TUNABLE ANTENNA DESIGN FOR COGNITIVE RADIOS IN THE UHF TV BAND.

K. M. M. W. N. B. Narampanawe[1], Chamath Divarathne[2], J. V. Wijayakulasooriya[3], Jagath Kumara[4]

[1] Department of Electrical and Electronic Engineering, University of Peradeniya,
Peradeniya, Sri Lanka
narampanawe@ieee.org
[2] Department of Electrical and Electronic Engineering, University of Peradeniya,
Peradeniya, Sri Lanka
chamath@ee.pdn.ac.lk
[3] Department of Electrical and Electronic Engineering, University of Peradeniya,
Peradeniya, Sri Lanka
jan@ee.pdn.ac.lk
[4] Department of Electrical and Electronic Engineering, University of Peradeniya,
Peradeniya, Sri Lanka
jagathk@ee.pdn.ac.lk

ABSTRACT

Presently, Ultra Wide Band (UWB) radio technology has attracted much interest in academics, industrial and standardization (IEEE) activities. UWB characterizes transmission systems with instantaneous spectral occupancy of higher bandwidth or higher fractional bandwidth. The antenna is one of the overlooked part of a RF (Radio Frequency) design. The range, performance, and legality of a RF link are significantly dependent upon the antenna. The UHF (Ultra High Frequency) TV Band is exclusively addressed in IEEE802.22 standardization. The UHF TV band is 336MHz wider according to CCIR (Consultative Committee on International Radio) standards. One major challenge in designing a UWB antenna for UHF band is limiting the physical size of the antenna. Authors have previously illustrated the design, implementation and testing of a UWB antenna for cognitive radios in the UHF TV Band[1].

Although it gives better results, performances at lower frequencies are slightly below than the higher frequencies. This problem can be rectified by introducing an impedance matching circuit at particular frequencies. Since it is required to cover a wider bandwidth several matching circuits could be introduced, but it is not practical because of size, complexity, losses, Electromagnetic interferences (EMI) and cost. Therefore this paper presents a simple and low cost Tuneable Antenna design which is controlled by software instructions. Hence this antenna design can be used in implementing cognitive radios in the UHF TV Band.

KEYWORDS

Antenna, Antenna tuning, Fixed Transceivers, IEEE802.22 Cognitive Radio, Monopole Antenna, software defined radio, UHF TV, Ultra Wide Band (UWB)

1. INTRODUCTION

A radio frequency antenna is an electrical element that converts RF waves in free space to electrical signal or vice versa, when receiving and transmitting respectively. There are many antenna types which perform different characteristics. While either Receiving or transmitting, antennas behave almost similarly.

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The transmitting antenna may generally be less efficient than the receiving antenna because it is possible to obtain high Effective Isotropic Radiated Power (EIRP) with high power amplifiers at the output of the transmitter. But at the receiver, obtaining higher gains are not simply feasible because even a Low Noise Amplifiers (LNA) amplifies both noise and signal powers where there is no improvement of Signal to Noise Ratio (SNR). Therefore the receiving antenna efficiency is essential to obtain higher signal power for maximizing the distance between the transmitter and the receiver [2, 3].

There are several types of wideband antennas. Among them log periodic antenna[4], horn antennas, spiral antennas[4] and Printed Bowtie antenna [5] are dominant. They have disadvantages like large dimensions and high directivity. Therefore they are not candidates for cognitive radios which require omni-directional transceiving and small form factors.

Omni directional antennas with gains of 0dBi or higher are used in cognitive radio networks for sensing and performing measurements. There is a demand for omni-directional UWB antennas in the UHF TV Band for wireless access systems such as IEEE802.22 [6].

The monopole antenna is a simple omni-directional antenna with relatively small physical dimensions. However, the bandwidths of monopole antennas are comparatively small [7]. Thus monopole antennas are suitable designs for cognitive radio applications, when the bandwidth of the antenna is improved. It can be observed that, having a relatively large radiating surface is a significant feature of the wideband antennas [8]. In monopoles, the radiating surface area can be increased if the diameter of the antenna pole is increased [9].

Authors' previous experimental results show that 12cm long copper tube with 0.75 inch diameter is the optimum length and the diameter to be used in designing a quarter-wave cylindrical monopole antenna to serve in the UHF TV band. This relatively compact, low cost design can be used specially in UWB wireless communication transceivers [1].

The test Antenna and 3D radiation pattern are shown in Figure 1. Measured and simulated reflection coefficients variation of the monopole Antenna with the frequency shown in Figure 2.

