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Strategies of Efficient Backlighting System for Portable Two-Way Radio Design

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ABSTRACT: In the 2-way radios market, long battery life has becomes an essential & critical customer requirement for communications during critical public safety or rescue missions. Thus in tandem with this need, various researches have been conducted by industry players to reduce the current consumption of the design with minimum sacrifices on product performance. This paper attempts to describe various key strategies that can be adopted in the design of backlighting system for portable two ways radio design to reduce the overall current drain consumptions. Case study was carried out on the keypad and liquid crystal display (LCD) backlighting systems of the off-the-shelf portable two-way radio in the market and recommendations for optimizations were laid forward which includes careful selection of LED, light guide and power management topology to drive the light emitting diodes (LEDs) in an efficient manner and successfully reducing current drain consumptions by a remarkable 24 %.

Keywords: Backlights, battery life, current drain reduction, efficiency.

I. INTRODUCTION

A. *Customer Requirement & Literatures Reviews*

Longer battery life has become an essential requirement to the customer during critical mission operations. For example, fireman on duty in a critical rescue mission during the night or in a dark environment (tunnel, drainage or mining shaft) may substantially require to turn ON the LCD and keypad backlighting system in the radio continuously for better accessibility and viewing in the dark environment for a minimum of 8 Hours operations (1 work shift).

However, the current battery life calculations for portable two-way radio in the market which adheres to the 5 % (Transmit) – 5 % (Receiving) – 90 % (Idle) cycles calculation does not include the current consumption of the backlighting system into the calculations at all [1], [2], [3].

Demanding customers (e.g. fireman) may require to include the current consumption of the LCD and keypad backlighting system into the existing battery life calculation in which significantly impacting the battery life of the portable radio. 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 tandem with this need, various researches have been conducted by industry players to reduce the current consumption of the design with minimum sacrifices on product performances.

Apparently, there are many research papers published in the area of backlights power consumption reduction in mobile devices by using software approaches [4], [5], [6], [7] but hardly any paper by hardware approach that offers comprehensive efficient solution combining all the areas of selection of LED drivers, LED light source and light guide. US Patent 2006/7834854 [8] 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 [9] 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 [10] 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

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Vol. 1, Issue 9, November 2012

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 [11]. The dissertation only addressed the keypad backlight system and but does not address the LCD backlight system at all which also 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 of them will be needed to drive the LCD and keypad backlights independently. Inherently it will occupy more space and increase the development cost. Aside, the author does not publish any calculation on efficiency to regulate the overall idea of the keypad backlighting system. Thus the efficacy of the proposed backlight system in portable two way radio design is not clear from the angle of electronics. Usage of light guide was also proposed in this dissertation but it was based on conventional polycarbonate (PC) material and not based on fiber optic sheet. Not only that, the dissertation proposed a total change of color of LED from yellow-green to white color to light up the keypad and will definitely require tedious human factor acceptance and buyoff.

In another words, the motivation of this research is to present a comprehensive hardware based novel backlighting approach for application in both keypad and LCD backlight systems in portable two-way radio design without the need to change the color of backlighting system to another. The paper is organized by presenting the case study conducted on the backlighting design approach on off-the-shelf portable radio in the market in Section I. Three strategies to reduce the current consumptions of the backlighting system design in the case study will be outlined and a novel solution combining all these strategies will be proposed in Section II. Experiments and evaluations on the proposed solution are discussed in Section III with proven calculations and bench measurements. Finally the summary and conclusions are drawn in Section IV .

B. Overview of The LCD and Keypad Back lightings Current and Power Consumptions in Portable Two-Way Radio

In this research, product teardown was conducted on keypad and backlighting system of an off-the-shelf portable two way radio developed by Motorola, called MOTOTRBO XPR6550 to be used as a case study. The current drains at battery input 7.5 V were measured and recorded when the backlights for the LCD and keypad are enabled independently. The measured current consumptions of the backlighting systems of the portable radio are at alarming figures of 34.61 mA @ 7.5 V (LCD backlight) and 47 mA @ 7.5 V (keypad backlight) when they are enabled as illustrated in Figure 1.0 and Figure 1.1.

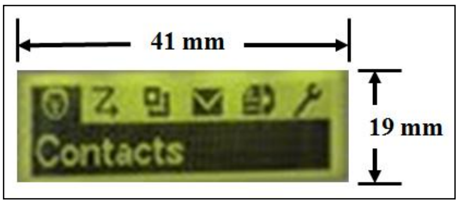

Figure 1.0: LCD backlight enabled [2].

