Reactive Near Field Ultra Wideband Detection

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Abstract

Most ultra wideband (UWB) target detections are mainly carried out in the radiated near field or far field. However, the success of the detection mainly relies on the distance between the sensor and the target which may require a large measurement space.

This research investigates the ability to sense targets in the reactive near field in case that the measurement space is constrained. Food detection in a smart fridge is chosen as the main application and test platform. At present, food can be detected by leveraging radio frequency identification (RFID) technology for intelligent fridge. Despite promising results have been shown, it may cause potential health risk and be costly due to tags being affixed to the food to obtain detailed information. Besides, RFID technology lacks of the ability to know the exact food amount such as the level of drink. There is therefore a need for developing new approaches being self content-aware in a low cost and reliable manner.

Due to the nature of low cost, relatively high accuracy and immunity to noise, UWB technology provides the potential to detect food as an alternative to RFID. Egg quantity determination, which is an initial and accessible platform of intelligent fridge will be investigated in this thesis. Egg quantity can be well determined in terms of polarisation information in the far field region. However, the challenges arise by taking practical fridge size into account in which the information of eggs will be known in the reactive near field. New approaches are proposed based on investigation of reflection and coupling coefficient correlation of in fridge sensors. Both simulations and measurements are conducted to study the feasibility of sensing the number of egg in the free space environment. Further to this, the effect of other food placed around and above the egg box is investigated in order to verify the robustness of the proposed approaches.

Finally, the study is extended to examine the capability of determination of liquid volume. In which, S-parameters are measured related to a variety type of drink in their unique topology and liquid level. The correlation coefficients are evaluated and analysed in both magnitude and phase domain exploiting the amount of liquid information that will be of great significant in the development of future smart fridge.

Key words: Reactive near field UWB, smart fridge, egg quantity detection, reflection coefficient correlation, coupling coefficient correlation, liquid level detection

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## Contents

Abstract ........................................................................................................................................... ii

Acknowledgments ......................................................................................................................... iii

Contents .......................................................................................................................................... iv

List of Figures ................................................................................................................................... vii

List of Tables ................................................................................................................................... xiv

Glossary of Terms ........................................................................................................................... xv

1 Introduction ...................................................................................................................................... 1

1.1 Motivation ................................................................................................................................... 1

1.2 Structure of Thesis ..................................................................................................................... 2

1.3 Original Contributions .............................................................................................................. 3

2 Background of UWB and Its Applications ................................................................................. 4

2.1 UWB System ............................................................................................................................. 4

2.1.1 UWB Signals and System ...................................................................................................... 5

2.1.2 Regulation Issues .................................................................................................................. 9

2.2 Pulse filtering ............................................................................................................................ 10

2.3 UWB Radar ............................................................................................................................. 18

2.3.1 UWB Imaging Radar .......................................................................................................... 18

2.3.2 Non-Imaging UWB Radar .................................................................................................. 21

2.3.2.1 Resonant Method ........................................................................................................... 21

2.3.2.2 Polarisation Method ....................................................................................................... 23

2.4 Material Characterisation ........................................................................................................ 24

2.5 Near Field UWB ..................................................................................................................... 32

2.6 Summary .................................................................................................................................. 34

3 Far Field Parametric Egg Quantity Detection ............................................................................ 35

3.1 Case study of Egg Quantity Detection ..................................................................................... 35

3.2 Evaluation of resonant based UWB radar ............................................................................... 36

3.2.1 Conventional Prony Method .............................................................................................. 36

3.2.2 Generalised Pencil of function Method (GPOF)/Matrix Pencil Method (MPM) .......... 38

3.3 Evaluation of Polarisation based UWB radar .......................................................................... 43
Near Field Egg Detection in Cluttered Conditions

4 Reactive Near Field Egg Quantity Detection

4.1 System setup ............................................................................................................................................. 66
  4.1.1 In fridge UWB antenna ......................................................................................................................... 67
  4.1.2 Description of test systems .................................................................................................................... 70

4.2 Correlation Coefficient Detection Metric .......................................................................................... 71

4.3 Feasibility study of egg quantity determination .................................................................................. 75
  4.3.1 Study of the detectable region of UWB antennas ................................................................................... 75
  4.3.2 Study of varying number of eggs .......................................................................................................... 80
    4.3.2.1 Reflection coefficient correlation (RCC) .......................................................................................... 81
    4.3.2.2 Coupling coefficient correlation (CCC) ........................................................................................... 82
    4.3.2.3 Group delay (GD) information ......................................................................................................... 83
  4.3.3 Study of multiple eggs and configurations in random locations .......................................................... 84
    4.3.3.1 RCC - sensor 1 ................................................................................................................................. 86
    4.3.3.2 RCC -sensor 2 ................................................................................................................................. 90
    4.3.3.3 RCC - sensor 5 ............................................................................................................................... 95
    4.3.3.4 RCC - sensor 6 ............................................................................................................................... 100
    4.3.3.5 CCC - sensor 1 to 2 ......................................................................................................................... 105
    4.3.3.6 CCC - sensor 1 to 5 ......................................................................................................................... 112
    4.3.3.7 CCC - sensor 1 to 6 ......................................................................................................................... 117
    4.3.3.8 CCC - sensor 2 to 6 ......................................................................................................................... 123

4.4 Discussion .................................................................................................................................................. 127

4.5 Blind test of egg quantity detection ..................................................................................................... 127
  4.5.1 Test 1 – One egg above sensor 1 .......................................................................................................... 128
  4.5.2 Test 2 – One egg in the centre of four sensors ...................................................................................... 128
  4.5.3 Test 3 – Two eggs in the skewed egg box ............................................................................................. 128

4.6 Summary .................................................................................................................................................. 129

5 Near Field Egg Detection in Cluttered Conditions .............................................................................. 131

5.1 Effect of general clutter ......................................................................................................................... 131
  5.1.1 Experimental setup for detection of a single egg .................................................................................. 132
5.1.2 Effect of food adjoined to the egg box containing a single egg .................................. 134
5.1.3 Effect of food placed above the egg box containing a single egg ................................ 137
5.1.4 Discussion ....................................................................................................................... 140
5.2 Worst case scenarios ........................................................................................................ 142
  5.2.1 Test setup of worst case scenarios .............................................................................. 142
  5.2.2 Results .......................................................................................................................... 143
5.3 Summary ........................................................................................................................... 145
6 Liquid Volume Test .............................................................................................................. 146
  6.1 Test Setup......................................................................................................................... 146
  6.2 Measurement results ....................................................................................................... 149
    6.2.1 One pint of milk case .............................................................................................. 149
      6.2.1.1 Vertical orientation inside the fridge ................................................................. 149
      6.2.1.2 Vertically oriented inside the fridge door .......................................................... 155
    6.2.2 Four pint milk container case .................................................................................. 156
    6.2.3 1.5L water case ......................................................................................................... 158
      6.2.3.1 Horizontal inside the fridge ................................................................................ 158
      6.2.3.2 Vertically oriented inside the fridge door .......................................................... 160
    6.2.4 1L fruit juice case .................................................................................................... 161
      6.2.4.1 Horizontal inside the fridge ................................................................................ 162
      6.2.4.2 Vertically oriented inside the fridge ................................................................... 163
    6.2.5 Two litre of Coke case .............................................................................................. 163
      6.2.5.1 Horizontal inside the fridge ................................................................................ 164
      6.2.5.2 Vertically oriented inside the fridge door .......................................................... 165
6.3 Discussion ........................................................................................................................ 167
6.4 Summary ........................................................................................................................... 169
7 Conclusions and Future Work .......................................................................................... 170
  7.1 Future Work .................................................................................................................... 171
Bibliography .......................................................................................................................... 173
Author's Publications ............................................................................................................ 186
List of Figures

Figure 2-1: Power spectral density of a signal ................................................................. 6
Figure 2-2: Interference reduction time hopping impulse radio ........................................ 7
Figure 2-3: (a) Pulse Amplitude Modulation (b) Pulse Position Modulation and (c) Binary Phase
Shift Keying ...................................................................................................................... 8
Figure 2-4: FCC and EC UWB regulation ....................................................................... 10
Figure 2-5: Geometry of microstrip line fed disc monopole antenna ............................... 12
Figure 2-6: (a) Magnitude and (b) phase of simulated reflection coefficient .................. 12
Figure 2-7: Simulated group delay of disc monopole antenna ........................................ 13
Figure 2-8: Schematic of study of pulse filtering............................................................. 14
Figure 2-9: (a) Normalised time and (b) power spectrum of input signal ......................... 15
Figure 2-10: Normalised radiated signal from probe ....................................................... 16
Figure 2-11: Simulated E-field radiation pattern of disc monopole antenna .................... 16
Figure 2-12: (a) Schematic and (b) computer model of investigation of a radiated wave in
different directions ........................................................................................................ 16
Figure 2-13: Normalised (a) input signal and radiated signal at evaluation angle $\theta$ of (b) 0°, (c)
30°, (d) 60°, (e) 90°, (f) 120°, (g) 150°, and (h) 180° .......................................................... 17
Figure 2-14: Model of ultra wideband breast cancer detection......................................... 19
Figure 2-15: Model of UWB GPR .................................................................................. 19
Figure 2-16: Illustration of (a) physical model of SAR and (b) spatial–time plot .............. 20
Figure 2-17: Illustration of illumination of a sphere ....................................................... 22
Figure 2-18: Probe frequency response of a perfect electric conductor sphere .............. 22
Figure 2-19: (a) Measurement schematic and (b) impulse response of an A-10 aircraft model
[Bau91] ............................................................................................................................. 23
Figure 2-20: Bend angle cases discriminated by [Ald09] (a) straight wire, (b) bent by 150°, and (c)
L-shaped wire .................................................................................................................. 24
Figure 2-21: Geometries of an ellipsoid and a cylinder with proximity cross section [Ald10] .... 24
Figure 2-22: Wave incident on the boundary .................................................................. 26
Figure 2-23: (a) Free space reflection method and (b) corresponding transmission line model.... 26
Figure 2-24: Illustration of transmission/reflection method ............................................. 27
Figure 2-25: Illustration of transmission radiated measurement for wall property extraction: (a)
free case and (b) real wall case ....................................................................................... 30
Figure 2-26: Field regions of an antenna ......................................................................... 33
Figure 2-27: Schematic of detection of a metal ball using near field UWB SAR ................ 34
Figure 3-1: Flow chart of extraction of complex natural resonances using generalised pencil of function method ................................................................. 43
Figure 3-2: Illustration of a polarisation ellipse with a tilt angle $\theta$ ................................................................. 45
Figure 3-3: Illustration of the parameters in a Poincare sphere (Stokes vectors: $g_1, g_2$ and $g_3$, tilt angle $\theta$ and ellipticity angle $\chi$) ................................................................. 46
Figure 3-4: Illustration of the Huynen polarisation fork ................................................................. 49
Figure 3-5: Flow chart of evaluation of characteristic polarisation states in the context of Ultra Wideband (UWB) ................................................................. 50
Figure 3-6: CST model of three targets for far field detection ................................................................. 51
Figure 3-7: Simulated pulse excitation signal for (a) time domain and (b) frequency domain ...... 52
Figure 3-8: CST model example of perfect electrical conductor sphere in far field detection ..... 52
Figure 3-9: Backscattered impulse response of conducting cube ................................................................. 53
Figure 3-10: Late time response of cube ................................................................................................. 53
Figure 3-11: Original and reconstructed cube late time response ................................................................. 54
Figure 3-12: Extracted poles for three targets (cube – asterisk, sphere – diamond, cuboid – circle) ................................................................................................. 54
Figure 3-13: (a) Side view and (b) top view of wireframe of the egg model in CST simulation ($r_1 = 6.2$ mm, $r_2 = 11.7$ mm, $r_3 = 16.2$ mm, $r_4 = 19$ mm, $r_5 = 20$ mm, $r_6 = 19$ mm, $r_7 = 16$ mm, $r_8 = 11.7$ mm, $r_9 = 6.2$ mm, $H_1 = 1.5$ mm, $H_2 = 4.2$ mm, $H_3 = 6.6$ mm, $H_4 = 8.4$ mm, $H_5 = 9.3$ mm, $H_6 = 6.2$ mm, $H_7 = 5.5$ mm, $H_8 = 4.4$ mm, $H_9 = 2.8$ mm and $H_{10} = 1.1$ mm) ................................................................. 56
Figure 3-14: (a) Real and (b) imaginary part of dielectric constant of eggs [Wan09] (fixed marker points) and its curve fitting (dashed line) ................................................................. 57
Figure 3-15: (a) Real and (b) imaginary part of dielectric constant of egg estimation (fixed marker points) and simulation used in CST (dashed line) ................................................................. 58
Figure 3-16: CST detection model of a single egg ................................................................................................. 59
Figure 3-17: All possible egg layouts ................................................................................................. 60
Figure 3-18: Orientation plot of all six eggs to plane wave ................................................................................................. 62
Figure 3-19: Extracted complex natural resonances for one egg scenarios with three configurations ................................................................................................. 62
Figure 3-20: Extracted third poles for varying numbers of eggs with six configurations ................. 63
Figure 3-21: Relationship between quantity and characteristic angle $\varphi$ ................................................................. 64
Figure 4-1: A three-layer UWB antenna: (a) top view (dotted line: lower patch, circle: probe, solid line: middle and top patches) and (b) side view [Zeh06] ................................................................. 67
Figure 4-2: Simulated reflection coefficient [Zeh06] ................................................................................................. 67
Figure 4-3: (a) Biconical antenna and (b) spiral antenna ................................................................................................. 68
Figure 4-4: (a) Simulated (unit: mm) and (b) fabricated ultra wideband antenna ................................................................................................. 69
Figure 4-5 Simulated and measured reflection coefficient ......................................................... 70
Figure 4-6: Fabrication of in fridge sensors: (a) top view and (b) bottom view ......................... 70
Figure 4-7: Schematic of measurement system .......................................................................... 71
Figure 4-8: Measured reflection coefficient of sensor 1 in the case of free space and an egg above sensor 1 ........................................................................................................... 73
Figure 4-9: Measured group delay of sensor 1 in the case of free space and an egg above sensor 1 ......................................................................................................................... 73
Figure 4-10: Measured coupling coefficient of sensors 1 and 2 in the case of free space and an egg above sensor 1 ........................................................................................................ 74
Figure 4-11: Measured group delay of coupling coefficient of sensors 1 and 2 in the case of free space and an egg above sensor 1 ............................................................................. 74
Figure 4-12: Model for study of detectable region (dashed line: egg movement trace) .......... 76
Figure 4-13: S-parameters with slant angle of (a) 0°, (b) 30°, (c) 60°, and (d) 90° .............. 78
Figure 4-14: Group delay with slant angle of (a) 0°, (b) 30°, (c) 60°, and (d) 90° .......... 80
Figure 4-15: Topology of the in fridge antenna array ................................................................. 81
Figure 4-16: Real part of RCC: (a) simulation and (b) measurement ........................................ 82
Figure 4-17: Imaginary part of RCC: (a) simulation and (b) measurement .............................. 82
Figure 4-18: Six possible configurations for one egg coupling study .................................... 83
Figure 4-19: CCC related with sensor 1 for six configurations: (a) simulation and (b) measurement ................................................................................................................................. 83
Figure 4-20: Measured group delay of sensor 1 with different configurations ..................... 84
Figure 4-21: Study of eggs in random positions ....................................................................... 85
Figure 4-22: Measured RCC of sensor 1, CCC of sensor 1 and 2 as well as sensor 1 and 5 for one egg being moved in the x direction while keeping y as 0 mm and fixing x as 0 mm and moving in the y direction ......................................................................................................................... 85
Figure 4-23: (a) Topology of one egg case with (b) simulated and (c) measured RCC of sensor 1, $\rho_{\text{Rx1Tx1}}$ ................................................................................................................................. 86
Figure 4-24: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 1, $\rho_{\text{Rx1Tx1}}$ ................................................................................................................................. 87
Figure 4-25: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 1, $\rho_{\text{Rx1Tx1}}$ ................................................................................................................................. 88
Figure 4-26: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 1, $\rho_{\text{Rx1Tx1}}$ ................................................................................................................................. 89
Figure 4-27: (a) Topology of one egg case with (b) simulated and (c) measured RCC of sensor 2, $\rho_{\text{Rx2Tx2}}$ ................................................................................................................................. 91
Figure 4-28: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 2, 
\(\rho_{Rx2Tx2}\) ................................................................. 92

Figure 4-29: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 2, 
\(\rho_{Rx2Tx2}\) ................................................................. 93

Figure 4-30: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 2, 
\(\rho_{Rx2Tx2}\) ................................................................. 94

Figure 4-31: (a) Topology of one egg case with (b) simulated and (c) measured RCC of sensor 5, 
\(\rho_{Rx5Tx5}\) ................................................................. 96

Figure 4-32: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 5, 
\(\rho_{Rx5Tx5}\) ................................................................. 97

Figure 4-33: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 5, 
\(\rho_{Rx5Tx5}\) ................................................................. 98

Figure 4-34: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 5, 
\(\rho_{Rx5Tx5}\) ................................................................. 99

Figure 4-35: (a) Topology of one egg case with (b) simulated and (c) measured RCC of sensor 6, 
\(\rho_{Rx6Tx6}\) ................................................................. 101

Figure 4-36: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 6, 
\(\rho_{Rx6Tx6}\) ................................................................. 102

Figure 4-37: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 6, 
\(\rho_{Rx6Tx6}\) ................................................................. 103

Figure 4-38: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 6, 
\(\rho_{Rx6Tx6}\) ................................................................. 104

Figure 4-39: Simulated and measured (a) magnitude and (b) phase of coupling coefficient \(s_{12}\) in 
the case of free space and egg presence .................................................. 106

Figure 4-40: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 1 
and 2, \(\rho_{Rx2Tx1}\) ................................................................. 108

Figure 4-41: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 1 
and 2, \(\rho_{Rx2Tx1}\) ................................................................. 109

Figure 4-42: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 1 
and 2, \(\rho_{Rx2Tx1}\) ................................................................. 110

Figure 4-43: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 1 
and 2, \(\rho_{Rx2Tx1}\) ................................................................. 111

Figure 4-44: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 1 
and 5, \(\rho_{Rx5Tx1}\) ................................................................. 113
Figure 4-45: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 1 and 5, $\rho_{RxSTx1}$ ................................................................. 114

Figure 4-46: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 1 and 5, $\rho_{RxSTx1}$ ..................................................................................... 115

Figure 4-47: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 1 and 5, $\rho_{RxSTx1}$ ..................................................................................... 116

Figure 4-48: RCC and CCC related to different diagonal distance .............................................. 117

Figure 4-49: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 1 and 6, $\rho_{RxSTx1}$ ..................................................................................... 119

Figure 4-50: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 1 and 6, $\rho_{RxSTx1}$ ..................................................................................... 120

Figure 4-51: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 1 and 6, $\rho_{RxSTx1}$ ..................................................................................... 121

Figure 4-52: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 1 and 6, $\rho_{RxSTx1}$ ..................................................................................... 122

Figure 4-53: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 2 and 6, $\rho_{RxSTx2}$ ..................................................................................... 123

Figure 4-54: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 2 and 6, $\rho_{RxSTx2}$ ..................................................................................... 124

Figure 4-55: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 2 and 6, $\rho_{RxSTx2}$ ..................................................................................... 125

Figure 4-56: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 2 and 6, $\rho_{RxSTx2}$ ..................................................................................... 126

Figure 4-57: Blind test detection mechanism ................................................................................. 127

Figure 4-58: Plot of third blind test (dashed line: egg box) ............................................................ 129

Figure 5-1: Schematic plot of egg detection in the general clutter scenario ................................. 133

Figure 5-2: Photograph of ten scenarios when food is adjacent to the egg box ......................... 134

Figure 5-3: Correlation coefficient for different food clutter scenarios around the egg box when the egg is above sensor 10 ..................................................................................... 135

Figure 5-4: Correlation coefficient for different scenarios in case of food around the egg being in the middle of sensor 10 and 14 ................................................................................. 136

Figure 5-5: Correlation coefficient for different scenarios in case of food is around the egg being above sensor 14 ........................................................................................................ 137

Figure 5-6: Photograph of ten scenarios when food is placed above egg box ............................ 138

Figure 5-7: Correlation coefficient for different scenarios in case of food above the egg that is above sensor 10 ........................................................................................................ 138
Figure 5-8: Correlation coefficient for different scenarios in case of food is above the egg that is in the middle of sensor 10 and 14 ........................................................................................................ 139
Figure 5-9: Correlation coefficient for different scenarios in case of food above the egg that is above sensor 14.................................................................................................................................... 140
Figure 5-10: Schematic plot of worst case scenario...................................................................................... 143
Figure 5-11: Measurement photograph of worst case scenario ........................................................................ 143
Figure 5-12: Correlation coefficient $\rho_{RxTx_{i,j,\text{water}}} \text{ between water only and free space }$ ....................... 144
Figure 5-13: Correlation coefficient $\rho_{RxTx_{i,j,\text{wateregg}}} \text{ referenced to free space of different configurations}$ ........................................................................................................................................ 144
Figure 6-1: Photograph of liquids under test .................................................................................................. 148
Figure 6-2: Tested volume of liquid: (a) Full, 100%; (b) three quarters full, 75%; (c) half full, 50%; (d) one quarter full, 25%; (e) nearly empty, 10%; and (f) empty, 0% (dashed line: liquid surface) .................................................................................................................. 148
Figure 6-3: (a) Schematic and (b) photograph of one pint of milk in a vertical orientation positioned on sensor 10 ....................................................................................................................................... 149
Figure 6-4: (a) Real part, (b) imaginary part and (c) absolute correlation $\rho_{RxTx_{i,\text{liquid}}} \text{ map of one pint of milk vertically positioned on the shelf of a fridge}$ ...................................................................................................................................... 150
Figure 6-5: Phase of $\rho_{Rx6Tx_{10,\text{liquid}}} \text{ and } \rho_{Rx14Tx_{10,\text{liquid}}} \text{ vs. one pint of milk level}$ .............................. 152
Figure 6-6: Measured cross coupling parameters $S_{Rx6Tx_{10}} \text{ and } S_{Rx14Tx_{10}} \text{ of empty bottle case}$ ............... 152
Figure 6-7: (a) Magnitude and (b) phase of cross coupling $S_{Rx6Tx_{10}} \text{ related to different milk levels}$ ............... 153
Figure 6-8: (a) Magnitude and (b) phase of cross coupling $S_{Rx14Tx_{10}} \text{ related to different milk levels}$ .......... 154
Figure 6-9: (a) Schematic and (b) photograph of one pint of milk in a vertical orientation placed in the door of a fridge ........................................................................................................................................ 155
Figure 6-10: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{RxTx_{i,\text{liquid}}} \text{ map of one pint of milk in a vertical orientation in the door of the fridge}$ .......................................................................................................................... 156
Figure 6-11: (a) Schematic and (b) photograph of four pints of milk vertically oriented inside the fridge door........................................................................................................................................... 157
Figure 6-12: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{RxTx_{i,\text{liquid}}} \text{ map of four pints of milk in vertical orientation in the door of the fridge}$ .................................................................................................................. 157
Figure 6-13: (a) Schematic and (b) photograph of water in horizontal orientation inside the fridge .............................................................................................................................................................. 158
Figure 6-14: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{RxTx_{i,\text{liquid}}} \text{ map of water horizontally positioned inside the fridge}$ ........................................................................................................................................... 159
Figure 6-15: Phase of $\rho_{Rx6Tx_{10,\text{liquid}}} \text{ and } \rho_{Rx14Tx_{10,\text{liquid}}} \text{ vs. water level}$ .......................................................... 160
Figure 6-16: (a) Schematic and (b) photograph of water vertically in the fridge door .................. 160
Figure 6-17: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{Rx/Tx_{\text{liquid}}}$ map of water vertically oriented in the fridge door........................................................................ 161
Figure 6-18: (a) Schematic and (b) photograph of fruit juice horizontally orientated inside the fridge .................................................................................................................. 162
Figure 6-19: Real part of the correlation $\rho_{Rx/Tx_{\text{liquid}}}$ map of fruit juice horizontally positioned on the shelf of the fridge ........................................................................................................... 162
Figure 6-20: (a) Schematic and (b) photograph of fruit juice container vertically oriented inside the fridge .................................................................................................................................... 163
Figure 6-21: Real part of correlation $\rho_{Rx/Tx_{\text{liquid}}}$ map of fruit juice vertically placed on the shelf .............................................................................................................................................. 163
Figure 6-22: (a) Schematic and (b) photograph of coke horizontally oriented inside the fridge . 164
Figure 6-23: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{Rx/Tx_{\text{liquid}}}$ map of coke horizontally positioned inside the fridge.................................................................................................................. 164
Figure 6-24: Phase of $\rho_{Rx/Tx_{10_{\text{liquid}}}}$ and $\rho_{Rx/Tx_{14_{\text{liquid}}}}$ vs. coke level .............................................. 165
Figure 6-25: (a) Schematic and (b) photograph of coke bottle with vertical orientation inside the fridge........................................................................................................................................ 166
Figure 6-26: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{Rx/Tx_{\text{liquid}}}$ map of coke vertically positioned inside the fridge door .................................................................................................................. 167
Figure 6-27: Phase of $\rho_{Rx/Tx_{10_{\text{liquid}}}}$ and $\rho_{Rx/Tx_{14_{\text{liquid}}}}$ related to different liquids at different levels .................................................................................................................................................................................. 168
List of Tables

Table 2-1: FCC emission limits for indoor and outdoor communications ........................................ 10
Table 3-1: Simulation environment for far field detection ................................................................. 52
Table 3-2: Extracted poles for three different targets ........................................................................ 54
Table 3-3: Measured dielectric constant of liquid whole egg [Wan09] .............................................. 56
Table 3-4: Egg configurations with related diagrams ......................................................................... 61
Table 4-1: Topology of eggs above sensors ....................................................................................... 81
Table 4-2: Topology of eggs in random location case ....................................................................... 84
Table 4-3: Resolved correlation and binary decision values for test 1 ............................................. 128
Table 4-4: Resolved correlation and binary decision values for test 2 ............................................. 128
Table 4-5: Resolved correlation and binary decision values for test 3 ............................................. 129
Table 5-1: Different food scenarios for clutter study ......................................................................... 133
Table 5-2: Coefficient of variation (CV) when egg is directly above sensor 10 ............................... 135
Table 5-3: CV when egg is in the middle of sensors 10 and 14 ........................................................ 136
Table 5-4: CV when egg is above sensor 14 .................................................................................... 137
Table 5-5: CV when egg is directly above sensor 10 ....................................................................... 139
Table 5-6: CV when egg is midway between sensors 10 and 14 ..................................................... 139
Table 5-7: CV when egg is directly above sensor 14 ....................................................................... 140
Table 5-8: Summary of coefficient of variation when food is around the egg box ..................... 141
Table 5-9: Summary of coefficient of variation when food is above the egg box ......................... 141
Table 6-1: Practical drink layout ........................................................................................................ 148
### Glossary of Terms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUT</td>
<td>Antenna Under Test</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>BPF</td>
<td>Band Pass Filter</td>
</tr>
<tr>
<td>CPS</td>
<td>Characteristic Polarisation States</td>
</tr>
<tr>
<td>CNR</td>
<td>Complex Natural Resonance</td>
</tr>
<tr>
<td>CCC</td>
<td>Complex Correlation Coefficient</td>
</tr>
<tr>
<td>CST</td>
<td>Computer Simulation Technology</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DS-CDMA</td>
<td>Direct Sequence Coded Multiple Access</td>
</tr>
<tr>
<td>DAS</td>
<td>Delay And Sum</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processor</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite-Difference Time-Domain</td>
</tr>
<tr>
<td>FFH</td>
<td>Fast Frequency Hopping</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground Penetration Radar</td>
</tr>
<tr>
<td>GPOF</td>
<td>Generalised Pencil of Function</td>
</tr>
<tr>
<td>GD</td>
<td>Group Delay</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>IR</td>
<td>Impulse Radio</td>
</tr>
<tr>
<td>IR-UWB</td>
<td>Impulse Radio Ultra Wideband</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>iFridge</td>
<td>intelligent Fridge</td>
</tr>
<tr>
<td>k-NN</td>
<td>k-nearest neighbours</td>
</tr>
<tr>
<td>LTR</td>
<td>Late Time Response</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>MAI</td>
<td>Multiple-Access Interference</td>
</tr>
<tr>
<td>MUT</td>
<td>Material Under Test</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean Square Error</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
</tr>
<tr>
<td>MCU</td>
<td>Microprocessor Unit</td>
</tr>
<tr>
<td>MPM</td>
<td>Matrix Pencil Method</td>
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<tr>
<td>NFC</td>
<td>Near Field Communication</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency-Division Multiplexing</td>
</tr>
<tr>
<td>Ofcom</td>
<td>the Office of Communications</td>
</tr>
<tr>
<td>PAM</td>
<td>Pulse Amplitude Modulation</td>
</tr>
<tr>
<td>PPM</td>
<td>Pulse Position Modulation</td>
</tr>
<tr>
<td>PEC</td>
<td>Perfect Electric Conductor</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
</tr>
<tr>
<td>RCC</td>
<td>Reflection Coefficient Correlation</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SEM</td>
<td>Singularity Expansion Method</td>
</tr>
<tr>
<td>SVD</td>
<td>Singular Value Decomposition</td>
</tr>
<tr>
<td>SMA</td>
<td>Sub Miniature version A</td>
</tr>
<tr>
<td>SFH</td>
<td>Slow Frequency Hopping</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal-to-Interference and Noise Ratio</td>
</tr>
<tr>
<td>TH-IR</td>
<td>Time Hopping Impulse Radio</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>TOA</td>
<td>Time-of-Arrival</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wideband</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyser</td>
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</table>
Chapter 1

1 Introduction

Unlike conventional narrowband systems, ultra wideband (UWB) systems have the advantage of high data rates, robustness against noise and low power consumption owing to the wide bandwidth. Impulse radio ultra wideband (IR-UWB) is a baseband format where a very short pulse is generated directly instead of utilising a carrier wave in a higher frequency. The IR-UWB technology has been usefully applied in radar applications as a non-invasive technology in which a UWB impulse illuminates the target directly and the received scattered fields contain useful information about the target. The majority of previous research concerns the far field or radiated near field region and this requires a large test space. There is very little research on the study of target detection and classification in the reactive near field since the antenna pattern is not formed in such a close range. This thesis focuses on the study of target detection and classification in the reactive near field. Egg detection in an intelligent fridge will be the main example application serving as a proof of concept.