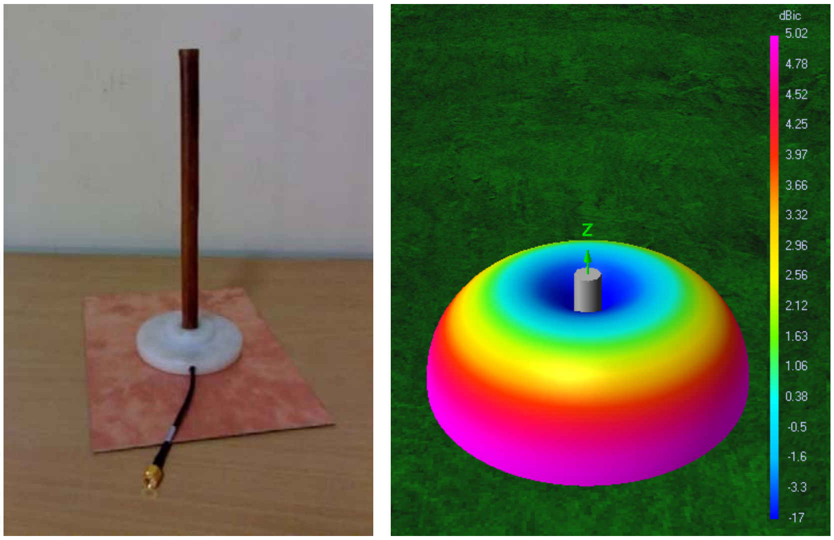

Figure 1. Test Antenna and 3D radiation pattern

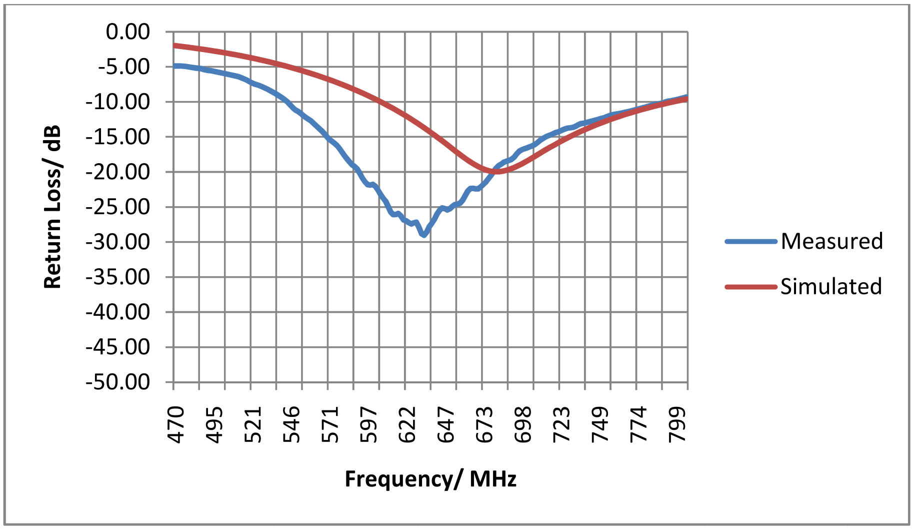

Figure 2. Reflection coefficient variation of the monopole Antenna

According to Figure 2 measured results, reflection coefficient of the antenna is below -10dB between 548MHz and 783MHz, where the band width is around 235MHz (70%). From 783MHz to 813MHz there is a slight increment of the reflection coefficient which reaches its maximum -9.28dB at 806MHz. But below 548MHz down to 470 MHz the reflection coefficient increases significantly up to -4.87dB.

The performances at lower frequencies are slightly below than the higher frequencies. This problem can be rectified by introducing impedance matching circuits at particular frequencies as shown in Figure 3. Since it is required to cover a 78MHz wider bandwidth (470MHz - 548MHz), several impedance matching circuits could be introduced, but it is not practical because of the size, complexity, losses, Electromagnetic interferences (EMI) and cost. Therefore a Tuneable impedance matching design is the realizable solution with compared to a mechanically tuned telescopic antenna which can fail because the user handle repeatedly and performances depend on the user as well [10]. Further mechanically tuned are not suitable systems such as software defined radios where frequency hopping techniques are used which needs short transient periods between frequency hops that cannot be achieved mechanically.

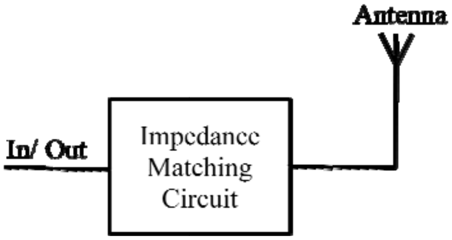

Figure 3. Basic Impedance matching circuit

2. TUNABLE ANTENNA DESIGN

Since impedance matching circuit is along the RF path, it should be linear not to generate spurious frequency components [10]. Further it should have a low insertion loss and higher quality factor (Q).

An impedance matching circuit usually consists of inductors and capacitors. A tunable impedance matching circuit can be constructed by means of variable inductors and variable capacitors. But the construction of a variable inductor is complicated and bulky. Therefore fixed inductors and variable capacitors is the realizable solution. There are several variable capacitors options as discussed in the following sub-sections.

2.1. Varactor Diodes and Barium Strontium Titanate (BST) ceramics capacitors

One option is varactor diodes. They are analog devices and they should be provided analog tuning voltages. Varactor diodes cannot usually withstand at high RF power and they do not meet linearity requirements. Similarly, Barium Strontium Titanate (BST) ceramics capacitors can be used as variable capacitors. High breakdown voltage of ferroelectric BST materials permits high intercept (IP3) matching circuits. Further they illustrate a 3:1 tunability at 0-10Volts and Q > 60 at 1.5GHz [11]. BST capacitors can be tuned by using specifically designed I.C.s with digital interface to have software controllability. Additionally, these I.C.s consist of boost converters to satisfy tuning voltages up to 30V [12] [13].

2.2. Capacitor Bank

Capacitor bank can be introduced to overcome the disadvantages of varactor diodes. The capacitors in the capacitor bank can be enabled and disable by using electronically controlled MOS RF Switches. Although this is a theoretically better solution which gives discreet capacitance variation, this approach has some practical limitations. Every capacitor should be connected to an independent RF switch, it is bulky, high power consuming and costly. Further, a bulk electronic system will introduce significant stray components that cannot be ignored. Additionally, these stray elements limit the minimum capacitance and the resolution.

2.2. RF MEMS capacitors

RF MEMS (microelectromechanical system) variable capacitors has demonstrated wide tuning range, high-Q and very high operating frequency. But their Control voltages are higher and switching speeds are slower [14]. In addition to those drawbacks, there are some other challenges still remain with MEMS approach. One is, high RF power level might cause the metal electrodes to self actuate or latch [15].

2.4. Digitally Tunable Capacitor

Digitally Tunable Capacitor (DTC) is another type of variable capacitor, controlled by a digital interface. The operation of DTC is similar to the capacitor bank described previously. The capacitors are enable and disabled by CMOS FETs. These FETs are governed by the data via the digital interface. Although DTC is similar to a conventional capacitor bank, its performances are superior than that of a conventional capacitor bank. A DTC is an integrated circuit consists of high-Q capacitors, FETs and digital control circuitry. DTC does not require external components for bias voltage generation or interfacing. The block diagram of DTC is shown in Figure 4 [16].

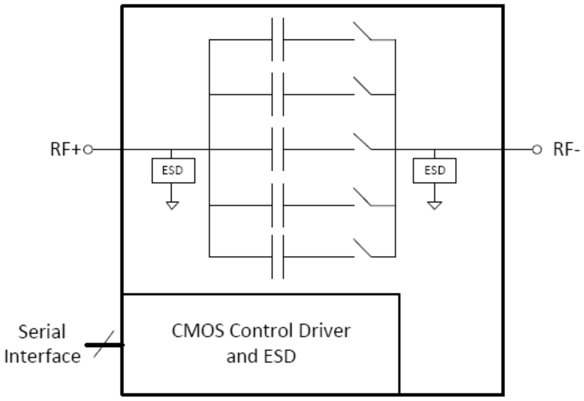

Figure 4. Block Diagram of DTC

3. DIGITALLY TUNABLE CAPACITOR EQUIVALENT CIRCUIT MODEL

In this paper, PE64904 Peregrine Semiconductor UltraCMOS^{TM} Digitally Tunable Capacitor is considered [16] [17]. Figure 5 shows the equivalent circuit model of Peregrine DTC.

