IMPROVED TECHNIQUES FOR POWER CONSUMPTION REDUCTION IN PORTABLE TWO-WAY RADIO

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IMPROVED TECHNIQUES FOR POWER CONSUMPTION REDUCTION

IN PORTABLE TWO-WAY RADIO

by

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SYMBOLS	
$2\theta_{1/2}$	Full Viewing Angle
ΔI_L	Inductor Ripple Current
$\Delta Battery\_Life$	Difference of Battery Life
λ_d	Color Dominant Wavelength
λ_{peak}	Peak Wavelength
η	Efficiency
η_1	Efficiency (1)
η_2	Efficiency (2)
η_3	Efficiency (3)
$\eta_{(BOOST)}$	Efficiency for Boost Topology
$\eta_{(PARALLEL)}$	Efficiency for Parallel Configuration
$\eta_{(SERIES)}$	Efficiency for Series Configuration
η_{Two_Stages}	Efficiency (Two Stages)
η_{Three_Stages}	Efficiency (Three Stages)
η_V	Luminous Efficacy
c	Velocity of Light in Vacuum
C	Capacitance
C_{load}	Load Capacitance
C_{OUT}	Output Capacitor
D	Duty Cycle
dI_L	Inductor Current Difference

dt	Time Difference
E	Energy
f	Frequency
f_{sw}	Switching Frequency
I	Current
I_1	Current at Branch 1
$I_{1(OFF)}$	Current at Branch 1 during OFF Condition
I_2	Current at Branch 2
I_n	Current at Branch n
I_{Avg}	Average Current
$I_{Avg\_Batt\_In}$	Average Current at Battery Input
$I_{Avg\_Batt\_In(initial)}$	Average Current at Battery Input of Initial design
$I_{Avg\_Batt\_In(improved)}$	Average Current at Battery Input of improved design
I_F	Forward Current
$I_{Idle(initial)}$	Current during idle mode of initial design
$I_{Idle(improved)}$	Current during idle mode of improved design
I_L	Inductor Current
I_{LOAD}	Load Current
I_{IN}	Input Current
I_{in1}	Input Current 1
I_{in2}	Input Current 2
I_{Out}	Output Current

$I_{in(TOTAL)}$	Total Input Current
$I_{Rx(initial)}$	Current during receive mode of initial design
$I_{Rx(improved)}$	Current during receive mode of the improved design
I_{Save}	Current Saving
I_{Sleep}	Sleep Current
$I_{Tx(initial)}$	Current during transmit mode of initial design
$I_{Tx(improved)}$	Current during transmit mode of the improved design
I_{Wake}	Wake Current
K	Temperature Coefficient of the Forward Voltage
kW	Kilo Ohm
L	Inductor
lm/W	Lumens per Watt
lv	Luminous Intensity
mA	Mili Ampere
mCd	Mili Candela
mW	Mili Ohm
mW	Mili Watt
mV	Mili Voltage
n	Refractive Index
n_x	Number of LEDs
P_D	Power Dissipation
$P_{D(RESISTiVE)}$	Resistive Power Dissipation
$P_{D(SWITCHING)}$	Switching Power Dissipation

$P_{D(TOTAL)}$	Total Power Dissipation
P_{IN}	Input Power
P_J	Power Dissipation at the Junction
P_O	Output Power
$P_{(OFF)}$	Power Consumption at OFF Condition
$P_{(ON)}$	Power Consumption at ON Condition
$P_{(PARALLEL)}$	Power Consumption in Parallel Configuration
$P_{(SAVE)}$	Power Saving
$P_{(SERIES)}$	Power Consumption in Series Configuration
$P_{(TOTAL)}$	Total Power Consumption
Rq_J	Thermal Resistance
$R1$	Resistor 1
$R2$	Resistor 2
$R_{ballast}$	Ballast Resistor
$R_{DS\ (ON)}$	Source to Drain ON Resistance
R_L	Load Resistor
T_J	Junction Temperature
T_0	Ambient Temperature
T_{OFF}	OFF Time
T_{ON}	ON Time
T_t	Test Temperature
t_{Sleep}	Sleep Time

t_{Wake}	Wake Time
v	Velocity of Light
V	Voltage
V_0	Forward Voltage at Reference Ambient Temperature
V_A	Voltage at Node A
V_{BE}	Base- Emitter Voltage
V_{CE}	Collector- Emitter Voltage
V_D	Voltage Across Diode
V_{DROP}	Voltage Drop
$V_{DROP(MIN)}$	Minimum Voltage Drop
V_{DS}	Drain-to-Source Voltage
V_F	Forward Voltage
$V_{F(LED)}$	Forward Voltage of LED
$V_{F(LED1)}$	Forward Voltage for the First LED
$V_{F(LED2)}$	Forward Voltage for the Second LED
$V_{F(LEDn)}$	Forward Voltage for the n LED
$V_{F(TOTAL)}$	Total Forward Voltage
$V_{F(TOTAL\_AT\_I_L)}$	Total Forward Voltage at I_L Condition.
$V_{F(TOTAL\_OFF)}$	Total Forward Voltage at OFF Condition.
V_{FB}	Flyback Voltage
V_{FLB}	Feedback Voltage
V_{IN}	Input Voltage

V_L	Voltage across Inductor
V_O	Output Voltage
V_{OMAP_CORE}	Voltage of the OMAP Core
$V_{(Rballast)}$	Voltage across Ballast Resistor
$V_{(Rballast\_OFF)}$	Voltage across Ballast Resistor at OFF Condition
V_{REF}	Reference Voltage
V_t	Forward Voltage at Temperature Test Condition.
x	Stages of voltage conversion

LIST OF ABBREVIATIONS

A/D	Analog /Digital
ADC	Analog to Digital Converter
ANA	Analog
ADDR	Address
CMOS	Complementary Metal Oxide Semiconductor
CMP	Comparator
CODEC	Compressor- Decompressor
CPU	Central Processing Unit
D/A	Digital/Analog
DC	Direct Current
DIG	Digital
DMM	Digital Multimeter
DRAM	Dynamic Random Access Memory
DSP	Digital Signal Processor
EIM	External Interface Module
EMIFS	External Memory Interfaces
EN	Enable
ESR	Equivalent Series Resistor
FGU	Frequency Generation Unit
FMC	Fixed- Mobile Convergence
GCAI	Global Communication Accessory Interface
GND	Ground
I2C	Inter-Integrated Circuits

IC	Integrated Circuits
IF	Intermediate Frequency
IEEE	Institute of Electrical & Electronic Engineering
I/O	Input/output
JTAG	Joint Test Action Group
LCD	Liquid Crystal Display
LDO	Low Dropout
LED	Light Emitting Diode
LiOn	Lithium-Ion
LNA	Low Noise Amplifier
LO	Local Oscillator
MHz	Megahertz
MOSFET	Metal-Oxide Semiconductor Field Effect Transistor
MPU	Main Processing Unit
OLED	Organic Light Emitting Diode
OPP	Operating Points
OTG	On-the-Go
PA	Power Amplifier
PC	Polycarbonate
PCB	Printed Circuit Board
P-N	Positive - Negative
PSM	Pulse Skipping Mode
PSRR	Power Supply Rejection Ratio
PWM	Pulse Width Modulation
RF	Radio Frequency