1.1 Motivation

UWB technology has had a profound impact on target detection and classification where the theoretical background of sensing targets has been well defined in the far field and radiating near field region. Sensing targets in the reactive near field is an unexploited area where studies are necessary to determine the capabilities. A number of applications could exploit material detection in the reactive near field, such as smart fridges detecting the quantity of different foods and smart packaging to ascertain the volume of liquid or items remaining in a package.

The detection of eggs in a smart fridge is chosen as the main application and test platform for this research. Conventionally, the identity of food inside a fridge is accomplished by radio frequency identification (RFID) technology in which a large reader antenna is affixed to the inner back of the fridge while tags are placed on each food item. Although RFID provides a solution to become aware of food inside the fridge, the limitations of such system can be summarised into three aspects. Firstly, it would be costly in the case that tags are placed on every food item, such as every egg within a box. Secondly, in order to obtain detailed eggs information such as its locations and remaining quantities inside a box, it will create a potential risk in terms of health
and hygiene to place a tag on every egg. Thirdly, it lacks the ability to ascertain the exact amount
or quantity of the food left, especially where it is liquid. This leads to the first challenge presented
in this thesis, which is the development of a low-cost system with the function to detect the exact
quantity of eggs. Non-imaging UWB radar was implemented as a compromise between cost and
accuracy. The scattered fields from the targets are a key parameter to discriminate between
different targets in terms of parametric-based UWB radar. The scattered waves, however, were
found to be obtained by illumination of a target by plane waves from the transmitter in the far
field, which is impractical for a number of applications, including detection in a fridge.

Given the limitations of non-imaging radar, this leads to the study of UWB detection in the
reactive near field. Eggs are chosen as the scenario for this research as they are relatively small
compared to other food items in the fridge as well as having a widely used form of box container.
In the reactive near field case, the detection method moves away from evaluating the response of
scattered fields and focuses more specifically on the filtering of impulse response owing to the
eggs close to antenna. This is not a simple capacitive sensing instead it is a measure of how eggs
influence the reactive near field, then leading to the detection. Measured and simulated S-
parameters are analysed using sensors in the reactive near field and their input reflection
coefficients are analysed, coupling between them and the change in group delay when comparing
with and without eggs present. A new form of correlation coefficient has also been derived to
quantify such comparisons. Further to this, other fridge scenarios are also investigated in which
the effects of food around and above the eggs are studied. This reliability of the reactive near field
detection method shows promising results even in the worst-case scenarios of clutter surrounding
the eggs. Using the results generated from a correlation map by the sensors, the fridge can
distinguish the exact quantity of eggs regardless of the position of the eggs over the sensors. The
method has also been extended to examine the level of liquid in a container, where the phase of
the correlation coefficient reveals a suitably accurate measure of the volume of liquid.

1.2 Structure of Thesis

Chapter 2 presents an overview of UWB systems, including the definition of UWB, group delay,
pulse filtering and near field UWB, which will be used throughout the thesis. UWB radar, as an
important element of this chapter, is reviewed in terms of imaging and non-imaging, with an
emphasis on parametric-based UWB radar. UWB material characterisation is also reviewed
outlining the drawbacks of conventional approaches.

Chapter 3 presents a detailed study of the determination of egg quantity in a box using non-
imaging UWB radar. The approach applied here is based on investigation of the characteristic
angle under the illumination of waves in different polarisations. However, the constraints required
with far field illumination lead to impractical implementation in a real smart fridge or any other form of UWB detection in a short range. This inevitably turns to detection of eggs in the reactive near field as presented in Chapter 4 where simulations are initially carried out to study the detectable region of a proposed sensor in the reactive near field. Secondly, an array of sensors is constructed and used to investigate the possibility of detecting the number of eggs when they are placed directly above a sensor. Finally, further investigation is made where the eggs are offset from being directly above a sensor.

Chapter 5 broadens the topic discussed in Chapter 4, where general fridge situations are taken into account through two real scenarios. The first one is to investigate the effect of other clutter in a fridge with a variety of foods arbitrarily placed around and above the egg box. The worst-case scenario is identified and studied further where detection can fail when vast quantities of liquid surround the eggs.

Finally, Chapter 6 extends the study to detection of liquid volume. The S-parameters are measured in accordance with different drinks and their corresponding level in their appropriate orientations. Conclusions and future work are presented in Chapter 7.

1.3 Original Contributions

The original contributions related to this study are listed below chronologically:

- Modelling and simulation of a box of eggs and investigation of the relationship between egg quantity and characteristic polarisation states using UWB radar in the far field.

- Quantifying bulk material identification in the reactive near field by defining reflection coefficient correlation and coupling correlation coefficients as suitable metrics for IR-UWB, in addition to a known metric of group delay, all of which quantify the filtering of the impulse.

- Quantitative results to evaluate the robustness of IR-UWB detection in several scenarios, including the target position relative to the sensor and the presence of other bulk materials. The smart fridge scenario was used as a suitable test platform in this instance.
Chapter 2

2 Background of UWB and Its Applications

For many years, ultra wideband (UWB) technology has been used in a variety of areas, such as radar, personal and military communications, and sensing. Compared with conventional narrowband systems, UWB is unique as it has a large bandwidth to provide high capacity and data rate, and immunity to noise [Har81]. In this Chapter, the UWB system is first reviewed, in which the evolution of UWB technology, signals and systems as well as regulation issues are described. Following this, key factors involving UWB antennas are described along with their effect on pulse filtering and group delay.

A review of radar using UWB technology is also covered in this Chapter, noting its particular qualities of low power consumption, non-intrusive detection and accuracy. Detection methods are compared including imaging based and non-imaging based UWB radars. However, more attention is focused on non-imaging UWB radar as it is inexpensive and in the scope of this thesis there is no need to reconstruct the full image for bulk material detection and classification. The final part of this Chapter will explore near field UWB in which the definitions of near field are clarified. In contrast to existing research in the radiating near field, the greater challenge exists in terms of target detection as the target is closer to the antennas in the reactive near field.

2.1 UWB System

Though research and development of UWB technology has received dramatic attention in the last decade, communication using UWB has a long history. It was in the late 1800s that a short pulse was generated using a spark-gap transmitter by Marconi [Wei04]. However, people were more interested in communication based on a narrowband system, partially due to lack of knowledge in how to manage signal spreading over a large bandwidth and also because no effective way could be found to counteract against noise and other wideband signals. Until the 1960s, after many decades where research on UWB communication was retarded, the military showed interest in UWB technology with spatial resolution (high accuracy for target detection) as the first consideration rather than spectral efficiency. Key components such as the design of a high-power short-pulse generator were conducted by the military in both the USA and the Soviet Union.
Chapter 2. Background of UWB and Its Applications

In the 1970s, UWB communication received renewed interest known as "baseband" or "carrier-free" communication [Har81]. It was found that such systems did not interfere with existing narrowband systems. However, the problem of multiple-access interference (MAI), which is caused by a signal illuminated by multiple transceivers on a single receiver, had not been solved until the beginning of the 1990s, where time hopping impulse radio (TH-IR) was developed [Win00] [Win98].

In 2002, the Federal Communications Commission (FCC) issued a ruling that allowed international UWB emissions in the frequency range between 3.1 GHz and 10.6 GHz, subject to certain restriction for emissions within a defined power spectrum [Com02].

Research into UWB technology grew rapidly after 2002 including the study of multiple access schemes and narrowband interference [Ram01] [Zha02] [Chu04] [Ber05] [Pia05] [Gez05] [Chi09] [Sun13], equalisation and Rake reception [Yan05] [Cas02] [Gen09] [Zuo12], channel estimation and synchronisation [Lot02] [LiY04] [WuL10] [Wan14], transmitted-reference and differential schemes [Cho02] [Que05] [Hoc02] [Wit05] [Tuf06] [Wun13] [Kha08], spectral shaping and the design of time hopping sequences [Nak06] [Fuj04] [Chu041] [LiB10] [Ria09]. Practical implementation was also investigated in terms of antenna and the radio [LeM02] [Bat04] [Fon04] as well as combining UWB with other antenna schemes, such as multiple-input multiple-output (MIMO) [Sir04] [Kum02] [Cha04] [Ral10], which supports radar applications used for through the wall imaging [Ral10][Yua13], medical imaging [Lai11] [Bia10] [Zha12] and ground penetration [Par03][Ven14].

2.1.1 UWB Signals and System

Ultra wideband signals have a substantially larger bandwidth than conventional signals. They are defined by either one of the following criteria:

- Bandwidth (BW) > 500MHz.
- Fractional Bandwidth (FBW) ≥ 0.2 if lower than 500MHz.

where the bandwidth of the signal is determined by the frequency difference with a -10 dB threshold [Siw04] (see Figure 2-1).
Therefore, the bandwidth is defined as follows [Siw04]:

\[ \text{BW} = f_H - f_L \]  \hspace{1cm} (2.1)

where \( f_H \) and \( f_L \) represent high frequency and low frequency, respectively.

The fractional bandwidth is defined as [Siw04]:

\[ \text{FBW} = \frac{\text{BW}}{f_c} \]  \hspace{1cm} (2.2)

where \( f_c \) is the centre frequency and is given by [Siw04]:

\[ f_c = \frac{f_H + f_L}{2} \]  \hspace{1cm} (2.3)

Since the bandwidth is inversely proportional to the width of the pulse, UWB signals are very short waveforms typically on a nanosecond (ns) scale and have a low duty cycle. There are several ways to generate a UWB signal, including impulse radio (IR), direct sequence coded multiple access (DS-CDMA) [Sim94], frequency hopping (FH) [Mol06] and chirping [Won09]. The impulse is the simplest form in which the ultra-short wave is illuminated directly by the transmitter. Alternatively, the DS-CDMA provides a direct way to generate UWB signals as the core idea is to generate multiple conventional narrowband signals with a spreading signal covering a large BW. However, such an approach has the disadvantage of complexity in generating continuous pulses as well as the power consumption involved in the narrowband signal generation. Unlike DS-CDMA, FH is a more flexible and reliable approach to generate UWB signals. Fast frequency hopping (FFH) changes the carrier frequency several times during the
transmission of one symbol while slow frequency hopping (SFH) transmits one or several symbols on each frequency. Different users can be assigned by different hopping sequences and therefore this can be used either in multiple access or combined with other schemes such as orthogonal frequency-division multiplexing (OFDM). Chirp UWB uses chirp waveforms having the properties of signal carrier frequency increasing or decreasing with time. Its advantages include easy generation, easy implementation of sub-band systems and being extremely robust against multipath delay spread. Though the above two approaches provide many benefits, the basic principle is based on the narrowband combination, thus high power consumption and complexity is still required, resulting in high cost. As a low-cost alternative, IR is used where information conveyed by symbols can be represented by a number of UWB pulses. However, a catastrophic situation would occur where several transmitters and one receiver are used for one pulse per symbol. Owing to unwanted information from other transmitters, high bit error rates (BERs) and low signal-to-interference and noise ratio (SINR) would result. Time hopping impulse radio (TH-IR) was developed in order to overcome this problem. The whole symbol period was divided into \( N_f \) "frames" (or smaller periods) evenly. The pulse can occupy random positions inside every frame leading to a unique pulse sequence for a unique user. The information would be retrieved at the receiver part even though pulse collisions from other devices occur (Figure 2-2), though such collisions could be identified and discarded by this method.

![Figure 2-2: Interference reduction time hopping impulse radio](image)

The information symbols of UWB signals can be modulated based on pulse amplitude modulation (PAM) [HoM01], pulse position modulation (PPM) [Aie03] and binary phase shift keying (BPSK) [Wel02] (Figure 2-3). PAM applies the idea that information bit ‘1’ and ‘0’ can be expressed in terms of different amplitudes. The other two modulation approaches maintain a constant amplitude but they will vary the time interval in the case of PPM while the polarity of pulse will be varied in the case of BPSK.
Figure 2-3: (a) Pulse Amplitude Modulation (b) Pulse Position Modulation and (c) Binary Phase Shift Keying
The modulated signals and pulse signals are denoted as $x(t)$ and $s(t)$ defined in the following ways:

\[
PAM: x(t) = d_{PAM,i}s(t) \tag{2.4}
\]

\[
PPM: x(t) = s(t - d_{PPM,i}) \tag{2.5}
\]

\[
BPSK: x(t) = s(t)e^{-j(d_{BPSK,i})} \tag{2.6}
\]

where $i$ is the bit transmitted (either “1” or “0”) and:

\[
d_{PAM,i} = \begin{cases} 
   A_1, & i = 1 \\
   A_2, & i = 0 
\end{cases} \tag{2.7}
\]

\[
d_{PPM,i} = \begin{cases} 
   a, & i = 1 \\
   0, & i = 0 
\end{cases} \tag{2.8}
\]

\[
d_{BPSK,i} = \begin{cases} 
   \pi, & i = 1 \\
   0, & i = 0 
\end{cases} \tag{2.9}
\]

### 2.1.2 Regulation Issues

Operating frequencies for UWB systems will inevitably overlap with other existing wireless systems, which leads to the importance of regulations as set by the FCC. The frequency masks revealing the maximum emitted power spectrum of the transmitted signal are defined in terms of application and environment. For indoor and outdoor communications, emission masks are both the same with a level of -41.3 dBm/MHz from 3.1 GHz to 10.6 GHz. Besides this, the operating frequency could be below 960 MHz for ground penetration radar (GPR) and the lower frequency would be lowered to 1.99 GHz for the application of through-wall and surveillance. Detailed information in association with frequency masks for a variety of applications is summarised in Table 2-1. The European Commission (EC) has also issued a decision with regard to UWB regulations [Nik10] [Maz11]. UWB devices can use 6.0–8.5 GHz with the level of -41.3 dBm/MHz. The band of 3.4–4.8 GHz with the same power density was also possible to use until the end of 2010. The regulatory body in the UK, the Office of Communications (OfCom),
permits the use of UWB technology as licence-free in the UK in August 2007. A bandwidth from 3.4 GHz to 4.8 GHz was assigned to UWB with mitigation techniques required while a lower emission level of -70 dBm/MHz was enforced after December 2010 [Gha07].

<table>
<thead>
<tr>
<th>Frequency Ranges (MHz)</th>
<th>Indoor Emission Mask (dBm/MHz)</th>
<th>Outdoor Emission Mask (dBm/MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>960–1610</td>
<td>-75.3</td>
<td>-75.3</td>
</tr>
<tr>
<td>1610–1900</td>
<td>-53.3</td>
<td>-63.3</td>
</tr>
<tr>
<td>1900–3100</td>
<td>-51.3</td>
<td>-61.3</td>
</tr>
<tr>
<td>3100–10600</td>
<td>-41.3</td>
<td>-41.3</td>
</tr>
<tr>
<td>Above 10600</td>
<td>-51.3</td>
<td>-61.3</td>
</tr>
</tbody>
</table>

Table 2-1: FCC emission limits for indoor and outdoor communications

![Figure 2-4: FCC and EC UWB regulation](image)

2.2 Pulse filtering

Due to the low transmit power under UWB regulations given in Figure 2-4, one of the biggest challenges is efficient radiation so that the signal pulse can be transmitted with minimum loss. The following section describes pulse filtering in association with UWB antennas and leads to group delay.
Return loss of an antenna is a measure of the effectiveness of power delivery from a transmission line to an antenna [Bir09]. If the power incident on the antenna-under-test (AUT) is $P_{\text{in}}$ and the reflected power to the source is $P_{\text{ref}}$, the ratio between $P_{\text{in}}/P_{\text{ref}}$ is proportional to the degree of mismatch level, which means that with a larger ratio, a better impedance matching is achieved. The return loss in decibel (dB) is expressed as [Bir09]:

$$RL = 10\log_{10}\left(\frac{P_{\text{in}}}{P_{\text{ref}}}\right)$$  \hspace{1cm} (2.10)

In terms of reflection coefficient, the return loss can be rewritten as [Bir09]:

$$RL = 10\log_{10}\left|\frac{1}{\rho}\right|^2 = -20\log_{10}|\rho|$$  \hspace{1cm} (2.11)

where $\rho$ is the complex reflection coefficient.

In present-day usage, whether from simulation or measurement using a vector network analyser (VNA), the S-parameters, which include the reflection coefficient, are always negative quantities in decibels from passive devices. A well designed antenna has a return loss better than 10 dB or the reflection coefficient is less than -10 dB in a certain frequency range. This indicates that a signal with a specific frequency range can be radiated effectively in terms of the kind of antenna, otherwise a high proportion of signals with frequencies outside the 10 dB return loss region are reflected back to the source. It is worth noting that the pulse fed to the antenna is different from the radiated pulse, thus, the antenna itself acts as a filter. An FR4-based UWB microstrip line fed disc monopole antenna [Lia05] is used as a prototype with the dimensions given in Figure 2-5. The simulated magnitude and phase of the reflection coefficient using computer simulation technology (CST)\(^1\) software are presented in Figure 2-6 (a) in which the bandwidth is from 2.46 GHz to 10.02 GHz. In addition to the magnitude of S-parameters, the phase response is another key parameter involved in pulse filtering as given in Figure 2-6 (b). The phase discontinuity can be observed at points with significant resonance, such as 3 GHz, 6.3 GHz, 8.9 GHz and 10 GHz.

\(^1\) www.cst.com

\(^2\) http://www.quirky.com/shop/619
Figure 2-5: Geometry of microstrip line fed disc monopole antenna

\( W = 42 \text{ mm}, L = 50 \text{ mm}, H = 1.5 \text{ mm}, L_1 = 20 \text{ mm}, h = 0.3 \text{ mm}, W_1 = 2.6 \text{ mm} \) and \( r = 10 \text{ mm} \)

Figure 2-6: (a) Magnitude and (b) phase of simulated reflection coefficient
Group delay, which can be extracted from the phase response, is a measure of the transmit time of a signal through a system (or device) versus frequency and can be expressed as [Wil97]:

\[ \tau_g = -\frac{d}{d\omega} \angle H(j\omega) \]

(2.12)

where \( \angle H(j\omega) \) denotes the phase response of the system or the device. It is known that phase response, which changes linearly with frequency, corresponds to a fixed time shift in the time domain. Thus, a constant phase gradient for UWB antennas over the frequency band of interest is essential to minimise group delay. The simulated group delay of the disc monopole antenna is depicted in Figure 2-7. The group delay is flat across the majority of the UWB band, however, two significant peaks occur (3 GHz and 13 GHz) owing to an abrupt change in reflection coefficient including a change in phase gradient, as illustrated in Figure 2-6.

![Figure 2-7: Simulated group delay of disc monopole antenna](image)

A far field probe is used in simulation in order to observe the radiated signal from the antenna. The distance between the observation point and the sensor is to meet the far field criteria defined by [Bal05]:

\[ d \geq \frac{2D^2}{\lambda} \]

(2.13)

where \( d \) is the distance between the antenna and the observation point, \( D \) is the largest dimension of antenna and \( \lambda \) is the free space wavelength. In this study, the distance is chosen as 30 cm as given in Figure 2-8. The location of the probe can be expressed in spherical coordinates with the radius \( r \) of 31.75 cm, evaluation angle \( \theta \) of 0° and azimuth angle \( \phi \) of 0°. The normalised signal
fed to the antenna in both time domain and frequency domain is given in Figure 2-9 in which the pulse covers a bandwidth from 0.78 GHz to 15 GHz. Figure 2-10 illustrates the normalised radiated signal by the antenna 30 cm away. Except for the time lag between the input signal and the radiated signal due to the transmission of wave, the shapes of the input signal and the radiated one are also different. This pulse filtering caused by the antenna due to the impedance mismatch causes an increase in the magnitude of S-parameter and discontinuity in the phase of S-parameter. Pulse filtering also has a relationship with the radiation pattern, which is a measure of the radiation properties of the antenna as a function of spatial coordinates [Bal05]. The simulated electric field (E-field) radiation pattern of the disc monopole antenna is presented in Figure 2-11. Though the radiation pattern is largely consistent across the UWB, differences can be observed at the higher frequency where gain is less than at the lower frequency and the patterns are offset by approximately 30° at 7 GHz and 9 GHz. This difference will cause the filtering of the radiated pulse as the change in path loss will not be consistent over the whole band. Several virtual probes are set to collect the radiated E-field from different angles. The radius of the observation platform \( r \) is 30 cm, which meets the far field criteria as before. The azimuth angle, \( \phi \) is fixed at 270° while the evaluation angle \( \theta \) ranges from 0° to 180° in 30° steps, as shown in Figure 2-12. The corresponding normalised signals recorded by the probes at different elevation angles as well as the input signal are given in Figure 2-13. The shape of the waveforms varies in accordance to different elevation angles owing to the radiation pattern. Thus, further filtering on the UWB impulse will result.

![Figure 2-8: Schematic of study of pulse filtering](image-url)
Figure 2-9: (a) Normalised time and (b) power spectrum of input signal
Chapter 2. Background of UWB and Its Applications

Figure 2-10: Normalised radiated signal from probe

Figure 2-11: Simulated E-field radiation pattern of disc monopole antenna

Figure 2-12: (a) Schematic and (b) computer model of investigation of a radiated wave in different directions
Figure 2-13: Normalised (a) input signal and radiated signal at evaluation angle $\theta$ of (b) 0°, (c) 30°, (d) 60°, (e) 90°, (f) 120°, (g) 150°, and (h) 180°
Chapter 2. Background of UWB and Its Applications

2.3 UWB Radar

Radar, which was developed during World War II, is widely used for target detection and ranging. The most general use is for aeroplanes and ships targets around them need to be known including the size, location, direction and velocity. The mechanism of radar is relatively simple: the transmitter illuminates an EM wave towards the interested area after which targets reflect the EM wave and finally receivers collect echoes from the target. Post processing is subsequently undertaken to retrieve the target’s signatures.

Radar using UWB technology has shown potential in the areas of [Siw04][All06][Tao11][Zha12]:

- Airport security for concealed weapons detection
- Ground penetration radar
- Surveillance radar
- Through the wall radar
- Biomedical application, such as breast cancer detection etc.

In general, the approaches of UWB radars can be divided into two categories: one is the imaging based method and the other is a parametric based method. In the next two sections, both approaches are reviewed.

2.3.1 UWB Imaging Radar

UWB imaging radar, as with cameras, can capture a picture of an area of interest and find unknown targets. UWB imaging radar has the capability in the cross-range (plane) and also the down-range (depth). Two typical UWB imaging radars exist: (1) direct UWB imaging radar and (2) synthetic aperture UWB radar (UWB SAR). Direct UWB imaging radar employs several sensors placed in different locations. Based on these sensors, images could be reconstructed using a simple imaging algorithm. Applications of direct imaging radar have shown great potential in the area of breast cancer detection [Fea02] [LiX04] [Kos06] [Che06] [Hag98] [Kle08] [LiX01] [Lim08] [Sil05] [Lai11] [Sal09] [Xia09] [Bia10] [Cut10] [Als09] [Zhu07] [Kho09] [Lak11]. The location of tumours can be well localised because of the significant difference between healthy and malignant tissues. A conventional breast cancer detection scenario is shown in Figure 2-14, where the system consists of a tumour model with a malignant tissue. Several transceivers are placed along the curve of the breast. The breast model is illuminated by each antenna sequentially, while all the elements act as receivers to record the backscattered signal. A delay and sum (DAS) approach is applied to reconstruct the image thus bringing the tumour into focus as recorded signals are added coherently at desired points while they are added incoherently at the other points.
In addition to the breast cancer detection, the direct imaging radars also show its capabilities in the sensing of mines buried underneath the ground [Par03]. The presence of mines as well as the dimensions and locations can be detected using GPR. The detection can be accomplished using a single sensor (monostatic mode) with which the sensor acts with both transmitter and receiver roles, or a pair of sensors (bistatic mode) whereby one acts as transmitter and the other as receiver, or an array of sensors (multistatic mode) whereby one of them can be worked as transmitter while the others as receivers. A conventional GPR detection scenario in multistatic mode is drawn in Figure 2-15, where the sensors are placed a certain distance away from the surface of soil whilst the landmine buried away from the surface. The EM wave is illuminated by one antenna to the air then it penetrates the soil at a lower speed as well as distortion occurs owing to the attenuation factor of soil. Strong reflected waves occur once the wave hit the metal obstruction such as landmines, and then the other sensors receive the echoes at different locations. The same procedure is carried out but the remaining sensors work as a transmitter sequentially. Therefore, with a prior knowledge of the locations of sensors as well as the distance between the air and surface, the imaging of the landmine can be reconstructed after calibration whereby the response without the mines is subtracted.

