A 100 MHz 4 channels Narrow-band Chebyshev Filter for LTE Application

Othman A.R.[*1], Ahmad A.[*#2], Hamidon A.H.[*3], Pongot K.[*#4]

[*] Universiti Teknikal Malaysia Melaka (UTeM)
Faculty of Electronics & Computer Engineering,
Centre of Telecommunication and Innovation (CETRI),
Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[1]rani@utem.edu.my
[3]hamid@utem.edu.my
[#] Bahagian Sumber Manusia,
Majlis Amanah Rakyat (MARA),
Tingkat 17 & 18 Ibu Pejabat MARA, Jalan Raja Laut, 50609 Kuala Lumpur, Malaysia
[2]azmanahmad888@gmail.com
[4]kamilpongot@yahoo.com.sg

Abstract— This paper presents the design of a 100 MHz bandwidth with suitable for 4 channels narrow-band using Chebyshev filter at 5.75 GHz frequency. The design development includes calculation, simulation, measurement and testing. The simulation has been simulated using Ansoft Designer software to determine the bandwidth and the insertion loss, $|S_{21}|$. The band-pass filter design used Duriod 5880 TLY-5A-0200-CH/CH microstrip substrate parameters and lumped components with Chebyshev passive filter topology. The design is useful for applications in multi-channel narrow-band of wireless communication systems for front-end receiver architecture design.

Keyword- bandpass filter, microstrip filter, LTE, Chebyshev filter, low pass filter

I. INTRODUCTION

Wireless is a communication between two points/stations commonly used radio frequency (RF) to transfer and receive the information and data. LTE (Long Term Evolution) is a wireless communication of high speed data for mobile phones and data terminals which was introduced by 3rd Generation Partnership Project (3GPP). Today, a fourth-generation (4G) technology is growing rapidly with the ability to address high speed data transfer and improve the performance and capabilities of to the 3G technologies.

To handle high data rates, the ability of the existing 3GPP LTE-Advanced channel bandwidth should be greater than 20 MHz [1]. Nowadays, the LTE has a channel or component carrier bandwidth of around 20 MHz and usually in a narrow-band. A single channel exists in the limited spectrum to most operators. Thus, the ability to combine a number of channels that are scattered around the spectrum will be major steps in order to achieve efficient bandwidth and this usually requires bandwidth up to 100 MHz or more. This means that some channel consisting of a spectrum of either contiguous or non-contiguous must be added together to allow this spectrum bandwidth to widen and be able to handle faster data rates [2]. Producing an RF front-end receiver with wider bandwidth can improve the efficiency of the network infrastructure.

The combinations of available channel in one spectrum bands called as carrier aggregation technique [3]. Therefore, with the design of a wider frequency spectrum, more channels can be uploaded or downloaded. Simultaneously, it helps to reduce the crowded spectrum band travel in the air. The use of filters in LTE communication is highly desirable, especially in designing the front-end receiver [5].

A typical front-end receiver consists of a low noise amplifier (LNA) and filter as shown in Fig.1. The filter is used to address the issue of poor-band rejection [6], for example to avoid any signal degradation due to images [5] and to control the transmission leakage self-mixing problem [7]. A band-pass filter applied before LNA is used to pre-select the required wideband frequency [4]. The filters also provide attenuation of out-of-band interferers and relax linearity requirements for LNA/Mixer [8]. A filter is used to either block a signal from being processed or allow a signal to be processed.

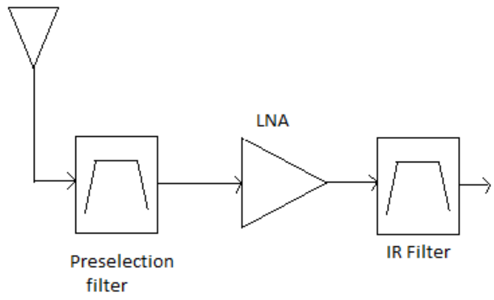

Fig. 1. A typical RF front-end receiver

A basic filter may be passive or active. A passive filter is made up of passive components such as resistor, capacitor and inductor and does not use amplifying element, such as a transistor or op-amp, it requires no power supply and is not restricted by the bandwidth limitation of op amps, so it can be used at very high frequency [9]. Meanwhile, active filters use an external power source and produce gain power during processing. The active filter also has frequency limits and is not as stable as passive filters.