Rx	Receive
SDRAM	Synchronous Dynamic Random Access Memory
SoC	System On Chip
SPI	Serial Peripheral Interface
SPICE	Simulation Program with Integrated Circuits Emphasis
SSI	Synchronous Serial Interface
TT	Typical bin
Tx	Transmit
UHF	Ultra High Frequency
USB	Universal Serial Bus
USD	United States Dollar
VCO	Voltage Controlled Oscillators
VHF	Very High Frequency
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network

PENAMBAHBAIKAN TEKNIK- TEKNIK UNTUK PENGURANGAN PENGGUNAAN KUASA DALAM RADIO DUA-HALA MUDAH ALIH

ABSTRAK

Dalam pasaran radio dua-hala mudah alih, jangka hayat bateri yang panjang telah menjadi satu keperluan pelanggan yang penting dan kritikal untuk komunikasi semasa misi keselamatan awam dan penyelamat yang kritikal. Sejajar dengan keperluan ini, pelbagai penyelidikan telah dilaksanakan oleh pihak industri untuk mengurangkan penggunaan kuasa rekabentuk dengan pengorbanan yang minimum terhadap prestasi produk. Tesis ini membentangkan pelbagai teknik-teknik utama yang boleh diguna pakai didalam rekabentuk radio dua-hala mudah alih untuk mengurangkan penggunaan kuasa keseluruhan radio dari perspektif rekabentuk peringkat sistem dalam tiga bidang utama iaitu, topologi pengedaran kuasa DC untuk pemproses berdasarkan CMOS, sistem cahaya latar LCD dan pad kekunci dan bahagian RF pada mod melahu. Dalam topologi pengedaran kuasa DC untuk pemproses berdasarkan CMOS, dua teknik-teknik telah dikenal pasti untuk mengoptimumkan kecekapan keseluruhan rangkaian pengedaran kuasa dengan mengurangkan kehilangan penukaran kuasa didalam rangkaian berperingkat tersebut dan penggunaan penukaran kuasa tunggal secara langsung didalam rekabentuk radio mudah alih untuk menjimatkan 58% kuasa pada terminal bateri dan memanjangkan hayat bateri radio dua-hala mudah alih dengan tambahan 2.23 jam. Sementara itu pada sistem cahaya latar LCD dan pad kekunci, tiga teknik-teknik telah dikenal pasti untuk mengurangkan penggunaan kuasa pada terminal bateri sehingga 24% termasuk permilihan LED, pemandu cahaya dan topologi pengurusan kuasa untuk memandu LED secara cekap dan memanjangkan hayat bateri radio dua-hala mudah alih dengan

tambahan 0.39 jam. Mekanisma penjimatan bateri untuk litar RF pada mod melahu untuk mengurangkan penggunaan kuasa sehingga 50% juga dibentangkan di dalam tesis ini untuk memanjangkan hayat bateri radio dua-hala mudah alih dengan tambahan 0.5 jam.

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ABSTRACT

In the two-way portable radios market, long battery life has become an essential and critical customer requirement for communication during critical public safety or rescue missions. Thus, in tandem with this need, various researches have been conducted by industry players to reduce the power consumption of the design with minimum sacrifices on product performance. This thesis presents various key techniques that can be adopted into the design of portable two ways radio to reduce the overall power consumptions of radio in three main areas in the portable radio architecture from system level perspective; DC power supply topology for CMOS based processor, LCD and keypad backlighting system and RF sections at idle mode. In the DC power supply topology for CMOS based processor area, two techniques were identified to optimize the overall efficiency of the power distribution network by minimizing the power conversion lost in the multiple power conversion line up and utilization of single and direct conversion in the portable radio architecture to save up to 58% of power at battery input and prolonging the battery life of the portable two-way radio by another 2.23 hours. Meanwhile, in the LCD and keypad backlighting system, three techniques are identified to reduce the power consumptions at battery input of up to 24% which includes careful selection of LED, light guide and power management topology to drive the LEDs in an efficient manner and prolonging the battery life of the portable two-way radio by another 0.39 hours. Current reduction mechanism for RF sections in idle mode is also presented in

this thesis to reduce the overall power consumption by 50% in idle mode and prolonging the battery life of the portable two-way radio by another 0.5 hours.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Two-way portable radio communication has been widely adopted and used by government officers (policemen, firemen, soldiers) around the globe for communications during public safety and rescue missions; due to its availability and reliability to operate in the absence of network services in havoc conditions which are affected by natural disasters (earthquake, tsunami, flood, volcano eruptions, forest fires) and public disorders (riots, crimes, terrorist attacks). Apparently, it has been a norm for government officers to work around the clock and long hours in critical missions to save lives and keep public orders in place. Due to this need, long battery life on portable two-way radio has become an essential and critical customer's requirement for communications during critical public safety and rescue missions.

Carrying additional battery packs may be a quick solution, however it becomes so impractical to carry so many of them along during critical mission. Increasing the capacity of the battery packs might be another alternative to solve this dilemma, but with trade-offs. In additional product mechanical dimensions, additional weight and increase in the overall product development cost.

In reality, the actual usage profile of the portable two-way radio in a work shift is typically 5 % in receiving mode, 5 % in transmitting mode and 90 % in idle mode (GLMOBILE, 2009; ICOM, 2011; Motorola, 2011; GALT, 2011). Hence it has been a norm for portable two-way radio manufacturers such as Motorola, ICOM, Kenwood and Hytera to publish the battery life specification for the portable two-way radio according to 5-5-90 profile. Inherently, it shows that 90 % of the time in a work shift, the radio is left idling and none of the users talk (Tx) and listen (Rx) the entire time. Thus, it justifies the need to keep the power consumption during idle mode as low as possible to prolong battery life.

1.2 Problem Statements

In practical, battery life for portable two-way radio is calculated based on 5 % receiving, 5 % transmission and 90 % standby (idle) operations; known as the 5-5-90 duty cycle battery life profile (GLMOBILE, 2009; ICOM, 2011; Motorola, 2011; GALT, 2011). Apparently, the minimum expectation of battery life for the portable two-way radio is always 8 hours for a typical work shift (GALT, 2011). However, over the years, the demands for longer battery life of more than 8 hours during critical missions have imperatively spurs the research initiatives to reduce power consumption of portable two-way radio to prolong battery life (Motorola, 2011; ICOM, 2011).

The current consumption of ICOM IC-F4021T/S UHF range portable two-way radio at standby mode is about 75 mA @7.5 V battery input which is equivalent to 562.5 mW power consumption (ICOM, 2011). In receiving mode (Rx), the radio is drawing about 200 mA @7.5 V (1500 mW) at 0.5 W rated audio delivery to an 8Ω internal speaker (ICOM, 2011). Meanwhile in transmit mode (Tx), the radio draws about 1500 mA @7.5 V (11250 mW) at battery input with the output transmission of 4 W (ICOM, 2011). ICOM IC F4021T/S portable two-way radio offers 13 hours of battery life that comes together with 2000 mAH of Lithium Ion (LiOn) battery pack that adds up to the weight of the radio to 296 g. This is indeed heavy for modern handheld products and will weight down the personnel at work during critical mission. Furthermore, fireman on duty in a critical rescue mission (forest fire/ mining accidents) may require substantially more than 13 hours of operation adhering to the 5 % (Transmit) – 5 % (Receiving) – 90 % (Idle) cycles.