Figure 2-14: Model of ultra wideband breast cancer detection

Figure 2-15: Model of UWB GPR
Direct UWB imaging radars have shown promising abilities in biomedical applications, though in order to achieve high-resolution images, UWB SAR would be necessary. The conventional synthetic aperture radar (SAR) is a form of radar whose aperture is synthesised on account of the movement of the sensor causing a large aperture size. Due to the large virtual aperture enhanced by SAR, the resolution of the image is greatly enhanced. Figure 2-16(a) illustrates a physical interpretation of SAR and its relative imaging plane by taking a top view of the sensors. Bistatic radar emits and receives backscattered signals from the target sequentially during movement and the features of the target would be further generated in terms of a spatial–time plot $B(X,n)$ in which $X$ denotes the spatial position and $n$ denotes discrete time. Due to the wide beamwidth of each antenna sensor, the reflected signals from the target will be received not only when the antenna is exactly over the target but also at other possible locations, causing a point like target behaving in a hyperbola shape in a spatial-time plot, as illustrated in Figure 2-16(b). UWB SAR has the same properties as conventional SAR except that the transmitted signal will use a wider bandwidth to achieve a higher precision. Several SAR imaging approaches have been given in the literature including geometrical migration, Kirchhoff migration and f-k migration [Ber81] [Yil87].

Figure 2-16: Illustration of (a) physical model of SAR and (b) spatial–time plot
(a point target represented in hyperbola in B-scan)

Geometric migration is a time-of-arrival (TOA) based imaging method. Suppose the locations of the transmitter $(X_n,Z_n)$, receiver $(X_r,Z_r)$ and target $(X_T,Z_T)$ are known. The TOA can be given:

$$\text{TOA} = \sqrt{(X_n - X_T)^2 + (Z_n - Z_T)^2} + \sqrt{(X_r - X_T)^2 + (Z_r - Z_T)^2}$$

(2.15)
where \( v \) is the wave propagation speed. The received spatial–time signal \( B_p(X, k) \) can then be used to reconstruct the image. One pixel \( I(X_T, Z_T) \) or migrated image can be expressed as:

\[
I(X_T, Z_T) = \frac{1}{N} \sum_{n=1}^{N} B_p(X, k = \text{TOA}_n)
\]  

(2.16)

where \( N \) is the number of antenna positions during SAR scanning, and \( B_p(X, k = \text{TOA}_n) \) represents the magnitudes of all the points for the target position \( (X_T, Z_T) \) and antenna positions where the TOA is constant.

The Kirchhoff migration imaging algorithm is based on solving the scalar wave equation where the detailed amplitude and phase of the wavefront are computed. The method is mathematically complex with detailed analysis provided in [Yil87] [Mar01]. The f-k migration provides another view to solve the wave equation based migration. The migration can be accomplished in the frequency domain with significant complexity reduction; however, the resolution does not enhance significantly [Sto78].

### 2.3.2 Non-Imaging UWB Radar

UWB imaging radar, as reviewed in the previous section, provides a straightforward view of targets under detection. Alternatively, UWB radar can be used to detect unknown targets based on parameters from the aspect of resonant frequency, polarisation and so on. In comparison to imaging radar, the parametric-based UWB radar systems are simpler and low cost with acceptable accuracy. Two popular methods have been widely applied in parametric UWB radar including the resonant method and polarisation method described in the following sections.

#### 2.3.2.1 Resonant Method

When an incident wave hits an object, part of the wave will reflect back and the rest will reflect inside the object in all possible directions. The interval during which the first reflection occurs is known as the early time response. As for the remaining incident field passing through the object, it will cause induced current through the body of the object, also known as creeping wave and shown in Figure 2-17. When the frequency coincides with the period of oscillation of induced current, a strong resonance will occur [Che97]. The frequency response of the perfect electric conductor (PEC) sphere with a radius of 15 cm illuminated by a UWB pulse (covering from 0 to 2 GHz) is plotted in Figure 2-18. Strong resonances can be observed at 0.34 GHz, 0.75 GHz, 1.1 GHz, 1.45 GHz and 1.8 GHz and suffer damping due to radiation of the creeping wave. The interval during which the resonant phenomenon occurs is called the late time response (LTR).
Therefore, the late time response contains significant information on target size. The PEC aircraft A-10 model in the scale of 1:100 was illuminated by a horn antenna from 0.5 GHz to 6 GHz [Bau91] with the measurement schematic given in Figure 2-19(a). The extracted impulse response revealing the start of the late time is given in Figure 2-19(b). It can be seen that the late time response consists of several waves at different frequencies contributing to the natural resonant frequencies. Additionally, the LTR decays as time elapses owing to the damping factor. The target can then be classified in terms of natural resonant frequencies and damping factor.

![Diagram of illumination of a sphere](image1)

**Figure 2-17: Illustration of illumination of a sphere**

![Graph of probe frequency response](image2)

**Figure 2-18: Probe frequency response of a perfect electric conductor sphere**
Figure 2-19: (a) Measurement schematic and (b) impulse response of an A-10 aircraft model [Bau91]

2.3.2.2 Polarisation Method

Target information can not only be described in terms of complex resonant poles, as mentioned in the previous section, but can also be investigated in terms of radar polarimetry. The basic principle of radar polarimetry is based on the concept of characteristic polarisation states (CPSs) first introduced by Kennaugh [Ken54], who demonstrated that there exist radar polarisation states for which the radar receives maximum/minimum power for both co-polarisation and cross-polarisation channels. The CPSs set reveals the symmetry and orientation information of the proposed target and the ability to depolarise the fully polarised wave illumination. Polarisation-based radar target detection is initially exploited in the narrowband system in which the degree of polarisation is close to unity [Boe91]. However, polarisation approaches have not been fully exploited in the context of the UWB scenario as the polarisation of targets will vary in accordance with frequency, and therefore spectrally non-uniform depolarisation occurs [Ald091]. CPSs incorporated with complex natural poles have shown the potential to overcome the problem and are proposed to achieve a better target discrimination ability in the field of impulse UWB. Three parameters in association with CPSs are evaluated, which are characteristic angle $\phi$, tilt angle $\theta$ and ellipticity $\chi$, which will be discussed in the next chapter. Through investigation of the CPSs corresponding to different orders of poles, three thin metal wires (Figure 2-20) with different bend angles have been discriminated [Ald09]. With the help of classification algorithm k-nearest neighbours (k-NN) and CPSs, Faisal further shows the ability to discriminate a metal ellipsoid and cylinder of which the cross sections are almost the same (Figure 2-21) [Ald10] [Ald091].
2.4 Material Characterisation

It is known that materials can be classified in terms of their electrical properties, most notably their unique dielectric properties. The dielectric properties, $\varepsilon$, consist of two parts, which are dielectric constant $\varepsilon'$ and dielectric loss factor $\varepsilon''$. The former parameter is a degree of how material can store microwave energy and the latter describes how microwave energy can be dissipated into heat. For lossless materials, only the dielectric constant exists. The mathematical expression for the permittivity of lossy material can be formulated as:

$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) = \varepsilon_0 \varepsilon_r(\omega)$$

(2.17)
where \( \varepsilon_0 \) denotes free space permittivity with a value of \( 8.854 \times 10^{-12} \text{F/m} \) and \( \varepsilon_r \) is the dielectric constant as a complex number expressed as:

\[
\varepsilon_r(\omega) = \varepsilon_r^\prime(\omega) - j\varepsilon_r^\prime\prime(\omega)
\]  \hspace{1cm} (2.18)

where \( \varepsilon_r^\prime \) and \( \varepsilon_r^\prime\prime \) are therefore the real and imaginary part of the dielectric constant, respectively.

If the material has conductivity \( \sigma \), ohmic loss will be taken into account and equation (2.18) will become:

\[
\varepsilon_r(\omega) = \varepsilon_r^\prime(\omega) - j\left( \varepsilon_r^\prime(\omega) + \frac{\sigma(\omega)}{\omega} \right) = \varepsilon_r^\prime(\omega)\left(1 - j\tan\delta(\omega)\right)
\]  \hspace{1cm} (2.19)

where \( \tan\delta \) is the loss tangent.

Knowledge of the permittivity of a bulk material is the key challenge for material classification. Generally, the techniques fall into two methods, namely resonant methods and non-resonant methods [Ong04]. The resonant method has the advantage of better accuracy and sensitivity over the non-resonant method. However, most permittivity extraction methods apply to the non-resonant technique due to its relatively simple construction, as cavities used in the resonant approach are not required for acceptable accuracy, and it gives a broad frequency range with less setup [Has092]. The non-resonant method is based on the transmission and reflection coefficient from materials. Figure 2·22 illustrates a wave incident on a boundary between two materials in which both characteristic wave impedance and wave velocity change causing reflection and transmission of the EM wave. In terms of wave propagation properties between materials, two main methods for the non-resonant method have been developed, which are the reflection method and the transmission/reflection method [Jam92] [Nic70] [Wei74] [Bak90] [Wil03] [Boi99] [Has09] [Has08] [Has091]. EM waves can be sent to materials in several ways, including a coaxial line, hollow metal waveguides, dielectric waveguides and free space.
In the case of free space, the wave would reflect, transmit and diffract due to the material under test (MUT). A typical reflection-based short-circuit permittivity extraction diagram is depicted in Figure 2-23(a). A metal plane is placed behind the sample to form a short. An equivalent transmission line model of reflection based short-circuit permittivity extraction approach is plotted in Figure 2-23(b) in which $Z_0$ represents electromagnetic impedance of free space, which is $377 \, \Omega$ while $Z_1$ and $Z_{metal}$ are that of the unknown sample and a metal plane, respectively. The electromagnetic impedance of metal is:

$$Z_{metal} = \sqrt{\frac{j\omega\mu}{\sigma + j\omega \varepsilon}} \approx 0 \quad \text{as} \quad \sigma >> j\omega \mu$$

(2.20)
The input impedance $Z_{in}$ as illustrated in Figure 2-23 (b) can be written as:

$$Z_{in} = Z_i \frac{Z_{metal} + jZ_i \tan(\beta d)}{Z_i + jZ_{metal} \tan(\beta d)} = jZ_i \tan(\beta d)$$  \hspace{1cm} (2.21)

The complex reflectivity $R$ at the interface is given by:

$$R = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} = \frac{jZ_i \tan(\beta d) - Z_0}{jZ_i \tan(\beta d) + Z_0} = \frac{jZ_i \tan(\beta d) - 1}{jZ_i \tan(\beta d) + 1}$$  \hspace{1cm} (2.22)

where $z_i$ is characteristic impedance of the sample normalised to the free space impedance given by:

$$z_i = \frac{1}{\sqrt{\varepsilon_r}}$$  \hspace{1cm} (2.23)

and phase constant $\beta$ is given by:

$$\beta = \frac{2\pi}{\lambda_0 \sqrt{\varepsilon_r}}$$  \hspace{1cm} (2.24)

where $\lambda_0$ is the free space wavelength. The complex dielectric constant can be extracted in terms of complex reflectivity $S_{11}$.

![Illustration of transmission/reflection method](image)
The transmission/reflection method not only concentrates on reflection of the MUT but transmissions are also taken into account. It provides better performance than that of reflection as the effect of surface roughness at high frequencies is reduced [Buy06] [Has07] [Has092] and can give overall performance spanning a large frequency range. A schematic diagram of material characterisation in terms of the transmission/reflection method is plotted in Figure 2-24. A linear polarised, uniform plane wave is normally incident on the sample resulting in reflection and transmission coefficients $R$ and $T$. According to [Gho89], $R$ and $T$ can be expressed based on reflection coefficient $R_b$ and transmission coefficient $T_b$ at the sample boundary:

\[ R = \frac{R_b(1-T_b^2)}{1-R_b^2T_b^2} \]  \hspace{1cm} (2.25)

\[ T = \frac{T_b(1-R_b^2)}{1-R_b^2T_b^2} \]  \hspace{1cm} (2.26)

where reflection coefficient $R_b$ at the boundary is given by:

\[ R_b = \frac{z_s-1}{z_s+1} \]  \hspace{1cm} (2.27)

and transmission coefficient $T_b$ at the boundary is:

\[ T_b = e^{-\gamma d} \]  \hspace{1cm} (2.28)

where $z_s$ is normalised sample impedance:

\[ z_s = \sqrt{\frac{\mu_r}{\varepsilon_r}} \]  \hspace{1cm} (2.29)

and $\gamma$ is the propagation constant of the sample:

\[ \gamma = \alpha + j\beta = \gamma_0 \sqrt{\varepsilon_r \mu_r} = \frac{j2\pi}{\lambda_0} \sqrt{\varepsilon_r \mu_r} \]  \hspace{1cm} (2.30)

where $\alpha$ denotes the attenuation constant as a degree of how signals are attenuated through the material, $\beta$ denotes the phase constant determining the phase shifts through a material and $\gamma_0$
represents the propagation constant in free space. The reflection and transmission coefficient at the boundary $R_b$ and $T_b$ can be rewritten as follows:

$$R_b = k \pm \sqrt{k^2 - 1}$$  \hspace{1cm} (2.31)

$$T_b = \frac{R + T - R_b}{1 - (R + T)R_b}$$  \hspace{1cm} (2.32)

with:

$$k = \frac{R^2 - T^2 + 1}{2R}$$  \hspace{1cm} (2.33)

The plus or minus sign in Equation (2.31) is chosen based on $|R_b| < 1$.

The propagation constant $\gamma$ can be written as:

$$\gamma = -\frac{\ln(T_b)}{d}$$  \hspace{1cm} (2.34)

From Equation (2.32) and (2.34), permittivity $\varepsilon_r$ and permeability $\mu_r$ can be expressed as:

$$\varepsilon_r = \frac{\gamma}{\gamma_0} \left(\frac{1 - R_b}{1 + R_b}\right)$$  \hspace{1cm} (2.35)

$$\mu_r = \frac{\gamma}{\gamma_0} \left(\frac{1 + R_b}{1 - R_b}\right)$$  \hspace{1cm} (2.36)

As transmission coefficient $T_b$ is a complex value, a unique solution can be found in the case of the thickness of the sample being less than a wavelength in the sample. For thickness larger than a wavelength in the sample, permittivity and permeability can be resolved by measurement of samples with the same material but different thickness.

Permittivity characterisation in the UWB band is a challenge in terms of traditional methods as the frequency span is relatively large. Zhang has shown the non-destructive and broadband ability to determine the permittivity in radiated measurements [Zha01]. Two types of material polymer PE500 and Tufnol were illuminated in a monostatic scenario such that permittivity was retrieved by finding the mean square error (MSE) of the measured reflection coefficient and the predicted
value obtained from a forward scattering model in which the reflection coefficient of a layered medium was derived from a transmission line model. The dielectric constant of a wall property at the UWB band has been investigated by Muquibel [Muq032] [Muq033] [Muq031] in which transmission radiated measurement was carried out to resolve the complex permittivity. Two measurement campaigns with normal plane wave illumination were undertaken: one was S-parameter measurement without samples as references and another with samples (Figure 2-25). The relationship between transmitted signal and incident signal for free space is given by [Muq031]:

\[ \frac{E_t(f)}{E_i(f)} = e^{-j\omega d} = e^{-j\omega d/c} \]  

(2.37)

where \( c \) is the speed of light. The insertion transfer function is defined as [Muq031]:

\[ H(f) = \frac{E_t(f)}{E_i(f)} = |H(f)|\exp^{j\phi_H(f)} \]  

(2.38)

Figure 2-25: Illustration of transmission radiated measurement for wall property extraction: (a) free case and (b) real wall case
Thus scattering parameter $S_{21}$ can be expressed in terms of insertion transfer function [Muq031]:

$$S_{21}(f) = \frac{E_2(f)}{E_1(f)} = H(f)e^{-j\omega f c}$$ (2.39)

In the case of the single pass scenario where the pulse is short compared with the transmit time through the material, multiple reflections inside the material are eliminated. The relationship between insertion transfer function and dielectric constant can be obtained as [Muq031]:

$$H(f) = \frac{4\sqrt{\varepsilon_r}}{(1 + \sqrt{\varepsilon_r})^2} e^{-j\omega(\sqrt{\varepsilon_r} - 1) f c}$$ (2.40)

The dielectric property for low loss material can then be solved based on equation (2.37) [Muq031].

$$\varepsilon_r \approx 1 - \frac{c}{2 \pi d} \frac{d\Phi_H(f)}{df}$$ (2.41)

$$\varepsilon_r = -\frac{c\sqrt{\varepsilon_r}}{\pi fd} \ln \left[ \frac{(1 + \sqrt{\varepsilon_r})^2 |H(f)|}{4\sqrt{\varepsilon_r}} \right]$$ (2.42)

When a single pass scenario is not satisfied, multiple passes occur as the incident wave would bounce inside the sample leading to a more complex situation. The insertion transfer function of the multiple pass scenario is given as [Muq031]:

$$H(f) = \frac{4e^{j\beta_0 d}}{e^{j\pi \sqrt{\mu_r \rho_d} \varepsilon_r} (2 + \sqrt{\varepsilon_r} + \frac{1}{\sqrt{\varepsilon_r}}) + e^{-j\pi \sqrt{\mu_r \rho_d} \varepsilon_r} (2 - \sqrt{\varepsilon_r} - \frac{1}{\sqrt{\varepsilon_r}})}$$ (2.43)

The exact solution of the dielectric properties can be obtained in terms of a two dimensional search algorithm. The dielectric properties can be retrieved with reasonable accuracy under the assumption of a low loss material, where [Muq031]:

$$\tan[\beta_0 d - \Phi_H(f)] + \frac{1 + QX}{1 - QX} \tan(\beta_0 d \sqrt{\varepsilon_r}) = 0$$ (2.44)
Chapter 2. Background of UWB and Its Applications

with:

\[ Q = - \left( \frac{\sqrt{\varepsilon_r} - 1}{\sqrt{\varepsilon_r} + 1} \right)^2 \]  
(2.45)

\[ X = \sqrt{\cos(2\beta_0d)(\varepsilon_r - 1)^2 + 8 \frac{\varepsilon_r'}{|H(f)|^2}} - \frac{\left( \sqrt{\varepsilon_r} - 1 \right)^4}{(\sqrt{\varepsilon_r} - 1)^4} \]  
(2.46)

and imaginary part of dielectric property is:

\[ \varepsilon_r'' = -\frac{c\sqrt{\varepsilon_r}}{\omega d} \ln(X) \]  
(2.47)

The dielectric properties of a material can be well resolved in a non-destructive and contactless way as described above. However, no matter whether the reflection method or transmission/reflection method is used, it is necessary to ensure the sample is placed in the far field region defined in equation (2.12). In application for small objects and constrained environments, these criteria to resolve dielectric properties of material will obviously not be met. Therefore, the possibility to determine material properties in terms of correlation coefficient in the near field region are desirable, which is described in later chapters.

2.5 Near Field UWB

As detailed in the previous section, UWB research has been widely investigated in the far field in terms of communication systems and radars as the field decays slowly alongside with the distance from the antenna. As opposed to well-developed far field UWB applications, near field UWB is relatively more recent and so both the theory and applications have not been exploited fully. There are two kinds of near field regions determined by the radiation mechanism. In the region that is in close proximity to the emitter, the electric and magnetic field do not propagate together as EM waves [Ram65] according to Poynting Theorem [Kra73]. The energy is not radiated away but instead it couples across capacitive or inductively; therefore the region is so-called reactive near field. The region between the reactive near field and far field is radiated near field in which
Chapter 2. Background of UWB and Its Applications

the EM radiation fields predominate and the shape of radiation pattern varies appreciably with distance [Bal05]. These two near field regions can be determined by the distance away from the antennas, as shown in Figure 2-26. The inner layer is the reactive near field region at a distance of \( r_i < 0.62 \sqrt{D^3/\lambda} \) and the outer layer is the radiating near field region between the reactive near field region and far field region \((0.62 \sqrt{D^3/\lambda} < r_i < 2D^2/\lambda)\).

![Figure 2-26: Field regions of an antenna](image)

Extensive studies have been carried out in near field UWB, especially for imaging applications [Yan09] [Yar07]. However, almost all of these studies are based on the radiating near field region. Yang has reported the detection of a metal ball with a radius of 1 cm positioned 1 m away from the sensor array [Yan09]. In the measurement campaign, eight patch antennas as receivers as well as one ridged horn antenna as the transmitter moved along the array and located at one of four points: -120 mm, -40 mm, 40 mm and 120 mm forming a synthesised-aperture radar with an aperture size of 240 mm (Figure 2-27) with an operation frequency of 10–18 GHz, which is between the reactive near field region and the far field region. Imaging of the metal ball was reconstructed to validate the possibility to sense in the radiated near field. Detection of metal mines as an application of GPR was also studied in the radiated near field such that the metal mines placed 47 cm away from the transmitter could be detected, which used a dielectric wedge antenna [Yar02] with aperture size of 22.62 cm at the operation frequency of 0.5–3 GHz.

In light of other research in the literature, few applications are deployed in the UWB reactive near field since communication links or radar are not concerned with EM wave transmission in the far field, but rather concerned with coupling between two devices, such as in near field communication (NFC) [Agb11].
Chapter 2. Background of UWB and Its Applications

2.6 Summary

In this chapter, an overview of UWB has been presented. Emphasis has been placed on the UWB radar in which imaging and parametric methods are reviewed. The imaging approach has a better ability to know the size and shape of an unknown target directly than the parametric approach, which is indirect and low cost. Material characterisation in the UWB band has also been reviewed, however, it is found that contactless permittivity extraction is limited to the far field and large areas. Finally, a review of UWB technology in the near field is presented. Compared with parametric methods, which are only suitable for the far field case, information of unknown targets such as metal mines could still be plotted through appropriate imaging algorithms in the radiating near field.

The signature of targets can be understood under illumination in the radiated near field and far field region. However, the main limitation that arose in these two regions is the factor of distance between the sensor and the target, causing difficulties in sensing targets when the measurement space is constrained. This therefore leads to the view from the detection in the far field or radiated near field detection to the reactive near field. It is clear that there are opportunities to consider the use of UWB for detection in the reactive near field, whereby the scenario is no longer a radar but the impulse response from the antenna is significantly filtered by objects placed close to the sensors. There will likewise be an impact on coupling between two sensors. Further chapters will investigate the possibility of using UWB radar to detect the quantity of bulk materials first in the far field then consequently concentrate on the reactive near field using the detection of eggs in a smart fridge scenario as the main test platform.
Chapter 3

3 Far Field Parametric Egg Quantity Detection

In the previous Chapter, the theory and background of low-cost parametric-based target detection was introduced. In this Chapter, the study of egg quantity detection positioned in the far field is presented first. Using this test scenario case, the methodology involving resonant and polarisation based ultra wideband (UWB) radar is evaluated. Following this, the late time response of a conducting sphere was studied to verify the validity of resonant based approach for this application. Three different targets were investigated, where they were extended to determine the egg quantity. The polarisation approach was implemented as a conventional resonant method, which failed to determine the number of eggs thus leading to the use of the characteristic angle approach. The constraints of this approach are discussed.

3.1 Case study of Egg Quantity Detection

Intelligent fridges (iFridge), as an application of the Internet of Things (IoT) in the home have drawn significant attention in recent years. Early stage intelligent fridges have been developed and manufactured by a large number of companies [Luo09]. The features of the iFridge include monitoring fresh food, ordering food online, as well as providing user interfaces using an embedded touch screen that connects to the Internet [Xie13]. At present, the content-awareness function for iFridge mainly relies on a radio frequency identification (RFID) system where each food or drink container has an RFID tag attached containing information such as production and expiration dates and quantity [Xie13] [GuH09] [Dar08] [Din07] [Che07]. As a complement to the iFridge, a company called Quirky has recently designed an egg minder gadget to remind users how many eggs remain in their smart fridge\(^2\). Though RFID systems and egg minders do provide a solution to content awareness, they come with limitations. For an egg minder to be simple and effective in its function, it requires the user to remove the eggs from the egg box and place them into the device, possibly losing information about the expiration date. It may also be more convenient to simply place an egg box in a smart fridge, whereby an additional technology to

\(^2\) http://www.quirky.com/shop/619
RFID is required to determine the remaining number of eggs. The same is similarly true for bottles or cartons of a drink, particularly milk, where it is useful to determine what quantity remains. UWB technology is a useful low-cost non-intrusive means to support these requirements whereby eggs will be evaluated as a radar target in this instance.

3.2 Evaluation of resonant based UWB radar

The background of resonant-based UWB target detection in terms of late time response (LTR) has been presented in Section 2.3.2.1. The extraction of complex natural poles consisting of a damping factor and a natural frequency from the LTR is an important role for target recognition in a resonant method. The development of the singularity expansion method (SEM), which was first reported by Baum in 1971 [Bau71], provides a convenient method to describe LTR by defining complex natural poles and their associated amplitude. There are two main techniques, which are Prony's method [Van75] and the Generalised Pencil of Function (GPOF) method [Hua89] [Sar95]. Prony's method is a polynomial method based on finding poles in a step process. The success of Prony's method depends on the prior knowledge of the exact number of poles contained in the transient data which is usually unknown. Underestimating the number of poles will result in errors, while overestimating the model will generate both correct poles and spurious poles. A matrix equation should be solved in order to obtain the complex natural poles. This could lead to problems such as the matrix being unsolvable due to the non-invertible matrix as well as high variance, which may be caused between the original signal and the reconstructed signal while also causing distortion in the presence of a low signal-to-noise ratio (SNR) [Hua89]. Compared with Prony's method, the GPOF is more efficient at analysing waveforms since it is a one-step process. The poles can be calculated through solving the eigenvalue problem. Therefore there are no practical limitations in determining the number of poles. Methodologies related to Prony's method and the GPOF method are given in the following sections.

