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RF Switching system for Biomedical Radar systems

by

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Prof Paul Strooper
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Dear Professor Strooper,

In accordance with the requirements of the degree of Bachelor of Engineering in the division of Electrical Engineering I present the following thesis entitled "RF Switching System for Biomedical Radar Systems". This work was performed under the supervision of Dr. Konstanty Bialkowski.
I declare that the work submitted in this thesis is my own, except as acknowledged in the text and footnotes, and has not been previously submitted for a degree at The University of Queensland or any other institution.

Yours sincerely,

Matt Pascoe

Matt Pascoe.

Abstract

This document is a skeleton thesis for 4th-year students. The printable versions (`skel.dvi, skel.ps, skel.pdf`) show the structure of a typical thesis with some notes on the content and purpose of each part. The notes are meant to be informative but not necessarily illustrative; for example, this paragraph is not really an abstract, because it contains information not found elsewhere in the document. The LaTeX 2_ε source file (`skel.tex`) contains some non-printing comments giving additional information for students who wish to typeset their theses in LaTeX. You can download the source, edit out the unwanted material, insert your own frontmatter and bibliographic entries, and in-line or `\include{}` your own chapter files. Of course the content of a particular thesis will influence the form to a large extent. Hence this document should not be seen as an attempt to force every thesis into the same mold. If in doubt about the structure of your thesis, seek advice from your supervisor.

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Chapter 1

Introduction

1.1 Background

There has been a growing demand for the development of wireless systems, to meet the increasing demands of consumers. In order to meet this demand researchers have looked to software defined radio's (SDR); this interest in SDR is due to the ease and simplicity for the development and implementation in various applications. This rise in interest has led to a large spike in development of SDR, which is resulting in a broadened application for SDR. [1]
SDR's are being applied in a variety of different scenarios, but this thesis focuses primarily on the development of a switching system to complement the research done using SDR as a tool for medical imaging. The use of SDR in microwave imaging has provided an alternative diagnostic tool that presents significant benefits of current technology, primarily because of its low cost, portability, non-invasiveness and uses non-ionization radiation. This allows the system to be compact and suitable for medical application in the field. [2] [3]
As the demand for faster wireless systems increases, so does the interest in researching the application of using multiple antenna wireless links for digital communication; using multiple antennas introduces a greater range of possibilities by increasing the speed of the networks traffic [**?**]. To accommodate for the control of multiple radio frequency (RF) front ends the communication system will require a RF switching system; there are two primary categories for RF and microwave switches, electromechanical relay (EMR) and solid-state relay (SSR).
There are advantages and disadvantages in use either, SSR's are available in smaller packages and have a higher switching speed but are restricted to single pole, EMR's have a lower isolation loss but are have slower speed due to their physical construction. SSR don't have a wearable switching mechanism while EMR do, making them impractical in scenarios which require large amounts of switching [**?**]. Therefore,

this thesis will primarily focus on utilising SSR's as opposed to EMR's, to meet the high speed requirements while maintaining a low cost and compact design.
This thesis project looks into the development of an RF switching system to allow an RF front end to be connected to a large number of antennas or sensors, by developing a RF switch matrix that provides a high speed switching on multiple antennas. The results obtained from this will facilitate and support the expansion in the current development of biomedical RF imaging systems as well as future projects.

1.2 Aims/Objectives

This thesis aims to evaluate the current available designs and products to develop a low-cost and portable RF switch matrix.
The primary objective are to complete the following tasks:

- Evaluate and Design a RF Switch matrix
- Develop and Construct the RF Switch matrix
- Finalise and construct a housing for the switch matrix

1.3 Thesis Structure

Chapter 2 investigates the prior technology available that can be adapted or utilised in order to assist in the development of RF switching system.
Chapter 3 defines the relevant theory that is required to understand the topics discussed in this thesis.
Chapter 4 looks into the analysis and development of RF switches.
Chapter 5 depicts the flow of the project, starting from the thesis's definition and following it through the solution, design, simulation, implementation and results.
Chapter 6 contains performance results of the RF switch matrix, and the RF switch matrix's characteristics.
Chapter 7 discusses the performance of the produced switch matrix and future work.