The battery input to portable two-way radio is commonly used at 7.5 V to power up the transmitter section in portable two-way radio (Motorola, 2008). It is further step down to various voltages to power up the entire subsections inclusive of the CMOS based processor which is commonly integrated into portable two-way radio design (Motorola, 2008). Apparently, with the continuous advancements of lower process nodes for CMOS based processor, the core voltage (VDD) for CMOS based processor has been significantly reduced to as low as 1.4 V for the 90 nm process node-CMOS based processor (OMAP 1710) (Texas Instruments, 2004) and 0.9 V to 1.15V for the 65 nm process node – CMOS based processor (OMAP 3503) (Texas Instruments, 2008). It had inevitably widen the voltage conversion gap from the battery input to the lowest voltage required to power up the CMOS based processor in the portable two-way radio and posing unnecessary power conversion loss on the voltage conversion chains.

Aside, in the existing battery life specifications of ICOM IC-F4021T/S (ICOM, 2011) and MOTOTRBO XPR6550 (Motorola, 2008), the battery life calculation does not include the current consumptions of the LCD and keypad backlighting system. In the MOTOTRBO XPR 6550, about 81.61 mA @ 7.5 V is used to light up both the LCD and keypad backlight system of the portable two-way radio. If it is included into the battery life calculation, it will significantly reduce the battery life of the radio to alarming 5.15 hours with a 1300 mAH battery pack (Motorola, 2011). This implies that the existing LCD and keypad backlighting system design of the MOTOTRBO XPR6550 portable two-way radio is power hungry and inefficient.

Furthermore, in the conventional portable two-way radio design, the RF sections are continuously enabled in idle mode for RF carrier signal monitoring process and there is no whatsoever current reduction mechanism available in the portable two way radio to turn ON and OFF the RF sections periodically to save current at idle mode (ICOM, 2011; Motorola, 2008).

1.3 Research Objectives

The objectives of this research are:-

(i) To identify and propose techniques to optimize the overall efficiency of the DC power supply topology for CMOS based processor in portable two-way radio to reduce current consumption at battery input which leads to lower power consumption in idle mode.

(ii) To identify and propose techniques to reduce the current consumption of the LCD and keypad backlighting system in portable two-way radio at battery input which leads to lower power consumption in idle mode.

(iii) To investigate and propose power reduction method for RF sections in idle mode.

1.4 Research Scopes

The power consumption reduction techniques researched and identified in this thesis encompass three main areas in the portable two-way radio design in idle mode. They are:-

(i) DC power supply topology for CMOS based processor.

(ii) LCD and keypad backlighting system.

(iii) Current Reduction Mechanism for RF sections.

1.5 Research Contributions

In this thesis, techniques for power consumption reductions in three major areas in the design of portable two-way radio in idle mode have been addressed. The techniques described in this thesis are specifically targeted for portable two-way radio design; which operates on 7.5V battery pack, where the need to manage the power consumption is so vital to meet the battery life of at least 8 hours in a work shift. The contributions of this research are:-

(i) Improved efficiency of DC power supply topology for CMOS based processor for portable two-way radio.

(ii) Improved efficiency of LCD and keypad backlighting system for portable two-way radio.

(iii) Power reduction of the RF sections with the implementation of current reduction mechanism for RF sections.

(iv) Extending the battery life of portable two-way radio without the need to increase battery capacity in which will affect the overall product’s weight and keeps the development cost at bay.

1.6 Thesis Organization

This thesis is organized in 6 chapters in chronological order as described below:-

Chapter 1 introduces the research background, problem statements, research objectives, scopes, contributions of this research and thesis organization.

Chapter 2 presents the overview of the general architecture for portable two-way radio and extensive literature reviews on the existing publications related to the DC power supply topology for CMOS based processor, LCD and keypad backlighting system design and current reduction mechanism for RF sections in portable two-way radio design. Extended theories on DC to DC voltage converters in portable devices, comparisons of linear and switching regulators in the market and consideration of multi-stages conversions in DC power distribution in portable electronic devices are covered in this chapter. Theories of LCD and keypad backlights system in portable devices, specifically in the areas of light source, light guide and backlighting topology and DC power source topology are also discussed in this chapter. Subsequently, theories of current reduction mechanism for RF sections are also presented in this chapter.

Chapter 3 presents the research methodologies for the entire identified research areas on DC power supply topology for CMOS based processor in portable two-way radio, LCD and keypad backlighting system in portable two-way radio and current reduction mechanism for RF sections for portable two way radio.

Chapter 4 presents the detailed implementations on optimization on efficiency of the DC power supply topology for CMOS based processor, efficient LCD and keypad backlighting system and current reduction mechanism for RF sections in reference to all the theories discussed in Chapter 3.

Chapter 5 presents all the results obtained based on all the implementations outlined in Chapter 4.

Chapter 6 concludes this thesis by presenting the summary of the conclusion in reference to the results obtained in Chapter 5. Suggestions for future works in reference to the limitations discussed in the conclusions are also included in this chapter.

CHAPTER 2

LITERATURE REVIEWS

2.1 Introduction

In this chapter, the background and general architecture for portable two-way radio will be outlined. Extensive literature reviews on the existing publications and theories on DC power supply topology for CMOS based processor, LCD and keypad backlighting system design, current reduction mechanism for RF sections and battery life calculation in portable two-way radio design will be covered too.

2.2 Background and Architecture of Portable Two-Way Radio

In general, a typical portable two-way radio consists of the baseband controller, frequency generation unit (Steward Becker and L. M. Leeds, 1936), receiver, transmitter , antenna and harmonic filter sections as illustrated in Figure 2.1 (Lee et al., 2006).

