DESIGN AND CONSTRUTION OF A DUAL SENSOR RF POWER-METER

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2001/11956EE

A Project Report Submitted to the Department of Electrical and Computer Engineering, Federal University of Technology, Minna, Niger State

November, 2007

DEDICATION

This work is dedicated to my mother and every other single parent out there, who against all odds are struggling to bring their children's dream to reality.

DECLARATION

I Bature Francis John declare that this work was done by me and has never been presented elsewhere for the award of a degree. I also hereby relinquish the copyright to the Federal University of Technology, Minna.

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ACKNOWLEDGEMENT

I appreciate God Almighty, the giver of life and wisdom from whom I continuously receive grace and strength to scale through all huddles of live. My special appreciation goes to my parent Mrs Grace T. Adedeji for her relentless investments into my education. Also, I appreciate my aunts for the love and care I've enjoyed from them all these years, my big brother; Danasabe Bature, the Awolade family and the Olatunji family for the warm reception they gave me during my Industrial Training. My special appreciation also goes to Engr. & Mrs. O.D. Adeoye, I wouldn't feel any better than I do with you If I had a home. I appreciate Ifeanyi, Bolaji and Zackeous who have been more than just friends to me. My profound gratitude goes to Arc. O.F. Adedayo, Mr. Okocha, for their support, my supervisor; Mr. Nathaniel Salawu and the entire staff of the Dept. of Elect/Comp Engr FUT Minna, Mr. Eng'r. Joe E, Mr. Abia O. and all other staff of Teledom Internatonal, my class mates; Christ, for his resourcefulness, Ramanu, whose academic life remain a source of motivation to me. Credit goes to my friend for their advice and the realization of the project work, to mention but few, Uche, Ruth, Sule, Evuti, Ronke, Sule, Abdul, Fisayo, Amudat.

ABSTRACT

The drive for globalization has made the need for effective and efficient spread of information inevitable. This has prompted the mounting demand for fast and cost effective means of internet connectivity, in turn placing more demand on the radio (microwave radio) engineers and radio armatures, whose work is no longer limited to handling low range frequency equipments such as TV and radio transmitters.

The radio engineer today is bound to use equipments radiating RF signals in the GHz range which requires proper radio planning for maximum utilization of equipment capacity. Thus, the need for a cost effective RF Power-Meter, capable of measuring the power of RF signals is unavoidable.

This project explores the use of two sensors; a Diode Sensor and a Thermal Sensor to realize the construction of a dual sensor microcontroller based RF Power-Meter meant to measure the strength of RF signal of frequency as high as 2.4GHz.

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Chapter One

General introduction

1.1 Introduction

Measurement generally involves using an instrument as a physical means of determining a quantity or variable. The instrument could be an extension of human faculties in many cases to enable a person to determine the value of an unknown quantity which unaided human faculties could not measure. An instrument then may be defined as a device for determining the value or magnitude of a quantity or variable. The electronic instrument as it name implies is based on electrical or electronic principles for its measurement function. [1]

An instrument may be a relatively uncomplicated device of simple construction such as a basic D.C current meter. As technology advance however, the demand for more elaborate and accurate instrument increases and produces new developments in instrument design and application. To use these instruments intelligently, one need to understand their operating principles and to appraise their stability for the intended application.

Measurements are made with measurement devices classified according to the function they perform. Measurement devices may be classified into standards (measures), transducers, measurement information system and measurement installations [1]. This project put together these various classes of measurement devices to facilitate the measurement of RF (Radio Frequency) power output of microwave radios operating at 2.4GHz. RF energy is essentially A.C voltage, except that the frequencies involved are much greater than those encountered Power distribution, Audio-Frequency (AF) amplifiers or Control systems. Radio Frequency extends well into the GHz region, where it is difficult to amplify and great care is required to be taken as normal components are usually useless. [2]

Power meters for measuring radio frequency power levels are essential tool for any RF design, test or repair laboratory. RF power is a key parameter to measure to determine the operation of a circuit at RF or microwave frequencies, because as frequency rises, detecting voltage and current is less easy to undertake. Also, RF power is one of the key parameters of interest, as RF circuits need to deliver power of various levels into other circuits or loads. A system's output signal level is often the critical factor in the design and performance of RF and microwave equipment. Measurement of the signal level is critical at every system level, from the overall system performance to signal the fundamental devices. In a system, each component in the signal chain must receive the appropriate signal level from the previous component and pass the proper signal level on to the succeeding component. If the output signal level becomes too low, the signal becomes obscured in noise and if on the other hand the signal level becomes too high, the performance goes nonlinear and distortion results.[25]

Among the factors affecting wireless transmission of data are multi-path effect, refraction and location of antenna. However, this project is aimed at solving the problem of locating antenna. The problem of locating antenna in wireless data transmission results mainly from distortion caused by obstructions. These obstructions could either be conducting or non-conducting. Conducting objects creates the most severe disturbance, large conducting structures causes several shadowing, which in effect results in spreading of the signal.

Spreading is the principal contributor to signal loss for line-of-sight (LOS) propagation. As a signal radiates or spreads into spherical surface the available RF power is distributed over the surface and weakens with increasing distance of transmission. Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance, whether in indoor or outdoor channels. Such models have been used extensively. [3]

The loss path is computed between the source radiators with spherical patterns using the following equation;

$$L_p = 92.45 + 20Log10F + 20Log10D \quad (1.0)$$

Where,

L_p = Loss path in decibels (dB)

F = Frequency in GHz

D = Distance in kilometers

Once L_p is determined and considered during power budget, channel loss can be minimized therefore leading to the optimum performance of the equipments [3].

Consequently, it is necessary to measure the signal power of a RF signal Radiated from a system during radio planning and the only way to achieve this is to convert the amplitude of the signal into an equivalent DC voltage first. Radio Frequency (RF) voltage is measured by rectifying the alternating voltage and amplifying the resulting DC output [2]. The piece of equipment that is able to do this conversion is usually referred to as a sensor (transduser). The DC voltage at the output of the sensor can be measured with a standard ADC (analog-digital-converter) or a cheap multimeter. If the transfer function of the sensor is known, the signal power of the input signal can be calculated from the measured DC voltage level.

Though, doing measurements on DC circuits today is easy and cheap. Digital multi meters sold at a very affordable price can conveniently measure voltage, current, resistance and often even frequency and transistor gain. Even oscilloscopes that show DC and audio signals graphically over time are affordable as well. Unfortunately, for the radio engineers, measurements get tricky once the frequencies rise higher into the radio frequency (RF) range. Multi meters are in some cases employed to measure RF of frequency up to 10kHz and reasonable oscilloscopes are usually limited to a couple of 10MHz. Above these frequencies, it is not trivial for the budget limited radio engineers to measure the characteristics of a signal [4]. Since measurement is the key to success for adequate utilization of RF equipments such as the fast spreading microwave radios as illustrated above, a reliable means of evaluating RF signals must be found.

This project provides a way of solving the stated limitations of standard measurement devices through the design and construction of an RF power-meter. The RF power-meter is made to measure RF signal strength of bandwidth of up to 2.5GHz. It is a battery-powered device with external power sensors meant to measure and generate a digital read out of the power of RF signals.

The power sensors are the key elements of any RF power meter, and the choice of the type of sensor will depend on the likely applications that are envisaged. The RF power meter technology falls into two basic categories namely;

- Heat based (thermal sensor)
- Diode detector based

Although both technologies have been available for many years, they have both been greatly refined over the years and are able to measure very high levels of performance. This project combines the two technologies for optimum performance.

The power-meter consists of two logic components. One is the digital part, consisting of the processor (microcontroller), the display and the batteries. The other components are the sensors that transform the RF input power into an analog DC level that can be read by the ADC in the digital part. The software knows the transfer function of different sensors from RF power to DC level and is therefore able to calculate the RF input power from the read DC level. The result of the calculation is then written to the LCD. In a special mode the software also displays the raw ADC value i.e. the DC voltage level without transforming it to the equivalent RF power. The meter is battery powered, handheld (small design), with two different external sensors (thermal sensor and diode sensor), resolution 1/100 dB, absolute and relative power reading, two power ranges, capable of displaying battery voltage reading.

1.2 Aims and objectives

This project is aimed at providing a cost effective and reliable alternative for the budget limited microwave radio engineers to have a precise measure of RF signal strength at any point while working out radio plan and when troubleshooting a wireless network. Thus, providing a basis for experimentation and training in state-of-the-art wireless techniques and networking

Most importantly, the project also brings into existence a locally made piece of apparatus for RF hobbyist and the professional radio engineers, aside providing a cost effective RF-Power measurement meter to enhance a better utilization of RF equipments and cut down on radio plan execution time.