Figure 1.1: Keypad Backlight enabled [2].

By close visual examinations, the backlighting systems (LCD and keypad) in the portable two way radio are constructed based on multiple branches of Light Emitting Diodes (LEDs) in parallel topology. In its LCD Module, 4 LEDs are used in 2 LEDs x 2 branches parallel topology with direct voltage source of 7.5 V. Meanwhile in the keypad backlight system, 10 LEDs are used in 2 LEDs x 5 branches parallel topology with direct voltage source of 7.5 V.

In general, the power consumption of the respective LCD and keypad backlighting systems can be calculated by multiplying the measured current (I) with the measured supply voltage (V) as given in equation 1.0.

$$P = I \times V \qquad (1.0)$$

By utilizing equation 1.0, the power consumed by the LCD backlight system is 259.58 mW and as for the keypad backlight system is 352.5 mW. In total, both of the backlighting systems consume 612.08 mW. Meanwhile in terms of current consumptions, both the backlighting systems draws 81.61 mA @ 7.5 V (battery input). If this cumulative current drain figure is included into the battery life calculation for two-way radio design, it will certainly be a real challenge for portable radio designer to meet the battery life requirements. Hence, the motivation of this research is to identify various strategies to reduce the current consumption in the backlighting system for portable two-way radio design while maintaining the crucial requirement on uniformity and

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Vol. 1, Issue 9, November 2012

luminance of light across the area of interest across the backlighting systems.

II. STRATEGIES TO REDUCE CURRENT CONSUMPTIONS OF BACKLIGHTING SYSTEM

In the quest to improve the current consumption of the backlighting system, three areas have been identified for improvements. They are:-

a) Regulation and Topology to light up the LEDs.
b) Light Source and Type of LEDs.
c) Light- Guide

A. Regulation and Topology to light up LEDs

In the portable two-way radio backlighting designs, the supply/regulation to the LEDs (LCD and keypad backlights) is provided directly from battery input (7.5V) [12]. The current to each of the LEDs parallel branches is controlled by the value of the ballast resistor connected in series at each of the respective branches. It was designed in such approach so that the brightness across the LEDs at its respective branches could be tweaked easily by varying the value of the ballast resistor to achieve uniform distribution of light across the area of interest. Utilizing this topology is indeed the simplest way to control the brightness of the LEDs however it might not be a good approach when power losses could be greatly attributed by the existence of the ballast resistors.

In order to overcome this, highly efficient LED driver (a current source device) will be utilized to provide sufficient regulation to power up the LEDs and control the amount of current across strings of LEDs. In line with this proposal, the strings of LEDs will be re-topologized from parallel topology to series topology to reduce the amount of current consumption at battery input (7.5V input). Two LED drivers will be used to drive the LEDs in two separate strings; one for LCD backlighting and the other for the keypad backlighting. However for space saving purposes, LED driver in a single chip with dual string outputs will be ideally preferred to cater for this need. In this research, two LED drivers (single chip with dual outputs) that closely match the desired requirements have been identified; they are the LT3466 and LT3497 LED drivers from Linear Technology. The evaluation and concerns of both of these LED drivers will be discussed in Section III.

B. Light Source and Type of LEDs

By close visual examination on the portable two-way radio, yellow-green (572 nm peak & dominant wavelength) top firing Chip LEDs (QSME-C198) from Avago Technologies are used to light up both the backlights for LCD and keypad. According to the QSME-C198 datasheet, the luminous efficacy of the LED is typically at 570 lm/W and the normalized luminous intensity is 1.0 @ 20mA load (*Bin P*: 45.0 - 71.5 mcd @ 20 mA) [13].

One of the quick ways to reduce current consumption is to use less LEDs and utilizing few side- firing with high brightness LEDs (at the higher bin) as the light source to light up an efficient light guide (fiber optic sheet) in which will be proposed in section II.C. In line with the direction to use the dual outputs LED driver and fiber optic sheet as light guide, five high brightness side-firing LEDs will be used to lit up the keypad while four high brightness LEDs will be utilized to lit up the LCD for the portable two-way radio. It shows that in contrast, the number of LEDs for the backlighting in portable two-way radio keypad could be significantly reduced from 10 LEDs to 5 LEDs which constitutes about 50 % reduction in total usage of LEDs. To cater for this reduction, 572 nm wavelength side firing yellow-green LED (HSMG-C110/120) from Avago Technologies is recommended because the LED provides exceptionally high brightness (Bin V: 715 -1125 mcd @20 mA) [14].