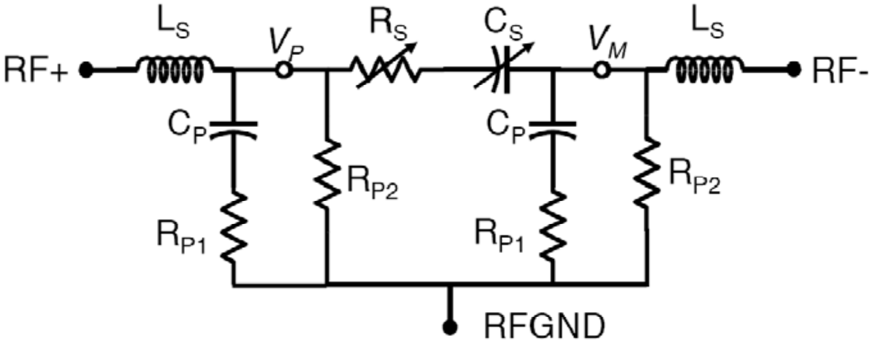

Figure 5. DTC Equivalent Circuit Model

This model consists of three parts; the tuning elements are R_S and C_S, the parasitic package inductance is $L_S = 0.27nH$ and the shunt parasitic elements are $C_P = 0.5pF$, $R_{P1} = 7\Omega$, $R_{P2} = 7\Omega$. R_S and C_S values are given by following two equations [17].

$$C_S(pF) = [0.129 \times state] + 0.6$$

$$R_S(\Omega) = \frac{20}{\left[\frac{state + 20}{state + 0.7}\right]} + 0.7$$

Where $'state'$ is an integer value from 0 to 31 which can be changed via the serial interface of the DTC chip. Hence $'state'$ is a five bit configurable register. R_S and C_S variation with the $'state'$ shown in Figure 6.

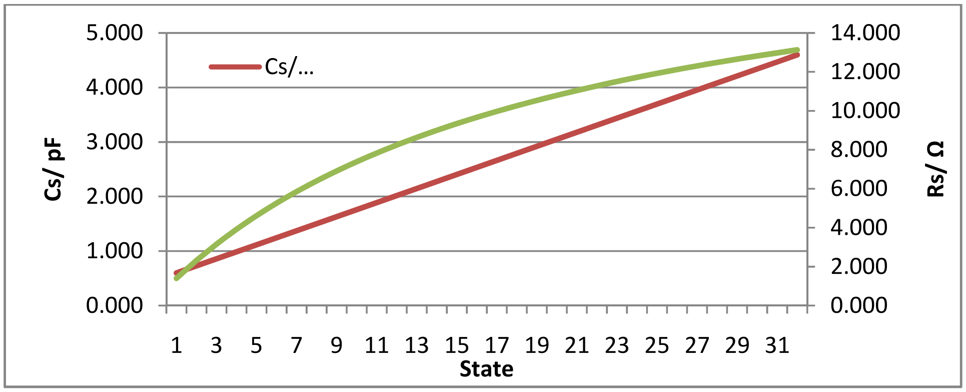

Figure 6. R_S and C_S Variations with State

Therefore C_S takes values from 0.600pF to 4.599pF in 0.129fF steps while R_S takes values from 1.4Ω to 13.131Ω.

It can be seen that Equivalent Circuit Model of the DTC is not a perfect capacitor hence the DTC shows a finite Q-factor. The Q-factor of PE64904 is typically larger than 25.

3.1. Characteristics of PE64904 DTC

The operating frequency range of PE64904 is from 100MHz to 3GHz and input third order intercept point (IIP3) is 65dBm at 18dBm per tone and switch time between two states is 12µs. It consumes very small current about 140uA at 2.6V operating voltage and operates even at high power 34dBm (>2W). The self resonate frequency of the device is larger than 3.1GHz.

Therefore PE64904 DTC is a suitable for designing a tunable impedance matching circuit in the UHF TV band.

3.2. Circuit configuration modes of PE64904 DTC

PE64904 DTC can be used either in series mode (C1) or shunt mode (C2) as shown in Figure 7 [16].

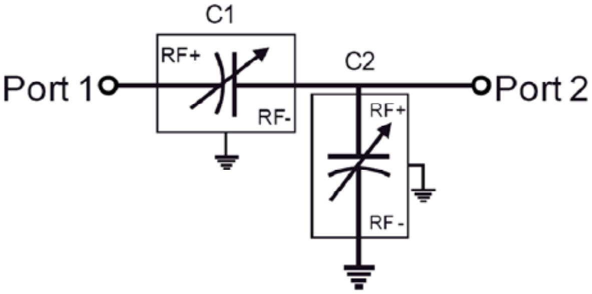

Figure 7. Configuration modes of PE64904 DTC

The series mode and the shunt mode show different equivalent properties those can be realized by analyzing the DTC Equivalent Circuit Model shown in Figure 5.

4. IMPEDANCE MATCHING CIRCUIT DESIGN

The antenna Impedance matching circuit designed using Smith Chart Utility of Agilent ADS.

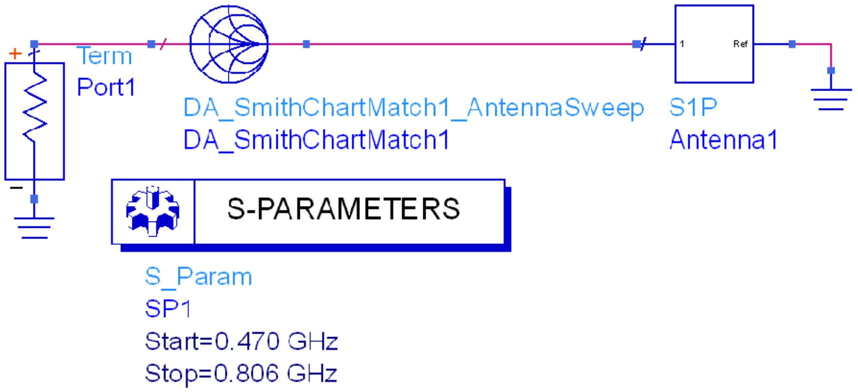

Figure 8 Antenna Impedance matching circuit design using Smith Chart Utility

The measurement data of the reference antenna was obtained as 1-port s-parameters which consist of Magnitude and phase information. The 1-port s-parameters block and a 50Ω ideal port were connected through Smith chart matching network as shown in Figure 8.

4.1. Generalize impedance matching circuit

It could be obtained that it is feasible to design a generalize impedance matching circuit for the whole bandwidth from 470MHz to 806MHz by changing only capacitor values. The generalize impedance matching circuit is show in Figure 9. It is a π-type of a circuit with a fixed 15nH inductor (L1) and two variable capacitors (C9 and C10). Inductor's and capacitors' Q-factor were taken as 50. The Maximum and Minimum capacitor values for the impedance matching circuit are given in the Table 1. All other capacitor values lie between them.