Chapter Two

Literature Review

2.1 Historical background of electrical signal measuring instruments

Electronic communication started in 1840 with the discovery of wire telegraph. The first telegraph cable was inaugurated in 1850, while the first telephone appeared after forty years. [5]

In 1888, Heinrich Hertz satisfactorily demonstrate the existence of electromagnetic radiation by building an apparatus to produce and detect UHF radio waves. Through experimentation, he proved that transverse free space electromagnetic waves can travel over some distance. Hertz later demonstrated that the velocity of radio waves was equal to the velocity of light. The electric field intensity and polarity was also measured by Hertz. His experiments help expand the field of electromagnetism transmission and his apparatus was developed further by others in the history of radio. Hertz also found that radio waves could be transmitted through different types of materials, was later investigated and exploited by others. In 1894 J. C. Bose publicly demonstrated radio control of a bell using millimetre wavelengths, and conducted research into the propagation of microwaves. This discoveries was later fully understood by others and has today formed the better part of the new "wireless age". [6]

Radio (wireless) communication did come into scene in the beginning of the 20th century when in 1901, the letter “S” of the Morse code transmitted at a pre-arranged time from Poidhu in Cornwell (United Kingdom) was heard across the Atlantic in New Found land (United State). Since this time, telecommunication system has gone through many revolutionary stages brought about mainly by the dynamic development in electronics. [5]

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transmit power was researched. In 1964, William C. Brown demonstrated a miniature helicopter equipped with a combination antenna and rectifier device called a rectenna. The rectenna converted microwave power into electricity, allowing the helicopter to fly.[7]

Measurement plays an important role in man's life. They turn up everywhere in his activities, from estimating a distance by eye to elaborate process control and scientific research. Progress in science has always been closely linked to advances in measurement capability. Measurements are effective tools of learning. They provide us with a means of describing the natural phenomena in quantitative terms. As Dmitry I. Mendeleyev, an outstanding chemist wrote: "science start where one begins to measure; exact science is unthinkably without measurements" [1], in 1883 another renowned scientist; Willian Thomson (Lord Kelvin) wrote: " I often say when you can measure what you are speaking about and express it in numbers, you know something about it, but when you cannot express it in numbers your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge but have scarcely in thought advance to the stage of a science whatever the matter may be". [8]

The history of science knows cases where new grounds broken in the field of measurement led to new discoveries, and advances in science prompted further improvements in the methods and means of measurements. The need to measure goes back to ancient times. Then man had to measure distances, areas, dimension, weights, time and many more. At first it was primitive measurements done often by eye. It was customary for man to compare the object of interest with say some part of his body. Thus the body's part served as standards with which man established units for various quantities. Obviously, both the standards and the units are arbitrary, and this made comparison of results difficult. [1]

Electrical measuring instruments appeared in the wake of early studies of electricity. G.V. Richmann of Russian in 1745 built the world first electrical measuring instrument designed to measure potential difference. In 1820, A. Ampere demonstrated the first galvanometer. The latter half of the 19^{th} century saw the emergence of electrical engineering, a division of science and technology concerned with practical uses of electricity (for communication, power generation and the like). This explains why so much effort was put into a variety of electrical measuring instruments. In 1867, W. Thomson proposed a galvanometer, which used moving coil and a fixed electromagnet, which was later improved by D. Depres and J.A. d'Arsonal in 1880 through the use of permanent magnet. [8]

Towards the end of the 19^{th} century, a light-beam ascillograph was developed to record electrical signals and early in the 20^{th} century, cathode ray tube came to be used in studies of electrical signals. The modern day oscilloscope used for measuring signals of lower frequencies took its root from this technology. However, their performance is limited when frequencies raise higher into the radio frequency (RF) range. This thus, prompted the need for the design of measurement devices capable of handling signals in the higher frequency spectrum such as spectrum analyzers. [9]

In the early 1980s, Braun Waren L. and Curt Walter M. of Harnsonburg VA, USA, invented a spectrum analyzer using frequency synthesis used in field to perform voltage amplitude measurement in multichannel configured coaxial cable environment. The instrument is a microprocessor-based system, which includes an RF input, and function switch inputs and provides both aural and visual outputs by means of a speaker and an LCD [9]. Wave analyzer usually measures one harmonic component at a time. The frequency spectrum of the input signal is produced by combining all the results. Spectrum analyzer produces the display of the frequency spectrum on the screen and this feature is very helpful in the analysis of any input signal because it gives the information about the location and strength of all the frequency components of the input signal. [2]

Various manufacturers have since adopted this innovative invention and series of modifications have made on the original design to make for better performance as well as a wider range of functionalities. Despite it tremendous usefulness, spectrum analyzers are not within the reach of a larger number of radio armatures due to its exorbitant price.

Consequently, a more specialized and cost effective alternative to spectrum analyzer needed to be found. Herbert Dinfelder of Ericsson Prototype R&D Center in Nurnberg, Germany, among other radio armatures designed a simple analog RF power-meter with thermal sensor. Few years later he redesigned the power meter using a diode sensor with a 68HC11 microprocessor functioning as the brain of the device and following his better understanding of the functionality of the AVR microprocessor, a review of the 68HC11 microprocessor based design was carried out. The new design, which he named Universal Measurement Device (UMD), was built with tiny surface mount components. This design however contained a few components that were had to get. Hence, several modifications were carried out to arrive at a design with readily available components. It was made up of two sensors (Thermal and Diode sensors) and since it was his third approach, he named it version DSPM03 (Dual Sensor Power Meter 03). DSPM03 was built around the Atmel AT90S4433 microcontroller and some other Integrated Circuits (ICs), which manufacturers have discontinued production. [10]

Thus, this project is aimed at redesigning the Herbert Dinfelder version DSPM03 RF power-meter to come up with a design with readily available components. The meter is designed specifically to measure signal strength of signals in the RF range. The design is centered on various transducers, an analog-dc-converter (ADC) in-built in the microcontroller.

2.2 Review of Free Space Propagation of RF Signal

In calculating the free space transmission loss, we consider a transmitter with power 'P_t' coupled to an antenna which radiates equally in all directions. At a distance 'd' from the transmitter, the radiated power is distributed uniformly over an area of $4\pi d^2$ (i.e. the surface area of a sphere of radius d), so that the power flux density is:

$$s = \frac{P_t}{4\Pi d^2} \quad \text{.. (1.1)}$$

The transmission loss then depends on how much of this power is captured by the receiving antenna. If the capture area, or effective aperture of this antenna is A_r, then the power, which can be delivered to the receiver, is:

$$P_r = sA_r \quad \text{.. (1.2)}$$

For the hypothetical isotropic receiving antenna, we have;

$$A_r = \frac{\lambda^2}{4\Pi} \quad \text{... (1.3)}$$

Combining equations (1.1) and (1.3) into (1.2), we have;

$$P_r = P_t\left(\frac{\lambda}{4\Pi d}\right)^2 \quad \text{....................................... (1.4)}$$

The free space path loss between isotropic antennas is P_t / P_r. Since we are dealing with frequency rather than wavelength, we can make the substitution $\lambda = c/f$ (where c is the speed of light), therefore;

$$L_p = \frac{P_t}{P_r} = \left(\frac{4\Pi}{c}\right)^2 f^2 d^2 \quad \text{.......................... (1.5)}$$

The free space path loss equation is more usefully expressed logarithmically (L_p in dB, f in GHz and d in Km);

$$L_p = 92.45 + 20\log f + 20\log d \quad \text{................. (1.6)}$$

This shows more clearly the relationship between path loss and distance; path loss increases by 20 dB/decade or 6 dB/octave, so each time the distance is doubled 6 dB of signal is lost under free space conditions. Of course, considering a real system, we must consider the actual antenna gains and cable losses in calculating the signal power P_r which is available at the receiver input.

$$P_r = P_t - L_p + G_t + G_r - L_t - L_r \quad \text{..........................(1.7)}$$

Where;

P_t = transmitter power output (dBm or dBW, same units as P_r)

L_p = free space path loss between isotropic antennas (dB)

G_t = transmiter antenna gain (dBi)

G_r = receiver antenna gain (dBi)

L_t = transmission line loss between transmitter and transmission antenna (dB)

L_r = transmission line loss between receive antenna and receiver input (dB)

L_t and L_r are constants associated with different cable types (Table 3.0). Once L_p is determined and considered during power budget, channel loss can be minimized therefore results to the optimum performance of the equipments. [3]

Table 2.1: Attenuation of some transmition lines in dB/100m. [19]

Cable Type	Attenuation at 2.4GHz (dB/100m)
RG-58	32.2
RG-8X	23.1
LMR-240	12.9
RG-213/214	15.2
LMR-400	6.8
LMR-600	4.4

2.2 Review of the microcontroller

Basically, a microcontroller is a device which integrates a number of components of a microprocessor system on a single microchip. The Atmel's newest microcontroller 'Atmega8' is employed in this design for it expedient features. ATmega8 is a low-power CMOS 8-bit microcontroller based on the AVR RISC architecture. By executing powerful instructions in a single clock cycle, ATmega8 achieves throughputs approaching 1 MIPS per MHz, allowing the system to optimize power consumption relative to processing speed. [11, 22, 27]

Chapter Three

Design and Implementation

3.1 Block Diagram

The block diagram in figure 3.1 describes the various stages involved in the processing of the inputted RF signal to arrive at the final output displayed on the 4x16 character LCD. The target RF signal is sensed by the input transducers (i.e. RF sensors) and converted to it equivalent analog DC voltage in the ADC (Analog to Digital converter) imbedded in the microcontroller. The digital voltage fed into the microcontroller chip (ATmega8) is compared with values in the look up table in the programmed microcontroller.