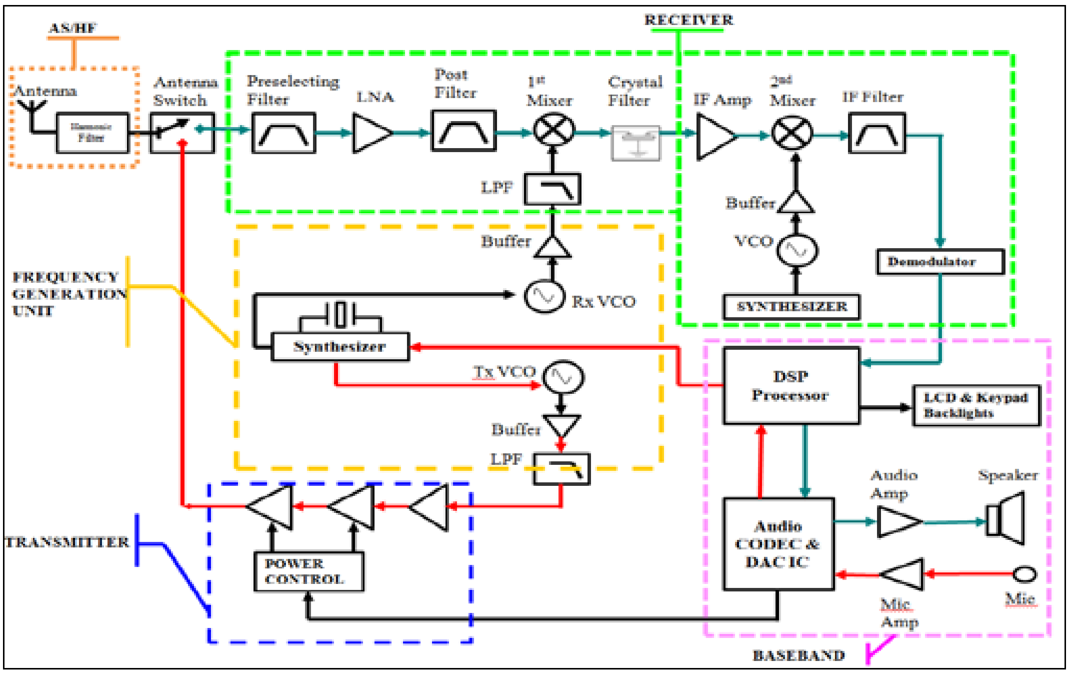

Figure 2.1: Typical Radio Architecture Block Diagram (Lee et al., 2006)

2.2.1 Baseband Controller Subsection

The baseband controller section is further divided into the following subsections; power management, processor/microcontroller and memory, audio codec and amplifier, LCD and keypad backlights and interface subsections as shown in Figure 2.2.

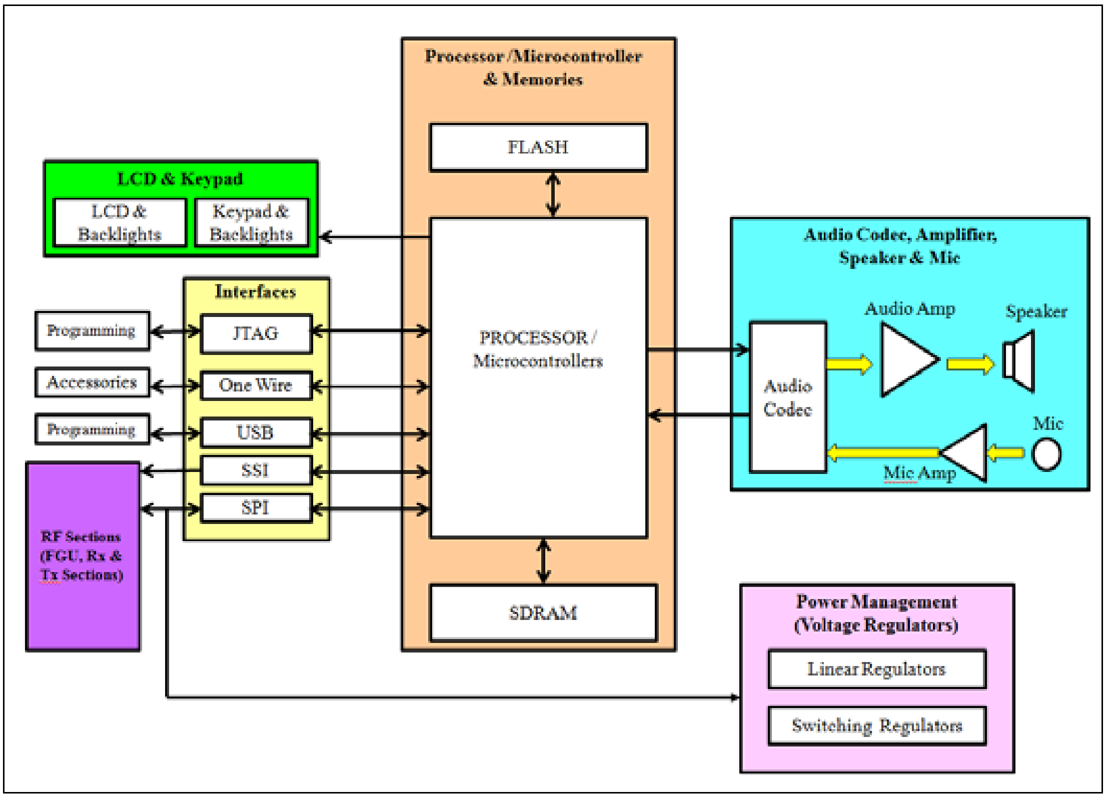

Figure 2.2: Typical Controller Block Diagram (Motorola, 2008)

The power management subsection provides regulated power supplies to power up the entire internal circuits in the radio. Processor or microcontroller unit is used for data communications in between the baseband controller and the adjacent subsections (audio, LCD, keypad, receiver, transmitter, frequency generation unit and accessories).

Audio codec and audio amplifier subsection work together to convert the digital data from the processor to analog format and subsequently amplifying the analog signal prior to transmitting it to the speaker. Apparently, the audio codec also takes the amplified analog information from the microphone (mic) and converts it to digital format to be further processed by the processor or microcontroller. LCD and keypad backlight subsection enhances the readability of the LCD and keypad of the portable radio in dark condition.

USB interface is used to program and load the compiled firmware from the computer to FLASH memory (non volatile) in the portable radio whereas JTAG interface is used for programming debug purposes. Meanwhile, serial peripheral interfaces (SPIs) are used by the processor to program and configure the power management and RF subsections upon immediate boot up of the processor. And finally, synchronous serial interfaces (SSI) are used in the portable radio for data transfers in between the controller and RF subsections.

The controller architecture used in the Motorola MOTOTRBO series portable radio is illustrated in Figure 2.3 (Motorola, 2008).

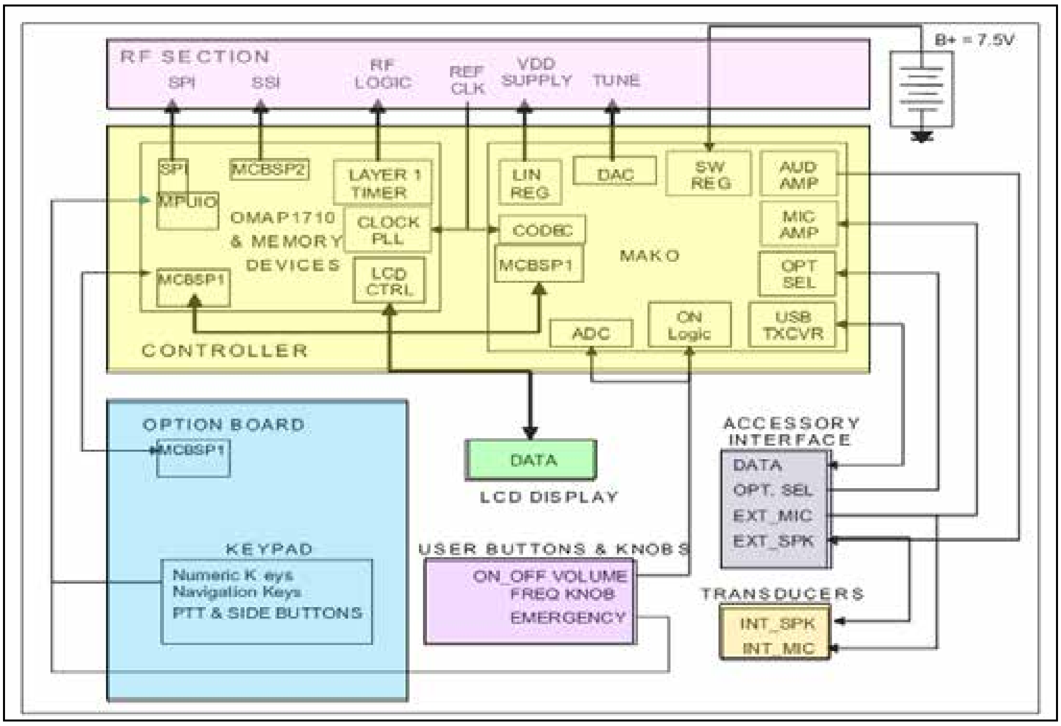

Figure 2.3: Baseband Controller Block Diagram in MOTOTRBO Portable Radio (Motorola, 2008)