3.2.1 Conventional Prony Method

Consider a time domain waveform \( f(t) \), which can be expressed as [Van75]:

\[
 f(t - t_0) = \sum_{m=1}^{N} c_m e^{s_m(t - t_0)}
\]

where \( s_m = \sigma_m + j\omega_m \) is poles in a complex plane; \( \sigma_m \), \( \omega_m \) and \( c_m \) are damping factors, resonant frequencies and complex amplitudes, respectively, associated with the \( m \)th complex natural resonant (CNR) mode, \( N \) is the maximum order number of the CNR modes. Note that, in the
general case, the LTR trends to attenuation and the damping factor should be negative, while those with positive values are meaningless. By expressing equation (3.1) in discrete form, the following is derived [Van75]:

\[ f((n-1)\Delta t) = \sum_{m=1}^{N} c_{m} e^{s_{n}(n-1)\Delta t} \quad n = 1, 2, 3 ... L \]  

(3.2)

where \( \Delta t \) is sampling time interval obeying the Nyquist criteria, \( N \) is the total number of CNRs and \( L = 2N \) is the number of data points. Equation (3.2) can be rewritten as [Van75]:

\[ f_{n} = f((n-1)\Delta t) = \sum_{m=1}^{N} c_{m} z_{m}^{n-1} \quad n = 1, 2, 3 ... L \]  

(3.3)

The above complicated nonlinear optimisation problem was solved by Prony by realising that \( f_{n} \) also satisfies the following autoregressive difference equation [Van75]:

\[ f_{n} = -\sum_{m=1}^{N} a_{m} f_{n-m} \quad N + 1 \leq n \leq 2N \]  

(3.4)

where the coefficient \( a_{m} \) can be solved by using \( 2N \) data points \( f_{1}, f_{2}, \ldots, f_{2N} \) and the following matrix equation \( Fa = f \), i.e. [Van75]:

\[
\begin{bmatrix}
  f_{N} & f_{N-1} & \cdots & f_{1} \\
  f_{N+1} & f_{N} & \cdots & f_{2} \\
  \cdots & \cdots & \cdots & \cdots \\
  f_{2N-1} & f_{2N-2} & \cdots & f_{N}
\end{bmatrix}
\begin{bmatrix}
  a_{1} \\
  a_{2} \\
  \vdots \\
  a_{N}
\end{bmatrix}
= 
\begin{bmatrix}
  f_{N+1} \\
  f_{N+2} \\
  \vdots \\
  f_{2N}
\end{bmatrix}
\]

(3.5)

Applying a complex Z transform to the above difference equation, it is easy to show that the coefficients \( a_{m} \) are also the coefficients of the following \( N^{th} \) order characteristic polynomial [Van75]:

\[ 1 + a_{1}z^{-1} + a_{2}z^{-2} + \ldots + a_{N}z^{-N} = 0 \]  

(3.6)
Then the complex natural poles can be determined by solving the above equation, namely [Van75]:

$$z_m = e^{s_m \Delta t}$$  \hfill (3.7)

The complex residues in association with natural poles can be determined by solving \( \mathbf{Zc} = \mathbf{f} \), i.e. [Van75]:

$$
\begin{align*}
\begin{bmatrix}
1 & 1 & \ldots & 1 \\
z_1 & z_2 & \ldots & z_N \\
\vdots & \vdots & \ddots & \vdots \\
z_1^{N-1} & z_2^{N-1} & \ldots & z_N^{N-1}
\end{bmatrix}
\begin{bmatrix}
c_1 \\
c_2 \\
\vdots \\
c_N
\end{bmatrix}
= 
\begin{bmatrix}
f_1 \\
f_2 \\
\vdots \\
f_N
\end{bmatrix}
\end{align*}
$$

(3.8)

The above three steps to find complex natural poles are known as the Prony method.

### 3.2.2 Generalised Pencil of function Method (GPOF)/Matrix Pencil Method (MPM)

Different from Prony’s Method introduced above, the GPOF method or the MPM can be used to find CNRs in terms of solving the eigenvalue and the eigenvector instead of solving polynomial equations [Hua89]. As it is known, the LTR can be written as [Hua89]:

$$y(t) = \sum_{i=1}^{M} R_i e^{s_i t}$$  \hfill (3.9)

where \( R_i \) is the complex residues and \( M \) is the maximum number of CNRs.

The discrete form is [Hua89]:

$$y(kT_s) = \sum_{i=1}^{M} R_i z_i^k \quad k = 1, 2, 3 \ldots N$$  \hfill (3.10)
Subsequently, two matrices are defined as follows [Hua89]:

\[
Y_1 = \begin{bmatrix}
y(0) & y(1) & \ldots & y(L-1) \\
y(1) & y(2) & \ldots & y(L) \\
\vdots & \vdots & \ddots & \vdots \\
y(N-L-1) & y(N-L) & \ldots & y(N-2)
\end{bmatrix}
\]  \hspace{1cm} (3.11)

and

\[
Y_2 = \begin{bmatrix}
y(1) & y(2) & \ldots & y(L) \\
y(2) & y(3) & \ldots & y(L+1) \\
\vdots & \vdots & \ddots & \vdots \\
y(N-L) & y(N-L+1) & \ldots & y(N-1)
\end{bmatrix}
\]  \hspace{1cm} (3.12)

where \( L \) is the pencil parameter and usually ranges from \( N/3 \) to \( N/2 \) in order to obtain satisfactory performance over noise. For these values of \( L \), the variance in the parameters \( z_i \) due to noise have been found to be a minimum [Sar95]. Further decomposition is carried out on \( Y_1 \) and \( Y_2 \) where [Hua89]:

\[
Y_1 = Z_1 R Z_2
\]  \hspace{1cm} (3.13)

\[
Y_2 = Z_1 R Z_0 Z_2
\]  \hspace{1cm} (3.14)

where [Hua89]:

\[
Z_1 = \begin{bmatrix}
1 & 1 & \ldots & 1 \\
z_1 & z_2 & \ldots & z_M \\
\vdots & \vdots & \ddots & \vdots \\
z_1^{N-L-1} & z_2^{N-L-1} & \ldots & z_M^{N-L-1}
\end{bmatrix}_{(N-L)xM}
\]  \hspace{1cm} (3.15)

\[
Z_2 = \begin{bmatrix}
1 & z_1 & \ldots & z_1^{L-1} \\
1 & z_2 & \ldots & z_2^{L-1} \\
\vdots & \vdots & \ddots & \vdots \\
1 & z_M & \ldots & z_M^{L-1}
\end{bmatrix}_{MxL}
\]  \hspace{1cm} (3.16)
where \( \text{diag}[] \) represents a \( M \times M \) diagonal matrix. Based on the above decomposition of \( Y_1 \) and \( Y_2 \), one can show that if \( M \leq L \leq N - M \), the poles \( z_i \) are generalised eigenvalues of matrix \( Y_2 - zY_1 \). This means that if \( M \leq L \leq N - M \), \( z = z_i \) is a rank reducing number of \( Y_2 - zY_1 \). To develop and illustrate the use of an algorithm for computing the generalised eigenvalues of the Matrix Pencil problem, it can be written as [Hua89]:

\[
Y_1^+Y_2 = Z_2^+R^{-1}Z_1RZ_0Z_2 = Z_2^+Z_0Z_2
\]

where the superscript \( ^+ \) denotes the (Moore-Penrose) pseudo-inverse, whereas \( ^-1 \) is used for the regular inverse. It can be seen from (3.19) that there exist vectors \( p_i \) (for \( i = 1, 2, \ldots, M \)) such that [Hua89]:

\[
Y_1^+Y_1p_i = p_i
\]

and

\[
Y_1^+Y_2p_i = z_ip_i
\]

where \( p_i \) are called generalised eigenvectors of \( Y_2 - zY_1 \). In order to compute the pseudo-inverse \( Y_1^+ \), one can use the singular value decomposition (SVD) of \( Y_1 \) as follows [Hua89]:

\[
Y_1 = UDV^H
\]

\[
Y_1^+ = VD^{-1}U^H
\]
where $U = \begin{bmatrix} u_1, u_2, \ldots, u_M \end{bmatrix}$, $V = \begin{bmatrix} v_1, v_2, \ldots, v_M \end{bmatrix}$ and $D = \text{diag}[\sigma_1, \sigma_2, \ldots, \sigma_M]$. The superscript $^H$ denotes the conjugate transpose matrix. $U$ and $V$ are matrices of the left and right singular vectors, respectively. Note that for contaminated $Y_1$ data due to environmental noise in Equation (3.19), one should choose $\sigma_1, \sigma_2, \ldots, \sigma_M$ to be the $M$ largest singular values of $Y_1$.

The choice of the number of poles, $M$, can be estimated from singular values by looking at the ratio of the various singular values to the largest ones. Typically, the singular values beyond $M$ are set equal to zero as follows [Hua89]:

$$\sigma_{M+1} = \ldots = \sigma_{\min(M-L,L)} = 0$$  \hspace{1cm} (3.24)

The way $M$ is chosen is as follows. Consider the singular values $\sigma_c$ such that [Hua89]:

$$\frac{\sigma_c}{\sigma_{\max}} \approx 10^{-p}$$ \hspace{1cm} (3.25)

where $M$ is the number of significant decimal digits in the data. For example, if the data is accurate up to six significant digits, then singular values for which the ratio in (3.25) is below $10^{-6}$ are essentially noise singular values. Those noise singular values should not be used for computing data. Since $Y_1^* Y_1 = VV^H$ and $V^H V = I$, then substituting (3.23) into (3.21) and left multiplying (3.21) by $V^H$ will yield the following equations [Hua89]:

$$(Z - Z_i I)z_i = 0$$ \hspace{1cm} (3.26)

where $i = 1, 2, \ldots, M$ and [Hua89]:

$$Z = D^{-1} U^H Y_2 V$$ \hspace{1cm} (3.27)

It is also noted that $z_i$ in (3.22) corresponds to the equation as follows [Hua89]:

$$z_i = V^H p_i$$ \hspace{1cm} (3.28)
Chapter 3: Far Field Parametric Egg Quantity Detection

Note that $Z$ is an $M \times M$ matrix, $Z_i$ and $z_i$ are the eigenvalues and eigenvectors of $Z$ respectively. The values of the poles, $s_i$ can then be extracted from the eigenvalues of $Z$ as follows [Hua89]:

$$s_i = \frac{\ln(z_i)}{T_s}$$

(3.29)

Note that (3.29) is the same as (3.7). Once $M$ and $z_i$ are known, the residues or complex amplitudes $R_i$ can be solved for from the following least squares problem [Hua89]:

$$
\begin{bmatrix}
  y(0) \\
  y(1) \\
  \vdots \\
  y(N-1)
\end{bmatrix}
= 
\begin{bmatrix}
  1 & 1 & \ldots & 1 \\
  z_1 & z_2 & \ldots & z_M \\
  \vdots & \vdots & \ddots & \vdots \\
  z_1^{N-1} & z_2^{N-1} & \ldots & z_M^{N-1}
\end{bmatrix}
\begin{bmatrix}
  R_1 \\
  R_2 \\
  \vdots \\
  R_N
\end{bmatrix}
\quad
(3.30)
$$

Figure 3-1 illustrates the flow chart of the CNRs and residues extraction in terms of GPOF/MPM for which the following target recognition will be applied.
3.3 Evaluation of Polarisation based UWB radar

As mentioned in Section 2.3.2.2, target detection by means of polarisation approach is used to find the characteristic polarisation states (CPSs) in which three kernel parameters are evaluated including characteristic angle \(\varphi\), tilt angle \(\theta\) and ellipticity angle \(\chi\). The background of wave polarisation is introduced firstly including the polarisation ellipse and Poincare sphere. The evaluation of characteristic polarisation states is then presented.

3.3.1 Polarisation ellipse and Poincare Sphere

In electromagnetic (EM) wave propagation, at a given position, the tips of the electric field vector traces a curve as time elapsed. The geometrical shape of the trace defines the polarisation of the waves. If the electric field vector at a point in space as a function of time always along a line, the field is said to linear polarisation. If the tip of electric field traces a circle, the field is said to be...
circular polarised and it traces an ellipse, the field is said to be elliptically polarised. In order to describe the trace of electric field of a single-frequency wave alongside the time, a polarisation ellipse is introduced. A time-varied plane wave travelling in the +z direction consists of two components and can be written as [Mot07]:

\[
\begin{align*}
\overrightarrow{E}_x &= E_{0x} \cos(\omega t - \beta z + \theta_x) e^{-\alpha z} \mathbf{a}_x \\
\overrightarrow{E}_y &= E_{0y} \cos(\omega t - \beta z + \theta_y) e^{-\alpha z} \mathbf{a}_y
\end{align*}
\]  (3.31)

\[
\overrightarrow{E}_z = E_{0z} \cos(\omega t - \beta z + \theta_z) e^{-\alpha z} \mathbf{a}_z
\]

where \(E_{0x}\) and \(E_{0y}\) are the amplitudes of electric field in the \(x\) and \(y\) directions. The relationship between two orthogonal electrical fields can be defined using the polarisation ratio \(P\) [Mot07]:

\[
P = \frac{E_{0x} \cos(\omega t - \beta z + \theta_x)}{E_{0y} \cos(\omega t - \beta z + \theta_y)}
\]  (3.33)

Then it can be deduced that [Mot07]:

\[
\frac{E_x^2}{|E_{0x}|^2} - 2 \frac{E_x}{|E_{0x}|} \frac{E_y}{|E_{0y}|} \cos(\theta_y - \theta_x) + \frac{E_y^2}{|E_{0y}|^2} = \sin^2(\theta_y - \theta_x)
\]  (3.34)

This is, therefore, the equation of an ellipse whose major axis is tilted at angle \(\theta\) to the \(\overrightarrow{E}_x\) axis as given in Figure 3-2. With the variation of time at fixed position \(z\), the tip of the electric field vector traces the ellipse. Tilt angle is defined over the range \(-\pi/2 \leq \theta \leq \pi/2\) and the ellipticity angle is in the range of \(-\pi/4\) and \(\pi/4\). Alternatively, wave polarisation can be represented graphically. Consider the Stokes vector, which can be written in Equation (3.35) [Mot07]:

\[
g = \begin{bmatrix}
g_0 \\
g_1 \\
g_2 \\
g_3
\end{bmatrix} = \begin{bmatrix}
|E_{0x}|^2 + |E_{0y}|^2 \\
|E_{0x}|^2 - |E_{0y}|^2 \\
2|E_{0x}| |E_{0y}| \cos(\theta_y - \theta_x) \\
2|E_{0x}| |E_{0y}| \sin(\theta_y - \theta_x)
\end{bmatrix}
\]  (3.35)

where \(g_0\) can be seen as total instantaneous power, \(g_1\) denotes horizontal power minus vertical power, \(g_2\) denotes the difference between +45° linearly oriented power and -45° linearly oriented power.
power and \( g_3 \) represents the difference between left hand circular power and right hand circular power. The relationship between elements in the Stokes vector can be deduced from Equation (3.35) so that [Mot07]:

\[
g_0^2 = g_1^2 + g_2^2 + g_3^2 \tag{3.36}
\]

\[
g_1 = g_0 \cos(2\chi) \cos(2\theta) \tag{3.37}
\]

\[
g_2 = g_0 \cos(2\chi) \sin(2\theta) \tag{3.38}
\]

\[
g_3 = g_0 \sin(2\chi) \tag{3.39}
\]

According to Equations (3.36)–(3.39), the polarisation status of a wave can be drawn as a sphere in the basis of elements \( g_1, g_2 \) and \( g_3 \), known as a Poincare sphere illustrated in Figure 3-3.

*Figure 3-2: Illustration of a polarisation ellipse with a tilt angle \( \theta \)*
3.3.2 Evaluation of characteristic polarisation states

The received power can vary by means of the polarisation states of the transmitting and receiving antennas which are a degree of polarisation of radiated wave or received wave for transmitting and receiving antennas respectively. The optimisation problem is to find such polarisation states of the transmitted and received waves for a target of a known scattering matrix such that the voltage developed across the receiving antenna terminals is maximised, or is minimised to a null. These polarisation states thus obtained are so-called target characteristic polarisation states. In order to find the polarisation states for the optimum received power, it is necessary to define the equation for received voltage, $V_R$ [Ken54] [Kos86] [Boe91]:

$$V_R = h_R^T E_R$$

(3.40)

where $h_R$ is a complex effective "antenna height" of the receiver and can be expressed as two dimensional coordinates [Boe91]:

$$h_R = \begin{bmatrix} h_{Rx} \\ h_{Ry} \end{bmatrix}$$

(3.41)
and $E_R$ is the received scattered wave, which can be expressed as [Boe91]:

$$E_R = \begin{bmatrix} E_{Rx} \\ E_{Ry} \end{bmatrix}$$

(3.42)

It is worth noting that the effective “antenna height” is not a physical quantity, but it is defined as a polarisation state of the transmitted wave in the monostatic case in Cartesian coordinates. The received power can be written as [Boe91]:

$$P_R = |V_R|^2 = V_R^* V_R$$

(3.43)

A more general expression for power is given as [Boe91]:

$$P = g_{MP} g / \|g\|$$

(3.44)

where $g$ is the Stokes vector defined in Equation (3.35) and $M_p$ denotes the Stokes reflection Matrix. For a monostatic or quasi-monostatic case, where one antenna acts as both a transmitter and receiver, the received power in the co-polarisation and cross-polarisation channel can be derived as [Boe91]:

$$P_c = |h_T(x, y)^T S(x, y) E_T(x, y)|^2 = \frac{g_T(x, y)^T M_e(x, y) g_T(x, y)}{\|g_T(x, y)\|}$$

(3.45)

where $h_T(x, y)$ denotes the complex effective antenna height of the transmitter, $S(x, y)$ denotes the scattering matrix on the basis of two orthogonal polarisations $x$ and $y$, and $g_T(x, y)$ denotes the Stokes vector of the antenna on the basis of $x$ and $y$ polarisations. Furthermore [Boe91]:

$$M_e(x, y) = (A(x, y)^{-1})^T S(x, y) \otimes S(x, y)^* (A(x, y)^{-1})$$

(3.46)
where $A(x,y)$ is Kronecker expansion matrix [Boe91]:

$$A(x,y) = \begin{bmatrix} 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 0 & j & -j & 0 \end{bmatrix}$$

(3.47)

and

$$P_i = |h_T(x,y)\perp^T S(x,y)E_T(x,y)|^2 = \frac{g_T(x,y)^T M_x(x,y)g_T(x,y)}{\|g_T(x,y)\|}$$

(3.48)

where subscript $\perp$ denotes the orthogonal channel and [Boe91]:

$$M_x(x,y) = (A(x,y)^{-1})^T k [S(x,y) \otimes S(x,y)^T] (A(x,y)^{-1})$$

(3.49)

$$k = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

(3.50)

Expressions of received power for co-polarisation and cross-polarisation in terms of Stokes vectors were revealed above. The main idea behind characteristic polarisation states is to extrapolate the Stokes vectors in order to obtain the optimum received power. One possible way to find the optimum received power is to apply Lagrange multipliers. The constrained conditions in terms of normalised Stokes Variables ($g_1, g_2, g_3$) of the incident wave are [Boe91]:

$$\phi(g_1, g_2, g_3) = \sqrt{g_1^2 + g_2^2 + g_3^2} - 1 = 0$$

(3.51)

$$\frac{\partial P}{\partial g_n} - \mu \frac{\partial \phi(g_1, g_2, g_3)}{\partial g_n} n = 1, 2, 3$$

(3.52)
By solving Equation (3.52), two pairs of co-polarisation Stokes variables or CPSs are deduced consisting of a pair of orthogonal points with maximum co-polarisation power and a pair of non-orthogonal points with null power revealing information of target symmetry about the radar-target boresight line.

By solving Equation (3.53), three pairs of cross-polar CPSs are obtained, including a pair of orthogonal points with maximum cross polarisation power, a pair of orthogonal saddle points and a pair of orthogonal with null cross polarisation power. The co-polarisation power and cross-polarisation power can then be solved by substituting the values obtained from the above two equations.

The CPSs related to the co-polarisation channel can also be expressed in the form of polarisation ratio defined in Equation (3.33). The two CPSs contribute to the maximum co-polarisation power with the polarisation ratios $P_1$ and $P_2$, while $P_3$ and $P_4$ denote the other two CPSs for null co-polarisation power. For a reciprocal scattering matrix $S(x, y)$, the CPSs related to the co-polarisation channel corresponding to polarisation ratios $P_1$, $P_2$, $P_3$ and $P_4$ form an interesting pattern on a Poincare sphere, see Figure 3-4, which resembles a fork with a handle and three fingers, known as a Huynen fork [Mot07]. The target characteristic angle can then be determined by half the angle between $P_2$ and $P_3$ or $P_2$ and $P_4$ owing to the symmetry.

\[
\frac{\partial P_x}{\partial g_n} - \mu \frac{\partial \phi(g_1, g_2, g_3)}{\partial g_n} = 0 \quad n = 1, 2, 3
\]  

(3.53)

Figure 3-4: Illustration of the Huynen polarisation fork

The corresponding tilt angle $\theta$, ellipticity angle $\psi$ and target characteristic angle $\varphi$ can be expressed using Equations (3.54)–(3.56) [Mot07]. In addition, the target characteristic angle,
which is one unique characteristic angle, and several tilt and ellipticity angles related to different received powers can be implemented to discriminate targets.

\[ \chi = \frac{1}{2} \tan^{-1} \left( \frac{g_2}{g_1} \right) \]  

(3.54)

\[ \theta = \frac{1}{2} \sin^{-1} \left( \frac{g_3}{\sqrt{g_1^2 + g_2^2 + g_3^2}} \right) \quad n = 1, 2, 3 \]  

(3.55)

\[ \phi = \tan^{-1} \left( \frac{P_{c_{\text{max} 2}}}{P_{c_{\text{max} 1}}} \right) \quad n = 1, 2, 3 \]  

(3.56)

The process of evaluation of CPSs has been presented above; however, they are confined to single frequency treatment. In the UWB context, the CPSs can be evaluated at the target dominant frequencies reflecting the target shape robustly. The process of evaluation of CPSs in the context of UWB is given in Figure 3-5 in which the scattering matrix of the target in the dominant frequency is of great interest.

**Figure 3-5: Flow chart of evaluation of characteristic polarisation states in the context of Ultra Wideband (UWB)**
3.4 Study of target detection based on complex natural resonance

A case study to verify the validity of CNR was undertaken through simulation. The simulation scenario is based on a Finite-Difference Time-Domain (FDTD) simulation package CST Microwave studio, within which the scattering scenarios from case study can be solved using a transient solver. In this case study, three targets are under consideration. Figure 3-6 shows the proposed targets, which are a cube with an edge length of 100 mm, a sphere with a radius of 75 mm and a cuboid with a length of 150 mm, width of 100 mm and depth of 60 mm made from a perfect electric conductor (PEC). The simulation environment is presented in Table 3-1. In order to reduce the computation complexity as well as simulation time, a Gaussian pulse signal with a bandwidth of 2 GHz ranging from 0 to 2 GHz is used, as shown in Figure 3-7. The form of wave is a linearly polarised plane wave that propagates in the z-direction, electric field (E-field) is in the x-direction and magnetic field (H-field) is in the y-direction. An E-filed probe used to record the backscattered signal is placed in the far field. A complete CST model of the detection of a PEC sphere is presented in Figure 3-8 in which the distance between the plane wave source and the front edge of target is about a quarter wavelength (75 mm), which is 2000 mm from the target to the receiver probe. Prior to applying the poles extraction algorithm, it is necessary to determine the late time, which given by [Bau71]:

\[ T_{late} = T_b + 2T_{tr} + T_p \]  \hspace{1cm} (3.57)

where \( T_b \) is the sum of time with incident wave hitting the edge of target and of the time reflecting back to the probe; \( T_{tr} \) is maximum one-way transmit time through the target, and \( T_p \) stands for pulse width time.

Figure 3-6: CST model of three targets for far field detection
Table 3-1: Simulation environment for far field detection

<table>
<thead>
<tr>
<th>Solver</th>
<th>Transient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh Size</td>
<td>10 Cells per Wavelength</td>
</tr>
<tr>
<td>Excitation</td>
<td>Plane Wave</td>
</tr>
<tr>
<td>Frequency</td>
<td>0-2 GHz</td>
</tr>
</tbody>
</table>

Figure 3-7: Simulated pulse excitation signal for (a) time domain and (b) frequency domain

Figure 3-8: CST model example of perfect electrical conductor sphere in far field detection

For a cube, the late time defined in Equation (3.57) starts at:

\[
T_{cube} = T_p + 2T_{tr} + T_{p} = \frac{2075}{300} + 2 \times \frac{100}{300} + 1 = 8.58 \text{ns}
\]  
(3.58)

For a sphere, the late time starts at:

\[
T_{cuboid} = T_p + 2T_{tr} + T_{p} = \frac{2075}{300} + 2 \times \frac{60}{300} + 1 = 8.32 \text{ns}
\]  
(3.59)
For a cuboid, the late time starts at:

\[
T_{\text{cuboid}} = T_p + 2T_{tr} + T_p = \frac{2075}{300} + 2 \times \frac{60}{300} + 1 = 8.32 \text{ns}
\]  

(3.60)

The backscattered signal of a cube is illustrated in Figure 3-9 with the corresponding late time response shown in Figure 3-10. The late time response is truncated to 200 points, thus \(N = 200\). The pencil parameter \(L\) is between \(N/3\) to \(N/2\), so here, the number 70 is chosen. The significant decimal number \(p\) defined in Equation (3.25) is chosen as 3. By applying the Generalised Pencil of Function (GPOF) method, the late time response can be well reconstructed. Good agreement has been obtained as shown in Figure 3-6. The poles can also be extracted in the same manner. The plot of poles associated with three different targets is revealed in Figure 3-12 and Table 3-2.
There are two findings from Figure 3-12 and Table 3-2. The first one is that the poles appear as complex conjugate pairs which the imaginary parts are offset in rebuilding real time backscattered signal defined in Equation (3.9). The other finding is that targets with different shapes have different complex natural poles. It is possible to discriminate between targets in terms of the value of poles.
3.5 Egg quantity determination

In the case study, scenarios with different numbers of eggs in a egg carton capable of storing six eggs is studied (2 x 3 geometry). The egg used in the simulation is considered to be an ellipsoid consisting of ten material layers, with the maximum radius of 2 cm and height of 5 cm. The side view and top view of wireframe of the egg model used in CST is shown in Figure 3-13. As can be seen that, except for layer 1 and layer 10, the remaining eight layers consist of two circles having different radius along with fine curve at the edge.

