Bus
GPS	Global Positioning System
GSM	Global System for Mobile Communications
H	Horizontal
HAPA	Harmonic Path
HDOP	Horizontal Dilution of Precision
HEDL	Half Elliptical-Shaped Dielectric Lens
HFSS	High-Frequency Structure Simulator
HMLD	Harmonic Multiple Loop Detection
HOC	Higher-Order Cumulant
HR	Heart Rate
I	In-Phase
IAA	Iterative Adaptive Approach
IB2IB	In-Body to In-Body

IB2OB	In-Body to On-Body
IC	Integrated Circuit
ICT	Information and Communication Technology
IFFT	Inverse Fast Fourier Transform
IMF	Intrinsic Mode Function
IMU	Inertial Measurement Unit
IN	Inner
IoT	Internet of Things
IR	Infrared
IR-UWB	Impulse Radio-Ultra-Wideband
ISI	Intersymbol Interference
ISM	Industrial–Scientific–Medical
ITU	International Telecommunication Union
KMC	K-Means Clustering
k-NN	K-Nearest Neighbour
L.	Left
L. AK	Left Ankle
LAN	Local Area Network
LCP	Liquid Crystal Polymer
LCR	Level Crossing Rate
LHM	Left-Handed Metamaterial
LO	Local Oscillator
LOS	Line of Sight
LS-SVM	Least Squares Support Vector Machine
LSTM	Long Short-Term Memory
LTCC	Low-Temperature Co-Fired Ceramic
LWA	Leaky-Wave Antenna
MARG sensors	Magnetic, Angular Rate, And Gravity
MAVA	Modified Antipodal Vivaldi Antenna
MC-SVM	Multi-Class Support Vector Machine
MCU	Microcontroller Unit
MDS	Micro-Doppler Signatures
MEMS	Microelectromechanical Systems
MHT	Multi-Hypothesis Tracking
MI	Microwave Imaging
MICS	Medical Implant Communications Service
MIMO	Multiple Input Multiple Output
MIS	Microwave Imaging System
ML	Machine Learning
MLDS	Millimetre-Wave Life Detection System
MLE	Maximum Likelihood Estimation
MLP	Multi-Layer Perceptron
mmWave	Millimetre Wave (mmW)
MoM	Method of Moments
MPA	Microstrip Patch Antenna

MPCs	Multipath Components
MPOC	Modified-Phase-Only-Correlator
MRC	Maximum Ratio Combining
MRI	Magnetic Resonance Imaging
MS	Mobile Station
MStrip	Microstrip
MTMs	Metamaterials
MWCNTs	Multi-Walled Carbon Nanotubes
MWDAS	Modified Weighted-Delay And Sum
MWI	Microwave Imaging
NB	Naive Bayes
NCA	Neighbourhood Component Analysis
NLOS	Non-Line-of-Sight
NN	Neural Network
OSUA	Octagonally Shaped UWB Antenna
OUT	Outer
PA	Power Amplifier
PANI	Polyaniline
PANs	Personal Area Networks
PBDEEMD	Pseudo-Bi-Dimensional Ensemble Empirical Mode Decomposition
PC	Personal Computer
PCA	Principal Component Analysis
PCB	Printed Circuit Board
PD	Power Detector
PDF	Probability Distribution Function
PDMS	Polydimethylsiloxane
PDP	Power Delay Profile
PEDOT:PSS	Poly3,4-ethylenedioxythiophene Polystyrene Sulfonate
PEN	Polyethylene Naphthalate
PET	Polyethylene Terephthalate
PH	Personalized Healthcare
PIFAs	Planar Inverted-F Antennas
PIIC	Position-Information-Indexed Classifier
PL	Path Loss
PL_0	PL at reference distance
PLA	Polylactic Acid
PMA	Printed Monopole Antenna
PNLOS	Partial NLOS
PPG	Photoplethysmogram or Photoplethysmography
PR	Pattern Recognition
P_r	Received Signal Power
PRF	Pulse Repetition Frequency
PSADEA	Parallel Surrogate Model-Assisted Hybrid Differential Evolution For Antenna Optimization