Table 1 Maximum and Minimum capacitor values for the impedance matching circuit

Range	C9/pF	C10/pF
Min	5.751	3.300
Max	15.297	15.168

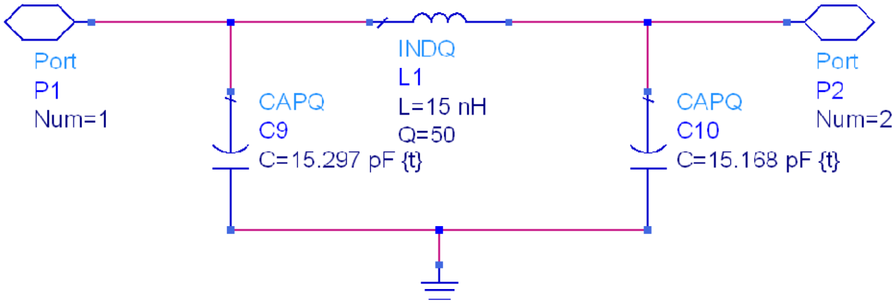

Figure 9 Generalize impedance matching circuit

4.2. Simplified Equivalent Circuit Model for Shunt configuration

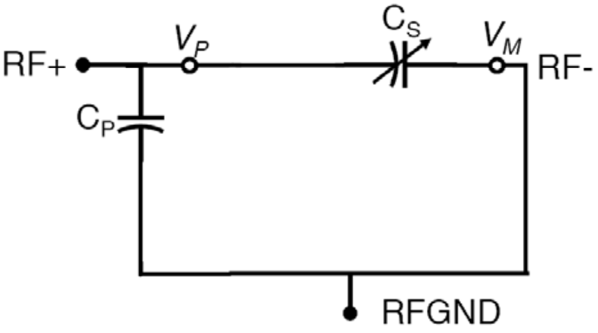

Figure 10 Simplified Equivalent Circuit Model for Shunt configuration

Simplified equivalent circuit model for the shunt configuration shown in

Figure 10 was used to determine the number of PE64904 variable capacitors because a single DTC cannot provide the maximum capacitance required. $R_{P1} = 0\Omega$, $R_{P2} = \infty\Omega$ and $R_S = 0\ \Omega$ were taken by approximation and $C_P = 0.5pF$ referred to Figure 5. By analyzing Figure 6 and

Figure 10, equivalent capacitance between RF+ and RFGND terminal (C_{eq}) can be expressed as;

$$C_{eq} = C_S + C_p$$

$$C_{eq}(pF) = [0.129 \times state] + 0.6 + C_p$$

$$C_{eq}(pF) = [0.129 \times state] + 1.1$$

Since ‘state’ can take minimum ‘0’ and maximum ‘31’, C_{eq} takes values from 1.1pF to 5.099pF. Therefore values given in the Table 1 can only be achieved by connecting three capacitors in parallel as shown in Figure 11. This can be expressed mathematically as;

$$C_{parallel} = 3 \times C_{eq}$$

$$C_{parallel} = 3 \times \{[0.129 \times state] + 1.1\}$$

$$\mathrm{C_{parallel}} = \begin{cases} \mathrm{C_{parallel,max}} = 3 \times \{[0.129 \times 31] + 1.1\} = 15.297\mathrm{pF} \\ \mathrm{C_{parallel,min}} = 3 \times \{[0.129 \times 0] + 1.1\} = 3.300\mathrm{pF} \end{cases}$$

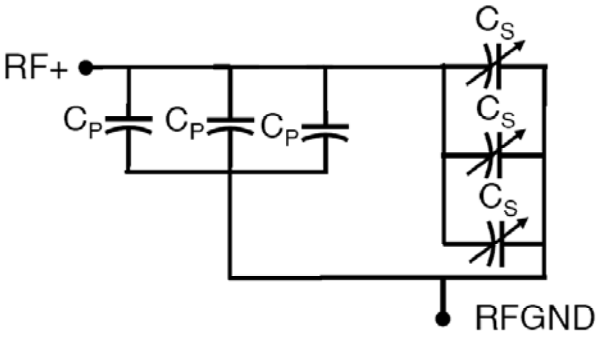

Figure 11 Three capacitors in parallel from simplified shunt model

Further, ‘State’ of every parallel capacitor can be changed independently. Therefore, by taking ‘state’ of capacitors as ‘state1’, ‘state2’ and ‘state3’, $\mathrm{C_{parallel}}$ can be re-written as;

$$\mathrm{C_{parallel}} = [0.129 \times (state1 + state2 + state3)] + 3.3$$

Since ‘State1’‘State2’ and ‘State3’ can be configured from ‘0’ to ‘31’, ‘State1+State2+State3’ can be adjusted from ‘0’ to ‘93’ in integer steps. Hence $\mathrm{C_{parallel}}$ can be tuned from 3.300pF to 15.297pF in 0.129pF steps.

4.3. Antenna Impedance Matching Circuit with Simplified Equivalent Circuit Model

The impedance matching circuit shown in Figure 9 was used to determine the values of C9 and C10. They were changed as tuning elements and their values were varied according to the $\mathrm{C_{parallel}}$ equation given above. During the tuning Process L1 (15nH) was kept constant and C9 was increased in 1.032pF (‘state’ by 8) steps from 5.751pF to 15.039pF, then C10 was increased so that S_{11} is minimum. C9 and C10 values obtained from the simulations for the simplified equivalent circuit given in Table 2. S_{11} Variation with Frequency for those values show in Figure 12. The antenna characteristic without the matching circuit is shown in black.

Table 2. C9 and C10 values for the Simplified equivalent circuit

Index	**state1+state2+state3 for C9**	**state1+state2+state3 C10**	**C9/pF**	**C10/pF**
1	19	0	5.751	3.300
2	27	6	6.783	4.074
3	35	12	7.815	4.848
4	43	18	8.847	5.622
5	51	25	9.879	6.525
6	59	31	10.911	7.299

7	67	37	11.943	8.073
8	75	46	12.975	9.234
9	83	58	14.007	10.782
10	91	72	15.039	12.588
11	92	79	15.168	13.491
12	93	83	15.297	14.007
13	93	88	15.297	14.652
14	93	90	15.297	14.910
15	93	92	15.297	15.168