Numerous measurements of dielectric properties of eggs have been reported in the literature considering the effect of storage time, temperature and moisture on the dielectric constant of the albumen, yolk and egg [Wan09] [ Guo07] [ Nel09]. Though conducted studies in previous research mainly focus on the frequency band in the range of 10 MHz and 1800 MHz, the value can still be estimated in terms of curves revealing the trend between permittivity and frequency. Approximate equations in association with the real and imaginary parts of the dielectric constant of a whole egg in terms of temperature at the four frequencies, namely 27 MHz, 40 MHz, 915 MHz and 1800 MHz, have been reported [Wan09]. The measured real and imaginary part of the dielectric constant of the liquid whole egg at 27 MHz, 40 MHz, 915 MHz and 1800 MHz are summarised in Table 3-3. Interpolation or extrapolation of the real and imaginary part of the dielectric constant can be curve fitted as shown in Figure 3-14 (a) and (b) respectively. The curve equation for the real and imaginary part of the dielectric constant can be expressed as follows:

\[
\varepsilon_r' = 97.633 f^{-0.071} \quad (3.61)
\]

\[
\varepsilon_r'' = 1684.2 f^{-0.687} \quad (3.62)
\]

where \(\varepsilon_r'\) denotes the real part of the dielectric constant while \(\varepsilon_r''\) represents the imaginary part of the dielectric constant and \(f\) is the interested frequency in MHz. Due to the lack of measured permittivity of eggs at UWB band, the permittivity can be estimated using curve fitting equations (3.61) and (3.62). Permittivity with a value of 54.1 and loss tangent of 0.105 are chosen as the simulation parameters which a good agreement is obtained between the estimated and simulated dielectric constant in Figure 3-15.
Chapter 3: Far Field Parametric Egg Quantity Detection

Figure 3-13: (a) Side view and (b) top view of wireframe of the egg model in CST simulation ($r_1 = 6.2$ mm, $r_2 = 11.7$ mm, $r_3 = 16.2$ mm, $r_4 = 19$ mm, $r_5 = 20$ mm, $r_6 = 19$ mm, $r_7 = 16$ mm, $r_8 = 11.7$ mm, $r_9 = 6.2$ mm, $H_1 = 1.5$ mm, $H_2 = 4.2$ mm, $H_3 = 6.6$ mm, $H_4 = 8.4$ mm, $H_5 = 9.3$ mm, $H_6 = 6.2$ mm, $H_7 = 5.5$ mm, $H_8 = 4.4$ mm, $H_9 = 2.8$ mm and $H_{10} = 1.1$ mm)

<table>
<thead>
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<th>Frequency (MHz)</th>
<th>$\varepsilon_r$</th>
<th>$\varepsilon_r'$</th>
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</thead>
<tbody>
<tr>
<td>27</td>
<td>79.31±2.8</td>
<td>197.7±12.9</td>
</tr>
<tr>
<td>40</td>
<td>72.65±1.6</td>
<td>139.1±8.5</td>
</tr>
<tr>
<td>915</td>
<td>61.25±1.9</td>
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</tr>
<tr>
<td>1800</td>
<td>56.62±1.1</td>
<td>12.28±1.3</td>
</tr>
</tbody>
</table>

Table 3-3: Measured dielectric constant of liquid whole egg [Wan09]
Figure 3-14: (a) Real and (b) imaginary part of dielectric constant of eggs [Wan09] (fixed marker points) and its curve fitting (dashed line)
Chapter 3: Far Field Parametric Egg Quantity Detection

Figure 3-15: (a) Real and (b) imaginary part of dielectric constant of egg - estimation (fixed marker points) and simulation used in CST (dashed line)

A plane wave source ranging from 0 to 2 GHz is placed 75 mm from the whole target and a probe is set 2000 mm away from the target to record the reflected signal. A detection prototype consisting of a single egg is plotted in Figure 3-16. It is worth nothing that the egg box is not included in the simulation as the egg box is made of thin clear plastic, which as a low dielectric has negligible effect in this case. All possible configurations for eggs with quantities ranging from
Chapter 3: Far Field Parametric Egg Quantity Detection

1 to 6 are illustrated in Figure 3-17 and their corresponding numerical representation is given in Table 3-4. The corresponding orientation of all six eggs case related to the plane wave is plotted in Figure 3-18 which E-field moves along the x-direction, H-field moves along the y-direction, wave propagates in the +z-direction and eggs are in parallel to the E-field. Figure 3-19 reveals the extracted complex natural poles of the single egg scenarios plotted in Figures 3-17 (a)–(c). The three orders from Figure 3-19 show stronger convergence or stability with the highest order, while it is weaker with lower order. The first order has a relatively larger damping factor and has been found on the left side of the poles. Significant differences can be observed for different layouts. The second orders are mainly laid in the middle part between the first and third order shown in Figure 3-19. However, they are much closer to each other compared to the first order and there is still a visible difference. Compared to the third order, the first and second orders have a corresponding large damping factor, which means a relatively short lifetime because it is inversely proportional to the damping factor. Thus, the first and second poles are not stable due to the short lifetime as they are expected to be overlapped with each other for only one egg case. The third order is highly stable compared with the other two orders and can be used for further implementation of egg quantity discrimination. The property can also extend to considering the other five different quantity scenarios, where the stable value of the poles floats around -0.01 ± 0.295j.

Figure 3-16: CST detection model of a single egg
Figure 3-17: All possible egg layouts
<table>
<thead>
<tr>
<th>Configuration</th>
<th>Diagram</th>
<th>Configuration</th>
<th>Diagram</th>
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<td>Figure 3-16 (a)</td>
<td>0 1 0</td>
<td>Figure 3-16 (b)</td>
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<tr>
<td>1 0 0</td>
<td>Figure 3-16 (c)</td>
<td>0 0 1</td>
<td>Figure 3-16 (d)</td>
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<td>1 0 0</td>
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<tr>
<td>0 0 1</td>
<td>Figure 3-16 (e)</td>
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<td>Figure 3-16 (f)</td>
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<td>Figure 3-16 (g)</td>
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<td>Figure 3-16 (h)</td>
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<td>1 0 0</td>
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<td>Figure 3-16 (j)</td>
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<td>1 0 1</td>
<td>Figure 3-16 (k)</td>
<td>0 1 1</td>
<td>Figure 3-16 (l)</td>
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<tr>
<td>0 1 1</td>
<td>Figure 3-16 (m)</td>
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<td>Figure 3-16 (n)</td>
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<td>0 0 0</td>
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<tr>
<td>0 0 1</td>
<td>Figure 3-16 (o)</td>
<td>1 0 1</td>
<td>Figure 3-16 (p)</td>
</tr>
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<td>1 1 0</td>
<td>Figure 3-16 (q)</td>
<td>1 0 0</td>
<td>Figure 3-16 (r)</td>
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<td>1 1 0</td>
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</tr>
<tr>
<td>1 1 0</td>
<td>Figure 3-16 (s)</td>
<td>0 1 0</td>
<td>Figure 3-16 (t)</td>
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<td>1 0 1</td>
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<td>Figure 3-16 (v)</td>
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<tr>
<td>0 1 1</td>
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<td>Figure 3-16 (x)</td>
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<tr>
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<tr>
<td>1 1 1</td>
<td>Figure 3-16 (cc)</td>
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</table>

Table 3-4: Egg configurations with related diagrams
Chapter 3: Far Field Parametric Egg Quantity Detection

Figure 3-18: Orientation plot of all six eggs to plane wave

Figure 3-19: Extracted complex natural resonances for one egg scenarios with three configurations
Figure 3-20: Extracted third poles for varying numbers of eggs with six configurations

Figure 3-20 illustrates a straightforward view of the extracted poles with different egg numbers. As can be seen from the graph, the third order poles with the least damping factor overlapped each other, which make the CNR method fail to ascertain the egg quantity. In order to resolve the drawback with the CNR method, polarisation information is used to study the possibility of determining the egg quantity. The scattered far fields of both co- and cross-polarisation are simulated and recorded by probe $R(t)$:

$$R(t) = \begin{bmatrix} r_{\text{HH}}(t) & r_{\text{HV}}(t) \\ r_{\text{VH}}(t) & r_{\text{VV}}(t) \end{bmatrix}$$

(3.63)

where $r_{\text{HH}}(t)$, $r_{\text{HV}}(t)$, $r_{\text{VH}}(t)$ and $r_{\text{VV}}(t)$ represent the backscattered signal for co- and cross-polarisation. The highest stable poles with a resonant frequency can be written as $\omega_r$. Consequently, the scattering matrix $S(\omega_r)$ in equation (3.45) can be written as:

$$S(\omega_r) = \begin{bmatrix} S_{\text{HH}}(\omega_r) & S_{\text{HV}}(\omega_r) \\ S_{\text{VH}}(\omega_r) & S_{\text{VV}}(\omega_r) \end{bmatrix}$$

(3.64)
As poles converge for all scenarios before, the element in scattering matrix $S$ could be rewritten as:

$$
A(\omega_r) = \begin{bmatrix}
a_{mH}(\omega_r)e^{j\phi_{mH}(\omega_r)} & a_{HV}(\omega_r)e^{j\phi_{HV}(\omega_r)} \\
a_{VH}(\omega_r)e^{j\phi_{VH}(\omega_r)} & a_{HH}(\omega_r)e^{j\phi_{HH}(\omega_r)}
\end{bmatrix}
$$

(3.65)

where $A(\omega_r)$ denotes the complex amplitude at the dominant resonant frequency $\omega_r$, while $a_{xy}(\omega_r)$ and $\phi_{xy}(\omega_r)$ represent amplitude and phase when the receiver is in the $x$ polarisation and the transmitter is in the $y$ polarisation. According to Equations (3.40)–(3.56), the relationship between characteristic angle $\phi$ and egg quantity is extracted from Equation (3.56) and displayed in Figure 3-21. The characteristic angle expresses the target polarisation property, which is a degree of how the polarisation status of a scattered wave of a target illuminated by the unpolarised wave varies. It can be found that the angle decreases while the egg number increases. The larger quantity with a more complex configuration is more prone to polarise an unpolarised wave due to the small value $\phi$. The result also validates that of [Mot07], which is applied to larger $\phi$ values, which are less able to polarise waves than those with smaller $\phi$ values.

![Figure 3-21: Relationship between quantity and characteristic angle $\phi$](image)

### 3.6 Constraints

It has been shown that egg quantity cannot be determined by investigating the complex natural poles that arise from GPOF. Further investigation from the polarisation aspects was carried out and has shown promising results, where it has been found that the quantity of eggs is inversely
proportional to the characteristic angle. However, the limitations accompanying both approaches are:

- A plane wave with linear polarisation is supposed to be the excitation sources as both approaches concentrate on the late time response containing target information. Targets should be placed in the far field of the antenna in order to fulfil the requirement. This would be critical for a real intelligent fridge scenario, or other small enclosures, as the physical size of the inside of the fridge is restricted.

- In addition to size consideration, to extract CPSs, co- and cross-polarisation would be required leading to increased complexity of the antenna and system, as well as cost.

- Though it has found that the characteristic angle is inversely proportional to the quantity of eggs as given in Figure 3-21, it is predictable that the characteristic angle will be converge as the quantity increases, thus leading to difficulty distinguishing when the number is more than six.

- The operation frequency used in the egg quantity detection is between 0 GHz and 2 GHz. The low frequency range will inevitably increase the dimension of sensors, contributing to the difficulty to deploy in a real fridge. Furthermore, an antenna covering such band does not exist.

### 3.7 Summary

In this Chapter, discrimination of three different targets based on natural poles has been presented. However, it has failed to distinguish egg quantity with different egg configurations for use in an intelligent fridge scenario as a case study. This drawback could be compensated for by finding the CPSs, which reveals target symmetry and complexity information. Both methods are based on the far field case and these would be impractical for an iFridge and possibly a number of other applications where space is a restriction. In the next chapters, the study of near field non-imaging egg quantity detection as an alternative method is detailed with extensive simulations and measurements for purposes of proving the concept. The smart fridge continues to be used as a case study, which has other potential applications to be discussed in later chapters.
Chapter 4

4 Reactive Near Field Egg Quantity Detection

Though the polarisation method has been implemented in resolving egg quantity in the far field, it is difficult to use in realistic scenarios owing to the limited space inside fridges as well as the fact that other items also occupy the same space. Furthermore, the frequency range in the previous study is at the lower end of the ultra wideband (UWB) spectrum with a lower power level mask below 2 GHz. Therefore, it is desirable to sense the eggs within the sub-band of UWB from 3–5 GHz as lower sampling rates are required at the receiver, thus reducing the system complexity and cost. Small antennas or sensors can be applied and they can also be placed just underneath the box in order to detect and quantify the presence of eggs. This therefore requires studying egg detection in the reactive near field region of the antennas in which the impulse radio UWB (IR-UWB) cannot be considered as a conventional radar. A better terminology to use is that the received impulse is filtered due to it being transmitted from one antenna to another (bistatic case), or back to the same antenna (monostatic case) through the medium it is detecting.

This Chapter will present the measurement setup representing a real scenario containing a box of six eggs, along with results of S-parameter measurements, which in turn can be used to evaluate the filtering characteristics of the impulse response, both with and without the presence of eggs. Such analysis in this instance would be relevant to an intelligent fridge scenario, which would have the ability to quantify the number of eggs contained in a box and is also used in this thesis as a useful case study for impulse response filtering. The impulse response filtering is analysed through computing a correlation coefficient in both the monostatic and bistatic radar cases while group delay (GD) is also analysed to show the impulse response filtering characteristics and how they can be used in egg quantity detection.

4.1 System setup

Evaluation of S-parameters requires the use of a vector network analyser (VNA) to measure the port parameters from sensors placed under the shelf of a fridge. In the measurements undertaken here, an antenna with 24 elements was used, which therefore corresponds to a 24 × 24 S-parameter network requiring extensive static measurements with the network analyser, though where necessary only the elements of interest are analysed later in the thesis.
4.1.1 In fridge UWB antenna

There are a variety of UWB antennas that can be categorised based on their radiation mechanism. A popular approach to broaden the bandwidth is to combine multiple resonant parts operating at each frequency, which overlap to achieve a broad bandwidth. The resonant parts can be combined in parallel, one as a passive radiator, the others as a parasitic elements. In [Zeh06], a three layer stacked antenna for UWB application is proposed. The top view and the side view of the antenna are shown in Figure 4-1. The probe is directly fed to the lower patch with a length $L$ (18 mm) and width $W$ (10.8 mm). The other two parasitic lower patches have the same width but different lengths, which are $L_2 = 13.4$ mm and $L_3 = 11.7$ mm. The offset distance ($x$) of the probe from the centre is 7 mm. The parasitic elements in the middle layer and top layer have the same dimensions ($L_1 = 15.4$ mm and $W = 10.8$ mm). All three patches are printed on a low-loss dielectric material ($\varepsilon_r = 2.2$) where the heights of each layer are $h_1 = 1.2$ mm, $h_2 = 5$ mm and $h_3 = 4$ mm. The simulated reflection coefficient is plotted in Figure 4-2. As can be seen, there are three resonant modes due to the parasitic elements, and the overlapping frequency of these three modes lead to a wide bandwidth from 4 GHz to 7 GHz. The main drawback of this type of antenna is the inconsistency of the radiation pattern i.e. the pattern differs from each other at different frequencies. In addition, the fabrication complexity could be inevitably increased owing to the properties of the multilayer as well as the cost.

![Figure 4-1](image1)

(a) (b)

Figure 4-1: A three-layer UWB antenna: (a) top view (dotted line: lower patch, circle: probe, solid line: middle and top patches) and (b) side view [Zeh06]

![Figure 4-2](image2)

Figure 4-2: Simulated reflection coefficient [Zeh06]
Another type of wide band antenna is called a frequency independent antenna. The first type to achieve frequency independent characteristics is where the antenna shape is specified only by means of angle of inclination of the discone [Rum57]. Figure 4-3 (a) illustrates an example of this type, which is a biconical antenna. Another type of frequency independent antenna is caused by self-complementarity [Mus92], in which the shape of the complementary structure is the same as the original structure. Mushiake found that the product of input impedance of a planar electric current antenna (plate) and its corresponding "magnetic current" antenna (slot) was real constant $\eta^2/4$, where $\eta$ is the intrinsic impedance ($120\pi \approx 377$ Ω for free space). Therefore, if an antenna is its own complementary, frequency independent behaviour is achieved. The antenna with this attribute contributes to a constant impedance of $\eta/2$ which is 188.75 Ω. A spiral antenna with equal width of strip, $w$, and gap between stripes, $s$ ($w = s$), is a self-complementary antenna as shown in Figure 4-3 (b). Though this type of antenna is very wideband, the angle based antenna configuration needs to be infinite in principle, but the size should be truncated in a realistic case. The antenna is therefore large in terms of the wavelength. Another issue is the dispersion using a frequency independent antenna, which radiates different frequency components from different parts of antenna, thus, a strong ringing effect and distortion occur.

![Figure 4-3: (a) Biconical antenna and (b) spiral antenna](image)

Taking the cost, size, performance and aesthetics into account, a conventional coplanar waveguide fed UWB planar monopole antenna [Lin06] (Figure 4-4(a)) is chosen for this study with the dimensions of 30 mm × 35 mm × 1.6 mm. The fabricated design used in this instance is modified to have a grounded probe feed so that the ground element and the radiation element are located on the opposite layers with a full ground plane on the rear side of the substrate, as shown in Figure 4-4 (b). This is therefore a suitable candidate antenna for the application since light can still pass through the array of elements in a smart fridge scenario. FR4 is a low-cost substrate with a dielectric constant of 4.55. The reason for modifying the antenna to have a grounded probe feed is that it is more suitable for the cases where multiple sensors are printed on a single FR4 board. CST is used in transient time mode and the mesh sizes that govern the accuracy of the solution are
increased, at the penalty of longer simulation time. To account for the simulation efficiency and accuracy, the mesh size is defined as 10 lines per wavelength as insignificant change to the simulated scattering data is achieved with a smaller mesh size. The antenna is excited by a waveguide port. The simulated reflection coefficient is shown as a blue curve in Figure 4-5. The frequency range defined by a -10 dB reflection coefficient is from 2.8 GHz to 10 GHz with three strong resonances occurring at 3.2 GHz, 6.1 GHz and 9.3 GHz. The reflection coefficient of the fabricated antenna is measured by using an Agilent N5230A network analyser. Prior to antenna measurement, the port is calibrated in terms of matched load, open circuit and short circuit standard cases. After the calibration, the measured reflection coefficient is shown as a green curve in Figure 4-5. The measured frequency range defined by -10 dB is from 3 GHz to 9.7 GHz, in which four resonances occur at 4 GHz, 6 GHz, 7.5 GHz and 9.2 GHz. The difference between the simulated and the measured results can be explained from two reasons: (a) the one is the fabrication tolerance as the hole drilling and soldering are done by hand and (b) the second is the difference in excitation sources between simulations and measurements as a 50Ω ideal waveguide port is used to excite the antenna in simulations while a practical Sub Miniature version A (SMA) connector is used in measurements. The waveguide port is a surface perpendicular to a transmission line on which the excitation modes that can propagate along the line are calculated. The waveguide port greatly reduces the number of meshes involving in simulations with reasonable accuracy. To take the simulation time and computer efficiency into account, SMA connector is not included in the simulation. Despite these differences, the reflection coefficient is still less than -10 dB in the band 3–5 GHz, which will be used later in this study.

![Figure 4-4: (a) Simulated (unit: mm) and (b) fabricated ultra wideband antenna](image-url)
4.1.2 Description of test systems

An A4 size antenna array (Figure 4-6) is fabricated with 24 elements with a $6 \times 4$ configuration suitable for use in a fridge testing scenario. The sensors will allow food containers, such as egg boxes, to be placed directly above them. A schematic diagram of the measurement system is given in Figure 4-7 consisting of a VNA, in-fridge UWB sensors and the foods of interest, which are eggs. One antenna is connected to port 1 of the VNA and another one is connected to port 2 of the VNA, leaving other sensors open. In conventional cases, the sensors should have 50-$\Omega$ loads when not measured, though in this study, the mutual coupling is low enough between sensors that applying loads to neighbouring sensors makes no difference to the reflection coefficient of the measured sensor and therefore, for convenience, they are not used.

![Simulation and measured reflection coefficient](image)

**Figure 4-5** Simulated and measured reflection coefficient

![Fabrication of in fridge sensors](image)

**Figure 4-6** Fabrication of in fridge sensors: (a) top view and (b) bottom view
4.2 Correlation Coefficient Detection Metric

For two real variable sets \( x(t) \) and \( y(t) \), the complex correlation coefficient can be expressed as [Kyr03]:

\[
\rho_{xy} = \frac{\mathbb{E}[(x(t) - \mathbb{E}(x(t)))(y(t) - \mathbb{E}(y(t)))]}{\sqrt{\sigma_x^2 \cdot \sigma_y^2}}
\] (4.1)

where the averaging using the expected value function \( \mathbb{E}[\cdot] \), is calculated by taking all samples.

And the variance of \( x(t) \) and \( y(t) \) are represented by \( \sigma_x^2 |_t \) and \( \sigma_y^2 |_t \), respectively, which can be expressed as [Kyr03]:

\[
\sigma_x^2 |_t = \mathbb{E}[(x(t) - \mathbb{E}(x(t)))^2]
\] (4.2)

\[
\sigma_y^2 |_t = \mathbb{E}[(y(t) - \mathbb{E}(y(t)))^2]
\] (4.3)

A positive correlation coefficient indicates that the trend of variation of one variable set is the same as another one, while a negative value indicates that the trend of variation of one variable set is the opposite of another one. The correlation coefficient for real variable sets is between \(-1 \) and \(1\).
as the high similarity of two sample sets will cause the correlation coefficient to reach 1 and 0 for low similarity.

The presence of eggs above a sensor in the reactive near field causes a filtering of the UWB impulse, while the reflection coefficient response of the sensors is also changed by the eggs, thus changing the magnitude of the S-parameters. In addition, the filtering effect will lead to a change in group delay (GD) defined in Equation (2.12). A measurement example of the reflection coefficient, $S_{11}$, when the sensor is covered and uncovered (free space) by the egg is plotted in Figure 4-8. In comparison to free space, the resonant frequency changes most from 3.8 GHz to 4 GHz as the egg is placed above the sensor due to detuning, while the egg also absorbs some fields causing a lower reflection coefficient at 4 GHz. The corresponding GD is evaluated in Figure 4-9, where a low GD always below 1.2 ns is observed in maximum GD due to the presence of the egg, which can be observed as a spike at 4 GHz, where the reflection coefficient resonates. This is due to a rapid phase change as the reflection coefficient reduces towards a null point at this frequency and the signal is largely absorbed by the egg. GD evaluates only one aspect of filtering of the impulse response and, as such, it does not change dramatically over the whole band except at the resonant frequency. Therefore, to account for the change in magnitude over the whole band (which is more significant) as well as phase variation, a complex correlation coefficient metric adapted from the complex correlation in Equation (4.1), the complex reflection coefficient correlation (RCC) is defined as follows:

$$\rho_{Rx.Tx_i} = \frac{E[S_{Rx.Tx_i\_egg} S_{Rx.Tx_i\_free}^*] - E[S_{Rx.Tx_i\_egg}] E[S_{Rx.Tx_i\_free}^*]}{\sqrt{\sigma^2[S_{Rx.Tx_i\_egg}] \sigma^2[S_{Rx.Tx_i\_free}]}}$$  \hspace{1cm}(4.4)$$

where $S_{Rx.Tx_i\_egg}$ denotes the S-parameters between the $i$th transmitter and receiver (or $s_{ii}$) when the eggs are present, and $S_{Rx.Tx_i\_free}$ denotes the S-parameters between the $i$th transmitter and receiver (or $s_{ii}$) in the free space case. The superscript * is the complex conjugate. The variance of $S_{Rx.Tx_i\_free}$ and $S_{Rx.Tx_i\_egg}$ is defined by:

$$\sigma^2[S_{Rx.Tx_i\_free}] = E[(S_{Rx.Tx_i\_free} - E[S_{Rx.Tx_i\_free}])^2]$$  \hspace{1cm}(4.5)$$

$$\sigma^2[S_{Rx.Tx_i\_egg}] = E[(S_{Rx.Tx_i\_egg} - E[S_{Rx.Tx_i\_egg}])^2]$$  \hspace{1cm}(4.6)$$

where the averaging using the expected value function $E[\cdot]$ is calculated by taking all of the frequency bins.

For the results shown in Figures 4-8 and 4-9, the measured RCC of sensor 1 above which egg placed $\rho_{Rx1.Tx1} = -0.7894 + j0.089$, where the S-parameter data was taken over the frequency range.
of 3 GHz to 5 GHz by using 45 frequency bins, though data of a total of 201 frequency bins covering from 2 GHz to 11 GHz was recorded. All the remaining experimental results presented in this chapter follow the same frequency range and bin size. The theoretical results also use the same frequency range and frequency bin size. The usage of lower sub-band of UWB from 3 GHz to 5 GHz allows lower sampling frequency, thus reducing the system complexity and cost. The choice of number of frequency bins is taken computer performance and time from both simulations and measurements into account.

Figure 4-8: Measured reflection coefficient of sensor 1 in the case of free space and an egg above sensor 1

Figure 4-9: Measured group delay of sensor 1 in the case of free space and an egg above sensor 1
Figure 4-10: Measured coupling coefficient of sensors 1 and 2 in the case of free space and an egg above sensor 1

Figure 4-11: Measured group delay of coupling coefficient of sensors 1 and 2 in the case of free space and an egg above sensor 1
The coupling coefficient correlation (CCC) is also evaluated as a measure of the effect of the presence of the eggs in the bistatic case, which can be expressed as:

\[
\rho_{Rx/Tx} = \frac{\mathbb{E}[S_{Rx/Tx, \text{egg}} S^*_{Rx/Tx, \text{free}}] - \mathbb{E}[S_{Rx/Tx, \text{egg}}] \mathbb{E}[S_{Rx/Tx, \text{free}}]}{\sqrt{\mathbb{V}[s_{Rx/Tx, \text{egg}}] \mathbb{V}[s_{Rx/Tx, \text{free}}]}}
\]  

(4.7)

where \(S_{Rx/Tx, \text{egg}}\) denotes the S-parameters between the \(i^{th}\) transmitter and \(j^{th}\) receiver (or \(s_{ji}\)) when the eggs are present, and \(S_{Rx/Tx, \text{free}}\) denotes the S-parameters between the \(i^{th}\) transmitter and \(j^{th}\) receiver (or \(s_{ji}\)) in the free space case. The variances of \(S_{Rx/Tx, \text{egg}}\) and \(S_{Rx/Tx, \text{free}}\) are defined in the same manner as Equations (4.5) and (4.6). Based on the results shown in Figures 4-10 and 4-11, the measured CCC of sensors 1 and 2 in case that egg is above sensor 1 \(\rho_{Rx/Tx} = 0.882 - j0.133\), where the S-parameter data was taken over the frequency range of 3 GHz to 5 GHz by using 45 frequency bins, though data of a total of 201 frequency bins covering from 2 GHz to 11 GHz was recorded. All the remaining experimental results presented in this chapter follow the same frequency range and bin size. The theoretical results also use the same frequency range and frequency bin size.

The correlation in equations (4.4) and (4.7) is complex and will have real and imaginary parts corresponding to a magnitude and phase. The magnitude is a measure of the comparison of the magnitudes of the S parameters over the band. However, it is possible that the magnitude can be highly comparable, while the phase is not, which will yield a high magnitude in correlation but there will be a significant imaginary part, thus resulting in a non zero phase in the complex correlation.

### 4.3 Feasibility study of egg quantity determination

Where eggs are placed near to sensors, the reflection coefficient or \(s_{nm}\) parameters of the sensors concerned will change dramatically, while some change will also result with regard to the coupling across to neighbouring sensors, \(s_{nm}\). This section will show the impact of the presence of eggs on the RCC and CCC to evaluate the filtering of the UWB impulse. Furthermore, which sensors are suitable for detecting the presence and quantity of eggs will be established.

#### 4.3.1 Study of the detectable region of UWB antennas

In contrast to detection in the far field region, where the pattern is consistent and independent of distance, the magnitude of the near field varies significantly over distance, causing capacitive and inductive coupling between conducting objects. In this study, eggs are placed 1 cm above the sensor nodes for the consideration of the thickness the of tray in a real fridge. It is necessary to
determine the region where the egg has influence on filtering the impulse response. The dimensions in Figure 4-12 illustrate the possible simulation positions. Only one quadrant is used for investigation as symmetrical performance is expected for other sensors. The zone can be described as a slant angle, $\psi$, ranging from $0^\circ$ to $90^\circ$ in the azimuth plane and the egg can be rotated around the centre of antenna with the angle step $30^\circ$. At each angle, the egg moves along the radius direction, $d$, with a step size of 5 mm.