1.4 Expected Contribution

The thesis will look at developing a low-cost RF switch matrix capable of providing a 2 input, 16 output switching matrix. It should reveal the possibility of developing switch matrix's that are better suited to low-cost, portable projects in contrast to commercially available switches.

This thesis is expected to produce a proprietary switch matrix that can enable the further development of low-power RF development in biomedical and radar applications.

Chapter 2

Literature review

2.1 Prior Art

This chapter looks into the currently available designs used for high speed RF switching as well as relevant theory that has and is being completed in the field.

2.1.1 Currently Available Technology

2.1.2 Previous designs

In order to develop the PCB

2.2 Software Defined Radio

The application of the RF switching system this thesis looks a developing, is to provide an RF front end such as a software defined radio (SDR) or Vector Network Analyser (VNA) with the ability to communicate multiple antennas or sensors. An SDR is a radio that is partially or entirely controlled by software in the physical layer in the Open Systems Interconnection (OSI) model. The OSI model is used to describe the subsystems of a communication system, where the physical layer represents the data. This allows for the software or firmware to be adjusted resulting in the change the carrier frequency, data rate, modulation, coding, etc. without having the reconstruct the hardware of the radio [6]. This project doesn't look into the control of an SDR, instead focuses on interfacing the switching system with the SDR. It is expected that the SDR will have an impedance of $50\,\Omega$ which is common of most SDR technology or a less common impedance of $75\,\Omega$ [7].

2.2.1 Analysing SDR Signals

2.2.2 Radar Signal Analysis

2.3 Microwave Theory

To design and develop microwave circuits a fundamental understanding of how microwaves operate and ... in ... is required

2.3.1 Transmission Line Theory

A transmission line is a medium that transfers electromagnetic energy along its path, an example can be seen in Figure 2.1. Transmission lines will form the primary basis of this thesis since it will be primary medium for the signal travelling through the RF switching system. It is crucial to ensure that the transmission line matches the source and antenna; otherwise it can cause the power to be reflected back.

To prevent this reflection, the impedances at each end must be matched to the transmission lines characteristic impedance. This can be done through L-section matching, stepped transmission lines or filters.

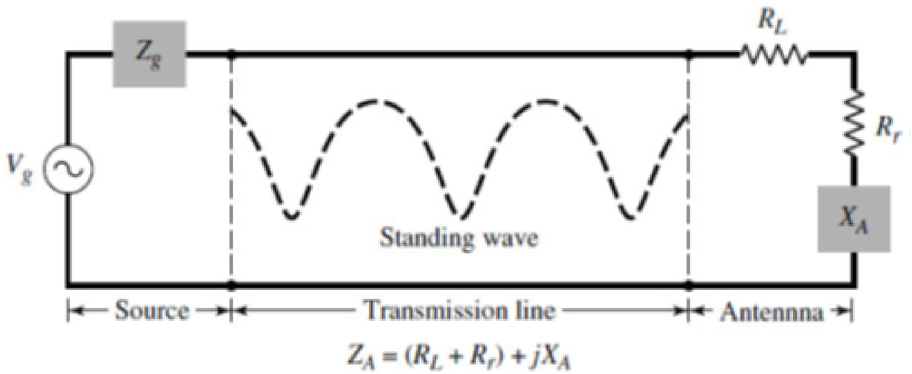

Figure 2.1: Transmission line Thevenin equivalent of antenna and transmitter

L-section is a method used for matching transmission lines; this involves using a capacitor and inductor in a series and parallel combination to match the load. Stepped transmission lines provides impedance matching for lumped elements. Finally, filters can also be used for impedance matching; they are typically used to provide an adjustable match for the circuit over different frequencies. By inserting a filter that is a perfect match for the transmission line at a known frequency [9]. This theory will be considered when evaluating the design for the development boards and if required the PCB so they are perfectly matched to reduce any unnecessary losses in the system.