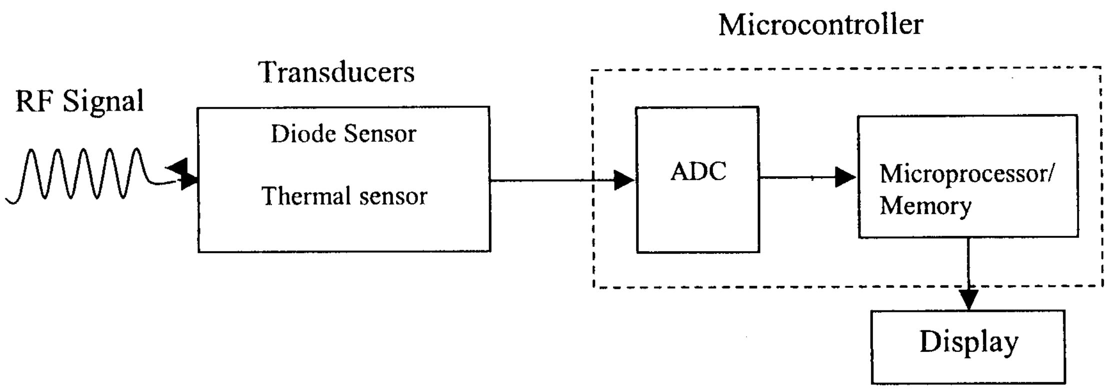

Fig 3.1: Block diagram of RF-Power Meters

Aside the look-up table in the program is a conversion table meant to match converted digital voltage with it power equivalent which is further passed on to the 4x16 character Liquid crystal Display where the final output (RF Power) is read. The detail circuit diagram is shown in Appendix C.

3.2 Transducers

In all electrical measurement, all non-linear quantities must be converted into electrical quantities using converters known as transducers. The Instrument Society of

America (ISA), defined transducer as a device, which provides a usable output in response to a specified measurand. Transducers are grouped into two broad categories, active and passive transducers. An active transducer is one, which generates output signal with no external source of energy. A passive transducer on the other hand, changes one or more of it characteristics electrical properties and thus need an external source of energy and signal conditioning device complexity in order to generate a signal in proportion to the variation in the measured non-electrical variable.[13]

The relationship between the non-electrical input signal and the output voltage or current generated is called the transfer characteristic of the transducer. It is desirable for the transfer characteristic to be linear over the entire range of input variable. The frequency response of the transducer is another vital characteristic, it is preferred that the transfer characteristics stay unaffected by the change in frequency over a wide range as possible for any real application. [13]

3.3 RF Power Sensors

Sampling a RF signal directly in the time domain (i.e. viewing the signal with an oscilloscope) is usually limited to frequencies below 20-100MHz, depending on the bandwidth of the oscilloscope. The other device that can show RF power (not in the time domain but in the frequency domain) is a spectrum analyzer which is very expensive. [4, 13]

Hence, there is no other way than to convert the amplitude of the signal into an equivalent DC voltage. The DC voltage can than be measured with a standard ADC (analog-digital-converter) or a cheap multimeter. Two methods (Diode Sensor and Thermal Sensor) are explored in this design.

3.3.1 Thermal Sensor (Thermistor)

Thermistor is a heat sensitive device whose resistance is a function of the temperature around it. Basically, thermistors are of two types [15];

i. Positive Temperature Coefficient (PTC): PTC thermistor exhibits a resistance increase with increasing temperature.

ii. Negative Temperature Coefficient (NTC): NTC thermistor exhibits a resistance decrease with increasing temperature.

An NTC thermistor was used in the design realization due to the amplifier arrangement used. The thermistor was placed in a very close proximity with a 50Ω resistance connected to the RF signal source is under evaluation. The incoming RF signal is absorbed in a small dummy load (R1 in Figure 3.2). Due to the power dissipation from the RF signal, the resistor warms up. The change in temperature can be used to determine the power as the resistance of the resistor changes. During calibration, the resistance of R1 is measured before and after the application of RF signal. When the same change in resistance is produced by a variable dc source of power, then the RF power is equal to the measured dc power. This relationship makes possible the direct calibration of a bridge circuit in units of power. In other words, one condition of balance exists when no RF power is applied; but in the presence of power, a second condition of balance exists because of the resistance changes of the bolometer. [14]

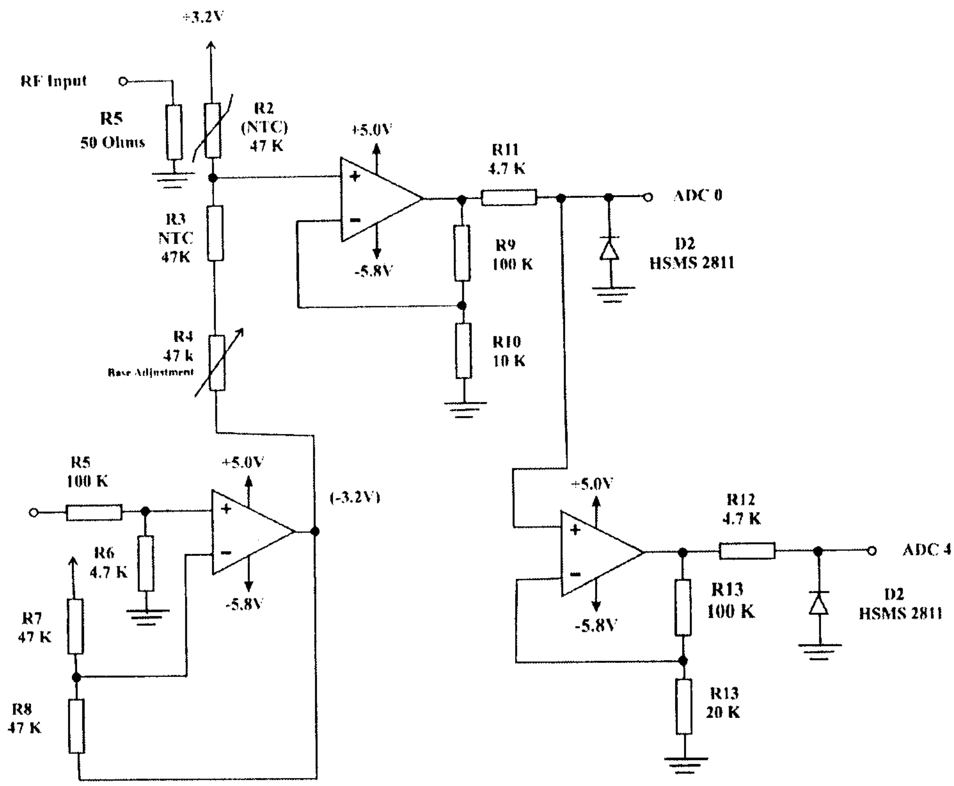

Fig 3.2: Thermal Sensor Module

The negative-resistance temperature coefficient of a thermistor and the need for high degree of precision makes it desirable for use in the design of RF power meter meant to measure RF signal strength of bandwidth of up to 2.5GHz. This is because excessive power has the effect of changing the resistance of the thermistor to an extent that causes a pronounced RF mismatch. [4]

The thermistor bridge circuit employed in this design as shown in figure 3.2 consists of other thermistor elements, referred to as compensating thermistors (R3) used to eliminate the ambient temperature influence. These thermistors respond to fluctuations in ambient temperature so that the bridge balances and calibration are maintained over a wide temperature range.

3.3.2 Diode Sensor

In order to convert an AC-signal level (i.e. RF signal) to an analog DC voltage that can be measured, we could employ the use of a special diode. This is essentially a microwave diode rectifier indicated for use at the GHz range. A special RF diode that is fast enough, with very little capacitance and is housed in a very small package to keep the series inductance as small as possible is employed in this design. [4]

There is a big prejudice on diodes stating that a diode only starts to conduct when the voltage is above the diode threshold voltage (0.3-0.7 Volts, depending on the technology of the diode), this property would indeed constitute a limitation when it is desired to measure RF-signals in the mW range. (1mW on 50Ω is only 223mV). [4]

However, the diode is always an un-linear component, so even with the tiniest AC-signal, there is a DC output voltage. There is indeed a change in behavior around a few hundred mV, but it is just a soft transition from the square law region to the linear region. In the square law region (below the threshold voltage) the diode already exhibits a different resistance in forward and backward direction. The difference is not as distinct as above the threshold voltage, but it is still there. The result is a DC-voltage that is proportional to the power of the signal (i.e. it is proportional to the square root of the peak voltage of the signal). [4, 21]

In the linear region the diode simply conducts at the positive half wave and isolates at the negative half wave (Figure 3.3B). That is exactly the behavior a diode is well known for from large signal rectifiers like in power supplies etc. The result is a DC voltage that is directly proportional to the peak value of the input signal, therefore the name linear region.

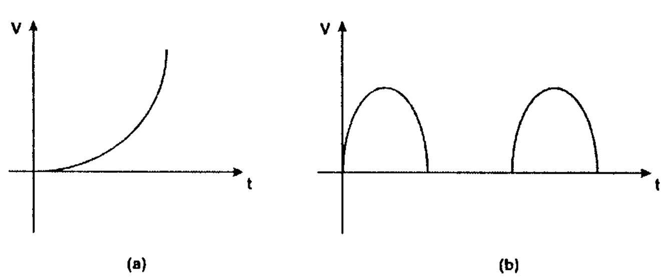

Fig 3.3: Diode Characteristic (a) Curve (b) Waveform of half wave rectified signal

A schottky diode also known as barrier diode or hot carrier diode mainly used as rectifier at signal frequency exceeding 300 MHz with more uniform junction region has the appropriate characteristics required for application as a diode sensor in this design. The unique features possessed by this diode as compared to an ordinary P-N junction diode are as follows [15, 16];

- It is a unipolar device because it has electrons as majority carriers on both sides of the junction.
- Since holes are available in metal, there is no depletion layer or stored charges to worry about. Hence schottky diode can switch on and off faster than a bipolar diode.
- The voltage drop in the forward direction is low.
- The reverse recovery time is short.