The forward voltage, V_F of the HSMG-C110/120 LED at 20 mA is about 2.1 V; which is exactly the same as the forward voltage specification of QSME-C198 LED used in the MOTOTRBO's keypad and backlighting systems. Apparently, HSMG-C110/120 LED also comes with lower intrinsic capacitance of 9 pF comparatively to QSME-C198 LED which is at 15 pF. It implies that HSMG-C110/120 LED turns on faster than the QSME-C198 LED. Moreover, HSMG-C110/120 LED also comes with an attractive thermal resistance value; 600 $^oC/W$ which is reasonably low, comparable to QSME-C198 LED and able to handle forward current of 20 mA constantly in within the ambient temperature of 0 ^oC to 65 ^oC. The full viewing angle of the HSMG-C110 LED and HSMG-C120 LED is about 60^o (from -30^o to 30^o) and 80^o (from -40^o to 40^o) respectively. Both of them are relatively wide enough to direct light into the fiber optic light guide that will be proposed in the next section. In this research the dominant color of the LED is maintained at 572nm (yellow-green); the original color which has been widely accepted by the customer of portable two-way radio design.

C. Light-Guide

Conceptually, LED is a point light source and it is hard for a single LED to cover uniform distribution of light on the area of interest. Apparently, this justifies the need to use a light guide to spread out the lights from the LEDs. In MOTOTRBO XPR6550 portable two-way radio, a plastic light guide is used to spread out the lights in the LCD backlighting system. However as for the keypad, there is no plastic light guide available at all to spread out the lights from the LEDs. That explains why 10 LEDs are used to light up the keypad so that all the areas under the keypad are sufficiently light up.

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Fiber optic light guide (Woven) is claimed to be one of the most efficient light guides that is able to light up reasonable area of interest with minimal amount of LEDs. The combination of fiber optic sheet with high efficiency LEDs could be one of the backlighting alternatives to the existing approach in MOTOTRBO two-way radio. Lights or photons are refracted or reuse internally in the fiber optic sheet. The cross section of the woven fiber optics and its internal construction are shown in Figure 2.0, Figure 2.1 and Figure 2.2 respectively [15].

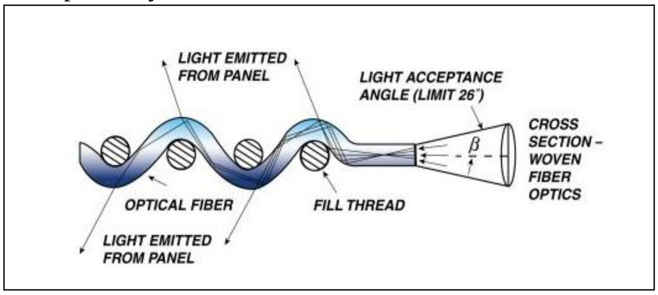

Figure 2.0: Cross section of the woven fiber optics [15].

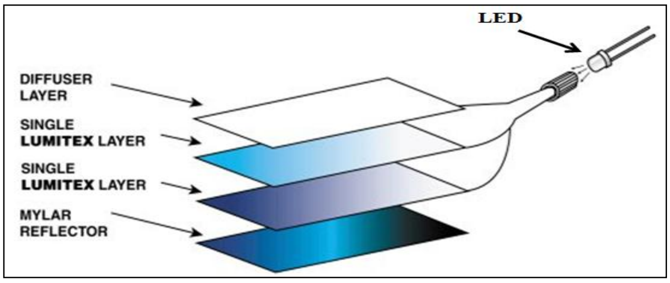

Figure 2.1: Internal construction of the woven fiber optic sheet [15].

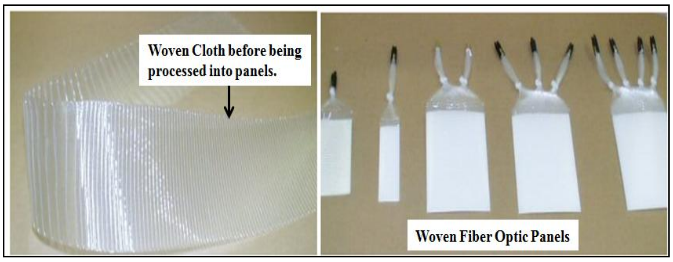

Figure 2.2: Actual form factor of the woven fibres optic [15].