2.3.2 Scattering Parameters

Scattering parameters (S-Parameters) are a matrix that describes the behaviour of linear electrical networks; this matrix is used over a broad range of disciplines of electrical engineering but is particularly useful in microwave engineering. Since the RF switching system this thesis is designing will not generating its own signal or provide any RF front end's; even though the system is switching, it will always have a single input and single output. Therefore, this design can be simplified to be a 2-port network, as shown in Figure 2.

2-port networks are most commonly used and can easily be adapted to systems that are more complex, Figure 2 shows a simple diagram of a 2-port network and Equation 1 shows the matrix and equations given for the network [9].

2.3.3 System Losses

2.4 RF Switches

This thesis topic looks into the development of a RF switching system, this will be done by utilising RF and microwave switches to create an RF switching matrix. An RF switch matrix are used to route RF signals from an input to an output. There are several different types of switching matrix's, there is multiple input multiple output (MIMO), multiple input single output (MISO), single input multiple output (SIMO) and single input single output (SISO) [12]. For this project we are looking at controlling multiple outputs with a single input, so will be implementing a SIMO RF switching matrix.

2.4.1 Switch Architecture

2.4.2 Switch Topologies

When constructing a RF switch there are two typical topologies, these are multiplexers and general purpose relays; examples can be seen in Figure 3. General purpose relays are commonly a SPDT or SDnT relay's that are used for routing a signal between multiple paths. Multiplexers are devices that route a single input to multiple outputs or vice versa, they are commonly built from multiple SPDT relays but have a greater inherited insertion loss from this configuration [13]. Looking at Figure 3 (b) it can be assumed that there will be losses through each path it takes, insertion loses through first switch, first cable/track, second switch, etc. Therefore, it is ideal to develop a topology as close to Figure 3 (a) to ensure there is little loss through multiple cascaded switches and cable/tracks. This thesis will be looking into designing a 1x12 SIMO multiplexer, similar to the design in Figure 3 (b) to provide the available ports as well as a consistent loss through the system.

2.5 Substrate Selection

There are various substrates that are available for developing the RF switching matrix. Four key substrates were looked at these include:

- FR-4
- Epoxy

Table **??** contains the characteristics of these four substrates that are utilised to calculate the dimensions of the RF tracks. When designing PCB's for

2.6 RF Track Design

For designing the RF tracks on the PCB there are three primary options available

- Micro-strip
- Coplanar Wave-guide, and
- Strip-line

RF tracks provide ...
For designing the tracks we need to consider:

$$\lambda = \frac{c}{f\sqrt{\epsilon_{eff}}} \tag{2.1}$$

$$\theta = \frac{2\pi}{\lambda} \tag{2.2}$$

We need to consider the Figure 2.1 and 2.2 as these are the fundamentals for designing any type of track. To determine which track is best suited this thesis will look at each available option.
These equations are used for the approximate design of RF tracks, in order to obtain a more precise design which consider a wider range of variables dedicated software is used to further verify the design of the tracks.

2.6.1 Micro-strip

Microstrip RF tracks are the most common RF transmission line currently used in practice. Figure 2.2 presents a typical microstrip which has been labelled the critical dimensions of this transmission line.

We are able to calculate the dimensions shown in Figure 2.2 by using the following:

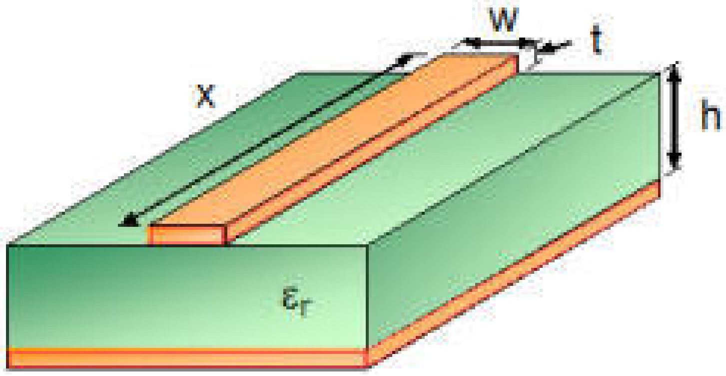

Figure 2.2: Microstrip diagram

$$W = \frac{t}{\pi}\left[ln\left(\frac{2h}{t}\right) + 1\right] \tag{2.3}$$

$$H = h - 2t \tag{2.4}$$

$$\epsilon_{eff} = \begin{cases} \frac{\epsilon_r + 1}{2} + \frac{\epsilon - 1}{2}\left[\frac{1}{\sqrt{1 + \frac{12H}{W}}} + 0.04\left(1 - \frac{W}{H}\right)^2\right] & when \left(\frac{W}{H}\right) < 1 \quad (2.5a) \\ \frac{\epsilon + 1}{2} + \frac{\epsilon - 1}{2\sqrt{1 + \frac{12H}{W}}} & when \left(\frac{W}{H}\right) > 1 \quad (2.5b) \end{cases}$$

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_{eff}}} \cdot ln\left(\frac{8H}{W} + \frac{W}{4H}\right), & when \left(\frac{W}{H}\right) < 1 \quad (2.6a) \\ \frac{120\pi}{\sqrt{\epsilon_{eff}} \cdot \left[\frac{W}{H} + 1.393 + \frac{2}{3}ln\left(\frac{W}{H} + 1.444\right)\right]}, & when \left(\frac{W}{H}\right) > 1 \quad (2.6b) \end{cases}$$

In order to calculate the dimensions of the micro-strip track we are required to make key decisions for the design. By selecting the frequency range, impedance, phase shift substrate and track thickness we are able to determine the dimensions for the track.

We are able to determine the width (W) and length(X) of the track by selecting a substrate determining the dielectric constant (ϵ_{eff}), copper thickness (t) and height(H). We can set the

2.6.2 Strip-line

Stripline RF tracks are ...

We are able to caluclate the dimensions shown in Figure 3.2

2.6.3 Coplanar Wave-guide

C

2.7 Radiation Emission

2.7.1 Picket Fencing Technique

2.7.2 Shielding

Chapter 3

RF Switch Evaluation

In this chapter the design of discrete RF switches is evaluated in comparaison to commercially available switches. This chapter will look into the design and simulations of SPDT, SP4T and SP8T RF switches within the frequency range of 100MHz-4GHz to gain a better understanding of RF switch functionality and variants.

3.1 RF Switch Design

There are two

3.1.1 PIN Diode

3.1.2 FET

3.2 Topologies

3.3 Available RF Switches

Chapter 4

Methodology

For this Thesis the design has been broken into five primary sections:

- Evaluation of RF switches
- Design a switch matrix
- Develop PCB design
- Evaluate the RF switch matrix
- Construction of matrix enclosure

This chapter will cover the progression of the design and development of the RF switch matrix for the thesis.

4.1 Evaluation

4.1.1 Evaluation Boards

We currently have 3 boards available

The three available evaluation boards we investigated using a ABCD VNA; each switch was wired so that the input is connected to the output, while all other ports were $50\,\Omega$ terminated. The switch was powered and the controls set to allow the signal to propigate down the open path, then changed the state to have a closed path; this was conducted for each evaluation board. The results were exported to a *.s2p* file to be analysed using ADS, and the results can be seen in Figure's **??**, **??** & **??**. These simulations

4.1.2 RF Switches

4.1.3 Transmission Line Design

4.2 Design

For the design of the RF switch matrix, several key design citerias were identified to be required for the final product of the switch matrix. These are:

- Two RF inputs
- Sixteen RF outputs
- Maximum path loss of 3dB
- Power-able from low-power device (such as USB)
- Input and output are 50 Ω

In order to meet these specifications

Using the evaluated RF switches two separate designs are developed ,

4.2.1 Design 1

4.2.2 Design 2

4.2.3 Design 3

4.2.4 Output 1

4.2.5 Output 2

4.3 Development

This section looks at the development of the RF switch matrix.