Figure 4-12: Model for study of detectable region (dashed line: egg movement trace)

The reflection coefficient is plotted versus $d$ for fixed values of $\psi$ of $0^\circ$, $30^\circ$, $60^\circ$ and $90^\circ$ in Figure 4-13 (a)–(d) and the corresponding GD is plotted similarly in Figure 4-14 (a)–(d). In both illustrations, it is shown that the resonant frequency gradually shifts from 4.3 GHz to the original antenna resonant frequency of 3.2 GHz as $d$ increases, regardless of $\psi$. The maximum detectable distances, where the resonant frequency reaches the original 3.2 GHz, are 40 mm for slant angles $0^\circ$ and $30^\circ$ and down to 35 mm for slant angles of $60^\circ$ to $90^\circ$. This indicates that the presence of eggs with a distance $d$ over 40 mm has a negligible influence on the reflection coefficient when positioned 1 cm above the antenna. Hence, this is derived as the maximum detectable region for a sensor.
Chapter 4: Reactive Near Field Egg Quantity Detection

(a)

(b)
Figure 4-13: S-parameters with slant angle of (a) 0°, (b) 30°, (c) 60°, and (d) 90°
Chapter 4: Reactive Near Field Egg Quantity Detection

(a)

(b)
4.3.2 Study of varying number of eggs

A box for six eggs with a $2 \times 3$ configuration is used in this study where the eggs are assumed to be placed above sensors 1, 2, 3 and 5, 6, 7, as shown in Figure 4-13. The RCC and CCC are
evaluated in accordance with these scenarios as given in the following sections, therefore sensors 1, 2, 3 and 5, 6, 7 could be directly covered by an egg, as illustrated in Figure 4-15.

![Figure 4-15: Topology of the fridge antenna array](image)

### 4.3.2.1 Reflection coefficient correlation (RCC)

The real and imaginary part of the RCC from both simulation and measurement can be viewed by a correlation map, as illustrated in Figure 4-16 and 4-17. The horizontal axis reflects the possible egg quantities ranging from 1 to 6 while the vertical axis stands for the antenna element number on the array. The topology in terms of which sensors the eggs are placed over as the quantity changes from 1 to 6 is listed in Table 4-1. High similarity is achieved between the simulated and measured real part of RCC, where it reduces to a low value in the case when an egg is placed on an antenna in each of the columns, while all antennas without an egg present have a high RCC above 0.9. Slight differences can be observed in the imaginary part of the RCC, though the evaluated value is less than 0.25 in all cases, which indicates that the averaged phase difference between the complex S-parameters with and without eggs is negligible. Therefore, the imaginary part of the RCC can be ignored in analysing egg quantity. Due to the maximum detectable region, a distinct change in RCC results when an egg is placed over the sensor, while neighbouring sensors still maintain a high RCC.

<table>
<thead>
<tr>
<th>Egg quantity</th>
<th>Covered Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>3, 5</td>
</tr>
<tr>
<td>3</td>
<td>2, 3, 5</td>
</tr>
<tr>
<td>4</td>
<td>2, 3, 5, 7</td>
</tr>
<tr>
<td>5</td>
<td>2, 3, 5, 6, 7</td>
</tr>
<tr>
<td>6</td>
<td>1, 2, 3, 5, 6, 7</td>
</tr>
</tbody>
</table>

Table 4-1: Topology of eggs above sensors
Chapter 4: Reactive Near Field Egg Quantity Detection

4.3.2.2 Coupling coefficient correlation (CCC)

The RCC for various egg numbers was investigated in the previous section establishing promising results for discrimination of egg quantity. In addition to the RCC information, coupling between the elements provides another aspect in association with eggs. For purposes of clarity, concentration will be drawn only on the coupling information in association with antenna 1 as the transmitter. In this case, there are 16 correlation coefficients in total (where sensors 1 to 16 were used), $\rho_{Rx_j Tx_1}$ taking each receiver as receiver $j$ while always transmitting from element 1. In other words, it is necessary to take measurements of $s_{1j}$ through to $s_{16j}$ and hence derive $\rho_{Rx_1Tx_1}$ through to $\rho_{Rx_{16}Tx_1}$. A single egg in this case is randomly positioned inside a box of two by three, leading to six possible configurations, as shown in Figure 4-18, where dashed lines outline the six configurations with label "CF$_n$" where $n = 1$ to 6. The simulated and measured coupling correlation map of antenna 1 is evaluated in Figure 4-19 where the horizontal axis contains the six configurations and the vertical axis contains the sixteen RCC values. Several interesting issues can be observed in the simulated results. Firstly, eggs have a great impact on cross talk in the y
direction rather than the $x$ direction as a significant difference is noticed for parameters $\rho_{Rx9Tx1}$ and $\rho_{Rx13Tx1}$ when an egg is above sensor 5 but CCC between sensor 1 and other sensors in the $x$ direction, such as parameter $\rho_{Rx2Tx1}$, $\rho_{Rx3Tx1}$ and $\rho_{Rx4Tx1}$, do not change regardless of the configuration. Nonetheless, the impact on CCC is only significant in the case of CF$_1$, where an egg is covering the only active antenna, number 1 reduces towards zero, especially with receiver sensors 6, 7 and 10. Therefore, as an egg can be detected when placed over sensor 1, CCC is not useful information in this test scenario and thus the RCC only is required.

![Figure 4-18: Six possible configurations for one egg coupling study](image)

![Figure 4-19: CCC related with sensor 1 for six configurations: (a) simulation and (b) measurement](image)

### 4.3.2.3 Group delay (GD) information

The same test case configurations as shown in Figure 4-18 are used here to analyse GD in the monostatic case. Figure 4-20 illustrates the GD of sensor 1 in all six configurations and a free space case where no egg box or eggs are present. As expected, all configurations have a relatively flat GD across the whole band except for CF$_1$ with an abrupt spike occurring at around 4 GHz.
4.3.3 Study of multiple eggs and configurations in random locations

In this section, a more general scenario is studied in which the eggs with different numbers and configurations and the egg box are randomly positioned such that eggs will be positioned at random locations between sensors. In order to concentrate on the relevant detectable region in the near field, only a 2 × 2 sensor array (Figure 4-21) and a quantity of four eggs with different configurations (Table 4-2) is considered. The total movement in the region by which the eggs move in this analysis is such that neither x or y shown in Figure 4-19 will exceed 50 mm.

<table>
<thead>
<tr>
<th>Egg Quantity</th>
<th>Covered Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1, 5</td>
</tr>
<tr>
<td>3</td>
<td>1, 2, 5</td>
</tr>
<tr>
<td>4</td>
<td>1, 2, 5, 6</td>
</tr>
</tbody>
</table>

Table 4-2: Topology of eggs in random location case
Chapter 4: Reactive Near Field Egg Quantity Detection

Figure 4-21: Study of eggs in random positions

The blue and red plots in Figure 4-22 are the measured RCC of sensor 1 and the CCC between sensors 1 and 2 when the egg moves in the $x$ direction at a step size of 5 mm while fixing the $y$ direction at 0 mm. Secondly, the green and turquoise plots are of the RCC of sensor 1 and the CCC between sensors 1 and 5 when the egg moves in $y$ direction with a step size of 5 mm while maintaining the $x$ direction as 0 mm. A coherence distance, defined as a measure of the distance at which the correlation coefficient starting from the maximum value reaches a threshold 0.7, is found to be 30 mm for the RCC regardless of either varying $x$ or $y$ directions, while it is 20 mm for the CCC in the $x$ direction and 10 mm for the CCC in the $y$ direction. The step size the eggs are moved by is 5 mm, which is 50% or less compared to the coherence distance, which will therefore provide sufficient resolution for analysis of the change in RCC or CCC when the position is changed.

Figure 4-22: Measured RCC of sensor 1, CCC of sensor 1 and 2 as well as sensor 1 and 5 for one egg being moved in the $x$ direction while keeping $y$ as 0 mm and fixing $x$ as 0 mm and moving in the $y$ direction
4.3.3.1 RCC - sensor 1

The RCC of sensor 1 for a single egg is plotted in Figure 4-23, showing a correlation map for both simulated and measured results. The horizontal axis of the correlation map represents the distance eggs move in the $x$ direction while the vertical axis corresponds to the $y$ direction as shown by the diagram in the figure. The colour in every correlation map grid represents the value of the real part correlation coefficient with scale shown at the right hand side of the map.

As can be seen from Figure 4-23, a deeper negative value in the measured case is shown (-0.6) rather than -0.2 to -0.3 in the simulated case when the egg is covering sensor 1. This is owing to
the magnitude of resonance at 4 GHz as indicated in Figure 4-8, where the precision of difference at this resonance causes changes for a lower value of correlation. Otherwise, the simulated and measured results are in good agreement where there is higher correlation. At any point, when the egg has moved 25 mm away from the centre of sensor 1, the correlation rises above 0.9 indicating that a negligible effect on sensor 1 is caused by the egg.

Figure 4-24: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 1, $\rho_{RCC1}$
Figure 4-24 reveals the effect of two eggs where one covers sensor 1 and the other covers sensor 5. The measured results show high similarity with the simulated ones as again low correlation region can be observed when an egg covers sensor 1. The RCC characteristic of sensor 1 does not change dramatically when compared with Figure 4-23 such that a second egg does not affect the ability to detect the first egg when covering sensor 1.

Figure 4-25: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 1, $\rho_{Rx1Tx1}$
The $s_{11}$ correlation map related to the movement of three eggs covering sensors 1, 2 and 5 is shown in Figure 4-25, while the four-egg case is plotted in Figure 4-26 in which the same consistencies are found when comparing with the single egg case in Figure 4-23. The third egg and forth egg do not affect the ability to detect the first egg when covering sensor 1.

Figure 4-26: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 1, $\rho_{R1TM1}$
4.3.3.2 RCC -sensor 2

The same process as that used in Section 4.3.3.1 is repeated here only in this instance the RCC from sensor 2 as opposed to sensor 1 is considered. Therefore, as can be seen from Figure 4-27, while good agreement has been achieved between the simulated and measured results, at the origin point which the egg is above sensor 1, the correlation value is above 0.9 indicating that no egg is present in the detectable region of sensor 2. The correlation reaches a minima as expected when the egg covers sensor 2 at (50, 0) from both simulations and measurements.

Figure 4-28 reveals the effect of movement of two eggs (starting above sensors 1 and 5) on the RCC of sensor 2, which has the same characteristics as that in Figure 4-27 for a one egg case, thus again the second egg does not have an effect on the ability of sensor 2 to detect an egg that is covering it.

Figure 4-29 and Figure 4-30 show the cases where there are three and four eggs present, respectively. In both of these cases, an egg is covering sensor 2 at the start position and a new correlation map is formed where two low correlation regions at both the origin (0, 0) and (50, 0) can be observed owing to the third egg covering sensor 2 initially. The map is almost symmetrical along the vertical line at which x equals 25 mm. This is owing to a low correlation in the start when sensor 2 is covered by an egg and the left hand egg will also cover sensor 2 as all three or four eggs move in the x direction. It is therefore possible to sense the presence of the first egg and third egg when they are above sensor 2, while the other eggs have no effect.
Figure 4-27: (a) Topology of one egg case with (b) simulated and (c) measured RCC of sensor 2, $\rho_{RCC_2}$.
Figure 4-28: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 2, $\rho_{252}$.
Figure 4-29: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 2, $\rho_{RxTy2}$
Figure 4-30: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 2, $\rho_{Rx2Tx2}$.
4.3.3.3 RCC - sensor 5

The third study necessary for evaluating the impact on the RCC is to consider sensor 5 in the same manner as that used in the previous two sections. This sensor is 45 mm from sensor 1 in the y direction and 50 mm from sensor 6 in the x direction.

Figure 4-31 shows the first case of a single egg where good agreement is shown between the simulated and measured results. The same is true for results of two, three and four eggs shown in Figure 4-32, Figure 4-33 and Figure 4-34, respectively. For the single egg case in Figure 4-31, a low correlation region at (0, 50) with a radius of 25 mm can be observed. This is a mirrored version of Figure 4-23, which is expected as the first egg on sensor 1 moves in the positive y direction and gradually moves over sensor 5 as the active sensor, while in the former case it moved away from sensor 1 as the active sensor. In Figure 4-32, there are two regions of low correlation with origins at (0, 0) and (0, 50) since two eggs are present over sensors 1 and 5 initially, while at the maximum y value, sensor 5 only is covered by the egg originally over sensor 1 and thus it has a low RCC.

Finally, in Figure 4-33 and Figure 4-34, the cases for three and four eggs present make no measureable difference when comparing with Figure 4-32 owing to the fact that the eggs are placed over adjacent sensors 2 and 6 and thus do not cause any effect on sensor 5. Therefore, sensor 5 has the ability to detect an egg when covering it and this is not affected by eggs on adjacent sensors.
Figure 4-31: (a) Topology of one egg case with (b) simulated and (c) measured RCC of sensor 5, $\rho_{\text{RESTS5}}$. 
Figure 4-32: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 5, $\rho_{\text{RCCs}}$
Figure 4-33: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 5, $\rho_{5STe5}$
Figure 4-34: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 5, $\rho_{Rc\text{5x5}}$
4.3.3.4 RCC - sensor 6

The fourth and final study necessary for completeness of evaluating the impact on the RCC is to consider sensor 6 in the same manner as that of the previous three sections. This sensor is diagonally opposite sensor 1. Therefore, again in this case the distance between sensors is different to the case of being above or adjacent and their nearest point of contact is a corner of each sensor.

Figure 4-35 through to Figure 4-38 plot the results in this instance where again good agreement is achieved between simulation and measurement. Some tiny discrepancies in low correlation are seen in Figure 4-38 for the case with four eggs present, where the lowest correlation values are about -0.4 and -0.2, respectively, though there is still a comparison of high and low correlation in the regions where it is expected. Figure 4-35 is a mirror reflection of Figure 4-23 taking the line of symmetry as the diagonal line from (0, 50) to origin (50, 0) of the correlation map. In Figure 4-36, two points of low correlation are seen at (50, 0) and (50, 50), as there are two possible instances that an egg covers sensor 6. The first low correlation region at (50, 0) is caused by the egg being above the sensor 1 initially which moves 50 mm in x direction to get into the detectable region of sensor 2, whilst another region at the right top corner (50, 50) is due to the egg being at sensor 5 initially and moving over to sensor 6. In Figure 4-37, there are three instances where an egg will cover sensor 6 owing to the third egg being above on sensor 2 initially leading to the low RCC value at (0, 50) while finally in Figure 4-38 there are four minimum RCC points occurring at every corner of the map.

In this and the preceding three sub-sections, the study of the effect on RCC has been evaluated in a way that it can be applied to any single sensor considering other sensors that may be adjacent to the sensor in the x or y direction and finally diagonally opposite a sensor. It can be concluded that the sensor can take effect once the egg is positioned at no more than a 25 mm radius distance to the sensor. However, for the region not covered by 25 mm radius based on four different sensors, the CCC between sensors will be considered in the remaining sub sections.
Figure 4-35: (a) Topology of one egg case with (b) simulated and (c) measured RCC of sensor 6, $\rho_{Rx6Tx6}$.
Figure 4-36: (a) Topology of two eggs case with (b) simulated and (c) measured RCC of sensor 6, $\rho_{6_{\text{sim}}}$.
Chapter 4: Reactive Near Field Egg Quantity Detection

Figure 4-37: (a) Topology of three eggs case with (b) simulated and (c) measured RCC of sensor 6, $\rho_{Rx6Tx6}$
Figure 4-38: (a) Topology of four eggs case with (b) simulated and (c) measured RCC of sensor 6, $\rho_{R6S7x6}$
4.3.3.5 CCC - sensor 1 to 2

Having evaluated the RCC, it is also necessary to evaluate the CCC with a similar methodology, particularly for scenarios where the egg is between two sensors because the RCC alone will not have the ability to detect eggs in such cases. Figure 4-40 through to Figure 4-43 evaluate the correlation of coupling from sensor 1 to 2 for one to four eggs, respectively. In these measurements, particularly where three and four eggs are used, the comparison between simulated and measured data is extremely obvious as a high CCC above 0.9 appears in simulation results while a low correlation can be found from the measured ones. To explain the differences, Figure 4-39 compares the simulated and measured magnitude and phase of coupling coefficient $s_{12}$ both when the egg is in the middle of sensors 1 and 2 and when no egg or box is present. As can be seen from Figure 4-39 (a), gaps in the simulated magnitude of coupling coefficient $s_{12}$ can be observed in the bandwidth of interest, which is 3 GHz to 5 GHz as mentioned at the beginning of this chapter, however, the two curves have high similarity resulting in a high correlation coefficient. In contrast to the simulated results, the measurements display significant differences across the bandwidth of interest and the phase information is equally dissimilar as plotted in Figure 4-39 (b). There are three notable reasons contributing to the significant differences in both magnitude and phase from simulations and measurements. Firstly, noise generated by the vector network analyser (VNA) exists in measurement, where low coupling values are measured, though the effect of the noise on correlation was found to be negligible. Secondly, the material for eggs in simulation is considered as homogenous in which the dielectric constant is the same for any point in the egg, however, it is unrealistic for the real egg as it consists of yolk as well as egg white and the dielectric values are significantly different. Thirdly, the effects of connectors are not considered in simulation, where cross coupling between coaxial feeders as well as the sensors will occur. Given that these real effects cannot be replicated in simulation, only measured results will be considered from this point, though simulation results are still shown for completeness.
Figure 4-39: Simulated and measured (a) magnitude and (b) phase of coupling coefficient $s_{12}$ in the case of free space and egg presence.
For the case of one egg in Figure 4-40, this result can be coupled with the RCC results for the same case in Figure 4-23 (b), which enables a single egg to be detected regardless of position between two adjacent sensors. It is now possible to detect the presence of an egg when placed midway between two sensors. This can be identified clearly in Figure 4-22, where at \( x = 25 \) mm, the RCC rises above 0.8 but the CCC between sensors 1 and 2 drops to a minima of 0.7. Where \( x < 20 \) mm, the RCC of sensor 1 is below 0.7 and thus can be used to detect when the egg is over the sensor, while for \( x > 30 \) mm, sensor 2 can be used for the same purpose. Where \( 20 \) mm < \( x < 30 \) mm, the CCC is consistently low at 0.7, therefore a suitably low threshold, for example 0.75, can detect the presence of an egg, regardless of position on the \( x \) axis, using the RCCs of the two sensors and CCC between the two sensors. It can be further noted by analysis of Figure 4-23 (b) and 4-40 (b) that the same criteria can be applied for fixed values of \( y \) up to 15 mm. This characteristic is unaffected by the presence of a second egg above sensor 5, shown in Figure 4-39, where the threshold correlation of 0.7 can still be applied.

For the cases of three and four eggs in Figure 4-42 and 4-43, the correlation holds the same property as the one egg and two eggs cases where the CCC at coordinate (25, 0) still falls below 0.7 when a third egg is initially covering sensor 2 at coordinate (0, 0). Therefore, parameter \( \rho_{T_2T_1} \) can be used to sense the presence of an egg when it is in the middle of these two sensors with up to 15 mm in the \( y \) direction.
Figure 4-40: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 1 and 2.

\[ \rho_{Rx2Tx1} \]
Chapter 4: Reactive Near Field Egg Quantity Detection

Figure 4-41: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 1 and 2, $\rho_{\text{RxT}}$. 
Figure 4-42: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 1 and 2, $\rho_{Rx\leftrightarrow Tx}$
Figure 4-43: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 1 and 2, $\rho_{R_2T_1}$
4.3.3.6 CCC - sensor 1 to 5

Figure 4-44 through to Figure 4-47 evaluate the correlation of coupling from sensor 1 to 5 for one to four eggs, respectively. As seen in Figure 4-44, the movement of the egg along the y direction, where it is obstructing sensors 1 and 5, causes the correlation to drop to a low state below a value of 0.6 at coordinate (0, 30), while the correlation is higher when the egg is placed over sensor 1 or 5. It can be seen in Figure 4-20 that for \( y < 25 \) mm, the RCC of sensor 1 is below 0.7, thus can be used to detect the egg when it is close to the sensor in the y direction. The presence of an egg can be detected by using the RCC of sensor 5 for \( y > 35 \) mm as given in Figure 4-31 (b). For the midpoint where \( 25 \) mm < \( y < 35 \) mm, both RCC parameters rise above 0.8, however, the CCC between sensor 1 and 5 given in Figure 4-22 is lower than 0.6 overall, which can be used to sense the presence of eggs with a suitable threshold of 0.7. Particularly, the existence of eggs also has impact even it moves up to 20 mm in the x direction with which low correlation can be found in the middle region from the plot. The addition of a second egg on sensor 5 does have some impact on the CCC when they are positioned above both sensors leading to low correlation at coordinates (0, 0) and (0, 50) of Figure 4-45 while, low correlation can be also found as the eggs move toward the middle as before. The third and fourth eggs do not provide any significant influence on the CCC of \( \rho_{R_{x_3}T_{x_1}} \) due to being used on other sensors from Figures 4-46 to 4-47.
Figure 4-44: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 1 and 5, $\rho_{RSTM}$.
Chapter 4: Reactive Near Field Egg Quantity Detection

Figure 4-45: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 1 and 5, $\rho_{51}$.
Figure 4-46: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 1 and 5, $\rho_{\text{RxTx}}$
Figure 4.47: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 1 and 5, \( \rho_{RxTxl} \).
4.3.3.7 CCC - sensor 1 to 6

The RCC of four sensors as well as the CCC of adjacent sensors in the x and y direction have been studied in the preceding sections. Figure 4-48 illustrates the extraction of the RCC and CCC curves of the one egg case related to the diagonal distance \( P \), which is defined as the Pythagoras combination of \( x \) and \( y \) where they are equal distance:

\[
P = \sqrt{x^2 + y^2} \quad (x = y)
\]

Hence \( P \) moves along the line \( x = y \).

![Figure 4-48: RCC and CCC related to different diagonal distance](image)

RCC less than 0.7 can be observed when \( P < 21 \text{ mm} \) \( (x = y \leq 15 \text{ mm}) \) for sensor 1 and \( P > 49 \text{ mm} \) \( (x = y \geq 35 \text{ mm}) \) for sensor 6, whilst a CCC of less than 0.7 can be found only in the case of \( P = 49 \text{ mm} \) \( (x = y = 35 \text{ mm}) \) for CCC of sensors 1 and 5. A dead zone exists when \( 21 \text{ mm} < P < 49 \text{ mm} \) \( (15 \text{ mm} \leq x, y \leq 30 \text{ mm}) \) in which the egg information cannot be retrieved in terms of either RCC of all four sensors or the CCC between sensors in the x and y directions. However, the presence of one egg in the dead zone can be retrieved in terms of CCC of sensors 1 and 6, as given in Figure 4-48, as the parameter is less than a defined threshold of 0.85 for this specific parameter, thus, the effect of different eggs on the CCC in the diagonal sensors 1 and 6 is studied (though equally sensors 2 to 5 could also be studied). Figure 4-49 through to Figure 4-51 evaluates the CCC from sensor 1 to 6 for one to four eggs, respectively. As seen in Figure 4-49 (b), the measured correlation map is somewhat different to the case of coupling for linearly separated elements due to highly different coupling characteristics that change more when an egg
is placed above sensors 1 or 6, yielding the lowest correlation at (0, 0) and (50, 50) below 0.8. The level of correlation below this threshold is, however, still maintained in the diagonal path between sensors 1 and 6. Hence, for a single egg, the CCC information can be used for detection where the egg is around the midpoint in such a diagonal separation and the RCC of either sensor is above 0.85. Figures 4-50 (b) to 4-52 (b) show that this condition is maintained with the addition of further eggs, thus allowing eggs to be detected between two sensors diagonally separated. Lower correlation maps emerge as more eggs are added, particularly with three and four eggs, which is expected given that the additional eggs are causing a greater barrier between sensors 1 and 6 and thus changing the coupling characteristics.

The dead zone is especially emphasised in the black square region added in Figures 4-49 (b)–4-52 (b). As shown in Figure 4-49 (b), within the square region the CCC between sensors 1 and 6 falls below a selected threshold of 0.85 and therefore it can be used for egg detection in this region. Though there are regions outside of the square where the egg falls below this threshold, but this is not relevant as other RCCs or CCCs would be used in this region for detection and the CCC between 1 and 6 would not be used. Figures 4-50 (b)–4-52 (b) show that this characteristic is maintained with an additional number of eggs in the measured case, though unfortunately, where there are four eggs, there are some instances when the CCC is on the threshold of 0.85, while at (15, 30) it rises above the threshold. In this instance, the coupling becomes very low and, as such, the computation of the CCC is vulnerable to precision error. This could therefore potentially cause detection failure in this region with a high number of eggs present. This shows where accuracy of detection has to be improved, and this would require higher-level power transmissions or a different design of sensors with higher density.
Figure 4-49: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 1 and 6, 
\[ \rho_{Rx6Tx1} \]
Figure 4-50: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 1 and 6, $\rho_{Rm\bar{T}x1}$
Figure 4-51: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 1 and 6, $\rho_{Rx_Tx_1}$
Figure 4-52: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 1 and 6, $\rho_{R4\times 6}$
4.3.3.8 CCC - sensor 2 to 6

Figure 4-53 through to Figure 4-56 evaluate the correlation of coupling from sensor 2 to 6 for one to four eggs, respectively. As seen in Figure 4-53 (b), the measured correlation values drop significantly when the egg is placed between sensors 2 and 6 at coordinate (50, 25) below a defined threshold of 0.7 in the case of measured data. The same property can be found from Figure 4-44 (b), which is the mirror version of that in Figure 4-53 (b). The second egg added on sensor 5 does not change the CCC map significantly, which holds the same property as the CCC between sensors 1 and 5 in Figure 4-54 (b). While, as given in Figures 4-55 (b) and 4-56 (b), a second low correlation region occurs at coordinate (0,25) due to the third egg starting on sensor 2 which agrees with CCC between sensors 1 and 5 well indicating the possibility to sense the presence of egg between sensors 2 and 6 with up to 15 mm in x direction.

Figure 4-53: (a) Topology of one egg case with (b) simulated and (c) measured CCC of sensor 2 and 6, $\rho_{\\text{Rx}6,\\text{Tx}2}$
Chapter 4: Reactive Near Field Egg Quantity Detection

Figure 4-54: (a) Topology of two eggs case with (b) simulated and (c) measured CCC of sensor 2 and 6, $\rho_{RxTy2}$.
Figure 4-55: (a) Topology of three eggs case with (b) simulated and (c) measured CCC of sensor 2 and 6, $\rho_{Rx6T_x2}$
Figure 4-56: (a) Topology of four eggs case with (b) simulated and (c) measured CCC of sensor 2 and $\rho_{Rx6Tx2}$
4.4 Discussion

Results obtained from both simulations and measurements have been presented in the previous section, in which multiple eggs in random locations were investigated. From the empirical information presented, the following points can be summarised:

- The RCC of a sensor can sense the presence of an egg within its region due to the drop in correlation below a threshold of 0.7, regardless of the quantity of other eggs in the box.
- When the egg falls into the margin between two sensors, such as 25 mm in the x or y direction, a high RCC above a defined threshold occurs, meaning that the number of eggs cannot be detected using RCC alone, and cannot be used when the box is placed in a random position such that eggs fall randomly between sensors.
- For the scenario of when the eggs are between sensors, it is essential that the CCC as well as the RCC are used jointly to define the presence of an egg. When an egg is between two sensors in the x or y direction, the egg will always yield a low CCC when it is placed in the middle of two sensors, while the RCC of those two sensors will be high.
- For the case where an egg is positioned between two diagonally separated sensors, the same principle can be applied where it is placed between two sensors in the x or y direction, though in some exceptional instances it may be subject to precision error.