This paper presents a 9th order Chebyshev band-pass passive filter. In section II, the calculation of the filter design is described using Chebyshev low-pass filter (LPF) and transformed into a band-pass filter (BPF). Section III, presents the simulation, measurement and testing for the results of the BPF design.

II. Filter Design

In this section, firstly is to know the specification of the design requirement. Then, focused on the design and development of band-pass filter using microstrip substrate Duriod 5880 TLY-5A-0200-CH/CH and lumped components band-pass filter.

Fig.2 shows the design concept using band-pass Chebyshev Filter to gather a multi-component carrier into one large spectrum. According to [10], there are benefits to expand more spectrums especially using unlicensed spectrum because it can help better performance like longer range and increase capacity, unified LTE network where common LTE network with common authentication, security and management, enhanced user experience and coexists with Wi-Fi where features to protect Wi-Fi neighbors.

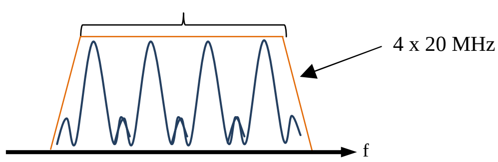

Fig. 2. Concept of carrier aggregation in wider band-pass Chebyshev Filter.

A. *Chebyshev Filter*

The Chebyshev filter frequency response has ripples in the pass-band compare to other filters. If more ripples are allowed, the initial slope at the beginning of the stop-band is increased and produces a more rectangular attenuation curve [11]. Choosing the type of filter is the initial process before proceeding to desired design, and then needs a filter specification to achieve goal and target design. Table I shows the Chebyshev BPF design specification for this project. From the specifications, we choose a Chebyshev filter design with ripple of 0.5 dB because the filter response has the steeper initial rate of attenuation beyond the cutoff frequency.

TABLE I
Band pass filter target design specification

Filter Specification	Value
Center Frequency	5.75 GH
Filter Type	Chebyshev
Insertion Loss S_{21}	<-10 dB
Stopband Attenuation	-25 dB @ 5.85 GHz
Bandwidth	100 MHz
Ripple	0.5 dB
Number of channels	4 channel/20Mhz

A band-pass filter also can be characterized by its Quality Factor (Q). A high Q factor will produce a narrow pass-band with high ripple of the response, while a low Q factor will produce a wideband with low ripple of frequency response.

B. Transform Low-pass filter (LPF) into Band-pass filter (BPF)

1) Microstrip Design Filter

The transformation from LPF into BPF is achieved by using an equation (1) to (5) from [12]. Δ is a bandwidth percentage which can be calculated using equation (2).

where

$$\omega_S = \frac{1}{\Delta}\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right) \tag{1}$$

and

$$\Delta = \frac{(\omega_2 - \omega_1)}{\omega_o} \tag{2}$$

$$\omega_o = \sqrt{\omega_1 \omega_2} \tag{3}$$

Substituting the values gives Δ = 0.174 and ω_s = 1.15. The following formula was used to calculate the n-order of Chebyshev Prototype LPF [12]:

$$n \geq \frac{\log\left(X + \sqrt{X^2 - 1}\right)}{\log\left(\omega_S + \sqrt{\omega_S^2 - 1}\right)} \tag{4}$$

where

$$X = \sqrt{\left(K_p^{-2} - 1\right)^{-1}\left(K_s^{-2} - 1\right)}$$
$$= \sqrt{(10^{0.1a_p} - 1)^{-1}(10^{0.1a_s} - 1)} \tag{5}$$

Substituting the values gives n $\geq$ 8.56, where the selecting n-order is 9. Based on Table II, the parameter value of 9th order LPF for Chebyshev filter is determined. The band pass ripple prototype is 0.5dB.

TABLE II
Parameter values of low pass prototype for Chebyshev filter

N	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}
9	1.7504	1.2690	2.6678	1.3673	2.7239	1.3673	2.6678	1.2690	1.7504	1.0000

(go = 1, c = 1, N = 1 to 9, 0.5 dB ripple)

Coupled line band pass applies filter can be manufactured by connecting the coupled lines [13] shown in Fig.3. To design equation for this type of filter, one coupled line is modelled into the equivalent circuit shown in Fig.4. The image impedance and propagation constant of the equivalent circuit can be calculated from this and it can be seen that these values approach to the values of coupled lines for θ = π/2, which corresponds to the center frequency of band pass response.