4.3.1 PCB Development

One of the key design parameters is for developing a portable device, this requires the switch matrix to be as small as possible. To determine the best solution ADS's LineCalc is used to

135 235

4.3.2 RF Switch Development

After the design of the PCB had been completed the order was processed by a PCB development company. During this project two companies were used: PCBZone

Table 4.1: Design ... Logic Table

and PCBWay. The key difference between these companies was price, quantity and quality;

The RF switch chips that were selected are only available in QFN, ... or ... packages; this limited the design capabilities to SMD

4.4 Physical Construction

4.5 Micro-controller Development

In order to control and operate the RF Switch system a some type of micro-controller is required to be used to switch the inputs and outputs of the system. The micro-controller needs to meet the following key design parameters:

- Capable of supporting 35 control pins.
- Enable a switch speed of 100 ns
- Low power requirements, less than 5 W
- Source power from USB, and communicate using 15260 Baud rate.
- Capability to sync other controllers,

The ideal device is a low-powered micro-controller, for this project the PSOC4-BLE has been selected to ensure that it is able to control the

4.5.1 Design

For each development board a logic table was developed, the table for the .... can be seen in Table 4.1. This table determines the logic required to ensure that the control is kept to its most simplistic form. Therefore using this we are able to determine:

4.5.2 Evaluation

Chapter 5

Verification

5.1 Individual Board's

This section looks at the results obtain from each of the individual boards, each board was tested with a ABCD VNA. By evaluating these boards it can be determined

5.1.1 Design 1

Design 1 has been tested with , there are 3

Losses

Figure 5.1: Design 1 S-Parameters

Switch Speed

Power Requirements

5.1.2 Design 2

Losses

Figure 5.2: Design 2 S-Parameters

Switch Speed

Power Requirements

5.1.3 Design 3

Losses

Figure 5.3: Design 3 S-Parameters

Switch Speed

Power Requirements

5.1.4 Output 1

Losses

Figure 5.4: Output 1 S-Parameters

Switch Speed

Power Requirements

5.1.5 Cabling

There are several different cabling options available; three different cabling options have been looked at, this includes flexable and rigid SMA cables, and UFL cabling. Looking at Figure 5.5 - **??** we can determine the effects of cabling in the final design

Figure 5.5: Flexable SMA cable S-Parameters

Figure 5.6: Rigid SMA cable S-Parameters

Figure 5.7: UFL cable S-Parameters

5.2 RF Switch Matrix

This section looks at the overall characteristics of the final RF switch matrix design. To determine the overall performance of the system, this required evaluating the performance, speed, size and power constraints.

5.2.1 Final Design

From looking at the results obtained in Section 5.1 it can be seen that the only option for the output SPDT switch is ‘Output 1’. Therefore the 16 output terminals will have the reflection seen in Figure 5.4 S_{22} signal, this will be connected to the SP16T via a UFL-UFL connector seen in Figure 5.7.
Looking at the results obtained, it can be seen that ‘Design ...’ has an insertion loss of ...dB

Therefore the final design will use ‘Design ...’ and ‘Output 1’.

5.2.2 Losses

In order to determine the characteristics of the designed RF switch matrix, its characteristics of can be modelled using S-Parameters to evaluate the final design. Using the ABCD VNA the switch matrix was analysed to determine the amount of losses that are present in the system.
Looking at Figure **??** we can determine the performance of the overall system. There are multiple paths that need to be considered in order to fully evaluate the RF switch, there are 9 different paths that can be taken; these can be seen below in Figure 5.8 - 5.16.