In reference to the Motorola MOTOTRBO service manual (Motorola, 2008) which is available to portable two-way customers, the controller section consists of four main integrated circuits (IC). They are:-

(i) OMAP1710 Host/DSP processor :

The OMAP1710 IC comes with integrated dual-core architectures (TMS320C55x DSP core and ARM926EJS core). The core of OMAP is powered with 1.4 V and the periphery and I/O interfaces are powered with 1.8 V (Jamil Chaoui et al., 2000).

(ii) Flash:

The Flash memory IC is a 64 Mbit CMOS device which is supplied with 1.8 V. The Flash memory has its 23 address lines and 16 data lines connected to the External Interface Module (EIM) of the OMAP IC through the EMIFS_ADDR (23:1) and EMIFS_DATA (15:0) busses. The Flash memory contains host firmware, DSP firmware, code plug data, and tuning values.

(iii) SDRAM memories:

The Synchronous DRAM (SDRAM) is a 128 Mb high-speed CMOS device which is designed to operate at 1.8 V low-power memory system. The SDRAM has 13 address lines and 16 data lines connected to the EIM of OMAP IC through SDRAM_ADDR (12:0) and SDRAM_DATA (15:0) busses.

(iv) Audio and Power Management chip (MAKO):

The MAKO IC provides DC power distribution and audio processing (i.e. audio amplification and analog-to-digital/ digital-to-analog conversions). It consist of switching and linear regulators, 1 W audio amplifier, 16-bit Voice

CODEC, 11-channel 10-bit A/D Converter, 10 bit D/A Converter, support 2xUSB "OTG" transceivers, One-Wire Option Detect, and GCAI ports.

2.2.2 Frequency Generation Unit Subsection

Frequency generation unit is used in portable radio to generate a stable carrier radio frequency signal for modulation purposes. In the MOTOTRBO portable two-way radio, the frequency generation subsection consists of an integrated synthesizer IC called as Tomahawk and two voltage controlled oscillators (Rx VCO and Tx VCO) as illustrated in Figure 2.4 (Motorola, 2008).

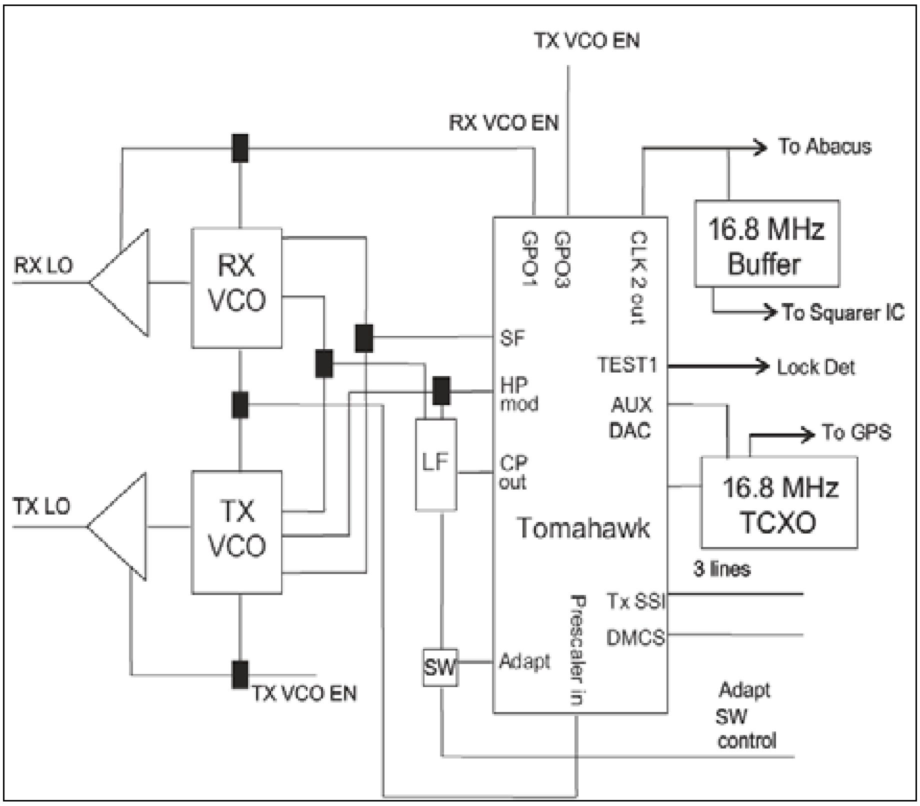

Figure 2.4: Frequency Generation Unit Block Diagram in MOTOTRBO Portable Radio (Motorola, 2008)

Tomahawk synthesizer IC is powered up by 2.8 V ANA, 2.8 V DIG, 1.875 V DIG and 5 V ANA supplies. It uses 16.8 MHz clock as reference clock in its operation. It generates a super filtered 2.5 V to power up the Tx VCO and Rx VCO. The Tomahawk IC communicates with the processor via synchronous serial interface and programmed by the processor via serial peripheral interfaces.

2.2.3 Receiver Subsection

The receiver subsection in portable two–way radio is utilized to filter, amplify and down convert the received modulated signals in RF to meaningful digital data before sending it over to the processor (OMAP) for further processing. In the MOTOTRBO portable two way radio, the receiver subsection consists of low noise amplifier, RF filters, mixers and intermediate frequency amplifiers as illustrated in Figure 2.5 (Motorola, 2008).