4.5 Blind test of egg quantity detection

Based on the principles established in Section 4.3, this section concentrates on how to sense and quantify the eggs in a blind scenario using an IR-UWB detection system. A flow setup of a simple detection mechanism is presented in Figure 4-57 in which the RCCs are first examined to determine if they will drop below a threshold of 0.7 and hence eggs are covering the sensors. However, if the RCCs of all four sensors (only four sensors are studied in this instance) remain high, then the CCCs are implemented whether or there is an egg between them based on a defined threshold of different CCCs. By inspection of Figure 4-57, no more than four logic outputs can give a true binary value.

Figure 4-57: Blind test detection mechanism
4.5.1 Test 1 – One egg above sensor 1

In this simple test, just one egg is placed over sensor 1 (x = 0 mm, y = 0 mm). The values of RCC for sensors 1, 2, 5, 6 and CCCs of sensors 1 and 2, 1 and 5, 1 and 6 and 2 and 6 are presented in Table 4-3 along with their corresponding binary decisions of high/low and a threshold of 0.7 has been chosen for the parameters of RCC of all four sensors and CCC of adjacent sensors in the either the x or y direction and 0.85 for the CCC of sensors in the diagonal direction, which is between sensors 1 and 6, to make this decision. Clearly, as expected, the RCC of sensor 1 is low indicating there is an egg above the sensor 1, while all other values of RCC and CCC are high except for CCC of sensors 1 and 6, though it is as high as about 0.8. However, the low value in the CCC of sensors 1 and 6 provides a meaningless effect on the egg sensing as the RCCs of the four sensors are highly reliable and it is not possible to have a second egg in the middle of sensors 1 and 6 owing to the topology of sensors and the egg box being tested.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(\rho_{Rx1Tx1})</th>
<th>(\rho_{Rx2Tx2})</th>
<th>(\rho_{Rx5Tx5})</th>
<th>(\rho_{Rx6Tx6})</th>
<th>(\rho_{Rx2Tx1})</th>
<th>(\rho_{Rx5Tx1})</th>
<th>(\rho_{Rx6Tx1})</th>
<th>(\rho_{Rx6Tx2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-0.7894</td>
<td>0.9699</td>
<td>0.959</td>
<td>0.9769</td>
<td>0.8919</td>
<td>0.8129</td>
<td>0.8004</td>
<td>0.9126</td>
</tr>
<tr>
<td>Binary State</td>
<td>LOW</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>LOW</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

Table 4-3: Resolved correlation and binary decision values for test 1

4.5.2 Test 2 – One egg in the centre of four sensors

In the same manner as in section 4.5.1, the value for test 2 where one egg is at the coordinate (x = 25 mm and y = 25 mm) is given in Table 4-4. All extracted RCCs of four sensors are relatively high, indicating there is no egg in the detected region of these four sensors and the CCC parameters in the either x or y directions also show binary high, indicating that there are no eggs between them. While with the help of CCC of sensors 1 and 6, the egg in the dead zone of these four sensors can be well retrieved.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(\rho_{Rx1Tx1})</th>
<th>(\rho_{Rx2Tx2})</th>
<th>(\rho_{Rx5Tx5})</th>
<th>(\rho_{Rx6Tx6})</th>
<th>(\rho_{Rx2Tx1})</th>
<th>(\rho_{Rx5Tx1})</th>
<th>(\rho_{Rx6Tx1})</th>
<th>(\rho_{Rx6Tx2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.9723</td>
<td>0.9598</td>
<td>0.9191</td>
<td>0.9616</td>
<td>0.9353</td>
<td>0.7495</td>
<td>0.7421</td>
<td>0.7712</td>
</tr>
<tr>
<td>Binary State</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>LOW</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

Table 4-4: Resolved correlation and binary decision values for test 2

4.5.3 Test 3 – Two eggs in the skewed egg box

The third test is to investigate RCCs and CCCs when the egg box containing two eggs is skewed 45°, anti-clockwise as given in Figure 4-58. The measured RCCs and CCCs for test 3 are given in
Table 4-5. As can be seen from the RCCs, correlation significantly below the threshold can be observed from sensors 1 and 6, indicating that there are two eggs located in the detection region of both sensors. In the same manner as in test 1, though the CCCs of sensors 1 and 5 as well as 1 and 6 are in binary low, the results are less reliable as it is not possible to have another egg in the middle of these sensors in this case.

![Figure 4-58: Plot of third blind test (dashed line: egg box)](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\rho_{Rx1Tx1}$</th>
<th>$\rho_{Rx2Tx2}$</th>
<th>$\rho_{Rx5Tx5}$</th>
<th>$\rho_{Rx6Tx6}$</th>
<th>$\rho_{Rx2Tx1}$</th>
<th>$\rho_{Rx5Tx1}$</th>
<th>$\rho_{Rx6Tx1}$</th>
<th>$\rho_{Rx6Tx2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-0.7145</td>
<td>0.9047</td>
<td>0.9341</td>
<td>0.1777</td>
<td>0.7965</td>
<td>0.7125</td>
<td>0.734</td>
<td>0.7865</td>
</tr>
<tr>
<td>Binary State</td>
<td>LOW</td>
<td>HIGH</td>
<td>HIGH</td>
<td>LOW</td>
<td>HIGH</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

Table 4-5: Resolved correlation and binary decision values for test 3

4.6 Summary

The details of UWB in fridge sensors and the study of egg detection inside a fridge scenario have been presented. Two cases were considered here where the eggs are directly above specific sensors or in the random locations between sensors. For the case of eggs placed directly above the sensors, both simulated and measured reflection coefficient and group delay information of the sensors provided sufficient data contributing the possibility of determining their quantity and corresponding configuration. Though this was applied to just four eggs, the same method is still applicable to any size of egg box. Where the eggs were in a random position, the RCC alone was insufficient to determine the quantity of eggs as a dead zone existed in the middle area between the two sensors. Using the CCC in addition, however, the presence of eggs could be known if they laid between two sensors, providing an opportunity to detect the presence of eggs together with the RCC information. This provides a robust solution when the egg box is placed in a random position and orientation, which can support a solution for smart packaging. Though it appears that
knowledge about eggs can be well retrieved regardless of where they are placed above the sensors, more general scenarios need to be evaluated where a variety of other foods surround the eggs, which will be presented in the next chapter.

The measured results presented here have been taken in the frequency domain using a VNA, however in a practical system the measurement would be made using an IR-UWB based system with time domain data being recorded and the frequency domain data being derived through the use of Fast Fourier Transform (FFT), a proposed system is described in Chapter 7. It is also possible to use time domain correlation data as an additional source of identification which is given in the future work in Chapter 7. The time domain signal can be generated and received by low cost IR-UWB radios and further processed by digital signal processor (DSP) module.
Chapter 5

5 Near Field Egg Detection in Cluttered Conditions

With implementation of several in-fridge sensors on the shelf components, the locations and quantities of eggs in the reactive near field have been obtained in the preceding chapter. The reflection coefficient and coupling information showed the promising ability to retrieve this information about the eggs, no matter what the static position of the eggs was over the sensors. However, the measurement environment considered was clutter free in which only a box of eggs was inside the fridge, which requires further experimentation for situations where the fridge is heavily cluttered.

This Chapter presents the measurement campaigns of egg detection for a cluttered fridge scenario in which a variety of other foods are placed around or above a box of eggs. Such tests are carried out in a way to determine instances where the presence and position of other food could cause the egg quantity detection method derived in the previous chapter to output an error. As an initial step, the effect of a general clutter situation involving different combinations of food with different topologies of three eggs will be detailed. Beyond this, the effect of extreme situations will be investigated in which different quantities of eggs are placed between sensors accompanied by two bottles of water located at both sides. Similar to the previous chapter, the effect of both scenarios on egg detection will be analysed by evaluation of the magnitude and phase of the measured S-parameters.

5.1 Effect of general clutter

In order to study the effect of common foods on the eggs and the degree to which the performance of egg detection deteriorates, ten types of food, being either fruit-based, bread-based or liquid-based, are randomly combined and used to form ten different scenarios where other foods are placed on top of or to the side of the egg box. Five metrics are compared in this study to show how reliable the approach is for these ten clutter scenarios, which are reflection coefficient correlation (RCC) of the original sensor and the sensor in the x and y direction, and the coupling correlation coefficient (CCC) between adjacent separated sensors in the x and y directions.
5.1.1 Experimental setup for detection of a single egg

A schematic plot of the measurement setup is shown in Figure 5-1 in which the egg box is surrounded by other food containing only one egg as a typical case study. The effect of other food will be studied when the egg is above sensor 10, in the middle of sensor 10 and 14, and above sensor 14. Ten different foods with their combinations are supposed to reflect a real fridge usage scenario as given in Table 5-1. These ten kinds of scenarios are proposed to be placed next to and above the egg box. S-parameters of sensor 10, $S_{1010}$, sensor 11, $S_{1111}$, sensor 14, $S_{1414}$, cross talk between two adjacent sensors in $x$ direction, $S_{1011}$, and separated sensors in the $y$ direction, $S_{1014}$, are measured using a vector network analyser (VNA). Correlation used in the previous case as a key parameter is evaluated by comparing between the case with only eggs present and eggs present with surrounding food or clutter. The mathematical definition can be expressed as:

$$
\rho_{RxTx_j \_cl} = \frac{E[S_{RxTx_jclutter} S^{*}_{RxTx_jegg}] - E[S_{RxTx_jclutter}] E[S^{*}_{RxTx_jegg}]}{\sqrt{\sigma_{S_{RxTx_jclutter}}^{2} \sigma_{S_{RxTx_jegg}}^{2} \sigma_{S_{RxTx_jclutter}}^{2} \sigma_{S_{RxTx_jegg}}^{2}}} \quad (5.1)
$$

where $S_{RxTx_jclutter}$ and $S_{RxTx_jegg}$ are S-parameters between transmitter $j$ and receiver $i$ in the case of egg with clutter and egg only, respectively. Further to this, in order to better interpret the variation involved in different scenarios quantitatively, the coefficient of variation (CV) is introduced as it is a measure of variability of a series of numbers [Abd10]. It has the unique advantage of being unitless as two sets of data can be compared with different measures, which is suitable for observation of the variation of correlation caused by the ten different scenarios. The expression of CV can be written as [Abd10]:

$$
C_v = \frac{S}{M} * 100 \% \quad (5.2)
$$

where $C_v$ is the coefficient of variation in percentage format, and $S$ and $M$ are the standard deviation and mean, respectively. In the case of eggs in cluttered scenarios, CV can be expressed as:

$$
C_{v_RxTx_j} = \frac{S}{\rho_{RxTx_j}} * 100 \% \quad (5.3)
$$
where $C_{\rho_p}$ is the CV the of correlation coefficient between $T_{x_j}$ and $R_{x_i}$ in percentage format, and $S_{\rho_{R_{x_i}T_{x_j}}}$ and $M_{\rho_{R_{x_i}T_{x_j}}}$ are the standard deviation and mean of the correlation coefficient between transmitter $j$ and receiver $i$ in different scenarios, given as:

$$S_{\rho_{R_{x_i}T_{x_j}}} = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left( \rho_{R_{x_i}T_{x_j}, cl} (k) - M_{\rho_{R_{x_i}T_{x_j}, cl} (k)} \right)^2}$$ (5.4)

where $N$ denotes the number of measurement scenarios, $k$ is the $k^{th}$ measurement campaign and $\rho_{R_{x_i}T_{x_j}, cl} (k)$ is the correlation coefficient for the $k^{th}$ measurement campaign. The mean is derived as follows:

$$M_{\rho_{R_{x_i}T_{x_j}(k)}} = \frac{1}{N} \sum_{k=1}^{N} \rho_{R_{x_i}T_{x_j}, cl} (k)$$ (5.5)
5.1.2 Effect of food adjoined to the egg box containing a single egg

Figure 5-2 illustrates the different scenarios when an egg is positioned above sensor 10. Five parameters $s_{1010}$, $s_{1011}$, $s_{1014}$, $s_{1111}$ and $s_{1414}$ are deduced by comparison between the egg only case and the egg with clutter case, as shown in Figures 5-3 to 5-5.

Figure 5-2: Photograph of ten scenarios when food is adjacent to the egg box
Chapter 5: Near Field Egg Detection in Cluttered Conditions

Figure 5-3: Correlation coefficient for different food clutter scenarios around the egg box when the egg is above sensor 10

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_v$</td>
<td>3%</td>
<td>1.88%</td>
<td>1.86%</td>
<td>0.74%</td>
<td>0.09%</td>
</tr>
</tbody>
</table>

Table 5-2: Coefficient of variation (CV) when egg is directly above sensor 10

High correlation, largely above 0.9 but no lower than 0.85, can be observed in the RCC parameters and also the CCC parameter, $\rho_{Rx14Tx10_cl}$. The consistency over all these scenarios is validated by the CV parameter where the largest for $\rho_{Rx10Tx10_cl}$ is 3%. This indicates that though the clutter has the most effect on the RCC of sensor 10 when the egg is above the sensor, with some correlations falling below 0.9 when comparing the clutter effect, such effect is negligible because the RCC itself is already at its lowest value. Though there is some free space over sensors 11 and 10 due to the egg box, $\rho_{Rx11Tx10_cl}$ frequently falls below 0.9 though the CCC in this instance is not of interest as the egg is covering a single sensor and only RCC is required for detection. Correlations are otherwise not severely affected by the presence of clutter, largely due to the space above the critical sensor that is "reserved" by the egg box.
Figure 5-4: Correlation coefficient for different scenarios in case of food around the egg being in the middle of sensor 10 and 14.

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_v$</td>
<td>1.09%</td>
<td>9.86%</td>
<td>2.12%</td>
<td>1.43%</td>
<td>0.95%</td>
</tr>
</tbody>
</table>

Table 5-3: CV when egg is in the middle of sensors 10 and 14.

The same RCC and CCC values are plotted for the ten clutter scenarios in Figure 5-4 with an egg in between sensors 10 and 14. In such a position, the parameters $\rho_{\text{Rx10Tx10},\text{cl}}$, $\rho_{\text{Rx14Tx10},\text{cl}}$, and $\rho_{\text{Rx14Tx14},\text{cl}}$ are of great interest where the correlation is above 0.9 in all cases, thus will not affect detection of the egg in its position. For the other two parameters, $\rho_{\text{Rx11Tx11},\text{clutter}}$ is also higher than 0.9 though $\rho_{\text{Rx11Tx10},\text{cl}}$ drops as low as 0.59. The latter case is expected, as the clutter will directly affect coupling between sensors 10 and 11, which in some instances could cause egg detection in error.
Chapter 5: Near Field Egg Detection in Cluttered Conditions

Figure 5-5: Correlation coefficient for different scenarios in case of food is around the egg being above sensor 14

Table 5-4: CV when egg is above sensor 14

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_v$</td>
<td>41.24%</td>
<td>55%</td>
<td>7.12%</td>
<td>58.57%</td>
<td>1.23%</td>
</tr>
</tbody>
</table>

Figure 5-5 illustrates the correlation coefficient for different sensors when the egg is above sensor 14. Strong fluctuations can be observed from $\rho_{Rx10Tx10_{\text{cl}}}$, $\rho_{Rx11Tx10_{\text{cl}}}$ and $\rho_{Rx11Tx11_{\text{cl}}}$ while the other two parameters $\rho_{Rx14Tx10_{\text{cl}}}$ and $\rho_{Rx14Tx14_{\text{cl}}}$ are less affected by the other foods around the sensor. This phenomenon is also validated in the CV as high percentages are obtained in the first three parameters (i.e. 10/10 11/10 and 11/11) while the other two (i.e. 14/10 and 14/14) are relatively low. It is worth noting that the RCCs and CCC of sensors 10 and 11 are substantially reduced owing to the fact that the egg box has moved above sensor 14 leading to the other foods being merged into the territory of sensors 10 and 11. However, the ability to detect an egg above sensor 14 is not affected as its RCC is not disturbed, nor is the CCC between sensors 10 and 14 affected were the egg to be in between the two sensors.

5.1.3 Effect of food placed above the egg box containing a single egg

Apart from scenarios where food is placed around the egg, it is also assumed that food can be above the egg box in a cluttered fridge. Figure 5-6 illustrates ten scenarios in the case of food placed above the egg box. RCCs and CCCs are plotted in Figures 5-7 to 5-9.
Chapter 5: Near Field Egg Detection in Cluttered Conditions

Figure 5-6: Photograph of ten scenarios when food is placed above egg box

Figure 5-7: Correlation coefficient for different scenarios in case of food above the egg that is above sensor 10
When the egg is directly above sensor 10, the presence of other food above the egg has negligible effect on all five parameters, except $\rho_{Rx11Tx10,cl}$, which has a high CV above 3% as given in Table 5-5. As before, however, this parameter is not relevant when the egg is covering sensor 10 as only RCC values are of interest.

![Figure 5-8: Correlation coefficient for different scenarios in case of food is above the egg that is in the middle of sensor 10 and 14](image)

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>1.18%</td>
<td>3.27%</td>
<td>1.24%</td>
<td>0.29%</td>
<td>0.32%</td>
</tr>
</tbody>
</table>

**Table 5-5: CV when egg is directly above sensor 10**

When the egg is midway between sensors 10 and 14, the parameter $\rho_{Rx14Tx10,cl}$ is shown to drop as low as 0.83 in Figure 5-8, though this effect is negligible since the CCC when the egg is in this position will already be low and the egg will be successfully detected since the RCC values of sensors 10 and 14 are suitably high. Similar to the case with clutter around the egg box, $\rho_{Rx11Tx10,cl}$ is found to vary more significantly than any other parameters and falls below 0.78 in scenario 9, where the clutter is so great it is actually also surrounding the egg box. The other nine scenarios have less impact than this with correlations above 0.9 meaning clutter strictly above the egg box is not likely to cause detection error.

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>0.94%</td>
<td>7.14%</td>
<td>4.06%</td>
<td>0.83%</td>
<td>1.37%</td>
</tr>
</tbody>
</table>

**Table 5-6: CV when egg is midway between sensors 10 and 14**
Chapter 5: Near Field Egg Detection in Cluttered Conditions

Figure 5-9: Correlation coefficient for different scenarios in case of food above the egg that is above sensor 14

<table>
<thead>
<tr>
<th>Rx/Tx</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_v$</td>
<td>37.99%</td>
<td>8.75%</td>
<td>3.82%</td>
<td>4.48%</td>
<td>2.45%</td>
</tr>
</tbody>
</table>

Table 5-7: CV when egg is directly above sensor 14

As the egg is positioned over sensors 14, the majority of parameters are above 0.85, as shown in Figure 5-9. However, parameters such as $\rho_{Rx10Tx10\_cl}$, $\rho_{Rx11Tx10\_cl}$ and $\rho_{Rx11Tx11\_cl}$ are badly deteriorated in scenarios 9 and 10, causing a low correlation value and a high $C_v$, as given in Table 5-7. In tests 8 and 9, the bulk volume of clutter is too large to be placed entirely above the egg box and several parts of them surrounded the egg box as well. The extreme clutter does affect the RCCs of sensors 10 and 11 and the CCC between sensors 10 and 11 just as in the case when food surrounds the egg box. However, detection of the egg above sensor 14 in this instance is not affected, which will still yield a low RCC.

5.1.4 Discussion

The effect of general clutter both surrounding the eggs and above the eggs has been studied in this chapter. To summarise the CV of different topologies as given in Tables 5-8 to 5-9 as well as the correlation coefficient plots from Figures 5-3 to 5-9, the following aspects have been found:

- When the egg is above a specific sensor, the change in RCC and the adjacent CCC for that specific sensor are negligible when other foods are placed around or above the egg box owing to the domination of the egg on the sensor and the space “reserved” by the egg box.
Table 5-8 summarises the effect on RCC and CCC in the scenarios studied for clutter around the egg box by ignoring cases where the CV is low (below 5%) and then noting cases where CV has some effect (but still under 10%) and a high effect (above 10%). In the three cases of high effect, the results are of no interest since the egg box is no longer covering those sensors, thus an egg above sensor 14 is still detected, while the one point of interest is the case where 11/10 has some effect when the egg is in between sensors 10 and 14, which could lead to detection of an egg between sensors 10 and 11 in error. Therefore, the impact of clutter around the eggs is not significant where an egg is between two sensors as again the space is “reserved” by the egg box.

<table>
<thead>
<tr>
<th>Topology</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above sensor 10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>In the middle of sensor 10 and 14</td>
<td>-</td>
<td>Effect</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Above sensor 14</td>
<td>High Effect</td>
<td>High Effect</td>
<td>Effect</td>
<td>High Effect</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5-8: Summary of coefficient of variation when food is around the egg box

Table 5-9 summarises the effect on RCC and CCC in the scenarios studied for clutter around the egg box by ignoring cases where the CV is low (below 5%) and then noting cases where CV has some effect (but still under 10%) and a high effect (above 10%). Similar to Table 5-8, the effects on 10/10 and 11/10 are irrelevant when the egg is above sensor 14. Where the egg is between two sensors, 10 and 14, 11/10 again has an effect, which again could cause detection of an egg between sensors 10 and 11 to be in error. The extreme cases identified where error is vulnerable are when significantly large items, particularly liquids, are placed next to the edge of the egg box and as such sensors in use are exposed to clutter, which will be studied in the next section.

<table>
<thead>
<tr>
<th>Topology</th>
<th>10/10</th>
<th>11/10</th>
<th>14/10</th>
<th>11/11</th>
<th>14/14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above sensor 10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>In the middle of sensor 10 and 14</td>
<td>-</td>
<td>Effect</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Above sensor 14</td>
<td>High Effect</td>
<td>Effect</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5-9: Summary of coefficient of variation when food is above the egg box
5.2 Worst case scenarios

General clutter scenarios have been investigated in the above sections in which the topology of a single egg is considered. To define the location of eggs as well as their corresponding quantity when they are placed between adjacent sensors with two bottles of water at both sides of a box is a challenge and, as such, the worst case extreme scenarios where the eggs cannot be detected need to be identified. RCCs and CCCs are evaluated in this regard in the following sub sections.

5.2.1 Test setup of worst case scenarios

As shown in Figure 5-10, the locations of the eggs are deliberately positioned between the gap of two sensors with two bottles of water in the proximity of an egg box. Three different topologies are considered to include one egg between sensors 10 and 14 (CF1), one egg between sensors 14 and 18 (CF2), and both eggs present between their respective sensors (CF3). A real time measurement is illustrated in Figure 5-11 in which information of CF1 is measured. Two different correlation coefficients are evaluated corresponding to different references with mathematical expressions given where the first one is defined as the correlation comparing S-parameters in free space (i.e not covered by anything) with the case when only water is present:

\[
\rho_{Rx/Tx,\text{water}} = \frac{E[S_{Rx/Tx,\text{water}} S^*_{Rx/Tx,\text{free}}]}{\sqrt{\sigma^2_{Rx/Tx,\text{water}}} \sqrt{\sigma^2_{Rx/Tx,\text{free}}}} - E[S_{Rx/Tx,\text{water}}] E[S^*_{Rx/Tx,\text{free}}]
\]

(5.6)

The correlation comparing free space with the case when both water and eggs are present is defined as:

\[
\rho_{Rx/Tx,\text{water\_egg}} = \frac{E[S_{Rx/Tx,\text{water\_egg}} S^*_{Rx/Tx,\text{free}}]}{\sqrt{\sigma^2_{Rx/Tx,\text{water\_egg}}} \sqrt{\sigma^2_{Rx/Tx,\text{free}}}} - E[S_{Rx/Tx,\text{water\_egg}}] E[S^*_{Rx/Tx,\text{free}}]
\]

(5.7)

where \( S_{Rx/Tx,\text{water}} \) and \( S_{Rx/Tx,\text{water\_egg}} \) are the S parameters between the \( j^{th} \) transmitter and \( i^{th} \) receiver when water only and water with egg, respectively, and the variance of these two parameters are \( \sigma^2_{Rx/Tx,\text{water\_egg}} \) and \( \sigma^2_{Rx/Tx,\text{water\_egg}} \), respectively.
5.2.2 Results

Figure 5-12 illustrates the relationship between the free space and the water only scenario. Low correlation coefficients $s_{1010}$ and $s_{1014}$ result due to the presence of the water container on the right hand side. However, as can be seen from Figure 5-11, the water box on the left hand side does not interfere with the performance as significantly since the egg box causes blockage of intrusion into the territory of sensor 18, while the quantity of water is also lower. Sensor 14 itself is less affected as it is not close to the water.
Chapter 5: Near Field Egg Detection in Cluttered Conditions

Figure 5-12: Correlation coefficient $\rho_{Rx/Tx,\text{water}}$ between water only and free space

Figure 5-13: Correlation coefficient $\rho_{Rx/Tx,\text{wateregg}}$ referenced to free space of different configurations

A correlation coefficient with a low value between different configurations and the free space case is summarised in Table 5-10. Three parameters $\rho_{Rx10Tx10,\text{wateregg}}$, $\rho_{Rx14Tx10,\text{wateregg}}$, and $\rho_{Rx18Tx10,\text{wateregg}}$ are relatively sensitive and give low values regardless of configurations. However, parameters such as $\rho_{Rx10Tx10,\text{wateregg}}$ and $\rho_{Rx14Tx10,\text{wateregg}}$ are not reliable due to the effect of water as given in Figure 5-12. Therefore, it is difficult to sense the egg in the middle of sensors 10 and 14 (CF$_1$).
Chapter 5: Near Field Egg Detection in Cluttered Conditions

The egg in CF₂ can be successfully detected in terms of CCC between sensors 14 and 18 as this parameter is not affected by the water in a lower quantity. In the case where both eggs exist, the RCC of sensor 14 reduces to as low as 0.75 which can be explained by the sensor being surrounded by two eggs. The same phenomenon can be observed in the RCC of sensor 5 for the two eggs case when they are moved 25 mm in the y direction in Figure 4-25. Hence, it is possible to sense the presence of two eggs in the worst case by examination of the RCC of sensor 14. These results therefore show a clear case where large quantities of liquid close to an egg box may cause error while smaller quantities are less vulnerable. The reliability of near field UWB detection is therefore only tolerable where other solid items are placed above or around the egg box with small liquid content and the sensors are not directly under the object to be detected.

5.3 Summary

The effect of clutter has been presented in this Chapter in which two egg configurations and 20 scenarios of food placed above or around the egg box have been considered. The worst cases have been presented in which eggs are placed between two sensors and clutter items containing high volumes of liquid are placed directly next to the egg box coming into close proximity of the sensors in use.

Where the egg is directly above a sensor, the RCC is not sensitive to such changes, while the CCC between sensors is more vulnerable. When the egg moves to the middle of two sensors in the y direction, the coupling information in the x direction varies significantly due to the existence of other food, while the CCC between two sensors in the y direction has little change since the egg dominates the covering of sensors. Thus, it may lead to error in sensing of the eggs in such positions. However, the presence of food clutter as solid items in general has little impact on the egg detection in the reactive near field.