Based on the proposal in section II.A and II.B, Lumitex fiber optic backlighting solution (Woven cloth) will be used as the light guide to direct and uniformly distribute lights emitted from the side firing LEDs. The recommended sizes for the fiber optic sheets in MOTOTRBO XPR6550 portable radio are:-

1) For keypad backlighting: 44 mm (Width) x 58 mm (Height) x 1 mm (Thickness)
2) For LCD backlighting: 41 mm (Width) x 19 mm (Height) x 1 mm (Thickness).

Quick evaluation was performed on the sample kit provided by Lumitex and the propagation of lights across the area of interest was bright, even and impressive as shown in Figure 2.3 and Figure 2.4

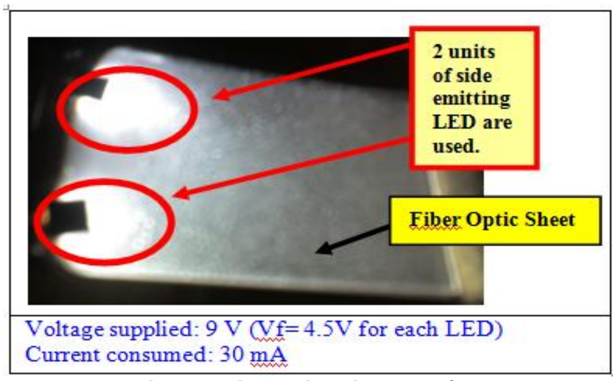

Figure 2.3: Fiber optic sheet with 2 white LEDs from Lumitex.

Figure 2.4: Fibre Optic Sheet with 2 white LEDs experimented on the keypad for RazR phone.

D. Theoretical or Desired Ideal Topology

The following strategies are adopted in the quest to design comprehensive LCD and keypad backlighting systems for portable two-way radio:-

1) Less LED will be used in the ideal or desired topology so that lower power consumptions could be achieved.
2) Four LEDs will be used for the LCD backlighting system and five LEDs for the keypad backlighting system, with the assumption that the LEDs are sufficiently bright enough to light up the entire area of the fiber optic sheets.
3) All the LEDs will be connected in series topology (a single string) instead of parallel topology.
4) The LEDs will be driven with a single LED driver IC with dual outputs (boost topology).
5) Fiber optic sheet will be used as light guide.

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Vol. 1, Issue 9, November 2012

The ideal/desired topology is illustrated in Figure 2.5.

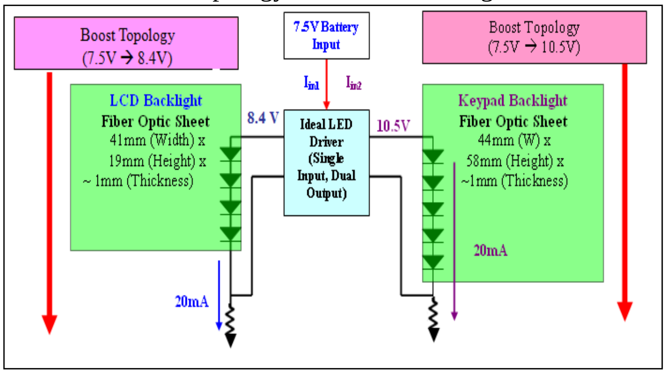

Figure 2.5: Ideal/ Preferred topology

The general equation for efficiency is defined as the ratio of output power over input power as shown in equation 2.0:-

$$Efficiency, \eta = \frac{P_O}{P_{IN}} = \frac{V_O \times I_O}{V_{IN} \times I_{IN}} \qquad (2.0)$$