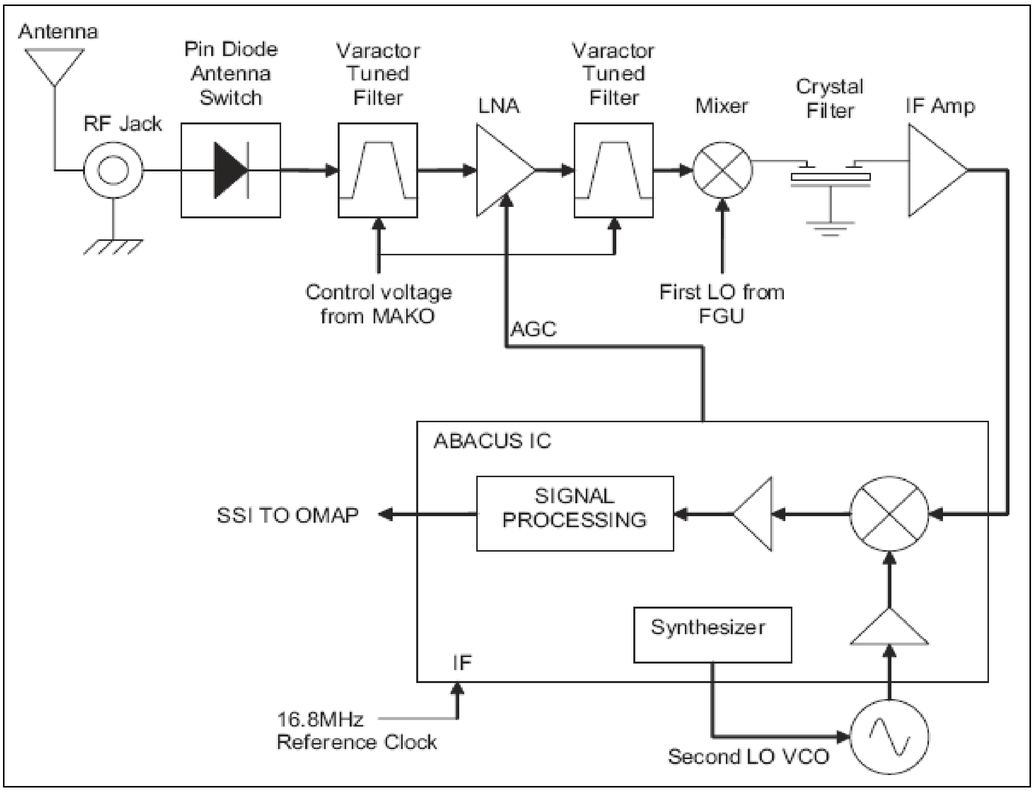

Figure 2.5: Receiver Block Diagram in MOTOTRBO Portable Radio (Motorola, 2008)

As soon as the RF signal is received by the antenna, the RF signal is filtered by the first varactor filter and subsequently propagates to the low noise amplifier for amplification. The desired amplified RF signal is then filtered by the second varactor tuned filter and subsequently down converted to intermediate frequency (IF) signal by the first mixer. IF signal is further amplified by the IF amplifier and down converted for the second time internally at the second mixer in the ABACUS IC. The second IF signal is converted from analog to digital data by the signal processing block in ABACUS IC and ready to be sent to the processor for further processing via the synchronous serial interface (SSI).

2.2.4 Transmitter Subsection

The transmitter subsection in portable two–way radio is utilized to amplify the modulated signal to desire RF output power before transmission via the antenna. In the MOTOTRBO portable two-way radio, the transmitter subsection consists of power amplifiers, power control, antenna switch, harmonic filter and antenna matching network as shown in Figure 2.6 (Motorola, 2008).

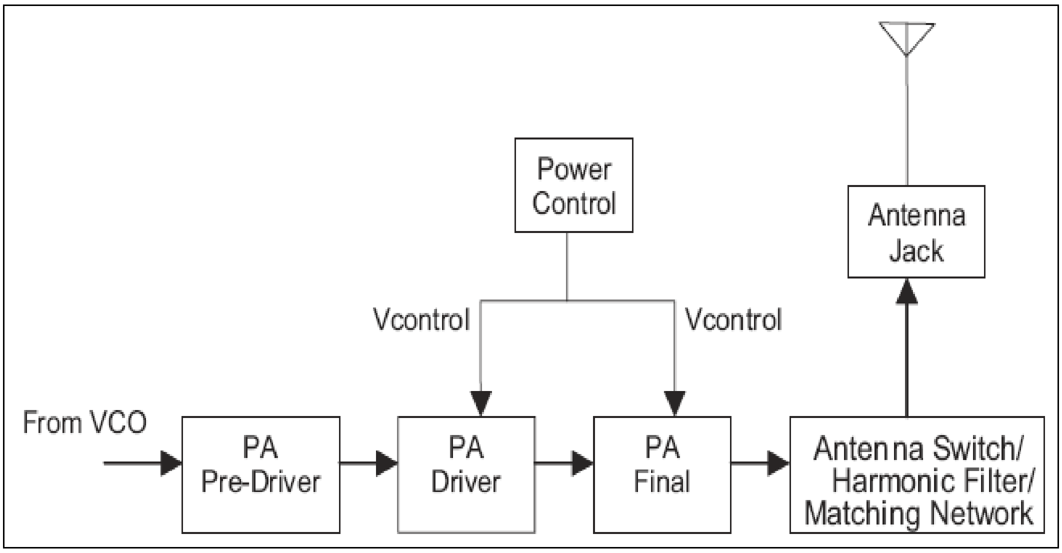

Figure 2.6: Transmitter Block Diagram in MOTOTRBO Portable Radio (Motorola, 2008)

Three stages of power amplifications (PA pre-driver, PA driver and final PA) are utilized in the MOTOTRBO portable radio to achieve 4 W of output transmission at the antenna. The voltage at the final PA output is continuously monitored by the power control block and adjusted automatically to maintain consistent transmission power.

2.3 Current State of the Art

Apart from review on the general architecture of the portable two-way radio, further literature reviews were also conducted mainly on the existing publications on three areas related to DC power supply topology for CMOS based processor, LCD and keypads backlighting system design and current reduction mechanism for RF sections.

2.3.1 DC Power Supply Topology for CMOS Based Processor in Portable Two-Way Radio

Over the years, intensive researches and developments in the area of linear and switching regulators by renowned DC regulator manufacturers such as Linear Technology, National Semiconductor and Texas Instruments have path the way for quicker integrations and product developments of electronic portable devices.

In 2008, Dongsuk Lee, Hyunseok Nam, Youngkook Ahn and Jeongjin Roh presented a paper on a 1.5 MHz, 300 mA buck switching regulator design using CMOS 0.18 um technology for the application of mobile devices and emphasize the importance of using switching regulator to achieve high efficiency and exceptional current driving capability (Dongsuk et al., 2008). Meanwhile in 2011, Jia Wang, Deyuan Gao, Ran Zheng, Hu C. and Yann Hu presented a paper on design of low drop out regulator using CMOS 0.35 um process to meet the low material and low noise requirements to internally supply the internal analog circuit (Jia et al., 2011). In 2010, Ong G.T. and Chan P.K presented a paper on the design of new micro power high power-supply-rejection ratio (PSRR) regulator without using op-amp for the application of micro power sensor circuits (Ong et al., 2010).

All of these research papers are published in the area of single stage DC to DC converters in both linear and switching topologies in which could be adopted directly into the design of mobile devices with the battery input of 3.6 V; e.g. mobile phones, a platform without a need for multi stages voltage conversion. That is the reason why hardly any paper been published with the overall design architecture of DC power distribution which requires multiple stages of voltage conversions, e.g. portable two-way radio.