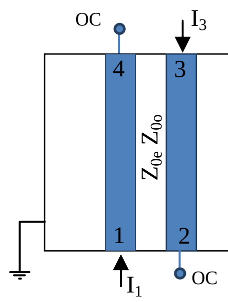

Fig. 3. 2-port coupled lines with the band pass response

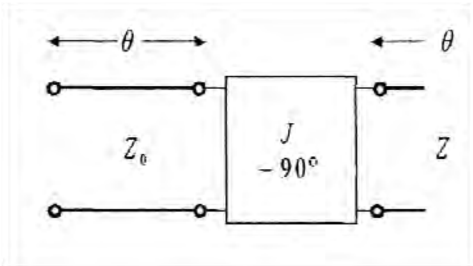

Fig. 4. Equivalent circuit of coupled lines [12]

The ABCD parameters of the equivalent circuit for a filter [14] can be represented as an equation (6) where

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} cos\theta & jZ_o sin\theta \\ \frac{jsin\theta}{Z_o} & cos\theta \end{bmatrix} \begin{bmatrix} 0 & -j/J \\ -jJ & 0 \end{bmatrix} \begin{bmatrix} cos\theta & jZ_o sin\theta \\ \frac{jsin\theta}{Z_o} & cos\theta \end{bmatrix}$$

$$= \begin{bmatrix} \left(JZ_o + \frac{1}{JZ_o} sin\theta cos\theta\right) & j\left(JZ_o^2 sin^2\theta - \frac{cos^2\theta}{J}\right) \\ j\left(\frac{1}{JX_o^2} sin^2\theta - Jcos^2\theta\right) & \left(JZ_o + \frac{1}{JZ_o}\right) sin\theta cos\theta \end{bmatrix} \quad (6)$$

Therefore, the image impedance of the equivalent circuit [12] is given by:

$$Z_i = \sqrt{\frac{AB}{CD}} = \sqrt{\frac{JZ_O^2 sin^2\theta - \left(\frac{1}{Jcos^2\theta}\right)}{\left(\frac{1}{JZ_O^2}\right) sin^2\theta - Jcos^2\theta}} \quad (7)$$

At center frequency θ = π/2, this reduces to:

$$Z_i = JZ_o^2 = \frac{1}{2}(Z_{oe} - Z_{oo}) \quad (8)$$

The propagation constant as an equation (9)

$$cos\beta = A = \left(JZ_o + \frac{1}{JZ_o}\right) sin\theta cos\theta$$

$$= \frac{Z_{oe} + Z_{oo}}{Z_{oe} - Z_{oo}} cos\theta \quad (9)$$

Therefore, it is assumed that when θ = π/2, sin θ = 1. These equations can be analyzed to give even and odd mode line impedance [12]:

where

$$Z_{oe} = Z_o[1 + JZ_o + (JZ_o)^2] \quad (10)$$

$$Z_{oo} = Z_o[1 - JZ_o + (JZ_o)^2] \quad (11)$$

and

$$Z_o J_1 = \sqrt{\frac{\pi\Delta}{2g_1}} \quad (12)$$

$$Z_0 J_n = \frac{\pi\Delta}{2\sqrt{g_{n-1} g_n}} \quad (13)$$

By using the attenuation for the normalized frequency graph in Fig.5, the order of the filter is determined by the slope of the attenuation curve. The graph shown the n-order of the filter and can be used to choose the target design required. Equations (10) to (13) shown the even and odd mode impedance that can be used in microstrip coupled line circuit.

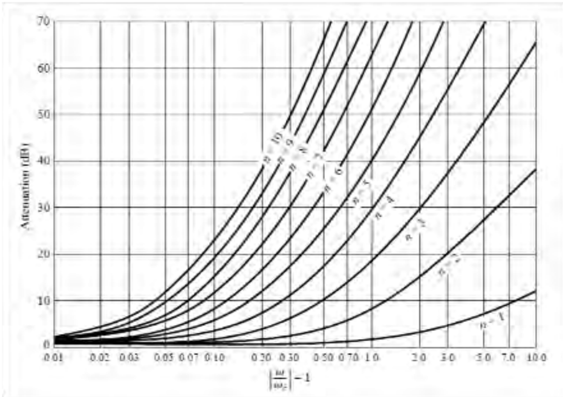

Fig. 5. Attenuation curves for a normalized frequency of Chebyshev (0.5dB ripple) filter prototype [14]

By using Ansoft software, the BPF was designed using coupled line circuit. Fig.6 shows the 9[th] order Chebyshev BPF with a loss tangent of 0.001, substrate thickness is 0.508mm and dielectric constant is 2.17.