Because of these qualities, schottky diode can easily rectify signal of frequency exceeding 300 MHz. The diode is connected in a special way on a copper strip to achieve a 50 Ω copper stripline (Fig 3.4). [10, 12]

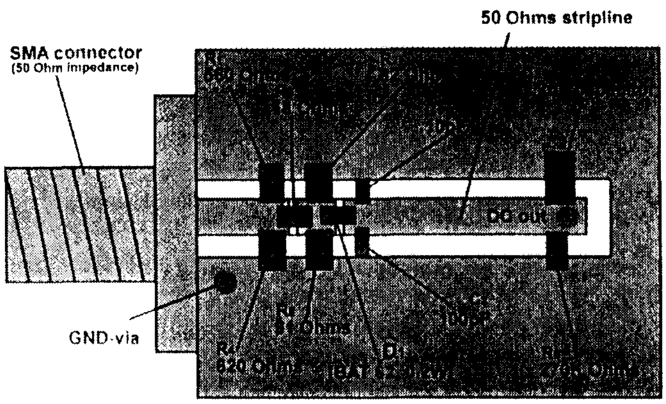

Fig 3.4: 50 Ω copper stripline

The 5 resistors (R1, R2, R3, R4 and R5) at the input form a combined 3dB resistive pad and RF termination. The RF diode (D1; BAT62-02W) rectifies the signal, the capacitors on the DC side form a broadband short circuit for RF. Having the different capacitance values in the arrangement shown in Fig 3.4 (C1) is very important for a flat frequency response. The ground is tapped at the point marked GND via, it is important to have several of such point for a constant frequency response.

The second stage amplifier has a non-inverting gain of 16, which can be calculated as follows;

$$\frac{V_{out}}{V_{in}} = \left(1 + \frac{R3}{R4}\right) = \left(1 + \frac{15K}{1K}\right) = 16$$

The overall gain for the two stages is obtained by multiplying the gain of the individual stage together as follows;

$$A_1 \times A_2 = 2 \times 16 = 32 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.2)$$

The two outputs of the two stages (a x 2 and a x 32) are fed separately into the ADC internal to the microcontroller.

3.4.2 Thermal Sensor Signal Conditioner

The thermal (thermistor) sensing interface is as shown in figure 3.6.

A_3 is a non-inverting amplifier with a gain of 11, A_4 is a differential amplifier with an output voltage given by:

$$V_0 = (V_1 - V_2)A_V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.3)$$

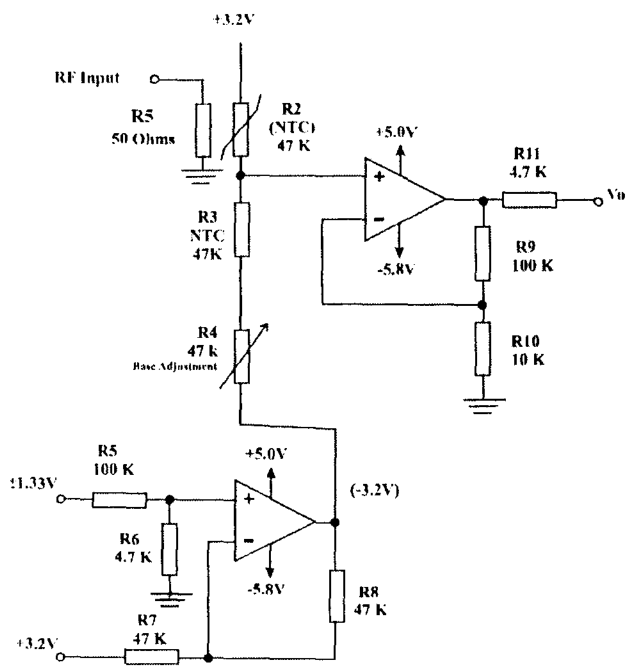

Fig 3.6: Thermal Sensor Signal Conditioner

The gain at the two stages can be calculated using superposition theory [17].

Figure 3.6 can be resolved as follows;

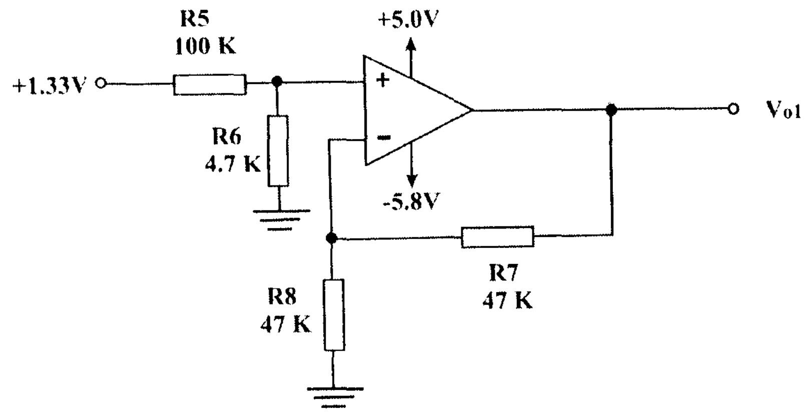

Figure 3.7a: Op Amp A4 with respect to the 1.33V input

$$V_{01} = \left(\frac{1.33 \times 4.7}{110 + 4.7}\right)(2) = 0.109V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

Similarly, the output voltage of the Op Amp with respect to the non-inverting input +3.2V can be computed as follows;

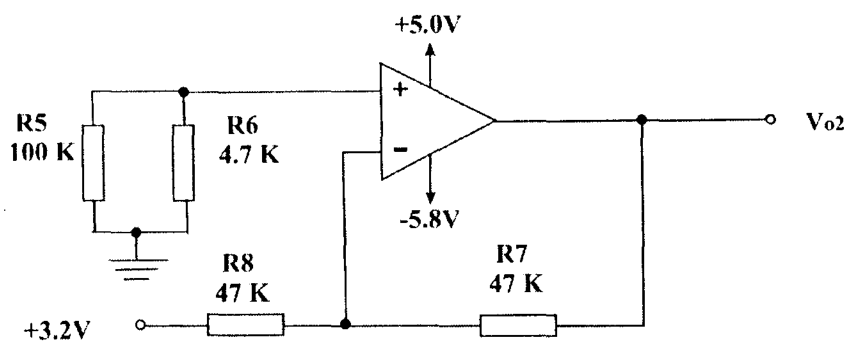

Figure 3.7b: Op Amp A4 with respect to the +3.2V input

$$V_{02} = -3.2\left(\frac{47K}{47K}\right) = -3.2V \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

The resultant output voltage is thus;

$$V_0 = V_1 + V_2 = 0.109 + (-3.2) = -3.1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

The lower end of the reference thermistor Th_2, is held at this value of voltage while the upper end of the sensing thermistor is held at +3.2volts. The resistance changes in the sensing thermistor when an RF source is connected to the 50Ω load causes the voltage at the non-inverting input to change.

The two thermistors are connected in a potential divider network (Fig 3.7). The voltage divider outputs a predictable fraction of the input voltage.

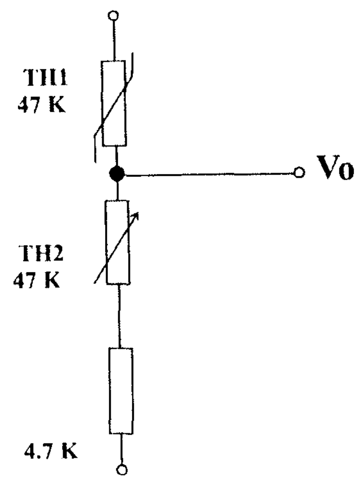

Fig 3.8: Thermistor potential divider circuit

Assuming equal resistance in both thermistor, the output voltage V_o is typically about 0volt. When RF power is fed into the 50Ω load, the resistance of the sensing thermistor falls, causing the voltage V_o to increase positively. This voltage is amplified by a factor of 11at the amplification stage and fed into one of the ADCs on the microcontroller.

3.5 Microcontroller (ATmega8)

A microcontroller is a single computer chip (Integrated Circuit) that executes a user program, normally for the purpose of controlling some device, hence the name microcontroller. [22]

The program is normally contained in a second clip called an EPROM, or within the same chip as the microcontroller it self. Microcontroller are used in devices that require some amount of computing power but don't require as much as computing power as that provided by a complex (and expensive) 486 or Pentium system which generally requires a large amount of supporting circuitry. Microcontroller based system are generally smaller, more reliable and cheaper. [22, 27]

The program for a microcontroller is normally stored in a memory Integrated Circuit (IC), called an EPROM (Electrically Programmable Read Only Memory) which could be internal or external to the microcontroller. An EPROM does nothing more than store program or data, but which is maintained even when the power to the EPROM is turned off. Once the software written for a particular problem is developed, it is normally programmed (or burned) into the EPROM chip (which could be on-chip or external to the microcontroller). The microcontroller access the program stored in the EPROM and executes it after off. [11]

The ATmega8 used for this design provides the following features: 8K bytes of In-System Programmable, Flash with Read-While-Write capabilities, 512 bytes of EEPROM, 1K byte of SRAM, 23 general purpose I/O lines, 32 general purpose working registers, three flexible Timer/Counters with compare modes, internal and external interrupts, a serial programmable USART, a byte oriented Two-wire Serial Interface, a 6-channel ADC (eight channels in TQFP and QFN/MLF packages) with 10-bit accuracy, a programmable Watchdog Timer with Internal Oscillator, an SPI serial port, and five software selectable power saving modes. [11]

3.5.1 Idle and Power-Down Mode

The Idle mode stops the CPU while allowing the SRAM, Timer/Counters, SPI port, and interrupt system to continue functioning. The Power-down mode saves the register contents but freezes the Oscillator, disabling all other chip functions until the next Interrupt or Hardware Reset.