The battery input to portable two way radio is commonly used at 7.5 V instead of 3.6 V. This is mainly due to the need of power amplifiers which resides in transmitter section in the portable radio to be powered up by 7.5 V to provide sufficient RF output power during transmission (Motorola, 2008). Meanwhile, with the advancements of CMOS based processor in IC designs arena into lower nanometer process nodes, the core voltage (VDD) to power up the CMOS circuits in the processor has been reduced significantly to 1.4 V for the 90 nm process node-CMOS based processor (OMAP 1710) (Texas Instruments, 2004) and 0.9 V to 1.15V for the 65 nm process node – CMOS based processor (OMAP 3503) (Texas Instruments, 2008). In another words, reduction in core voltage (VDD) of the CMOS based processor will be observed in the advancements of lower process nodes. Having said that, integrating the CMOS based processor as part and parcel into the portable two-way radio design has been a common approach adopted by portable two-way radio designer. Thus, raising the battery input voltage to 7.5 V to power up the transmitter section in portable two-way radio will inevitably widen the voltage conversion gap from the battery input to the lowest voltage required to power up the CMOS based processor in the portable two-way radio. Inherently, it spurs the need to use multi-stages voltage converters to keep the core voltage regulated to the CMOS based processor, in which will cause unnecessary power conversion loss on the voltage conversion chains, significant reduction in efficiency, higher current consumption to be observed at 7.5 V battery input at idle mode and shorter battery life according to the 5-5-90 battery life calculation. This is simply because, 90 % of the total usage of the portable two-way radio in a typical work shift operates in idle mode.

2.3.2 LCD and Keypad Backlighting System Design in Portable Two-Way Radio

Apparently, many research papers are published in the area of backlights power consumption reduction in mobile devices by using software approaches (Chakraborty S. and Ye Wang, 2009; Chih-Chang Lai and Ching-Chih Tsai, 2008; Sang Oh Park et al., 2011; Tae-Hyun Kim et al., 2010; Yeong-Kang Lai et al., 2011) and specific designs of LED drivers (Chun-Yu Hsieh et al., 2009; Wing Yan Leung et al., 2008; Yang Lu et al., 2011) but hardly any paper by hardware approach that offers comprehensive efficient solution combining all the areas of selection of LED driver, LED light source and light guide.

US Patent 2006/7834854 (Kyong-Youm Kim, 2010) claims an invention on a keypad backlighting device which includes a light source having an emission chip and a fluorescent material applied to the emission chip, the emission chip and the fluorescent material interacting with each other and generating white light. It uses an elastic pad as a light guide to reflect the lights generated from the emission chip but it does not claim any novelty on fiber optic light guide nor covering the aspect of LED driver at all. Similar work was also outlined by US Patent 1997/5640483 (Falcon Lin, 1997) which claims an invention on a backlighting system for liquid crystal display (LCD) panel constructed based on at least a light source and a flat light pipe to reflect the lights generated from the light source to light up the LCD. However, it also does not claim any novelty on utilizing fiber optic light guide nor include the aspect of LED driver as well. Meanwhile, US Patent 1998/5736973 (Tim Godfrey and David C. Hughes, Jr., 1998) claims an invention on a backlighting system for personal digital assistant (PDA) which consists of a backlight driver circuit on printed circuit board (PCB) that comes with on-off switch and diming control features to control the amount of lights to be reflected into the electroluminescent film. The patent only focuses on the invention on backlight driver circuit and suggests electroluminescent film as light guide but does not include the factor of light source which plays a significant role in backlighting system.

In 2012, Trukesh Nadarajan published a Master dissertation on effective keypad backlight design approaches for portable two-way radio (Nadarajan, 2012). The dissertation only addressed the keypad backlight system and does not address the LCD backlight system at all, which plays a significant role in the portable two-way radio backlighting system. Furthermore, the proposed LED driver (TPS61060) can only be used to drive a single string of LEDs at an instance and if it is used in the portable two way radio backlighting systems, two units of LED drivers will be needed to drive the LCD and keypad backlights independently. Inherently it will occupy more space and increase the development cost. Aside, the dissertation does not publish any calculation on efficiency to regulate the overall idea of the keypad backlighting system. Thus, the efficiency of the proposed backlight system in portable two way radio design is not clear from the angle of electronics. The usage of light guide was also proposed in the dissertation which is purely based on conventional polycarbonate (PC) material. In addition, the dissertation proposed a total change of color of LED from yellow green to white color to light up the keypad which deviated from the original design.

2.3.3 Current Reduction Mechanism for RF Sections in Portable Two-Way Radio

Over the years, many research papers work published in the area of power consumption reduction on processor specifically in processor based platform (Goossens, Gert., 2007; Shui-An et al., 2012; Teuscher et al., 2011; Watanabe et al., 2007). Apparently, Baltus P.G.M., Yan Wu, J.H.C. van del Heuvel and J.P.M.G. Linnartz have published a paper in 2010 to derive an optimal specifications consisting of the gain, linearity and noise figures to minimize the power dissipations in the RF front end section and reduce 50 % power consumption from initial 20.5 mW to 10.0 mW (Baltus et al., 2010). However, these power saving approaches do not address power saving on hardware RF sections by wake-sleep mechanism.

Jang Sung-Bong and Kim Young-Gab published a paper in 2010 on turning off Radio Frequency (RF) transceiver to prolong battery life-time of a Smart Phone equipped with WLAN-based Fixed-Mobile Convergence (FMC) service by managing the sleep threshold of the RF transceiver adaptively and adjust it according to the network traffic in service to conserve power (Jang et al., 2010). The paper focused on the power saving approach in smart phone based platform by integrating wake-sleep mechanism into the WLAN protocol of the firmware for smart phone.

Jang et al, claims that when the RF transceiver is turned off for 2 hours, the power consumption reduces by 6.15% from 342.18 mW to 321.12 mW.

Rohit Naik, Subir Biawas and Samir Datta proposed a new 802.11 Wi-Fi wireless protocol in 2005 that utilizes a distributed sleep-synchronization algorithm to reduce up to nearly 49 % power consumption of the wireless network during idle listening mode (Naik et al., 2005). It discusses power saving approach on a wireless network that uses 802.11 wireless protocol but not on a portable two-way radio system as well. Similar work had also been demonstrated by Fangmin Xu, Wei Zhong and Zheng Zhou in 2006 in proposing a WiMax IEEE 802.16 protocol that utilizes sleep mode to instruct the mobile subscribe station to sleep and wake-up at periodic interval to check the traffic and make a decision whether to remain in sleep mode or start to wake-up (Fangmin et al., 2006). Fangmin et al. claims that the modified protocol is able to reduce power consumption by 8%. However the approach focuses in the implementation of wake-sleep mechanism in WiMax system. Both of these papers (Fangmin et al., 2006; Naik et al., 2005) described the utilization of wake-sleep mechanism on protocols for WiMax based system but did not suggest a current reduction (wake-sleep) mechanism for RF sections for hardware based architecture in portable two-way radio where the access to the controller is available to do the job.

The percentage of power consumption saving attributed by each of these works are summarized in Table 2.1. Furthermore, according to the conventional portable two-way radio design, the RF sections are continuously enabled in idle mode for RF carrier signal monitoring process and there is no current reduction mechanism available in the portable two way radio to turn ON and OFF the RF sections periodically to save current at idle mode (ICOM, 2011; Motorola, 2008).