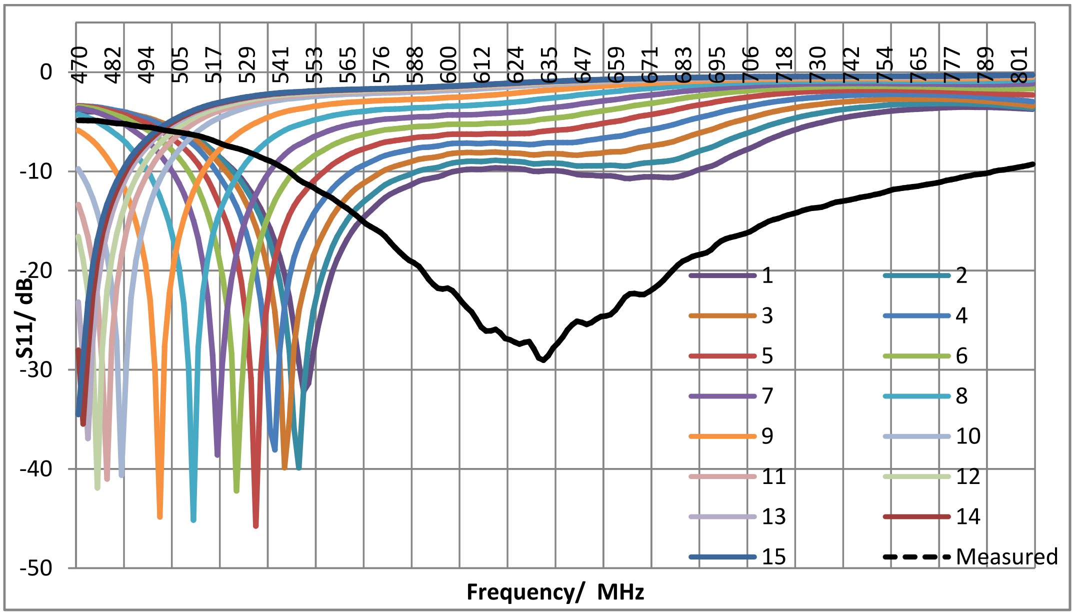

Figure 12. S_{11} Variation with Frequency for C9 and C10 values

It could be observed that lower frequency matching is feasible with two sets of three parallel DTC when simplified equivalent circuit was used. Therefore a detailed analysis was required for the verification of the impedance matching circuit.

4.4. Antenna Impedance Matching Circuit with Equivalent Circuit Model

Figure 13 shows PE64904 DTC Equivalent Circuit Model for Shunt configuration. All values of the equivalent circuit are fixed, except R83 and C83 that vary with the 'state'.

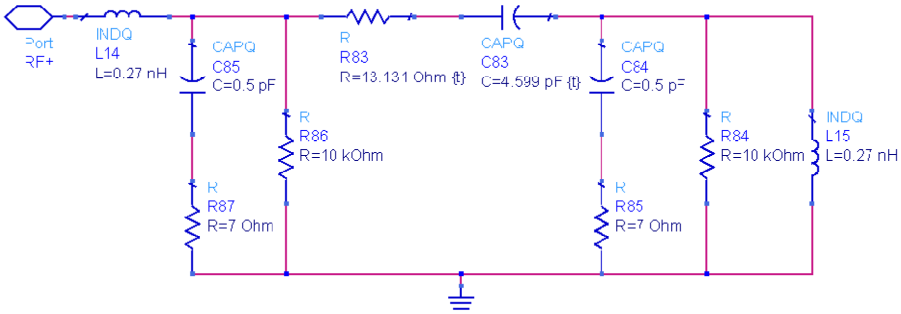

Figure 13 Equivalent Circuit Model for Shunt configuration

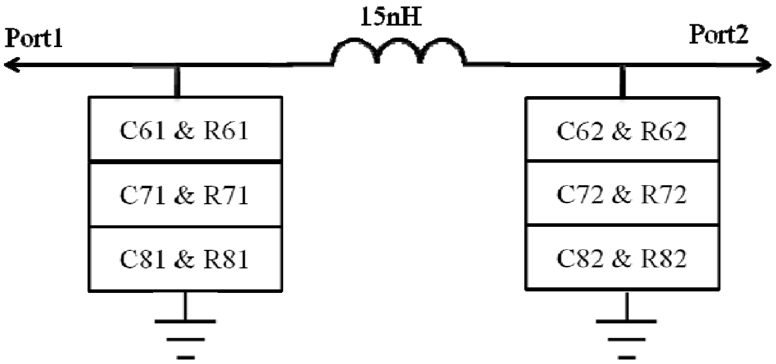

Figure 14. Impedance matching circuit with two, three parallel equivelent circuit models

Since it is required to connect at least three DTC to obtain the desired capacitance, two sets of three parallel capacitors equivelent circuit models were connected as shown in Figure 14. C & R represent variable values change with the ‘state’.

The ‘State’ values of DTCs were change so that matching circuit follows the characteristics shown in Figure 12. The tuned values of DTCs’ ‘state’ are given in Table 3 and relevant C & R values are given in Table 4.

Table 3. DTCs’ tuned 'state' values

Index	C82/ R82	C81/ R81	C72/ R72	C71/ R71	C62/ R62	C61/ R61
1	0	0	0	0	0	19
2	0	0	0	0	6	25
3	0	0	0	4	16	31
4	0	0	0	10	22	31
5	0	0	0	15	29	31
6	0	0	6	20	31	31
7	0	0	14	25	31	31
8	0	13	15	31	31	31
9	7	2	31	31	31	31
10	20	7	31	31	31	31
11	26	8	31	31	31	31
12	31	8	31	31	31	31

Table 4. C & R tuned values

In.	C82	C81	C72	C71	C62	C61	R82	R81	R72	R71	R62	R61
1	0.600	0.600	0.600	0.600	0.600	3.051	1.400	1.400	1.400	1.400	1.400	10.803
2	0.600	0.600	0.600	0.600	1.374	3.825	1.400	1.400	1.400	1.400	5.854	12.122
3	0.600	0.600	0.600	1.116	2.664	4.599	1.400	1.400	1.400	4.617	9.978	13.131
4	0.600	0.600	0.600	1.890	3.438	4.599	1.400	1.400	1.400	7.833	11.510	13.131
5	0.600	0.600	0.600	2.535	4.341	4.599	1.400	1.400	1.400	9.671	12.822	13.131
6	0.600	0.600	1.374	3.180	4.599	4.599	1.400	1.400	5.854	11.050	13.131	13.131
7	0.600	0.600	2.406	3.825	4.599	4.599	1.400	1.400	9.347	12.122	13.131	13.131
8	0.600	2.277	2.535	4.599	4.599	4.599	1.400	9.003	9.671	13.131	13.131	13.131
9	1.503	0.858	4.599	4.599	4.599	4.599	6.404	3.155	13.131	13.131	13.131	13.131
10	3.180	1.503	4.599	4.599	4.599	4.599	11.050	6.404	13.131	13.131	13.131	13.131
11	3.954	1.632	4.599	4.599	4.599	4.599	12.309	6.914	13.131	13.131	13.131	13.131
12	4.599	1.632	4.599	4.599	4.599	4.599	13.131	6.914	13.131	13.131	13.131	13.131

S_{11} Variation with Frequency for different values of DTCs' 'state's shown in Figure 15 and magnified view on lower frequency range from 470MHz to 600MHz show in Figure 16 to highlight the performances of the matching circuit.