3.5.2 Power-Save Mode and ADC Noise Reduction Mode

In Power-save mode, the asynchronous timer continues to run, allowing the user to maintain a timer base while the rest of the device is sleeping. The ADC Noise Reduction mode stops the CPU and all I/O modules except asynchronous timer and ADC, to minimize switching noise during ADC conversions.

3.5.3 Standby Mode

In Standby mode, the crystal/resonator Oscillator is running while the rest of the device is sleeping. This allows very fast start-up combined with low-power consumption.

The features however, can be categorized into two broad sections; the hardware and the software section. The microcontroller is driven by instruction sets imbedded in the running in it memories.

3.5.4 Software/Hardware Integration

The microcontroller used is a high-integration processor programmed in C language using the free WinAVR GNU C compiler [. The software (program) contain the transfer function for converting the D.C. voltage output of the various sensors to it equivalent RF power value in dBm, as well as the relevant instructions for presenting the values on the LCD (see Appendix B for detail program code).

In a special way, the software allows the setting of pre-attenuation that is added to all measured results or instantaneous attenuation added differently to each measured value at every instance. This is very helpful if there is an attenuator or a directional coupler at the input of the meter to measure higher input powers. It is also helpful when it is desired to compensate for the loss along the cable between signal source and the sensor. And since even negative pre-attenuation values are possible, it is also possible to compensate for amplifiers that are used to measure very tiny signals below the sensitivity of the meter.

3.5.5 Hardware (Pin description)

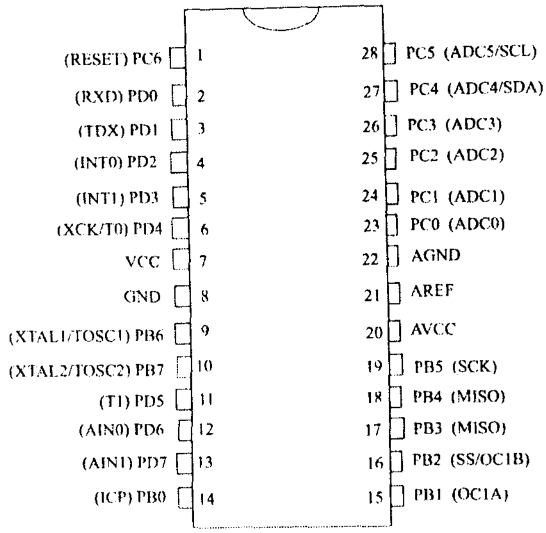

Fig 3.9: Pin configuration ATmega8

Table 3.0 : Pin configuration of Microcontroller.

Pin Number	Function	Function as Applicable to the Design in Question
1	Reset	Reset on ISP
2	PD0	LCD databit 0
3	PD1	LCD databit 1
4	PD2	LCD databit 2
5	PD3	LCD databit 3
6	PD4	LCD databit 4
7	Vcc	Vcc +5 Volts
8	GND	GND
9	XTAL1	crystal pin 1
10	XTAL2	crystal pin 2
11	PD5	LCD databit 5
12	PD6	LCD databit 6
13	PD7	LCD databit 7
14	PB0	User key "mode select"
15	PB1	PWM output for zero-adj. of the thermosenss.
16	PB2	LCD Strobe
17	PB3	MOSI on ISP, User key "Relative-Reset" (former abs/rel)

Pin Number	Function	Function as Applicable to the Design in Question
18	PB4	MISO on ISP, User key "ADC/freq select"
19	PB5	SCK on ISP, User key "Zero adjust"
20	AVcc	Vcc for PORTC
21	ARef	ADC reference set to +3.2 Volts
22	AGND	GND for PORTC
23	PC0	ADC 0 for thermal sensor input 1
24	PC1	ADC 1 for diode sensor input 1
25	PC2	ADC 2 for diode sensor input 2
26	PC3	ADC 3 for monitoring the battery voltage
27	PC4	ADC 0 for thermal sensor input 2
28	PC5	LCD Register select

3.6 Visual Display Unit

The display unit used is a 4 x 16 Liquid Crystal alphameric display. It is a complete display system. Communication via the LCD unit is implemented by the microcontroller by initializing the unit using it industry-standard commands and then the data to be displayed. Various operational modes are possible with an LCD, but only the simple text-based mode is used here.

3.7 Power supply unit

Basically, the RF power-meter is energized by two 9volt D.C. sources (transistor radio batteries). Aside the batteries, the power supply unit consists of a positive voltage regulator and a negative voltage regulator configured as illustrated in figure 3.9. The two regulators are fed by two 9volts DC connected to their input sides.

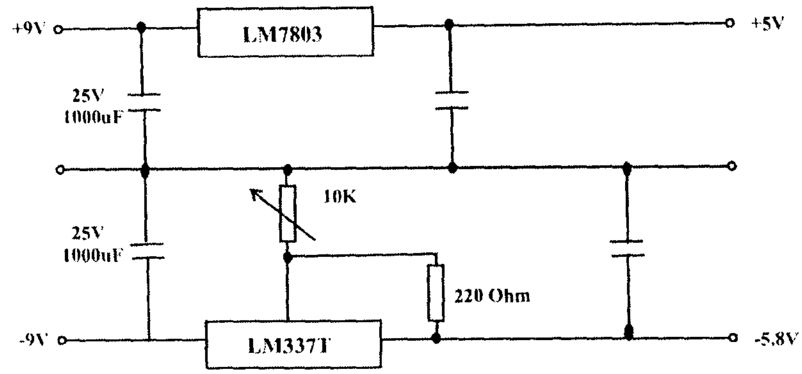

Fig 3.9: Circuit diagram of +5 and -5.8volt power supply unit

The 7805 regulator reduces the 9volts input voltage to 5volts while the LM337T, a three terminal adjustable regulator is adjusted to produce a -5.8volts. The LM337T and 7805 are both capable of providing current in excess of 1Ampere each. The 7805 is a fixed voltage regulator while the LM337T is made user adjustable.

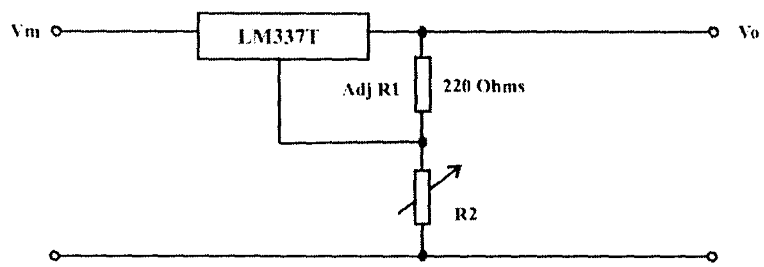

Fig 3.10: User adjustable -5.8volt power supply circuit

$$V_0 = \left[1.25\left(1 + \frac{R2}{R1}\right)\right]V_{in} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3.10)}$$

Where;

R2 = Resistance between the adjust (adl) pin and ground

R2 = Resistance between output and adjust pin

1.25 = Internal reference voltage

The DC inputs to the regulators are buffered by 1000µF capacitances on each DC input before the regulator.

Chapter Four

Tests, Results and Discussion

4.1 Calibration of Sensors

The sensors were calibrated after construction to determine the DC voltage corresponding to various values of RF signal strength. The values obtained were embedded in the microcontroller software to serve as the look-up table for the transfer function of DC voltage to the corresponding RF signal power.

Table 4.0: RF Power to DC voltage conversion table [10]

RF Power (dBm)	DC Equivalent (Volts)
-40	0.000082
-35	0.000153
-30	0.000358
-25	0.000965
-20	0.002844
-15	0.008720
-10	0.023927
-5	0.059510
0	0.135295
5	0.292280
10	0.585346
15	1.130943

4.2 Testing of power Supply Module

The RF Power-Meter is energized by two 9 volt D.C. sources arranged (Fig 3.9) to supply the various voltage level required in different parts of the Meter. Though, in some cases the exact values were not attained, the discrepancies still lied within the tolerance values of the components.

4.3 Testing of the Digital Part

The digital part of the circuit which essentially consist of the microcontroller, signal conditioners (Op-Amps), the power supply module and the 4 x 16 LCD were tested after soldering the various circuitries into place. In effect, immediately the power switch was turned on, the greeting message was display on the LCD for three seconds as programmed, and then the various modes (Diode Sensor Mode, Thermal Sensor Mode, Pre-attenuation Mode, Battery Level Display, ADC-Raw Value Display Mode) were observed on pressing button 1 (see Appendix A for users manual).