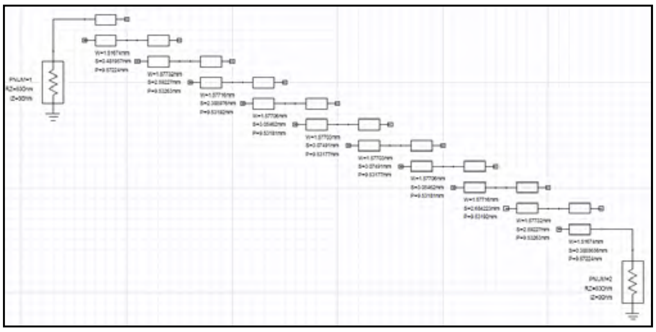

Fig. 6. Schematic of the 9th Chebyshev bandpass filter using the Microstrip coupled line

The Z_{oo} and Z_{oe} impedance can be calculated using equation (10) to (11), while the length (L), width (W) and the separation (S) can be determined using the Ansoft Designer tool. The result of W, S and L calculated can be referred to Table III.

TABLE III
9[th] Order Chebyshev Odd (Z_{oo}), Even (Z_{oe}) Impedance and Dimension of W, S and L

N	Z_{oe} (Ω)	Z_{oo} (Ω)	W (mm)	S (mm)	L (mm)
1	57.034889	44.529067	1.51884	0.480608	9.89362
2	50.935265	49.098473	1.57858	2.61606	9.85274
3	50.754992	49.267145	1.57829	3.01745	9.85201
4	50.726961	49.293584	1.57818	3.09193	9.85189
5	50.719328	49.300794	1.57814	3.11288	9.85186
6	50.719328	49.300794	1.57814	3.11288	9.85186
7	50.726961	49.293584	1.57818	3.09193	9.85189
8	50.754992	49.267145	1.57829	3.01745	9.85201
9	50.935265	49.098473	1.57858	2.61606	9.85274
10	57.034889	44.529067	1.51884	0.480608	9.89362

2. Design using lumped components

A nine element Chebyshev LPF schematic in Fig.7 has been designed based on Table II parameter values of the Chebyshev LPF prototype. The capacitor is arranged in parallel and the inductor is arranged in series. Each capacitor value is in Farad and each inductor value is in Henry and the cut off frequency of each filter is 1 radian per second.

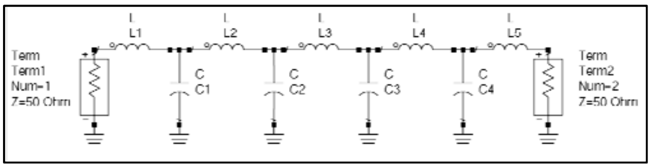

Fig.7. 9th order Chebyshev low pass filter circuit

After LPF prototype has been design, each L element at LPF is transformed to the BPF element by series of L`n and C`n circuit, while each C element at LPF is transformed to BPF by parallel of L`m and C`m circuit as shown in Fig.8. Then, next process it to scale the entire element to the frequency and impedance with the equation given from (14) to (17).

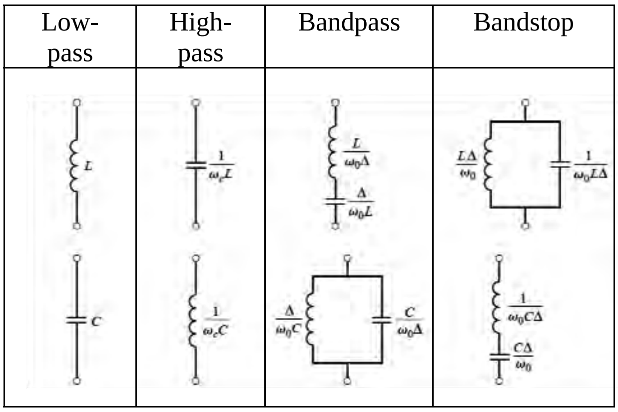

Fig.8. Prototype filter transformation [12]