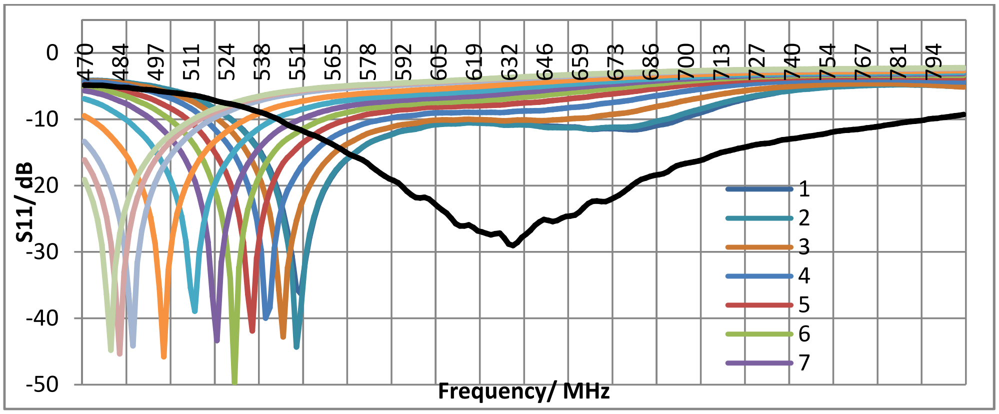

Figure 15. S_{11} Variation with Frequency for different DTCs' 'state's

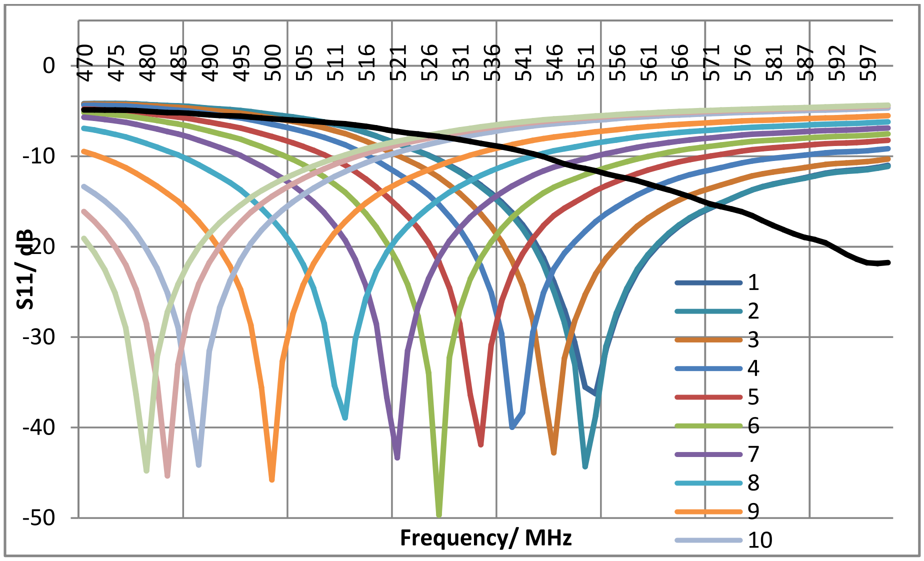

Figure 16. S_{11} Variation with Frequency for different DTCs' 'state's at Lower frequency range

According to Figure 15 and Figure 16, it was observed that S_{11} can be kept below -10dB throughout the whole 336MHz bandwidth with proper ‘state’ settings. When the frequency is reaching 573MHz and above impedance matching circuit can be bypassed because the antenna performance is better at higher frequencies.

5. IMPEDANCE MATCHING CIRCUIT SELECTION

Since it is required to omit the Impedance matching circuit at higher frequencies (> 573MHz), a bypass arrangement was introduced. It was constructed by connecting Two SPDT (Single Pole, Double Throw) switches as shown in Figure 17. To enable the Impedance matching circuit, SPDT1 switch position should be ‘2’ and SPDT2 switch position should be ‘1’. These switches should be able to control electronically for flexible operation.

HMC595 is a low cost SPDT switch in 6-lead SOT26 package with; Low Insertion Loss: 0.25dB, High Input IP3: +65 dBm, Input Power for 1dB Compression: 35dBm (3W); Isolation: 30dB while working up to 3GHz and operate from 3V under very low 40µA current [18]. Hence

HMC595 is an appropriate option for the Impedance matching circuit bypass arrangement. Even if the antenna is used in a fast frequency hopping scheme, HMC595 can perform well at 120ns switching speed.

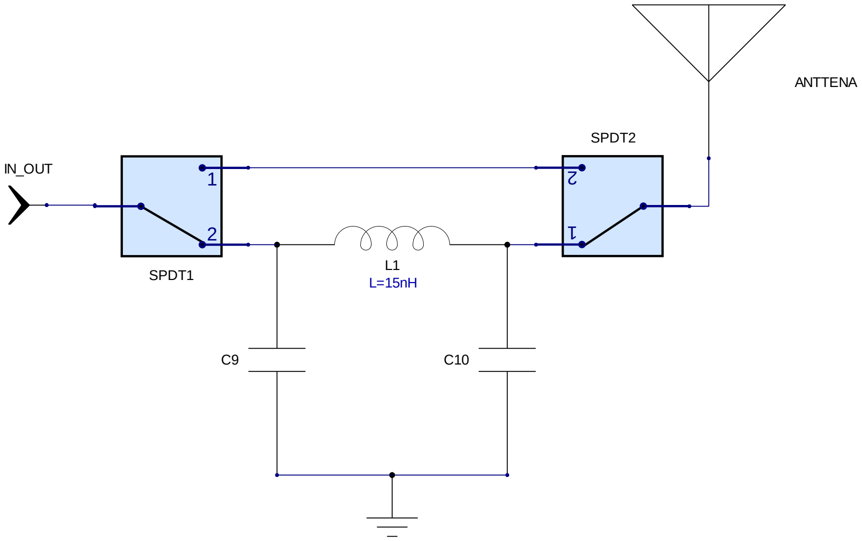

Figure 17. Impedance matching circuit with Bypass arrangement

5. IMPEDANCE MATCHING CIRCUIT TUNING APPROACH

Since there is a solution for antenna impedance matching, tuning techniques should be introduced to optimize the antenna performance dynamically. There are two practical approaches know as Open loop and closed loop [19].

5.1. Open Loop Tuning Approach

Open loop approach is simpler approach than closed loop approach. The ‘state’ of capacitors and their valid frequency ranges are stored in a Lookup table. According to the frequency channel, ‘state’s are retrieved from the lookup table (Table 3) and DTCs are tuned accordingly.

Since the lookup table is constructed during the design stage following method can be used to find the suitable ‘state’ for a required frequency.

According to Table 3, there are 12 states that cover the lower frequency range and Figure 15/ Figure 16 shows the frequency bands covered by states. At every discreet frequency point, there is a state which optimizes the S_{11} value. When the state index increases, minimum S_{11} point moves towards lower frequency. The state which optimizes S_{11} can be used to construct the lookup table and the optimized state vs. Frequency shown in Figure 18. In the figure, high value represents the optimized state and low value represents non-optimized state.