4.4 Field test of RF Power-Meter

The main emphasis of this project is on predicting the path loss of a link and setting aside the necessary margin during power budget, so that one can approach the installation of the antennas and other RF equipment with some degree of confidence that the link will work.

Firstly, the meter was tested with a video sender radiating RF signal at a frequency of about 224 MHz, the power was observed to be -14.4 dBm using the diode sensor module. The diode sensor was observed to be more sensitive compared to the thermal sensor that could not respond to the low frequency signal.

Finally, the meter was tested with a Tranxio 2.4 GHz rated microwave Radio, which was marked to operate within a radios of 2.7Km. The absolute output power of the radio was observed to be +16dBm which was fed into an antenna of 10dBi gain. The receiver was connected to an antenna of 10dBi

From equation 2.6, the path loss can be calculated as follows;

$$L_p = 92.45 + 20\log f + 20\log d \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

$$L_p = 92.45 + 20\log 2.4 + 20\log 2.7 = 108.68dBm$$

Similarly, equation 2.7 gives the power received at receiving end as follows;

$$P_r = P_t - L_p + G_t + G_r - L_t - L_r \text{ .... } (2.7)$$

Where;

P_t =16dBm, L_p =108.68dBm G_t =10dBi, G_r =10dBi, (considering L_t and L_r to be negligible)

$$P_r = 16 - 108.68 \quad + 10 + 10 - 0 - 0$$

$$P_r = -72.68 dBm$$

Receivers have a minimum received power threshold, which according to WLAN specifications should lie between -78dBm and -82 dBm signal level in order to deliver a low bit error rate (BER). Therefore, the wireless network configuration is correct will work perfectly well when connected as illustrated in the analysis above. For a proper WLAN performance, the Transmitting Power + Propagation Loss + Receiving Sensitivity must be greater than zero. The remaining gives the margin of the system. A good WLAN link has 6 to 10 dB margin. [18, 19]

4.5 Limitations

Unavailability of well stocked semiconductor sales outlets in the locality greatly influenced the design work thus, imposing the use of close substitutes which are not cost effective and in most cases do not offer the most favorable results.

The probe picks up stray signals as soon as the Meter is powered before any device is connected to it thus, inflating the initial reading, and thereby rendering the displayed relative measurement inaccurate. Also, the sensors drain battery fast and microcontroller is observed to be relatively unstable when the battery voltage drops below 8 volts. The drift of zero-point introduces some error in Meter readings.

The corruption stigma on the nation (Nigeria) as viewed by foreigners affected this project in great measure. Contrary to what is obtainable relatively smaller and less developed African countries, many prominent semiconductor manufacturers (e.g Atmel) don't have sale outlets nor sales agent in Nigeria thus, placing a great limitation on the level of transaction that could be carried out with these companies.

As observed during the research in preparation for the implementation of this project, some free sourced on-line assistance offered by various international organizations and individuals to students willing to understudy or review a design of interest to them are limited to some selected countries among which in most cases not included.

Chapter Five

Conclusion and Recommendations

5.1 Conclusion

RF Power-Meter is an inevitable tool in the wireless networking field. It avails the network engineer the means of giving network planning a better engineering approach. RF Power-Meter comes handy when it is desired to know the exact power output of a microwave radio and most especially when it is required to determine the attenuation along the length of a network cable (coaxial cable).

The RF Power-Meter design employs the use of two radio frequency power sensor, which are independently used based on the nature of the signal in question. Essentially, the choice of the sensor to be used at each instant depends on the foreseen application. The diode sensor is suitable for instantaneous measurements and measurement of low level signals, while the thermal sensor is more suitable for a wider range of power measurement.

5.2 Recommendations

The design, through a prototype is constructed with the most suitable available components. A better performance can be achieved with an NTC with higher resistance for the construction of the thermal sensor. The introduction of a frequency range selection mode in the software will further enhance the use of the Power Meter in the laboratory for troubleshooting low frequency RF power radiators such as the TV transmitter used in chapter four.

The implementation of a general reliability analysis on the design will substantially reduce the limitations observed in the RF Power-Meter.

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Appendix A

Users Manual

After power-on, a greeting message will be displayed for three seconds. After that, there are five different screens, which can be switched through by pressing button No. 2.

i. Diode-Sensor Screen (interprets the ADC readings as output of the diode sensor and displays the calculated RF input power in dBm). Line two shows the absolute power in dBm, line 3 shows the power in dB relative to the power at "relative reset".

ii. The pre-attenuation screen lets you select a fixed attenuation value that is added to every displayed result. Positive values mean attenuation (like resistive attenuators, directional couplers), negative values are used if there is an amplifier of a certain gain before the sensor. Buttons 3 and 4 are to increase and decrease the shown value. Whenever a pre-attenuation other than 0dB is selected, this is indicated by an 'A' in the upper right corner of the result screens.

iii. Thermal-Sensor Screen (interprets the ADC readings as output of the thermal sensor and displays the calculated RF input power in dBm). Line two shows the absolute power in dBm, line 3 shows the power in dB relative to the power at "relative reset". Line 4 shows the zero-indicator. A <> in the middle of the LCD indicates perfect zeroing. A drift of the zero-point is shown by longer and longer arrows to one side.

iv. Battery voltage Screen (shows the Battery voltage in volts and shows "Status good" at voltages above 8 Volts, "Status poor" at voltages below 8 Volts. At status poor the sensor results are not reliable.)

v. Raw-ADC value Screen (shows the readings from the four used ADCs as raw hex-value)

vi. Button No. 1 is used to choose the power range (or switch to auto range when you use the diode sensor, which is default).

With button No. 3 you can reset the relative power reading. The input power at that moment is used for later relative readings

Button No. 1 is triggering the automatic zero adjust for the thermo sensor. It is only functioning when thermal sensor data are shown. A "Z" in the upper right corner of the LCD shows that automatic zeroing is just on. Automatic zeroing will automatically switch itself off, as soon as the zero point is reached. It should be noted that the internal zero point for thermal sensors 1 and 2 is different, i.e. when you switching from one sensor to the other, the zeroing has to be triggered again.