PSG	Polysomnography
PSSPs	Parasitic Surrounding Stacked Patches
P_t	Transmit Power
PTFE	Polytetrafluoroethylene
Q	Quadrature
QC	Quasi-Circulator
QL	Quadruple Loop
R.	Right
R. AK	Right Ankle
R. SH	Right Shoulder
R. SL	Right Step Length
R. SW	Right Stride Width
R.TH	Thigh Region
RCSRR	Rectangular Complementary Split-Ring Resonator
RD	Range-Doppler
RF	Radio Frequency
RF	Random Forest
RFID	Radio Frequency Identification
RGW	Ridge Gap Waveguide Feed
rms	Root Mean Square
RMSE	Root Mean Squared Estimator
ROI	Region of Interest
RP	Range Point
RPM	Range-Point Migration
RR	Respiration Rate
RSNR	Relative Signal-to-Noise Ratio
RSRR	Rectangular Split-Ring Resonator
RSS	Received Signal Strength
RT	Ray-Tracing
RT-TOF	Round Trip-Time of Flight
RVSM	Remote Vital Sign Monitoring
Rx	Receiver
S_{11}	Reflection Coefficient
S_{21}	Transmission Response
SAGE	Space Alternating Generalized Expectation Maximization
SAR	Specific Absorption Rate
SCADA	Supervisory Control and Data Acquisition
SCNR	Signal-to-Clutter Noise Ratio
SDLA	Successive Detection Logarithmic Amplifier
SFCW	Stepped-Frequency Continuous Wave
SFF	System Fidelity Factor
SHAPA	Spectrum-Averaged Harmonic Path
SIW	Substrate Integrated Waveguide
SL	Side Left
SLE	Step Length Estimation

SMA	Sub-miniature Version A
SMOTE	Synthetic Minority Oversampling Technique
SMR	Signal-to-Mean Ratio
SNCR	Signal-to-Noise Clutter Ratio
SNR	Signal-to-Noise Ratio
SoC	System-on-Chip
SP	Strongest Path
SPGP	Sparse Pseudo-Input Gaussian Process
SPN	SleepPoseNet
SPO_2	Saturation of Peripheral Oxygen
SPT	Sleep Postural Transition
SR	Side Right
SRR	Split-Ring Resonator
SSM	State-Space Method
SSRR	Square Split-Ring Resonator
ST	S Transform
STDEV	Standard Deviation
STFT	Short-Time Fourier Transform
SUS	Scene Under Surveillance
S-V	Saleh-Valenzuela
SVD	Singular Value Decomposition
SVM	Support Vector Machine
$tan\delta$	Loss Tangent
TDOA	Time Difference of Arrival
TE	Transverse Electric
T–F	Time–Frequency
THz	Terahertz
TLs	Transmission Lines
TM	Transverse Magnetic
TMMs	Tissue Mimicking Materials
TN	True Negative
TO_L	Upper Torso Left
TOA	Time of Arrival
TOF	Time of Flight
TP	True Positive
TROI	Time Region of Interest
TSA	Tapered Slot Antenna
TTW	Through-the-Wall
TW	Through Wall
TWDP	Two-Wave Diffuse Power
TWI	Through-Wall Imaging
TWIR	Through-Wall Imaging Radar
TWR	Through-the-Wall Radar
Tx	Transmitter
UAV	Unmanned Aerial Vehicle

US	Ultrasound
UTD	Uniform Theory of Diffraction
UWB	Ultra-Wideband
UWB-SP	Ultra-Wideband Short Pulse Radar
V	Vertical
VDOP	Vertical Dilution of Precision
VMD	Variational Mode Decomposition
VNA	Vector Network Analyser
WBANs	Wireless Body Area Networks
WCE	Wireless Capsule Endoscopy
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMTS	Wireless Medical Telemetry System
WPAN	Wireless Personal Area Network
WR	Wrist
WRTFT	Weighted Range-Time–Frequency Transform
WSNs	Wireless Sensor Networks
XETS	Exponentially Tapered Slot-Based Antenna
γ	PL Exponent
ε_r	Relative Permittivity
κ	Kurtosis
μD	Micro-Doppler
σ_τ	RMS Delay Spread
τ_m	Mean Excess Delay