Figure 5.8: S-Parameters of RF switch matrix
(Left) Path 1, (Right) Diagram

Figure 5.9: S-Parameters of RF switch matrix
(Left) Path 2, (Right) Diagram

Figure 5.10: S-Parameters of RF switch matrix
(Left) Path 3, (Right) Diagram

Figure 5.11: S-Parameters of RF switch matrix
(Left) Path 4, (Right) Diagram

Figure 5.12: S-Parameters of RF switch matrix
(Left) Path 5, (Right) Diagram

Figure 5.13: S-Parameters of RF switch matrix
(Left) Path 6, (Right) Diagram

Figure 5.14: S-Parameters of RF switch matrix
(Left) Path 7, (Right) Diagram

Figure 5.15: S-Parameters of RF switch matrix
(Left) Path 8, (Right) Diagram

Figure 5.16: S-Parameters of RF switch matrix
(Left) Path 9, (Right) Diagram

5.2.3 Speed

We know from Section 4.5 that micro-controller is capable of controlling the switches at .... ns, but the SSR's are not capable of operating at this speed. Therefore the maximum switching frequency needs to be determined for this RF switch.
Looking at the datasheets it can be seen that the .... is the slowest chip in this system which bottlenecks the maximum performance of the switch. Therefore we can say that theoretical switching speed is limited to .... μs.

With the fully developed RF switch matrix it can be fully evaluated to determine its performance in regard to speed; as can be seen in Figure 5.17 the switch matrix is wired so that one input and output are connected to the VNA.

Figure 5.17: Speed test set-up for RF Switch Matrix

Using the set-up shown in Figure 5.17 the VNA monitor's the signal strength to determine the speed which causes the insertion loss to drop bellow the level seen in Figure 5.8. By doing this it was determined that the maximum switching speed of the micro-controller is ... μs, which is close to the expected limitaion of the ..... RF chip.

5.2.4 Power Requirements & Control

Chapter 6

Discussion

6.1 Problems

6.1.1 Resource Availability

6.2 Objective Fulfilment

6.3 Contributions

Chapter 7

Conclusions and Future Work

7.1 Conclusion

7.2 Future Work

Appendix A

PCB Design

A.1 Design 1

A.2 Design 2

A.3 Design 3

A.4 Output Design 1

A.5 Output Design 2

A.6 Output Design 3

Appendix B

Substrate Parameters

The following tables contain the parameters and details for the substrates investigated in this thesis.

Parameter	Value
Er	4.7
Mur	1
H	even

Table B.1: *Parameters for simulation of FR-4 substrate*

Appendix C

Bill of Materials

In order to construct the design of the Switching Matrix we require the following components, a Bill of Materials has been constructed and can be seen in Table **??**.

Name	Description	Digikey Part no.	Min Order no.	Price	Quantity	Total
					Total:	$100

Table C.1: *Bill of Materials*

Appendix D

RF Switch Controls

D.1 Design 1

Table D.1: Add caption

Design 1															
Input				**Output**											
				$SPDT_1$		$SPDT_2$		$SPDT_3$		$SPDT_4$		$SPDT_5$		$SPDT_6$	
$\boldsymbol{x_3}$	$\boldsymbol{x_2}$	$\boldsymbol{x_1}$	$\boldsymbol{x_0}$	**Input 1**	**Input 2**	**Input 1**	**Input 2**	**Input 1**	**Input 2**	**Input 1**	**Input 2**	**Input 1**	**Input 2**	**Input 1**	**Input 2**
0	0	0	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
0	0	0	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
0	0	1	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
0	0	1	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
0	1	0	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
0	1	0	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
0	1	1	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
0	1	1	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	0	0	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	0	0	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	0	1	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	0	1	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	1	0	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	1	0	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	1	1	0	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$
1	1	1	1	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$	x_0	$\bar{x_0}$

D.1.1 Design 2

D.1.2 Design 3

D.1.3 Output 1

D.1.4 Output 2

Appendix E

Companion disk

If you wish to make some computer files available to your examiners, you can list and describe the files here. The files can be supplied on a disk and inserted in a pocket fixed to the inside back cover.

The disk will not be needed if you can specify a URL from which the files can be downloaded.

Bibliography

[1] "Wireless prototyping with software defined radio.(ni usrp rio software defined radios)(product feature)," *Microwave Journal*, vol. 57, no. 5, p. 208, 2014.

[2] J. Marimuthu, K. S. Bialkowski, and A. M. Abbosh, "Software-defined radar for medical imaging," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 64, no. 2, pp. 643–652, 2016.

[3] ——, "Software-defined radar for medical imaging," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 64, no. 2, pp. 643–652, 2016.