Appendix B

Program (C Language)

```
/* --- Includefiles --- */
#include <avr/io.h>     // Universal .h for AVR, does automatically load the device-specific .h file, //the
                          device type is read from the makefile.
#include <avr/pgmspace.h>     // enables reading of data from the flash- memory
/* --- Prototypes for functions --- */
void i2c_start(void);
void i2c_send(unsigned char sendbyte);
void init_lcd(void);
void update_lcd(void);
void pause(unsigned char n);
unsigned int read_adc(unsigned char adc_number);
unsigned char hex2asc(unsigned char hexbyte);
void preset_videoram(unsigned char screen);
void char2lcd(unsigned char lcdchar);
int lcd_delay(int loops);
/* --- Define names for special registers and bits --- */
// 36 bytes for the lcd videoram (+1 for \n) as global variable
unsigned char videoram[64];
unsigned char mode=1;          // mode determines the screen that is currently used
unsigned char diode_adc_select=1; // number of ADC which is currently used for diode-sensor reading
unsigned char therm_adc_select=0;          // number of ADC which is currently //used for
                          // therm-sensor reading
#define ON                1          // turned on
#define OFF               0          // turned off
unsigned char auto_select=ON;   // ON if ADC is autorange,
                                     //          OFF = manual ADC sel.
int rel_value;            // memory for reference power for relative displaying the
                   // value interpredation is in 1/100 dBm
int pre_attenuation=0; // memory for the fixed preattenuation
unsigned int fuzzy_full_db=0;
#define FUZZY_TIME 50          // this data is kept in the flash, it is not copied to the datamemory // this
                          line is only for numbering the coloums on the LCD
                          //012345678901234*012345678901234*0123456789012
                          // 34*012345678901234*
unsigned char PROGMEM greeting[]=   " Dual-Sensor   RF Powermeter  DSPM03  Vers 2.0(c) 2005
                          DL5NEG";
unsigned char PROGMEM adc_screen[]=   " ADC-rawvalue  for calibration AD0 AD1 AD2 AD4 --- --- --
                          - --- ";
```

```
unsigned char PROGMEM diode_screen[]= "Diode-Sensor    abs: :xx.xx dBm rel: :xx.xx dB   xxxx  sensor
                                - ";
unsigned char PROGMEM thermo_screen[]= "Thermal-Sens.x  abs: :xx.xx dBm rel: :xx.xx dB                ";
unsigned char PROGMEM battery_screen[]="Battery Voltage    -.- Volts     Status: -oo-              ";
unsigned char PROGMEM overld_screen[]= "WARNING OVERLOAD  reduce input   power to avoid
                                damage of sensor";
unsigned char PROGMEM preatt_screen[]= "Pre-Attenuation set: :xx.xx dB  use Rel-Reset &  Zero-Adj to
                                set";

/* The lookup tables for the different sensors start here. Stated is the ADC-value for each dBm-value.
    Each following value is one dB more. Since the sensors have different dynamic ranges, the arrays have
                                different lengths. Each string is terminated by the value FFFF hex.
  For the diodesensor the autorange-switching-limits for both tables (range1 and range2) are also stated. */

// look-up-table for the diode sensor adc1
unsigned int PROGMEM lut_ds1[]= { 4, 6, 7, 10, 12, 16, 19, 24, 29, 35,  42, 51, 60, 71, 83, 98, 114, 133,
                                155, 179, 208, 240, 276, 318, 365, 418, 480, 548, 639, 812, 0xFFFF};
#define start_ds1 -14
#define lut1_lowerlimit 35
// look-up-table for the diode sensor adc2 these adc values represent the dbm values
// termination is marked by the value $FFFF
unsigned int PROGMEM lut_ds2[]= { 3, 4, 5, 6, 7, 9, 11, 14, 18, 22, 28, 35, 44, 55, 68, 85, 105, 129, 158,
                                194, 236, 286, 346, 415, 497, 592, 704, 833, 983, 0xFFFF};
#define start_ds2 -30
#define lut2_upperlimit 983
/* define the adc-value defined as zero for the thermo-sensor */
#define thermo_zero 0x10
// look-up-table for the thermo sensor 1 these adc values represent the dbm values
// termination is marked by the value $FFFF
unsigned int PROGMEM lut_th1[]= { 21, 22, 24, 26, 28, 31, 35, 40, 46, 54, 64, 76, 92, 111, 136, 166, 204,
                                251, 310, 383, 472, 581, 713, 871, 0xFFFF };
#define start_th1 -3
// look-up-table for the thermo sensor 2 these adc values represent the dbm values termination is //marked
                                by the value $FFFF
unsigned int PROGMEM lut_th2[]= { 22, 23, 25, 27, 30, 34, 39, 45, 52, 61,
73, 88, 106, 130, 159, 196, 243, 302, 376, 469, 586, 734, 919, 0xFFFF};
#define start_th2 -10
int main(void)
{
        unsigned int adc_value;
```

```
unsigned char keystatus,dash;
int marker_pos
char z,e;
int k;  // all 8 pins of PORTD as output for the LCD data bits
DDRD = 0xFF; // set C5 as output for LCD reg-sel.
DDRC = 0x20; // set PB1 as output for the PWM zero adjust for the
                        // thermo sensor and PB2 as output for LCD-Strobe
DDRB = 0x06;
/* set PB0,3,4,5 to high to activate the internal pull-ups */
PORTB = 0x39;  // switch on PWM mode for thermal sensor zero adj
TCCR1A = 0x83;  // non inverting PWM with 10bit resolution
TCCR1B = 0x01;  // counter clock = 1x system clock
zero_adj = 0x0200; // set 10 bit PWM value to 1/2 of full value
OCR1AH = ( zero_adj>>8 & 0xFF );
OCR1AL = ( zero_adj    & 0xFF ); // initialize the 4x16 LCD
init_lcd();
/* load the greeting message into the video ram */
preset_videoram(1);
/* transver data from video ram to lcd display*/
update_lcd();
/* wait 3 seconds to present the greeting message*/
pause(0xFF);
pause(0xFF);
pause(0xFF);
mode=3; // set the start mode, 2=rawadc, 3=diode sensor
preset_videoram(mode);
while(1)                // main loop
{
        update_lcd();           // transfer data from video ram to LCD
        if( zadj_status != OFF ) // if automatic zero-adj is on
        {
                adc_value = read_adc(therm_adc_select);
                if( (zadj_status == UPWARDS)   && ( adc_value >= thermo_zero) )
                 zadj_status = OFF;
                if( (zadj_status == DOWNWARDS) && ( adc_value <= thermo_zero) )
                 zadj_status = OFF;
                zero_adj += zadj_status;
OCR1AH = ( zero_adj>>8 & 0xFF ); // set 10 bit PWM to new value
OCR1AL = ( zero_adj    & 0xFF );
        }
```

```
keystatus = PINB; // read the status of the input keys
if( !(keystatus & 1) ) //if key1 (mode select) is pressed
{
        mode++;     //switch to next screen mode
        if( mode > 6 ) mode = 2;
        smoothkey(); //update the LCD with all current data
         //and wait some time to avoid key repetition
}
if( !(keystatus & 16) ) //if key2 (ADC select) is pressed
{
// in mode 3 (diodesensor) key2 is used to switch the used ADC (man ACD1, man ADC2,Autoselect)
        if( mode==3 )
        {
         if( auto_select == ON )
         {
                auto_select = OFF;
                diode_adc_select=1;
         }
         else
         {
                if( diode_adc_select==1 )
                        diode_adc_select++;
                else
                {
                        diode_adc_select=1;
                        auto_select = ON;
                }
         }
        }//end if mode=3
        // in mode 5 (thermal sensor) key2 is used to switch the used
        // ADC between sensor 0 (coarse reading) and sensor 4
        // (fine reading)
        if( mode==5 )
        {
        if( therm_adc_select != 0 )
                therm_adc_select = 0;
        else
                therm_adc_select = 4;
        }       //end if mode=5
// here comes the real action - reading the adc and diplaying the results in dBm
```

```
{
        case 2: // mode 2= raw adc values are displayed
        {
        // show status of zero-adjusting if switched on
        parameter2videoram();
/* read ADC channel 0 (thermal sensor 1) */
        adc_value = read_adc(0);
        /* write the adc_value to the videoram */
        videoram[50] = hex2asc(  adc_value     & 0x0F );
        videoram[49] = hex2asc( (adc_value>>4) & 0x0F );
        videoram[48] = hex2asc( (adc_value>>8) & 0x0F );
        /* read ADC channel 1 (diode sensor 1) */
        adc_value = read_adc(1);
        /* write the adc_value to the videoram */
        videoram[54] = hex2asc(  adc_value     & 0x0F );
        videoram[53] = hex2asc( (adc_value>>4) & 0x0F );
        videoram[52] = hex2asc( (adc_value>>8) & 0x0F );
        /* read ADC channel 2 (diode sensor 2) */
        adc_value = read_adc(2);
        /* write the adc_value to the videoram */
        videoram[58] = hex2asc(  adc_value     & 0x0F );
        videoram[57] = hex2asc( (adc_value>>4) & 0x0F );
        videoram[56] = hex2asc( (adc_value>>8) & 0x0F );
        /* read ADC channel 4 (thermal sensor 2) */
        adc_value = read_adc(4);
        /* write the adc_value to the videoram */
        videoram[62] = hex2asc(  adc_value     & 0x0F );
        videoram[61] = hex2asc( (adc_value>>4) & 0x0F );
        videoram[60] = hex2asc( (adc_value>>8) & 0x0F );
        }break;
    case 3: // mode 3= diode sensor values are displayed in dBm
        {
        /* read ADC on selected channel */
        adc_value = read_adc(diode_adc_select);
  if(auto_select); // automatically select the best sensor setting
    {
// if adc_value is to low switch to adc2 (if adc2 was already
// used it simply stays select and nothing can be done anyhow)
  if(adc_value < lut1_lowerlimit)
    diode_adc_select=2;
```

```
//if adc_value is to high switch to adc1
        if(adc_value > lut2_upperlimit)
        diode_adc_select=1;
        /* now read ADC on automatically selected channel */
                        adc_value = read_adc(diode_adc_select);
                }

/* interpolate to calculate the dBm value and write that to LCD */
        interpol(adc_value);
                }break;
case 6:  // mode 6= Battery voltage in Volts is displayed
        {
        /* read ADC channel 3 */
                adc_value = read_adc(3);
                if( adc_value > 640 ) // if Vbatt >= 8.0 Volts
                        {
                        videoram[45]='d'; // write 'good'
                                }
                        else
                        {
                                videoram[45]='r' // write 'poor'
                                        }
// battery voltage is divided by 4 by a resistive divider before it enters // ADC3;
        } //+++++++++++++++++ end of main loop ++++++++++++++++++++++
        return(0);   // to avoid a compiler warning
}
/*--------------- subroutines from here on ------------------*/
//------------------------------- read adc -------------------------------
// reads the selected adc (does some averaging to stabilize the value)
{
        unsigned char adlow, adhigh, counter;
unsigned int adsum; // status for ADC: enable adc, start 1st conversion, free run,clock //prescaled with
                factor 64 ->57kHz clock with fq=3.686MHz
        ADCSR = 0xE6;
// select ADC, i.e. switch the MUX to the selected ADC
        ADMUX = adc_number;
        // reset the averaging sum
        adsum = 0;
        for(counter=0; counter<_BV(average); counter++ )
        {
```

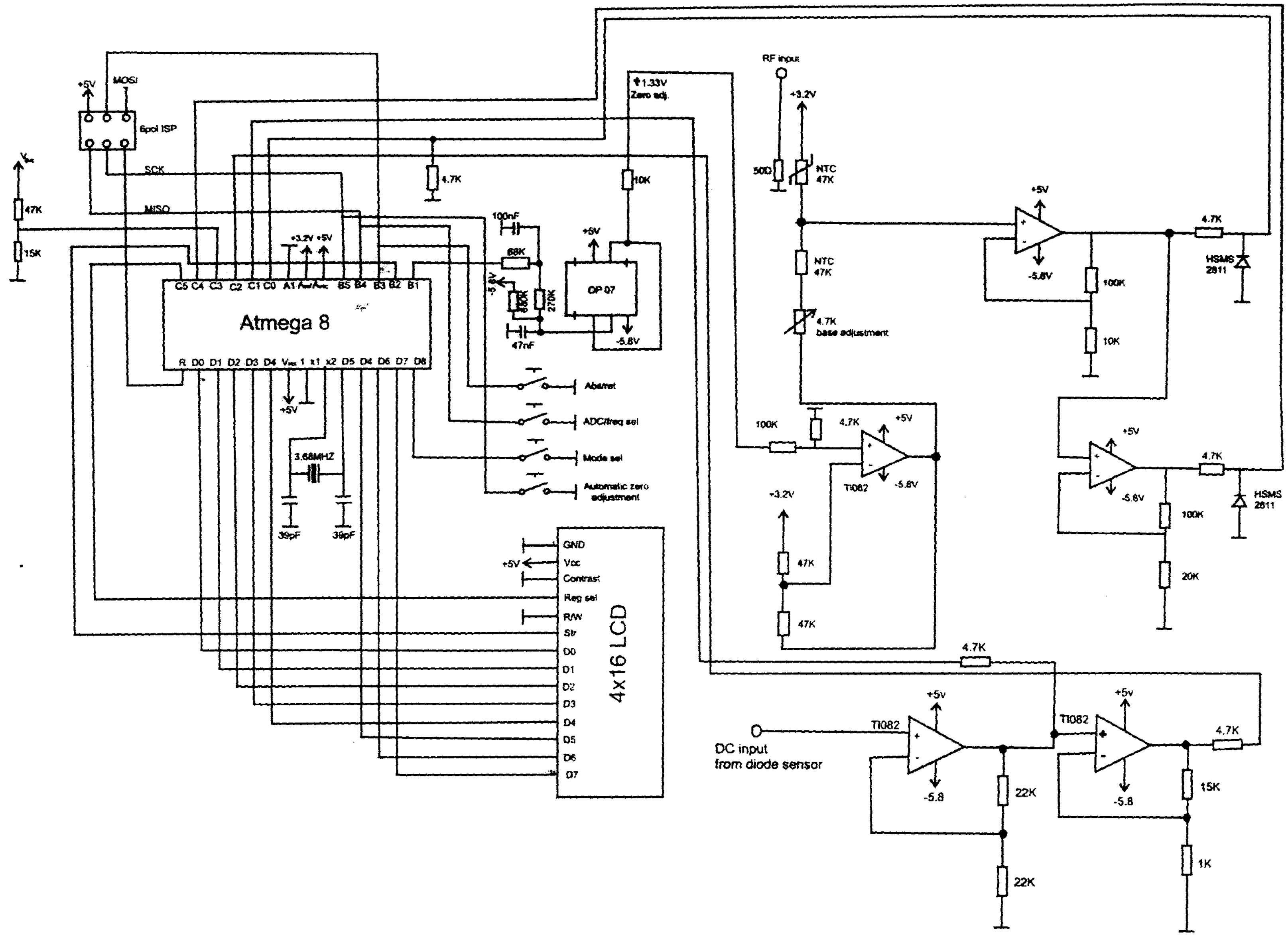
```
// wait N times 4.4ms in subroutine pause (here N=1) for AD-conversion to be performed
                    pause(1);

                    // read adc-value (low byte must be read first !!!
                    adlow  = ADCL;
                    adhigh = ADCH;
                    // add the read value to the averaging sum
                    adsum += (adhigh<<8) + adlow;
          }s
          // divide the averaging sum by the number of values
          adsum >>= average;
          return adsum;
}
//---------------------------- pause ------------------------------------
// waits for n times 4.4 ms
void pause(unsigned char n);
{
// this function had to be rewritten to use the 8bit counter instead of the16bit counter
// since the 16bit counter is now used for the PWM output for the zero adjust of the
// thermal sensor
          unsigned char pcnt;    // set 8bit counter back to zero
TCNT0 = 0x00; // switch the counter on with prescaler set to 64 -> 8bit overflow occurs every 4.4ms
          TCCR0 = 0x03;
          // reset counting variable
          pcnt = 0;
// count the numbers of overflows until parameter n is reachedwhile( pcnt < n )
          {
                    if( TIFR & _BV(TOV0) )          // if overflow
                    {
                              pcnt++;               // increment counting variable
                              TIFR |= _BV(TOV0);  // reset overflow flag
                    }
          }
}
//-------------------------- hex to asc ---------------------------------
// converts a hex value (00..0F) into the ASCII-character '0'..'F'
unsigned char hex2asc(unsigned char hexbyte)
{
          hexbyte += 48;                    // ASCII code for 0-9 is 48-57
          if(hexbyte>=58)       // ASCII code for A-F is 65-70 -> in that case add 7
```

```
                hexbyte += 7;
        return hexbyte;
}
// -------------------------------------------------------------
// This subroutine fetches two values from a lookup table (one correlating to the next value
// smaller than adc and one correlating to the next value above adc. The correct value is
// interpolated between these two values.
void interpol(int adc)
{
        int d,k,x;
        unsigned char counter=0;
        int lut_c0=0, lut_cm1=0;
        int startvalue=0;
        overload = OFF;         // reset old overload flag depending on the currently selected
                                // look-up-table the dBm values directly above and
                                // below the measured value are searched
        if(mode == 3)           //if diode-sensor is selected -> use the diode sensor
        {
 //look-up-tables values according to the selected adc
                if(diode_adc_select==1)
                {
                for( counter=0 ; PRG_RDI(&lut_ds1[counter]) <= adc ; counter++ );
                        startvalue=start_ds1;
                        lut_c0  = PRG_RDI(&lut_ds1[counter]);
                        lut_cm1 =  PRG_RDI(&lut_ds1[counter-1]);
                }
if(mode == 5)           //if thermo-sensor is selected -> use the thermo-senor
  {
        //look-up-table values
        if(therm_adc_select==0)
        {
                for( counter=0 ; PRG_RDI(&lut_th1[counter]) <= adc ; counter++ );
                        startvalue=start_th1;
                        lut_c0  = PRG_RDI(&lut_th1[counter]);
                        lut_cm1 = PRG_RDI(&lut_th1[counter-1]);
                }
        else
        {
                for( counter=0 ; PRG_RDI(&lut_th2[counter]) <= adc ; counter++ );
                        startvalue=start_th2;
```

```
                        lut_c0  = PRG_RDI(&lut_th2[counter]);
                        lut_cm1 = PRG_RDI(&lut_th2[counter-1]);
                }
        }
// values are fetched out of the valid look-up-table, now the
// processing of the data can begin independent of the mode adc
        if( counter == 0 ) // if adc_value is lower as lowest table value
        {
        videoram[20]='<'; // put '<' before numbers to inidicate low signal
                videoram[36]='<';
        }
        if( lut_c0 == 0xFFFF )// if adc_value is higher as highest table v.
        {
                preset_videoram(7); // write overload message to screen
                        return;         // leave this subroutine immediately
        }
        // calculate the difference between prev. and next known value
        d = lut_c0 - lut_cm1;
        // calculate the difference between adc-value and prev. known value
        k = adc - lut_cm1;
        // multiply with 100 since the result shall be in 1/100 of a dBm
        k = k *100;
        // do the interpolation and add the meaning of the prev. value
        x = k / d + (startvalue + counter-1)*100;
        int2lcd(x); // output the value dezimal on the lcd display
                        // paramters unit is 1/100 of dBm
        }
// reads an integer (2 bytes) from the flash (program memory) parameter is the address of the data, //i.e. a
                        call of this function is like: a=PRG_RDI(&table[i]); with table[] being an
                        array of integers
unsigned int PRG_RDI( unsigned int *prgmem )
{
  return (pgm_read_byte(((unsigned char*)prgmem)+1)<<8) + pgm_read_byte(prgmem);
}
// ------------------------ init LCD ---------------------------
void init_lcd( )
{
        unsigned char initcnt;
        pause(10); // wait 4x4.4ms (datasheet requires at least 15ms)
        PORTC &= ~0x30;    // strobe and reg-sel to low
```

```
        // according to datasheet the init-byte must be clocked in 3 times
        // (Register Select must stay low to indicate an instruction)
        for( initcnt=1 ; initcnt<=3 ; initcnt++ )
        {
                char2lcd(48);           // value given in datasheet for init
                pause(1);   // wait 4.4ms
        }
        char2lcd(56);           // datalines =8, one-line-mode =off, Font= 5x7
        pause(1);               // wait 4.4ms
        char2lcd(12);           // display on, cursor off
        pause(1);               // wait 4.4ms
        char2lcd(1);            // display clear
        pause(4);               // wait 4x4.4ms
        char2lcd(2);            // cursor home
        pause(4);               // wait 4x4.4ms
}
// ---------------------- character to LCD --------------------
// sends one byte to the LCD and takes the strobe high shortly (depending on the reg-sel
// line this is recognized as character or as instruction by the LCD. For some instructions
// additional pauses may be necessary and must be cared for externally)
void char2lcd(unsigned char lcdchar)
{
        PORTD = lcdchar;    // write the byte to Port D
        PORTB |=  0x04;     // strobe to high
        PORTB &= ~0x04;     // strobe to low this 4ms pause makes the update to
                            // slow, the LCD //requires 37us according to datasheet
        lcd_delay(50);
}
        // delay loops for microsecond-delays (for LCD etc.)
        // one loop is roughly 1 microsecond with a 3.686MHz crystal
int lcd_delay(int loops)
        {
        while(loops) loops--; //simply count down to zero
        return loops;           //just to avoid that the compiler is ignoring the whole
                                // function because it has no "real" effect
        }
```

Appendix C



Detail Circuit Diagram of Dual Sensor RF Power-Meter