Assuming that if a 80 % efficiency boost LED driver is used to step-up from 7.5 V to 8.4 V to regulate the string of LEDs with 20 mA current for the LCD backlighting, the current consumption at battery input in reference to equation 2.0 is :-

$$Iin1 = \frac{8.4 \times 20}{7.5 \times 0.8} = 28mA$$

And if a 80 % efficiency boost LED driver is used to step-up from 7.5 V to 10.5 V to regulate the string of LEDs with 20 mA current for the keypad backlighting, the current consumption at battery input in reference to equation 2.0 is :-

$$Iin2 = \frac{10.5 \times 20}{7.5 \times 0.8} = 35mA$$

If both of these current consumption figures are added, the total current consumption of the proposed LCD and keypad backlighting solution is about 63 mA @ 7.5V. Therefore, the amount of current saving comparatively to MOTOTRBO XPR6550 portable radio backlighting system is:-

= (81.61 -63) mA

=18.61 mA (22.80 % Savings)

III. EXPERIMENTS & EVALUATIONS

The purpose of these experiments is to find the closest solution that matches the ideal or desired topology as discussed in the section II. Two experiments are conducted on the LT3466 and LT3497 LEDs drivers from Linear Technology and the details are discussed in the following sections:

A. Regulation and Topology to light up LEDs with LT3466 LED Driver

A single chip LED driver with dual output from Linear Technology (LT3466) is utilized in this evaluation. Both of the outputs of LT3466 are only functional in boost manner (Linear, 2004). Four LEDs are connected to Vout1 terminal for LCD backlighting and 5 LEDs are connected at Vout2 terminal for keypad backlighting. Forward voltage, V_f of the each of the LED is about 2.1 V @20 mA (HSMG-C110/120). Hence, 8.4 V will be required to drive the 4 LEDs (LCD backlight) and 10.5V for the 5 LEDs (keypad backlight) with 20 mA current.The schematic is shown in Figure 3.0 and the test board of LT3466 is shown in Figure 3.1. Voltage and current measurements are performed on the configured test board and the total efficiency is calculated.

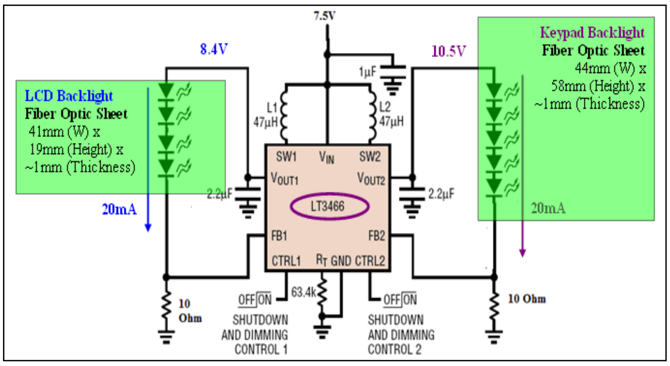

Figure 3.0: Regulation and topology to light up the LEDs with LT3466 LED driver.

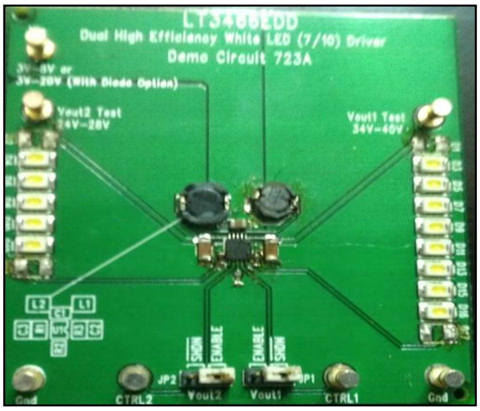

Figure 3.1: Test board of LT3466 LED driver

Based on bench measurements, the current consumed by the LCD backlights at 7.5V battery input is 28mA. Hence, in reference to equation 2.0, the efficiency of the LCD

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Vol. 1, Issue 9, November 2012

backlighting system can be calculated as follows:-

$$Efficiency\_LCD\_backlighting = \frac{8.4 \times 20}{7.5 \times 28} = 80\%$$

Meanwhile the current consumed by the keypad backlights at 7.5V battery input is 34mA. Hence, in reference to equation 2.0, the efficiency of the keypad backlighting system can be calculated as follows:-

$$Efficiency\_Keypad\_backlighting = \frac{10.5 \times 20}{7.5 \times 34} = 82.35\%$$

Hence, the total current consumed at 7.5 V by both of the LCD and keypad backlighting systems is 62 mA.