Table 2.1: Percentage of Power Consumption Reduction According to Research

Research	Percentage of Power Consumption Reduction (%)
Optimal on gain, linearity and noise figures (Baltus et al.)	50
Adaptive RF transceiver turns off method (Jang et al.)	6.15
Distributed sleep-synchronization algorithm on 802.11 Wi-Fi (Naik et al.)	49
Sleep and Wake Modes for WiMax IEEE 802.16 (Fangmin et al)	8

2.4 Theories

In order to gage better understanding, extensive theories were also conducted on the area of DC power supply topology for CMOS based processor, LCD and keypads backlighting system design, current reduction mechanism for RF sections and battery life calculation in portable two-way radio design.

2.4.1 DC Power Supply Topology for CMOS Based Processor

In the DC power distribution of the battery powered electronic portable devices, DC to DC converters are commonly integrated to provide stable and regulated voltages to power up the entire circuits in the electronic portable devices (Chunlei Shi et al., 2007). The DC to DC converters which are also known as regulators are sub-categorized into two main categories; they are linear regulator and switching regulator.

2.4.1.1 Linear Regulator

A typical linear regulator consists of a series pass element (transistors), an error amplifier and two feedback resistors as shown in Figure 2.7 (Abraham L.

Pressman, 2001; Hu Yueli et al., 2011). It is designed to work in step down (buck) topology only, whereby the output voltage will be lower than the input voltage.

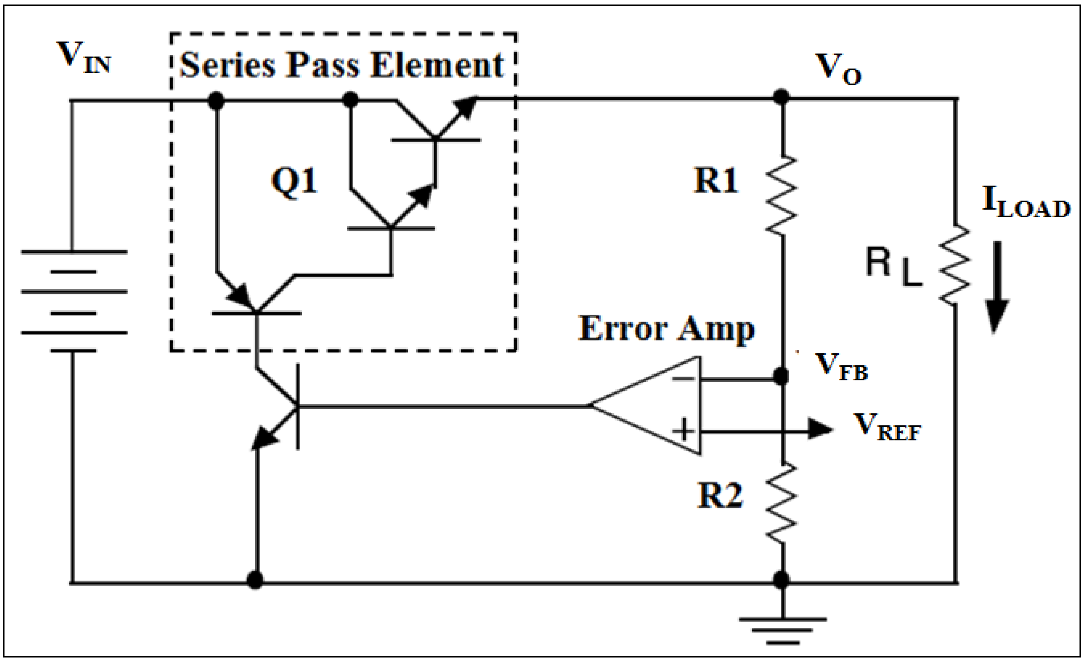

Figure 2.7: Typical Schematic of Linear Regulator (Abraham, 2001)

The output voltage is obtained by adjusting the voltage drop across the series pass element, V_{DROP} by the error amplifier according to Equation 2.1:-

$$V_O = V_{IN} - V_{DROP} \tag{2.1}$$

The minimum voltage drop needed to regulate the output voltage can be expressed by Equation 2.2:

$$V_{DROP(MIN)} = 2V_{BE} + V_{CE} \tag{2.2}$$

$V_{DROP(\mathrm{MIN})}$ is also known as minimum drop-out voltage. V_{BE} is the voltage across the base and emitter terminals and V_{CE} is the voltage across the collector and emitter terminals of the Q1 transistors. The output feedback voltage, V_{FB} is continuously monitored by the error amplifier. It compares V_{FB} with a stable reference voltage (V_{REF}) and adjusts the voltage drop across the series pass element automatically to maintain constant output voltage (V_O). V_{FB} can be computed based on Equation 2.3:-

$$V_{FB} = \left(\frac{R2}{R1 + R2}\right) V_O \tag{2.3}$$

Meanwhile, the power dissipation (P_D) across the series pass element is calculated based on Equation 2.4:-

$$P_D = V_{DROP} \times I_{LOAD} \tag{2.4}$$

From Equation 2.4, it clearly shows that the higher the amount of load current (I_{LOAD}) been pulled by the load, higher number of power dissipation will be expected at serial pass element inside the linear regulator. Apparently, the amount of current that will be reflected at the input terminal of the linear regulator will be approximately the same as the amount of current pulled by the load.

$$I_{IN} \approx I_{LOAD} \tag{2.5}$$

Hence, the efficiency, η of the linear regulator can be estimated based on Equation 2.6:-

$$Efficiency, \eta = \frac{P_O}{P_{IN}} = \frac{V_O \times I_{LOAD}}{V_{IN} \times I_{IN}} = \frac{V_O}{V_{IN}} \tag{2.6}$$

Equation 2.6 shows that the efficiency of the linear regulator is the ratio of the output regulated voltage over the input voltage. In another words, the efficiency of the linear regulator drops significantly if the gap in between of the input voltage versus the output voltage widens. Thus, linear regulator will be best suited for applications where the desired regulated output voltage is close to the input voltage.

2.4.1.2 Comparisons of Linear Regulators

In order to better understand the main specifications of linear regulators in the market, quick comparisons are performed on various adjustable output linear regulators offered by Texas Instrument, National Semiconductor and Linear Technology. The comparisons include:-

(i) The amount of quiescent current (leakage current) at standby mode.

(ii) Range of input voltage accepted by the regulator

(iii) Output voltage of interest.

(iv) Maximum current driving capability of the regulator.

(v) Ability of the regulator to reject input supply noise, known as power supply rejection ratio (PSRR).

(vi) Dropout voltage introduced by the series pass element at load current of interest.

(vii) Package size of regulator.

(viii) Cost of regulator.

The comparisons of various linear regulators with adjustable output are summarized in Appendix A1 (Linear, 2003; Linear, 2005; Texas Instrument, 2001; Texas Instrument, 2008; Texas Instrument, 2009; Texas Instrument, 2011). In practice, linear regulator with low quiescent current, low dropout voltage, low output noise, high PSRR ratio, within current capability of interest, small package size, lowest possible cost and within the input and output voltage of interest will be selected to be integrated into the designs of portable radio.

From Appendix A1, LT1761-5 from Linear Technology is a better linear regulator with quiescent current as low as 20 uA, accepting wide input voltage from 1.8 V to 20 V and comes with adjustable output voltage at maximum current