Frequency and impedance scaled for series-resonant branches [12]

where

$$L_n' = \frac{L_n R_o}{\omega_o \Delta} \tag{14}$$

and

$$C_n' = \frac{\Delta}{\omega_o L_n R_o} \tag{15}$$

Frequency and impedance scaled in parallel-resonant branches [12]

where

$$L_m' = \frac{\Delta R_o}{\omega_o C_m} \tag{16}$$

and

$$C_m' = \frac{C_m}{\omega_o \Delta R_o} \tag{17}$$

The number of channels can be calculated using equation (18).

$$Num\ of\ channel = \frac{f_H - f_L}{\left(\frac{100\ MHz}{number\ of\ cc\ for\ 100\ MHz}\right)} \tag{18}$$

Fig.9 shows the complete schematic after BPF transformation. The number of elements is increased from nine to eighteen elements. Although increasing the numbers of element, the attenuation bandwidth of BPF ratio remains same with the LPF.

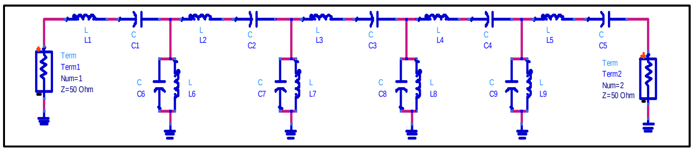

Fig.9. 9th Chebyshev Bandpass filter using Lumped Component

The values in Table IV were obtained by calculation, using frequency and impedance scaling equation (14) to (17).

TABLE IV
(a) and (b) Shown the Scale Inductor and Capacitor Value

Components	Values (nH)
L1	139.2
L2	212.3
L3	216.8
L4	212.3
L5	139.3
L6	0.01897
L7	0.0176
L8	0.0176
L9	0.01897

(a)

Components	Values (pF)
C1	0.0055
C2	0.00361
C3	0.00353
C4	0.00361
C5	0.0055
C6	40.39
C7	43.52
C8	43.52
C9	40.39

(b)

Fig.10 shows the fabrication of the band pass filter. The designed circuit was tuned and optimized in order to get an optimum layout. Somehow, the performances of the simulated circuit are remained.

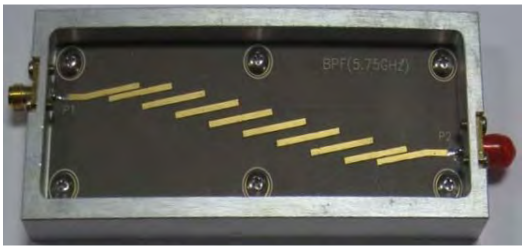

Fig.10. Fabricated bandpass filter

III.SIMULATION RESULTS

The result of Ansoft software simulations is depicted in Fig.11 and Fig.12. The fabrication BPF measurement is shown in Fig.13. The bandwidth of simulation for the BPF using lumped component and TLY-5A is 100 MHz. The measurement of the fabrication BPF bandwidth is 103 MHz. Both simulation and measurement achieved the target requirements.