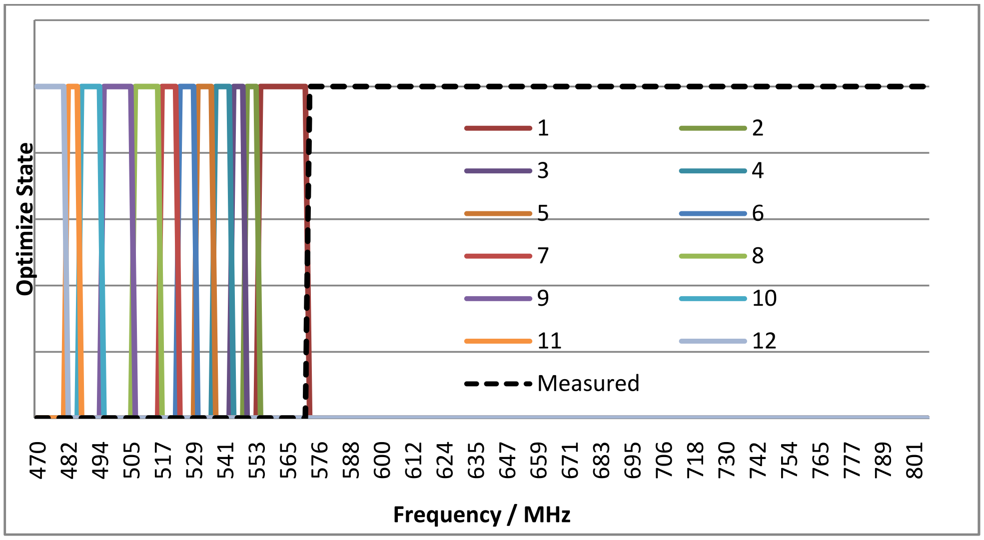

Figure 18. Optimized state vs. Frequency

The open loop approach is simpler one because lookup table is constructed in the design stage and no feedback path components required. Further, the control system (typically a microcontroller) is able to tune the impedance matching circuit fast because the decision making time to find ‘state’ values is less. This leads to higher frequency hopping rates and reduce the processing power. Ultimately, the open loop approach is a low cost one.

But it cannot be guaranteed that antenna operating environments are always similar like in the design stage therefore the antenna characteristics are slightly varying on operating condition. Hence at extreme operating conditions there might be an uncertainty about the pre-defined lookup table values. Although there is a such situation, since the bandwidth (< -10dB) of each state wider as shown in Figure 16, there is a very high probability of getting a matched condition even at different environments.

5.2. Closed Loop Tuning Approach

In the closed loop tuning approach a Bi-Directional Coupler is included between the impedance matching circuit and transmitter/ receiver. A bi-directional coupler couples both forward and reverse RF and DC signals separately as shown in Figure 19. Those signals can be used to calculate S_{11}/ voltage standing wave ratio (VSWR) by means of Logarithmic Detectors. Mini-Circuits® BDCN-20-13 bi-directional is a suitable selection because main line loss: 0.25dB; operating frequency: 360MHz~1000MHz; Input power: up-to 15W [20]. Analog Devices AD8313 fits for Logarithmic Detectors as operating frequency: 0.1 GHz~2.5 GHz; High dynamic range: 70 dB; High accuracy: ±1.0 dB [21].

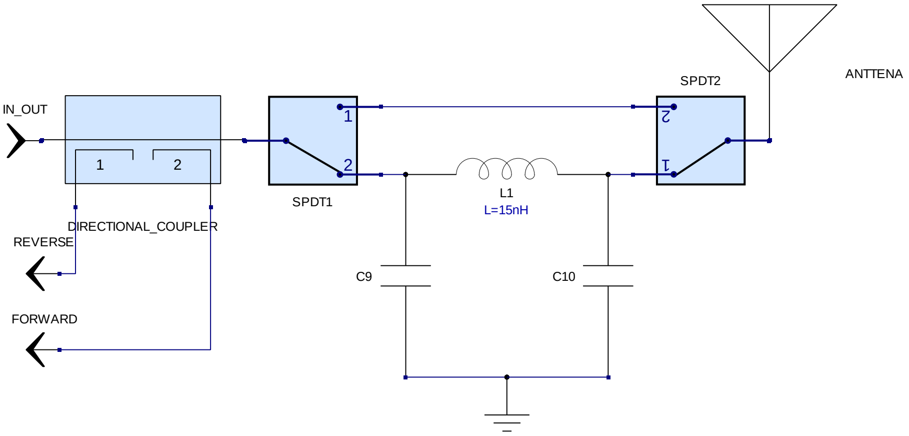

Figure 19. Impedance matching circuit with bi-directional coupler

S_{11} can be measured continuously with the bi-directional coupler arrangement. Then DTCs are tuned according to the S_{11} measurement for obtaining the optimum matching condition. There should be an algorithm to handle the dynamic tuning process. Such algorithms have been discussed in [22] and [23]. Since algorithms must be run on a microcontroller typically, a special attention should be given on the processing power.

When the antenna operating environment changes, algorithm can be run to obtain the optimum operating 'state' of DTCs. Therefore closed loop approach is slower than open loop approach. This leads to limit frequency hopping rates and increase the processing power. Although the closed loop impedance matching system adapt with the environmental condition, it requires additional hardware components that contributes to the cost of the overall antenna system.

6. OVERALL CIRCUIT DESIGN

Overall circuit design of the Tunable Antenna Design is shown in Figure 20. There, a system control microcontroller was included. The microcontroller obtains bi-directional coupler forward and reverse levels through the Logarithmic Detectors and converts those analog voltage levels to digital values using its analog to digital converter (ADC) to calculate present S_{11}/ VSWR value. Based on S_{11}/ VSWR feedback data the tuning algorithm is run to tune DTCs or disable the impedance matching circuit with the aid of SPDTs. The microcontroller communicates information such as operating frequency and frequency hopping rate with the transceiver. Since it is required analog inputs, digital outputs, serial inputs/ outputs and high-processing power to execute the tuning algorithm, microcontroller like PIC18F2550 can be used [24].