In comparison to the topology used in MOTOTRBO XPR6550 portable radio, the amount of current saving
= (81.61 – 62) mA
= 19.61 mA (~24 % of saving)

B. Regulation and Topology to light up LEDs with LT3497 LED Driver

A single chip LED driver with dual outputs from Linear Technology (LT3497) is also tested in this evaluation. Four LEDs are connected to Vout1 terminal for LCD backlighting and 5 LEDs are connected at Vout2 terminal for keypad backlighting. The forward voltage, V_f of the each of the LED is about 2.1V @20mA (HSMG-C110/120). Hence, 8.4V will be required to drive the 4 LEDs (LCD backlight) and 10.5V for the 5 LEDs (keypad backlight). Meanwhile, the schematic is shown in Figure 3.2 and the test board is illustrated in Figure 3.3. Voltage and current measurements are performed on the configured test board and the total efficiency is calculated.

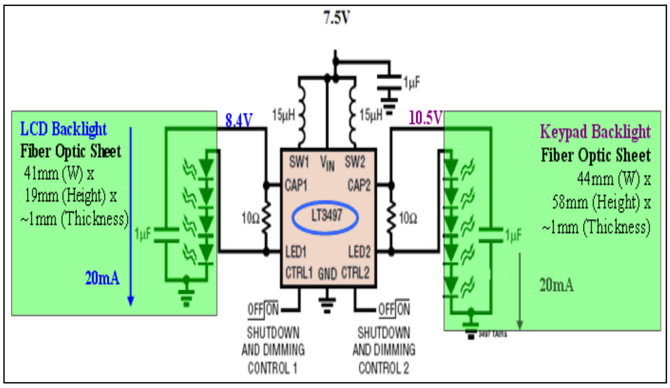

Figure 3.2: Regulation and topology to light up the LEDs with LT3497 LED driver.

Figure 3.3: Test Board of LT3497 LED Driver

Based on bench measurements, the current consumed by the LCD backlights at 7.5V battery input is 35mA. Hence, in reference to equation 2.0, the efficiency of the LCD

$$Efficiency\_LCD\_backlighting = \frac{8.4 \times 20}{7.5 \times 35} = 64\%$$

Meanwhile the current consumed by the keypad backlights at 7.5V battery input is 37mA. Hence, in reference to equation 2.0, the efficiency of the keypad backlighting system can be calculated as follows

$$Efficiency\_Keypad\_backlighting = \frac{10.5 \times 20}{7.5 \times 37} = 75.7\%$$

Hence, the total current consumed at 7.5 V by both of the LCD and keypad backlighting systems is 72 mA. In comparison to the topology used in MOTOTRBO XPR6550 portable radio, the amount of current saving
= (81.61 – 72) mA
= **9.61 mA (~11.78 % of saving)**

C. Comparison of the Existing Solution vs. Proposed Solution

LT3497 LED driver is less efficient compared to the LT3466 LED driver. Therefore, LT3466 will be the best available solution if the preference is to implement the configurations (4 green LEDs for LCD backlight and 5 green LEDs for keypad backlight) as illustrated in Figure 2.5. However LT3497 has the capability to drive (or buck down) when supply voltage (Vin) is higher than the total forward voltage of the LEDs strings. LT3466 driver does not have this capability. According to HSMG-C110/120 LED datasheet the LED gives exceptionally high brightness (Bin V: 715 -1125 mcd @20 mA). Therefore the total calculated maximum

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Vol. 1, Issue 9, November 2012

luminous intensity delivered by the 4 LEDs of the LCD backlights at 28 mA @ 7.5V is about 4500 mcd. Meanwhile the total maximum luminous intensity delivered by the 5 LEDs of the keypad backlights at 34 mA @7.5V is about 5625 mcd.

It showed that, the amount of luminous intensity per unit area delivered by the proposed LEDs to the LCD is about 18 times higher than the existing LCD backlighting solution offered by MOTORBO XPR6550 portable two-way radio. Whereas, the amount of luminous intensity delivered by the LEDs to the keypad is about 17 times higher than the existing keypad backlighting solution offered by MOTORBO XPR6550 portable two-way radio. Comprehensive comparisons in between the existing backlighting system used in Motorola XPR6550 and proposed backlighting approach are summarized in Table I.