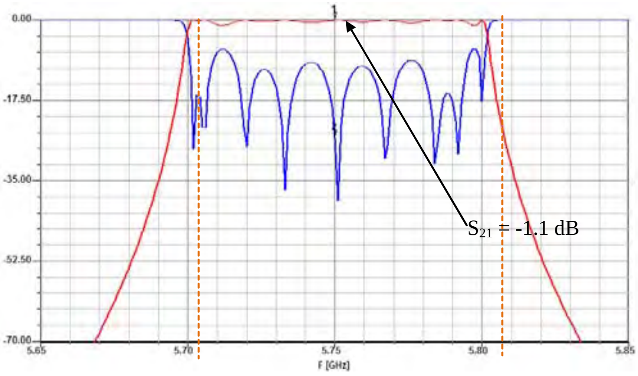

Fig.11. Frequency response using lumped BPF

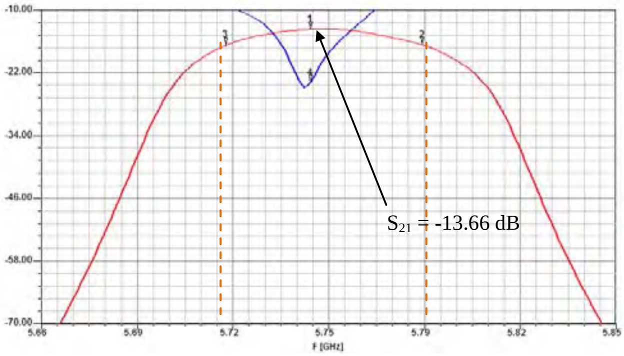

Fig.12. Frequency response of TLY-5A BPF

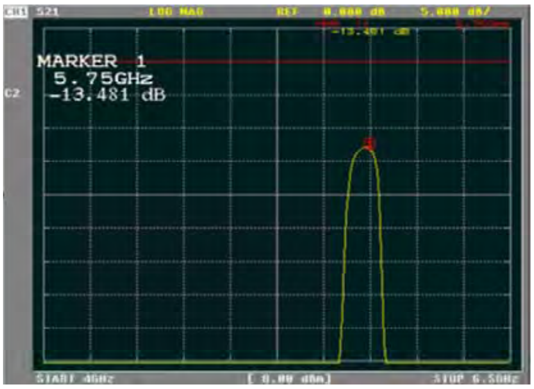

Fig.13. Frequency response of fabrication BPF

Table V shows the comparison of parameters for Chebyshev 9th order band pass filter using lumped components on TLY-5A.

TABLE V
Simulation Results between Lumped Component and TLY-5A Band Pass Filter

Parameter	**Target**	**Lumped Comp.**	**TLY-5A**	**Fabricated**
Frequency (GHz)	5.75	5.75	5.75	5.75
Bandwidth (MHz)	100	100	100	103
Insertion loss (S_{21}) dB	-10	-1.1	-13.66	-13.48
Number of channels	4	4	4	4

IV. CONCLUSIONS

In this paper, we simulated the performance of the BPF using lumped component and Duriod 5880 TLY-5A-0200-CH/CH. Both simulations have been compared with the output of the fabrication BPF prototype. The simulation result of insertion loss (S_{21}) shown that the microstrip TLY-5A is -13.66 dB and the lumped component is -1.1 dB. The result for the fabrication BPF is -13.48 dB. All the results achieved 100 MHz bandwidth and suitable for carrier aggregation technique with 4 channels in one spectrum band. The contribution is to build a part of the LTE front-end receiver with a combination of the multi-channel in large spectrum.

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AUTHOR PROFILE

Azman AHMAD was born in Penang in 1979. He received the B. Eng. Degree in (Electrical- Electronic) Engineering from University Technology of Malaysia in 2002. He received the Master Degree in Electronic (Electronic System) Engineering from Universiti Teknikal Malaysia Melaka in 2013. From 2002 to 2008, he was with Sony EMCS Sdn Bhd, based in Malaysia where he worked as a Senior Product Engineer. He worked as a lecturer at MARA Technical College. Currently is working toward the Ph.D. degree in new RF front end receiver architecture for Wireless Application at the University Teknikal Malaysia Melaka.

Abdul Rani OTHMAN was born in Kedah in 1964. He received B. Eng (Hons) in Electrical and Electronic from University of Strathclyde, Scotland and Master Degree in Electrical and Electronic from University Technology of Malaysia in 1987 and 1989 respectively. He received Ph.D in RF front-end receiver for wireless application from University of Teknikal Malaysia Melaka in 2010. He is currently an Associate Professor and also Dean at the Faculty of Electronic and Computer Engineering, University Teknikal Malaysia Melaka. His research interests include a variety of RF communication design and microwave application. He also investigates radiowave propagation in wireless communication systems.

Abdul Hamid HAMIDON was born in Penang in 1950. He received the B. Eng. Electrical from Monash University, Australia in 1976 and M. Sc degree in Electronics from University of Wales. He is currently a Senior lecturer and Professor at the Faculty of Electronic and Computer Engineering, Universiti Teknikal Malaysia Melaka, where he teaches electronic system, communication principles, microwave engineering, and embedded system. His research interests include Industrial Electronics, Analog Electronics, RF Subsystems, and Instrumentation.

Kamil PONGOT was born in Johor in 1977. He received the Dip. Eng and B. Eng. Degree in Electrical Telecommunication Engineering from University Technology of Malaysia in 1998 and 2000 respectively. He received the M. Sc Degree in Electronic and Computer Engineering from Hanyang University, South Korea in 2009. From 2000 to 2002, he was with STMicroelectronics, based in Malaysia where he worked as Testing Engineer. He worked as a lecturer at MARA Technical College. Currently is working toward the Ph.D. degree in new RF front end receiver architecture for WiMAX/Wireless Application at the University Teknikal Malaysia Melaka.