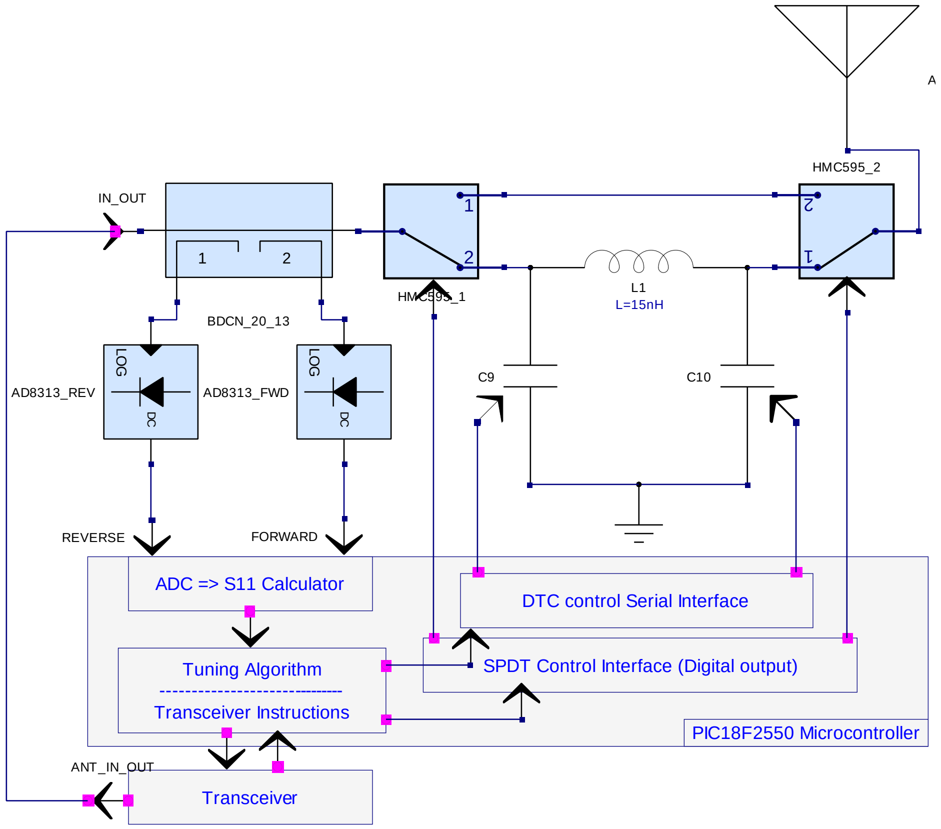

Figure 20. Overall Circuit Design

7. CONCLUSIONS

This Tunable Antenna Design in The UHF TV Band can be used in application such as spectrum sensing [25], wideband TV transmitters [26], wireless microphone, wireless sensor networks [27], broadband communication [6] and many other applications. Cognitive radios are the future trend of wireless communication architecture which will definitely occupy UHF TV band under standardisations. According to Figure 16, it can clearly be seen that the antenna design described here can full fill the demands by these devices.

Further, number of states can be reduced, if there is no requirement of high level matching where only -10dB matching is sufficient. The impedance matching technique explained here can be used for tunable filter designs as well.

The quarter-wave cylindrical monopole antenna with a tunable matching circuit is a simple and low cost wideband antenna solution. This relatively compact design can specially be used in stationary and mobile wireless communication transceivers.

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Authors

K.M.M.W.N.B. Narampanawe earned B.Sc. Engineering (Hons) degrees in Electrical & Electronics Engineering at University of Peradeniya, Sri Lanka, in 2007. He worked as an Engineer from 2007 to 2008 at Sri Lanka Telecom PLC and from 2008 to 2009 at Dialog Telekom PLC. He left industry to join academia in 2009 and worked as a lecture at University of Peradeniya until 2012. He is the author of numerous technical papers covering embedded systems, wireless communication and optical communication. His research interests are Cognitive Radios, Software Defined Radios, Wireless Sensor Networks, Ambient Energy Harvesting, Audio and Video Broadcasting, Radio Frequency Circuits, Embedded Systems, GPS systems

Chamath joined Electrical and Computer Systems Engineering Department of Monash University as a postgraduate student in 2011. His research interests include wireless communication related signal processing and chipless RFID systems. His PhD thesis is on MIMO based chipless RFID s ystems. He also works as a teaching associate at Monash University since July 2012. Chamath is an alumni of Carnegie Mellon University (CMU) from which he received a master's degree in Information Networking (2010). His bachelor's degree is on Electrical and Electronic Engineering from University of Peradeniya (2007).

Dr. Janaka Wijayakulasooriya received his B.Sc.Eng. degree with first class honours from University of Peradeniya, Sri Lanka in 1994 and he was awarded the Prof. E.O.E. Perera Gold Medal (1994) for the most outstanding graduate of the Faculty of Engineering. He received his PhD degree from U niversity of Northumbria at Newcastle Upon Tyne, UK in 2000. In July 1994, he started his career as an instructor in the Department of Electrical and Electronic Engineering, University of Peradeniya and at present he is working as a senior lecturer. He was the head of the department of electrical and electronic engineering from March 2009 to October 2010 and also the director of computing center from May 2007 to November 2011. He has worked as a student counsellor from 2005 to 2007. Further, he was the founder deputy chair of IEEE Sri Lanka central region subsection in 2007 and the chair of the IEEE Sri Lanka Central Region subsection in 2010. He was a resource person for more than 25 CPD courses/workshops and an invited speaker in many forums. His research interest covers the areas of Instrumentation, Signal processing and Intelligent Systems. In detail, they include application of advanced signal processing techniques and artificial intelligence in solving problems related to instrumentation such as sensor fusion, automated signature detection in signals, estimation and tracking, adaptive noise cancellation, and wireless sensor networks.

Dr. K. D. R. Jagath-Kumara graduated with a BSc degree specializing in Electrical and Electronic Engineering from the University of Peradeniya in Sri Lanka in 1985. He received the MEngSc degree majoring in Communications Engineering from the University of New South Wales in Australia in 1992 and the PhD degree from the University of South Australia in 1997. He was employed as an electrical engineer from 1986 to 1987 in Ceylon Electricity Board and as an electronic engineer at the Airports and Aviation Services Ltd. in Sri Lanka from 1987 to 1989. He held a research fellow position at the Australian Centre for Test and Evaluation of the University of South Australia from 1996 to 1997 and a visiting fellow position at the Faculty of Engineering of the University of Technology in Sydney from 1997 to 1998. He was a lecturer at the Institute of Information Sciences and Technology, College of Sciences, Massey University in New Zealand from 2000 to 2006. He was employed as an electrical engineer from 1986 to 1987 in Ceylon Electricity Board and as an electronic engineer at the Airports and Aviation Services Ltd. in Sri Lanka from 1987 to 1989. He held a research fellow position at the Australian Centre for Test and Evaluation of the University of South Australia from 1996 to 1997 and a visiting fellow position at the Faculty of Engineering of the University of Technology in Sydney from 1997 to 1998. He was a lecturer at the Institute of Information Sciences and Technology, College of Sciences, Massey University in New Zealand from 2000 to 2006. Since 2006, K D R Jagath-Kumara has been a senior lecturer in the Department of Electrical & Electronic Engineering, Faculty of Engineering, University of Peradeniya, Sri Lanka. His research interests include burst-error modelling and frame error-content probability, decoder metric processing and hybrid-ARQ schemes and RF & Sound Energy.