TABLE I. COMPARISON IN BETWEEN PROPOSED VS. EXISITNG BACKLIGHTING APPROACH

ITEMS	EXISTING APPROACH (MOTOTRBO XPR6550)	PROPOSED APPROACH (LT3466)
Regulation and Topology to light up the LEDs. (LCD module)	**4 LEDs** (2 LEDs x 2 branches in parallel topology with direct voltage source of 7.5 V)	**4 LEDs** in series topology and regulated with LT 3466 LED driver at left output terminal.
Regulation and Topology to light up the LEDs. (Keypad)	**10 LEDs** (2 LEDs x 5 branches in parallel topology with direct voltage source of 7.5 V.)	**5 LEDs** in a series topology and regulated with LT 3466 LED driver at right output terminal.
Light Source and Type of LED	**Top firing Chip LEDs (QSME-C198)** *Bin P*: 45.0 - 71.5 mcd @20 mA)	**Side firing LEDs (HSMG-C110/120)** Bin V: 715 -1125 mcd @20 mA
Maximum Luminous Intensity Delivered (LCD Backlight)	**247.46 mcd** (34.61 mA @ 7.5 V with four Bin P LEDs)	**4500 mcd** (28 mA @ 7.5 V with four Bin V LEDs)
Maximum Luminous Intensity Delivered (Keypad Backlight)	**336.05 mcd** (47 mA with ten Bin P LEDs)	**5625 mcd** (34 mA @ 7.5 V with four Bin V LEDs)
Light Guide (LCD Module)	**Plastic Polycarbonate Light Guide:** 41mm (Width) x 19 mm (Height) x thickness (~1mm).	**Fiber Optic Sheet:** 41mm (Width) x 19 mm (Height) x thickness (~1mm).
Light Guide (Keypad)	Not Available	Fiber Optic Sheet: 44mm (Width) x 58mm (Height) x thickness (~1mm)
Power Consumption (LCD module)	259.58 mW	210 mW (19.1 % saving)
Power Consumption (Keypad backlight)	352.5 mW	255 mW (27.66 % saving)
Efficiency (LCD Module)	55.47 %	**80 %**
Efficiency (Keypad)	54 %	**82.35 %**
Distribution of Light per Unit Area (LCD Backlight)	(247.46 mcd / 779mm^2) = **0.32 mcd per mm^2**	(4500 mcd / 779mm^2) **= 5.78 mcd per mm^2 (~18 times brighter)**
Distribution of Light per Unit Area (Keypad Backlight)	(336.05 mcd / 2552 mm^2) = **0.132 mcd per mm^2**	(5625 mcd / 2552 mm^2) **= 2.204 mcd per mm^2 (~17 times brighter)**
Uniformity of Light Across Areas of Interest.	Poor (In reference to distribution of light per unit area).	Excellent (In reference to distribution of light per unit area).

IV. CONCLUSION

If the fiber optic backlighting solution is to be adopted, (HSMG-C110/120 LED from Avago Technologies (572 nm wavelength side firing green LED) is recommended because this LED gives exceptionally high brightness (Bin V: 715 - 1125 mcd @20 mA) [14].

As for the LED driver, preference is with the LT3466 LED driver compared to the LT3497 since that it warrants superb efficiency (>80 %) at both of the strings (LCD and Keypad backlights). Furthermore, LT3466 is capable to drive dual outputs in which subsequently provides the advantage of space saving while warranting constant brightness across the LEDs in the series topology. It helps to eliminate the manual, time consuming and tedious process of tweaking the brightness of the LEDs with ballast resistor. However the only drawback of LT3466 is the quiescent current is about 5-7.5 mA when it is enable. In the event of standby mode, it is advisable to turn OFF/Shutdown the chip via the CTRL1 and CTRL2 pins so that the quiescent current could be minimized to 16-25 uA.

Apparently, the fiber optic solution gives the advantage of current savings of about ***19.6 mA @ 7.5 V (~24 % saving)*** comparatively to the existing backlighting solutions in portable radio (81.61 mA @ 7.5 V) which are rigid and inefficient.

The proposed backlighting solution is not only power friendly but it has inevitably increased the distribution of light per unit area by 18 folds for the LCD backlight and 17 folds for the keypad backlight. This is indeed a solution which kills two birds with a stone throw.

However, as part and parcel of future works, further studies have to be performed from the mechanical standpoints (durability and reliability) before the proposed backlighting systems with fiber optic solution can be fully adopted and implemented into the real product design. Alternatively, the future works can be further extended to develop efficient and backlight-less LCD and keypad systems for portable two-way radio design in which utilizes built-in low power sensors and organic LED (OLED).

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