It is clear from these results that where the position of the egg box is known, such as in a smart package application, and the sensors are fixed in relation to the package, a single sensor will still have the ability to detect an egg directly above it despite the effect of other clutter. This would therefore indicate that, in the case of a smart fridge, it would be desirable to position the egg box in a location within the fridge such that sensors can reliably detect the egg quantity when other clutter is present.
6 Liquid Volume Test

A comprehensive study of egg detection in the reactive near field has been carried out in the preceding chapters. The quantity of eggs and their geometry information have been determined in terms of correlation coefficient and group delay matrices in the clutter-free scenarios. Further to this, a study of egg quantity has been carried out in the general clutter scenarios with a variety of foods placed on top of and surrounding the eggs. In the case of eggs being above a sensor with surrounding clutter, the egg information can still be well retrieved in terms of reflection coefficient correlation (RCC). However, the egg detection could lead to error if the egg is in the middle of two sensors while the clutter is around the egg box. The same problem can be found in the worst case situation where the eggs located in the middle of two sensors are surrounded by items containing liquid. To determine the number and location of eggs is one useful application of near field ultra wideband (UWB) detection in a smart fridge and other forms of smart container.

To obtain knowledge of the level of liquid within a container in a non-destructive way is a further useful application of near field UWB detection not only in a smart fridge scenario but other cases where quantities of liquid have to be monitored within a smart container for liquids.

This chapter will present measurement setups reflecting real scenarios involving various drinks or liquids in a smart fridge scenario as the test platform in which S-parameters are recorded in association with different volumes of liquid and orientations of the container. Unlike previous chapters where only the real parts of the correlation coefficients are implemented, the effect of liquid quantity has an impact on the real, imaginary part (or phase) as well as the absolute value of the correlation coefficient. Therefore, volume of liquid is measured using the phase information from the coupling correlation coefficient between adjacent sensors.

6.1 Test Setup

The liquid volume detection consists of three orientation scenarios including where the container or bottle is horizontal within the fridge, vertical within the fridge and vertical within the fridge door, which in all three cases will affect how the bottle interacts with the sensors. The S-parameters and their phase information for each of the sensors are measured with a vector network analyser (VNA). Five typical drink containers or bottles were investigated, which respectively contained 1.5 litres of water, 2 litres of coke, 4 pints of milk, 1 pint of milk and 1 litre of...
of fruit juice (Figure 6-1). For each container or bottle, measurements were conducted where the volume of liquid inside was full (100%), three quarters full (75%), half full (50%), one quarter full (25%), nearly empty (10%) and completely empty (0%) (see Figure 6-2). Table 6-1 lists the orientations that were measured based on how such containers would be typically placed into a fridge. Unlike an empty egg box, which has a negligible effect on the S-parameters when placed on top of the sensors, an empty bottle or container had a higher dielectric constant and thickness, which had some effect. For this reason, the correlation coefficient for liquid detection is defined as:

\[
\rho_{R_sT_{xi, liquid}} = \frac{E[S_{R_sT_{xi, liquid}}] - E[S_{R_sT_{xi, box}}]}{\sqrt{\sigma^2[S_{R_sT_{xi, liquid}}]} \cdot \sqrt{\sigma^2[S_{R_sT_{xi, box}}]}}
\]

(6.1)

where \( S_{R_sT_{xi, liquid}} \) and \( S_{R_sT_{xi, box}} \) are S-parameters between transmitter \( i \) and receiver \( j \) in the case of a container with some liquid and an empty container, respectively. The phase information of the two sensors can be written as:

\[
\phi_{\rho_{R_sT_{xi, liquid}}} = \tan^{-1}\left(\frac{\text{imag}(\rho_{R_sT_{xi, liquid}})}{\text{real}(\rho_{R_sT_{xi, liquid}})}\right)
\]

(6.2)

where \( \text{real}(x) \) and \( \text{imag}(x) \) denote the real and imaginary parts of complex number \( x \).
Figure 6-1: Photograph of liquids under test

Figure 6-2: Tested volume of liquid: (a) Full, 100%; (b) three quarters full, 75%; (c) half full, 50%; (d) one quarter full, 25%; (e) nearly empty, 10%; and (f) empty, 0% (dashed line: liquid surface)

<table>
<thead>
<tr>
<th>Drink</th>
<th>Horizontal inside fridge</th>
<th>Vertical inside fridge</th>
<th>Vertical on the fridge door</th>
</tr>
</thead>
<tbody>
<tr>
<td>One pint milk</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Four pint milk</td>
<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>1.5L water</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>1L Fruit Juice</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>2L Coke</td>
<td>√</td>
<td>√</td>
<td></td>
</tr>
</tbody>
</table>

Table 6-1: Practical drink layout
6.2 Measurement results

Measurement results are presented in this section for five drinks with different liquid levels in different orientations. Both the magnitude and phase of the correlation coefficient are used to obtain knowledge of the liquid level.

6.2.1 One pint of milk case

In this section, one pint of milk is studied in two orientations, including vertical inside the fridge and vertical on the fridge door. It would often be impractical to normally orientate such a container horizontally, especially after opening. Sensors 2, 6, 10 and 14 are of the most interest for both orientations being the sensors in proximity to the container as shown in Figures 6-3 and 6-9. Correlation results and phase information are evaluated for both orientations.

6.2.1.1 Vertical orientation inside the fridge

Figure 6-3: (a) Schematic and (b) photograph of one pint of milk in a vertical orientation positioned on sensor 10
Chapter 6: Liquid Volume Test

Figure 6-4: (a) Real part, (b) imaginary part and (c) absolute correlation map of one pint of milk vertically positioned on the shelf of a fridge.

Figure 6-4 illustrates the correlation coefficient related to one pint of milk in a vertical orientation on the shelf. Five parameters including the reflection coefficient correlation (RCC) of sensors 6, 10 and 14 ($\rho_{Rx6Tx6\_liquid}$, $\rho_{Rx10Tx10\_liquid}$, $\rho_{Rx14Tx14\_liquid}$), and the coupling coefficient correlation (CCC) of sensors 6 and 10 as well as 10 and 14 ($\rho_{Rx6Tx10\_liquid}$ and $\rho_{Rx14Tx10\_liquid}$) are used here as the milk is mainly positioned above sensor 10. It is worth noting that the real part reflects the value of the cosine of the phase, while the imaginary part is for the sine of the phase. Values less than a threshold of 0.7 can be observed from the real part of parameters $\rho_{Rx6Tx6\_liquid}$, $\rho_{Rx10Tx10\_liquid}$ and $\rho_{Rx6Tx10\_liquid}$. This can be explained by the orientation of the milk, as shown in Figure 6-3(b), where the container is directly above sensor 10 and a considerable part of the container covers sensor 6. A correlation value as high as 0.8 can be observed from the imaginary part of parameters.
\( \rho_{Rx6Tx10\_liquid} \) and \( \rho_{Rx10Tx10\_liquid} \) owing to a large averaged phase difference. However, the quantity of milk is still unknown as these parameters remain largely constant regardless of the volume of milk.

In order to ascertain the milk quantity, the phase of CCC as a measure of the averaged phase offset among different milk levels is evaluated from the measured real and imaginary parts of the correlation coefficients \( \rho_{Rx6Tx10\_liquid} \) and \( \rho_{Rx14Tx10\_liquid} \). Figure 6-5 illustrates the relationship between the phase and milk level for these two parameters. It can be seen that the phase angle of \( \rho_{Rx6Tx10\_liquid} \) is relatively flat when the milk level is more than 10%, but a significant drop by 10° can be found when the milk level is less than 10%. The phase of parameter \( \rho_{Rx14Tx10\_liquid} \) on the other hand reveals that the correlation angle is almost proportional to the liquid level. The discrepancy is caused by two reasons: one is the asymmetric milk carton causing the coupling characteristics from sensor 10 to be different to sensors 6 and 14, which is also validated through the RCC of sensors 6 and 14 such that a lower real part and a higher imaginary part are observed from sensor 6 in comparison to that of sensor 14. Another reason is the difference in the mutual coupling \( S_{Rx6Tx10} \) and \( S_{Rx14Tx10} \). Figure 6-6 illustrates the plot of both measured coupling parameters when the milk bottle is empty. In the band of interest from 3 GHz to 5 GHz, a difference can be observed over 4 GHz as a significant valley can be observed at 4.4 GHz for \( S_{Rx6Tx10} \) and \( S_{Rx14Tx10} \). The magnitude and phase of \( S_{Rx6Tx10} \) with different milk levels are plotted in Figure 6-7 in which multiple resonances phenomenon occurs at 3.2 GHz, 3.5 GHz, 4.05 GHz, 4.5 GHz and 4.9 GHz when the level is full and resonance behaviours become weaker as the fill level decreases with a trend of closing to the curve of the empty bottle case from Figure 6-7 (a). These resonances also contribute to the discontinuity in the phase response, as given in Figure 6-7 (b), and thus a relatively constant angle when the level is more than 25% in \( S_{Rx6Tx10} \) in Figure 6-5. Due to the first reason, there is not a significant number of resonances in the magnitude of cross coupling \( S_{Rx14Tx10} \) revealed in Figure 6-8 (a) and the curves relating to different levels have the same resonant frequencies at 3.2 GHz, 3.7 GHz and 4.1 GHz. This therefore leads to a high similarity in the real part of CCC but a slight difference in the phase part due to different level in the resonance frequency causing a relatively low angle compared to that of \( S_{Rx6Tx10} \). Nevertheless, the level when nearly empty contributes to a low degree, no matter what the parameters are.
Figure 6-5: Phase of $\rho_{Rx6Tx10,\text{liquid}}$ and $\rho_{Rx14Tx10,\text{liquid}}$ vs. one pint of milk level

Figure 6-6: Measured cross coupling parameters $S_{Rx6Tx10}$ and $S_{Rx14Tx10}$ of empty bottle case
Figure 6-7: (a) Magnitude and (b) phase of cross coupling $S_{Rx6Tx10}$ related to different milk levels
Figure 6-8: (a) Magnitude and (b) phase of cross coupling $S_{Rx14/Tx10}$ related to different milk levels
6.2.1.2 Vertically oriented inside the fridge door

The correlation map of one pint of milk orientated vertically in the door of a fridge is shown in Figure 6-10. The RCC of the three sensors, $\rho_{Rx2Tx2\text{-liquid}}$, $\rho_{Rx6Tx6\text{-liquid}}$ and $\rho_{Rx10Tx10\text{-liquid}}$ are more significant in this setup when detecting the milk quantity as shown in Figure 6-9. When the level of milk falls below one specific sensor, the real part of that sensor returns a high correlation value, while it was low beforehand, as shown in Figure 6-10 (a). Interestingly, as shown in Figure 6-10 (b), the inverse is the case such that that a phase inversion, rather than a change in magnitude, is being caused to the reflection coefficient when liquid is taken away or introduced. Therefore, the liquid does not absorb the incident fields as it is a dielectric but rather has an impact on the phase of the reflection over the whole measurement band. This, therefore, provides a reliable way to distinguish the quantity of milk in terms of RCC information alone.

![Figure 6-9: (a) Schematic and (b) photograph of one pint of milk in a vertical orientation placed in the door of a fridge](image)
6.2.2 Four pint milk container case

In this section, a four pint milk container is analysed for the scenario of being placed in the fridge door. It is uncommon to place a four pint of milk horizontally on the fridge shelf as the milk can spill while vertically on the shelf is not practical for many fridges. Therefore, only the scenario where the container is oriented vertically in the fridge door is analysed here.
Figure 6-11: (a) Schematic and (b) photograph of four pints of milk vertically oriented inside the fridge door

Figure 6-12: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{x,y,\text{liquid}}$ map of four pints of milk in vertical orientation in the door of the fridge
The parameters in the second column of the in-fridge sensors are investigated including six RCC parameters of sensors 2, 6, 10, 14, 18 and 22 and two CCC parameters between sensor 6 and 10 as well as sensor 10 and 14. Similar to the results in Figure 6-10, the measured results of a four pint milk container further validate the possibility of determining the level in terms of the RCC since the real part of the correlation coefficient becomes high while the imaginary part is close to 0 when the level falls below the sensor. The inverse is true for the imaginary part for the same reasons explained for a one pint milk container.

6.2.3 1.5L water case

In this section, a plastic box of water of 1.5 litres is used as the third prototype of this study. Two possible orientations are considered here, which are horizontal inside fridge and vertical in the fridge door. Measured correlation coefficient map as well as phase information are evaluated.

6.2.3.1 Horizontal inside the fridge

The real part of the RCC of all six sensors has a low value as expected due to the orientation of the bottle shown in Figure 6-13 and 6-14. However, as with the situation discussed in section 6.2.1.1, both RCC and CCC are independent of the water level in this orientation.

![Figure 6-13: (a) Schematic and (b) photograph of water in horizontal orientation inside the fridge](image)
Figure 6-14: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{Rx/Tx,\text{liquid}}$ map of water horizontally positioned inside the fridge.
The phase of $\rho_{Rx6Tx10\_liquid}$ and $\rho_{Rx14Tx10\_liquid}$ are plotted in Figure 6-15. As can be seen, the angle of coupling correlation coefficient gradually increases as the level becomes high. These two parameters have high similarity when the level is no more than 50% as the angle converges to 20° when the level is as low as 10%, while a large margin with about 15° in phase difference can be seen when the level is larger than 50%. This is mainly due to the mutual coupling characteristic in $S_{Rx6Tx10}$ and $S_{Rx14Tx10}$ discussed in the one pint of milk scenario. Therefore, to utilise parameter $\rho_{Rx14Tx10\_liquid}$ will be a better solution to sense the level of liquid.

6.2.3.2 Vertically oriented inside the fridge door

![Figure 6-16: (a) Schematic and (b) photograph of water vertically in the fridge door](image)
Chapter 6: Liquid Volume Test

Figure 6-17: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{Rx/Tx_{\text{liquid}}}$ map of water vertically oriented in the fridge door

A photograph of water in the vertical orientation in the fridge door is shown in Figure 6-16 with the corresponding correlation coefficient map plotted in Figure 6-17. Analogous to the findings in Figure 6-10 and 6-12, it is the case that the volume of water can be easily obtained in terms of the real part of RCC.

6.2.4 1L fruit juice case

One litre of fruit juice is chosen as the fourth sample in the study of liquid volume detection in a non-invasive way. Two orientations are considered, which are horizontal inside the fridge (Figure 6-18) and vertical inside the fridge (Figure 6-20). Measured correlation coefficient values are evaluated and discussed in the following sub-sections.
6.2.4.1 Horizontal inside the fridge

Figure 6-18: (a) Schematic and (b) photograph of fruit juice horizontally orientated inside the fridge

Figure 6-19: Real part of the correlation $\rho_{Rx/Tx, liquid}$ map of fruit juice horizontally positioned on the shelf of the fridge

The real part of the RCC and CCC of fruit juice has a highly scattered distribution of values over the correlation map bearing no relation to the volume of liquid and what is measured. The main reason is the conductive coating inside the fruit juice box used to maintain the freshness of the juice. The coupling into the carton is therefore weakened and this unfortunately leads to failure to detect the level of juice in such scenarios.
6.2.4.2 Vertically oriented inside the fridge

Figure 6-20: (a) Schematic and (b) photograph of fruit juice container vertically oriented inside the fridge

Figure 6-21: Real part of correlation $\rho_{Rx/Tx_{\text{liquid}}}$ map of fruit juice vertically placed on the shelf

In comparison to Figure 6-19, all parameters in Figure 6-21 are larger than 0.9 overall due to the metal coating, which again causes the failure to detect the juice quantity.

6.2.5 Two litre of Coke case

A two litre coke bottle, which is chosen as the last prototype drink of this study is measured in two possible topologies, including horizontal inside the fridge (Figure 6-22) and vertically orientated inside the door (Figure 6-25). The bottle of coke is mainly positioned over the second column of sensors and therefore S-parameters are recorded to evaluate the correlation map.
6.2.5.1 Horizontal inside the fridge

Figure 6-22: (a) Schematic and (b) photograph of coke horizontally oriented inside the fridge

Figure 6-23: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{Rx/Tx, liquid}$ map of coke horizontally positioned inside the fridge
A correlation map of coke in the horizontal orientation is presented in Figure 6-23. As can be seen, all values of the real part are relatively low, at no larger than -0.6. Meanwhile, the majority of values of the imaginary part are less than 0.8. The parameter $\rho_{Rx2Tx2_{\text{liquid}}}$ is exceptionally different as sensor 2 covers the bottom edge of the bottle, which is a different shape of bottle compared to the other sensors. Therefore, the correlation becomes high for sensor 2 when the quantity of coke is less than three quarters and the same pattern can be found in the map of the absolute correlation in Figure 6-23(c). Nevertheless, information related to quantity is ambiguous as both RCC and CCC maintain a constant magnitude regardless of level across the remaining sensors.

Similar to earlier, the level of coke can be well defined in terms of the phase of the coupling correlation coefficient. The relationship between liquid level and the phase of $\rho_{Rx6Tx10_{\text{liquid}}}$ is almost linear; however, the maximum phase offset is about 13°. The phase of $\rho_{Rx14Tx10_{\text{liquid}}}$ is almost the same with that $\rho_{Rx6Tx10_{\text{liquid}}}$ at an angle of 25° when the quantity is no more than 25%. However, an average phase difference of 20° can be observed in both parameters when the level is larger than 50%. The reason for this has been explained in the scenario with water in the horizontal case.

![Figure 6-24: Phase of $\rho_{Rx6Tx10_{\text{liquid}}}$ and $\rho_{Rx14Tx10_{\text{liquid}}}$ vs. coke level](image)

### 6.2.5.2 Vertically oriented inside the fridge door

The correlation map relating to different liquid levels with vertical orientation in the fridge door is plotted in Figure 6-26. In terms of the real part of the correlation coefficient, the level of coke can be well determined with a very high correlation in the case where level is below the height of the sensor.
Figure 6-25: (a) Schematic and (b) photograph of coke bottle with vertical orientation inside the fridge door.
Figure 6-26: (a) Real part, (b) imaginary part and (c) absolute part of correlation $\rho_{Rx/Tx, liquid}$ map of coke vertically positioned inside the fridge door

6.3 Discussion

A study of liquid levels in various topologies has been investigated in this chapter. The following points can be found:

- In the case of a bottle positioned vertically with sensors positioned along the height, the liquid level has a significant impact on the real part of the RCC of each sensor. This is based on a direct detuning and group delay on each sensor where liquid is in close proximity, which is verified in the experiments. Therefore, the quantity of drink can be ascertained in terms of RCC of each sensor.
- In the case of drink located vertically and horizontally on top of a plane of sensors, the real,
imaginary and absolute part of the RCC and CCC is relatively constant regardless of liquid level. This is also expected due to the impact of dielectric loading on the sensors, caused by the liquid, which is a dielectric material and this loading will not change regardless of the volume. The phase of CCCs $\rho_{Rx6Tx10\_liquid}$ and $\rho_{Rx14Tx10\_liquid}$ relating to different liquid level for different scenarios is shown in Figure 6-27. There are three main findings: firstly, the overall angle of $\rho_{Rx6Tx10\_liquid}$ is less than $\rho_{Rx14Tx10\_liquid}$ which can be explained by the different coupling characteristics thus, the phase of coupling between sensors 10 and 14 is more sensitive. Secondly, large differences can be observed in $\rho_{Rx14Tx10\_liquid}$ as it is 60° for coke, 40° for water and 20° for one pint of milk. One reason for this discrepancy is the difference in the dielectric constant of these three drinks as coke is a carbonated drink with high sugar content and milk is a combination of water, lactose, fat and protein. Another factor is the height above sensors as the absolute volume for different levels when comparing drinks is not the same. Lastly, the phase angle reduces with liquid level. Deep interpretation of this phenomenon is based on the theoretical increase in phase delay through a dielectric medium as the volume increases, which results in several strong resonances and causes significant difference in the magnitude as well as the phase. This inevitably contributes to a lower real part and a higher imaginary part of CCC, thus producing a large phase angle. It can be seen that for all scenarios, the angle converges to 19–25° except for $\rho_{Rx14Tx10\_liquid}$ of one pint of milk caused by the asymmetric shape of the carton. Using this information, the level of liquid of a container on top of a plane of sensors can be resolved by encompassing of the phase of both CCCs, though error is vulnerable in the case when the level is less than 25%.

![Figure 6-27: Phase of $\rho_{Rx6Tx10\_liquid}$ and $\rho_{Rx14Tx10\_liquid}$ related to different liquids at different levels](image)
6.4 Summary

A feasibility study to determine the liquid volume in a smart liquid container using ultra wideband sensors in the reactive near field has been presented in this chapter. Five typical drink containers or bottles were chosen in this study, including one pint of milk, four pints of milk, fruit juice, water and coke. According to real scenarios, the drinks were considered in three orientations, which are vertical on the shelf, horizontal on the shelf and vertical inside the fridge door. These also correspond to how the sensors could be positioned on a smart container for liquid. The volume of four kinds of drink were used in this study, while one example case for a fruit juice container failed to work due to the metal coating inside the box. The level of drink with vertical orientation inside the fridge door is relatively simple using the real part of RCC, while the scenarios where the container is vertical or horizontal on the shelf of the fridge, the additional complexity of the phase of the CCC is required to provide a solution to estimate the volume of liquid.
Chapter 7

7 Conclusions and Future Work

In this research, consideration was given to detection methods where primarily the detection of egg quantity in a smart fridge was used as the main test platform while the quantity of liquids was considered later in the study.

As an initial study methodology, complex natural poles based ultra wideband (UWB) target detection was reviewed and the limitations were found to be that it is insufficient to discriminate similar objects in which different quantities of eggs are used as a prototype. The characteristic polarisation states (CPSs) are then implemented to overcome the issue revealing the characteristic angle is inversely proportional to the quantity of eggs. The limitations of the CPS approach are clearly defined from the consideration of size, complexity of antenna and post processing, thus, leading to the difficulty of detecting targets when they are close to the sensors, most notably the minimum late time required.

Having established the unsuitability of CPS, a new non-radar domain was moved to whereby filtering is applied directly to the UWB impulse response through both absorption and de-tuning when eggs are placed on top of a sensor or in close proximity. In evaluating this filtering, reflection coefficient correlation (RCC) and coupling coefficient correlation (CCC) are derived and implemented to quantify targets in the reactive near field. Through the measurements and simulations carried out, the robustness of correlation-based approaches was examined, which displayed reliability in terms of when the eggs are positioned both on top of or in close proximity to a sensor. Use of both RCC and CCC provides the opportunity to detect the presence of eggs due to their strongly changing characteristics compared to no eggs present regardless of where they are positioned in relation to the sensors. Trials were also carried out to analyse the impact of clutter, where it was found that there was negligible effect in the majority of cases with solid items placed on top of or next to the eggs being detected by their nearest sensors. The one instance where a significant effect occurred was where liquids in large volumes were placed next to the egg box and that led to the likelihood of detection error.

Finally, the study also extended to investigate the level of liquid in a container by examining the phase of complex correlation coefficient. For non-metallic containers made of dielectric material, this property was found to be a suitable metric for ascertaining the volume of liquid to the nearest
25% by investigation of the phase of the derived complex correlation coefficients. Through this study, the correlation-based approach has the advantage of low cost, simplicity and reliability as a solution to detection in the reactive near field.

UWB has been proved as an optimal radio frequency (RF) band for this technique. Due to the spectral mask of UWB and wide bandwidth, low cost radios for impulse radio ultra wideband (IR-UWB) without carrier can be implemented. The concept proved in the research has a promising prospective, whereby several carrierless IR-UWB transceiver modules integrated with a DSP module can be manufactured. The RF module shares the same antenna used as transmitter and receiver mode. The PIN diode which is controlled by direct current (DC) voltage can be used as a slow switch in the circuit. By deploying PIN diodes and DC blocking capacitors, the antenna can be easily switched between transmitter and receiver mode. The transmitter and receiver circuits can be made on the same board but in different areas as they consist of different components, such as a pulse generator for the transmitter part and low noise amplifier (LNA), band pass filter (BPF), sampler etc. for the receiver area. The received signals with a prior transmitted signal can be converted into frequency domain and then correlated using the DSP module. The correlation coefficients can be sent to the MCU, where the blind test flow diagrams demonstrated in Section 4.5 in Chapter 4 can be implemented for further evaluations.

There are also other ways to detect targets, such as optic-based detection system and ultrasound detection. The drawbacks of using camera in these applications are: a) high error rate as there exists some dead zone, b) algorithms necessary increase the complexity and c) cost increase due to the processing of images on chip. There are three main disadvantages by using ultrasonic detection: firstly, the size of detection system is inevitably bulky due to the size of the transducer. Secondly, ultrasonic sensors have a minimum sensing distance so the detection may fail when the target is in close proximity to the sensor. Thirdly, the ultrasonic sensor is sensitive to temperature, humidity, pressure and so on. In comparison to these two conventional detection approaches, reactive near field UWB detection has the advantages of low cost, low profile and reliability in a variety of environments. Furthermore, this technique can be adopted to the development of smart packaging integrated with radio frequency identification (RFID) tags containing general product information to build a comprehensive system.

### 7.1 Future Work

The following main areas of future work from this research have been identified:

- A vector network analyser (VNA) is used to measure the reflection coefficient and coupling coefficient in order to evaluate the RCC and CCC to obtain the quantity as well as the location of the eggs. However, the VNA will not be provided in practise. Therefore, a system
of using a low-cost UWB carrier-less impulse module as well as the post processing need to be designed, manufactured, validated and integrated with the real fridge case.

- Though a conventional UWB antenna has shown the ability to detect the presence of eggs and the volume of drink, it is still possible that the antennas could be further adapted to be low profile or fitted in with the aesthetics of the fridge. For this application, there would be more appropriate antenna designs and materials to use with different requirements, such as higher directionality and gain, which will yield different correlation coefficients, from which suitable calibration procedures can be carried out at the stage of development.

- The volume of a variety of drinks has been evaluated mainly above the nearest sensor as presented in Chapter 6. However, the ability to sense the volume of drink in cluttered scenarios is still unknown. Furthermore, it will be important to study the effect of drink volume detection in further random locations.

- Only two types of food or material have been investigated throughout the whole thesis, which are eggs and drinks. Other varieties of foods, such as vegetables and fruits, could be investigated further for the smart fridge scenario, which could further the capabilities of the smart fridge, which ultimately would contain smart containers for these purposes in which items are randomly positioned and approximate volumes need to be evaluated.

- Though the studies involved in the thesis show that the correlation coefficient can be a key parameter in the determination of the quantity and location of eggs, decision algorithms are required to develop precisely, for which an initial guess has been given in Chapter 4.

- The ability to detect eggs in the near field has been validated in this thesis. However, it lacks the ability to understand the type of food. Therefore, it is worth investigating the ability to classify different foods in the reactive near field.

- The applications can be applied to build a smart packages and smart containers for both solids and liquids thus leading to enhanced smart Internet of Things solutions. The smart packages/containers could be enabled potentially by passive and active solutions connected to the Internet. Examples are using a passive/active RFID tag to relay information about the package contents to a data hub or to have direct connectivity from the smart package to the Internet via a wireless or cable based fixed link.
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Author's Publications

The following paper has been submitted to IEEE Transactions on Antennas and Propagation:


The following papers have been published:

