Design of a Low-Cost, One-Way, Wireless Digital Communication System

Kristopher L. Young

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Design of a Low-Cost, One-Way, Wireless Digital Communication System

Kristopher L. Young
Honors Senior Project
Spring 1997
Dr. R. Adhami, Advisor
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ABSTRACT

As information becomes increasingly valuable in today's world, the collection and dispersion of information becomes more important. There is a need for a low-cost solution to conveniently get information from one point to another. This project is concerned with investigating the design of a generalized low-cost, one-way wireless digital communication system, particularly the radio frequency and modulation / demodulation sections of the system. Various off-the-shelf electronic components are evaluated with respect to cost and features. An optimum set of components is then selected and the specifications are analyzed for performance. This design is then constructed and bench tested to verify satisfaction of the design performance requirements.
The modem era is often called the "information age", since society's need for and use of information is increasing at an astounding rate. It seems as if the more information we have, the more we need and the more we can use. As the need for information increases, the need for efficient collection and dispersion of information also becomes more important. The rapid growth in the telecommunications industry has expanded the ability to efficiently achieve this.

This project examines a design which satisfies a limited set of needs for the movement of information from one point to another. This design, the one-way wireless digital communication system, takes digital information and transmits it from one point to another by radio frequency transmission. This communication system must be low-cost so that it can be mass produced for a unit cost small enough to be easily used where cost currently prohibits the use of such a device.

A device of this type could be used in applications where a wire currently links the source and destination of information. These wires are often prone to damage, are inconvenient, and can limit the range and use of a device. An low-cost, one-way wireless digital communication system could replace the wire in some applications, making the device more reliable and useable. An example of this would be the replacement of a corded barcode scanner in retail stores with a wireless unit, which would be more convenient, especially for scanning large items, and would cut down on down time associated with damaged cables.

A wireless digital communication system could also be used in applications where price, convenience, and practicality stand as obstacles to data collection. Some examples of these types of applications would be smart identification tags for inventory tracking, wireless sensors for scientific data collection in the field, automatic utility meter reading systems, and security sensors. These applications
could all use the wireless digital communication system to obtain and use information in a way that was previously unavailable.

One more possible use for this type of system is the reception of broadcast information. With low cost digital receivers, it could be feasible to broadcast information in the form of audio, video, data, or a combination of the three to a large audience. The receiving device could then use this information in a variety of ways, expanding the capabilities and the quality of broadcast services.

This project is an exploration of the available technology, as well as the design of a basic building block that could make all of these different applications possible. The result of this project will be the first step towards the development of a practical low-cost communication system. With the large amount of potential uses, the design of the low-cost, one-way, wireless digital communication system could be very important as a tool for the efficient management of information.
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1.0 INTRODUCTION

With the currently increasing supply and demand for information, the efficiency of data communication systems is becoming more of an issue. There is a need for low cost data communication systems that exhibit versatility in applications. Most wireless data communication devices currently available are either limited application units such as keyless entry devices, or high cost units for wireless local area networks (LANs). These devices ignore a tremendous niche for devices with versatile uses and low cost.

This project was concerned with finding the design for the radio frequency (RF) and modulation / demodulation portions of a generalized one-way, wireless digital communication system. This system must have a low cost for mass production quantities and must consume little power for potential use in battery powered systems. Particular focus was put on evaluating off-the-shelf (OTS) integrated circuits, which have been appearing more and more over the past few years. The system must also be able to be sold commercially to users in the United States without requiring individual FCC licenses. This requires conformity to the FCC guidelines in Part 15 of Title 47 of the US Code of Federal Regulations (11).

The following design criteria were set to obtain a reliable short-range digital communication system. A bit error rate (BER) for this design was set at $1 \times 10^{-6}$, or one error in one million bits sent through the system. The minimum distance between the transmitting and receiving antennas for reliable communication should be 100 feet (around 30 meters). There was no minimum data rate for the design, but the higher the data rate, the more versatile the system because more information can be transferred.
2.0 THEORY

For wireless digital communication to take place, the signal must be modulated for transmission. Modulation techniques include amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK). These techniques are accomplished in a variety of ways and have different bit error characteristics in the presence of noise. Discussion and analysis of these techniques is found in many textbooks, such as Ziemer and Tranter's Principles of Communications: Systems, Modulation, and Noise (1). Noise analysis techniques are also presented in this textbook, as well as in Mischa and Swartz's Information Transmission, Modulation, and Noise (2).

Wireless digital communication also makes use of electromagnetic theory to use RF energy to transmit a signal through the air. Paul and Nasar's Introduction to Electromagnetic Fields contains the theory necessary to calculate electric field strength, as well as a discussion of near-field and far-field transition (3). This text also contains a detailed treatment of Friis's transmission formula, developed by H.T. Friis in 1948. Antenna Analysis by Wolff contains information on the characteristics of specific types of antennas (4).

Information theory is also important to digital communication. In 1948, C.E. Shannon published the theorem which states that there is a maximum data rate for a digital communication channel with a given bandwidth and signal-to-noise ratio (SNR), and that signaling with arbitrarily high reliability is possible for any rate less than this rate with the use of error correction coding (5). While this project did not address error correction coding issues, this theorem profoundly affects the final system of which this design would be a part. Detailed treatment of information theory and error coding issues is developed in Chambers' Basics of Communications and Coding.
(6). Some of these issues are also developed in Clark's *Principles of Digital Data Transmission*

(7).

### 3.0 METHOD

This project involved three phases of research: component selection, system design, and system testing. The component selection phase involved examining various OTS components for potential use in the system design. These components were evaluated with respect to the design criteria, and a candidate set of components were selected. The system design phase used the candidate set of components to create a design. The specifications of the components were then analyzed to make sure the components could be used to satisfy the design requirements. The system testing phase involved testing the designed hardware in the laboratory to ensure compliance with the design requirements.

#### 3.1 Component Selection

Finding potential OTS components for the design involved consulting product catalogs and World Wide Web pages of various component manufacturers, as well as looking at electronics trade magazines. Table 1 lists the various potential components and the associated characteristics used in the evaluations. Component prices are the price estimates quoted by distributors or from the manufacturing companies. Ten thousand was the desired production pricing quantity, however, pricing for this quantity was not readily available for all products. Transmitter and receiver pairs are listed consecutively.
Table 1. Potential OTS Components and Characteristics

<table>
<thead>
<tr>
<th>Component</th>
<th>Trans./Recv.</th>
<th>Price/Ea. ($)</th>
<th>Priced Quantity</th>
<th>External Component Count</th>
<th>Max. Data Rate (KBits/s)</th>
<th>Modulation Type</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF9901</td>
<td>Trans.</td>
<td>1.95</td>
<td>10,000</td>
<td>Low</td>
<td>1000</td>
<td>FSK</td>
<td>RF Micro Devices (8)</td>
</tr>
<tr>
<td>RF9902</td>
<td>Recv.</td>
<td>1.95</td>
<td>10,000</td>
<td>Low</td>
<td>1000</td>
<td>FSK</td>
<td>RF Micro Devices</td>
</tr>
<tr>
<td>AT2000</td>
<td>Trans.</td>
<td>5.00</td>
<td>10,000</td>
<td>Low</td>
<td>10</td>
<td>ASK</td>
<td>RF Monolithics</td>
</tr>
<tr>
<td>RX2010</td>
<td>Recv.</td>
<td>28.00</td>
<td>500</td>
<td>Medium</td>
<td>10</td>
<td>ASK</td>
<td>RF Monolithics</td>
</tr>
<tr>
<td>KEFTX01C</td>
<td>Trans.</td>
<td>1.30</td>
<td>10,000</td>
<td>Low</td>
<td>50</td>
<td>ASK</td>
<td>GEC-Plessey</td>
</tr>
<tr>
<td>KEFRX01E</td>
<td>Recv.</td>
<td>2.80</td>
<td>10,000</td>
<td>Medium</td>
<td>50</td>
<td>ASK</td>
<td>GEC-Plessey</td>
</tr>
</tbody>
</table>

The top selection criteria for the system was price. The number of external components is a rough estimation that signifies additional cost in manufacturing the functional unit. Versatility was also an important criteria for the system. For this reason, data rate and modulation technique were also important for the optimum component selection. The BER of the system depends on the available SNR as well as interference. The relationship between BER, SNR, and interference depends to some degree on the modulation technique. With higher data rates, Shannon's theorem shows the potential to use error correction coding techniques to achieve arbitrarily low BERs at a lower data rate (5).

The RF Micro Devices component set of RF9001 and RF9002 were selected as the candidate components for use in the design for this project. Although the GEC-Plessey ASK set was around the same cost as the RF Micro Devices set, the RF Micro Devices set exhibited a much higher data rate. Also, FSK modulation has a higher on-channel interference rejection than ASK modulation. This added resistance to interference could be vital to the reliable operation of the one-way communication link.
3.2 System Design

The RF9901 FSK transmitter and RF9902 FSK receiver are designed for low RF power applications over the frequency range of 400 to 930 MHz. The RF9901 uses a phase locked loop (PLL) with an external frequency reference crystal for modulation around a stable carrier. The RF9902 is a high gain FSK receiver and demodulator. The RF9902 is a single conversion receiver, therefore it requires an external stable frequency reference for demodulation.

Since the output radio frequency range of the RF9901 is from 400 to 930 MHz, the frequency of operation was chosen to be 916 MHz, which falls within the Industrial-Scientific-Medical (ISM) band from 902-928 MHz. According to the FCC guidelines, an intentional radiator may be operated without a license in this band subject to the field strength of the fundamental frequency being no more than 50 mV/m at 3 meters and no harmful interference (11:15.249). The low RF power usage intended for this system design fall within these legal usage limits given by the FCC.

The external components and values given in the RF Micro Devices Designer Handbook were used for the transmitter design (8). The design schematic is given in Appendix A. This circuit can operate on a supply voltage of +3.0 V to +5.0 V. The typical value of +4.0 V is specified for the design.

The upper frequency limit on the modulation input is specified as 500 KHz. This sets the upper limit for the bit rate of the system to 1Mbit/s for no intersymbol interference, due to Nyquist's theorem (7.100). The design specification adopted in this project is a 500Kbit/s no return to zero (NRZ) format data code.
Omnidirectional pattern antennas were chosen for this system due so that the communication system would function independently of radial direction between the transmitting and receiving antennas. Since the RF9901 transmitter can tolerate a VSWR of up to 50:1, any type of omnidirectional antenna could satisfy the design requirements. The monopole antenna was selected for the design, since it is one of the simplest antennas to build. Monopole characteristics are examined in Wolff's text (4:13,74). This antenna can be constructed as a thin, straight wire extending above a ground plane.

Like the transmitter, the external components and values given in the RF Micro Devices Designer Handbook were used for the receiver design at 916 Mhz. The intermediate frequency (IF) was chosen to be 20 Mhz. The schematic is given in Appendix A. A stable frequency reference of either 896.3 MHz or 936.3 MHz at a level between -6 dBm and -3 dBm is required to demodulate the signal. This could be accomplished with a low cost PLL Frequency Synthesizer and voltage controlled oscillator (VCO), which were not part of this design.

The remaining design requirement of a BER of $1 \times 10^{-6}$ at a range of 100 feet (30 meters) is dependent on the SNR of the receiver. The SNR of the receiver can be increased a great deal with the use of a low noise amplifier (LNA), however, the addition of an LNA would add some cost to the receiver. The specified system design was analyzed to determine whether the requirements could be met without an additional LNA.

This analysis involved a series of calculations, found in Appendix B. The internal noise of the receiver was calculated in B.1.1 and B.1.2 by calculating the effective noise bandwidth of the IF filter and by using the noise figure of the amplifier. The maximum legal power was then found in B.1.3, and used in the Friis transmission equation in B.1.5 to find the signal power at the
receiver after the isotropic signal power loss between the ideal monopoles. This result was then
used in B.1.6 to find the SNR and in B.1.7 to find the signal energy-per-bit to noise power
spectral density ratio \( (E_b/N_0) \). The standard formula for BER as a function of \( E_b/N_0 \) for
noncoherent FSK demodulation was used to estimate the maximum range in B.1.8. Although this
formula is not derived for the particular form of noncoherent demodulation used in the RF9902, it
was assumed to be close enough to be a rough estimate for performance.

3.3 System Testing

With the acceptable values obtained from the design analysis, the decision was made to
obtain hardware for testing to verify operation satisfying the design requirements. The
RF9901.PCBA and RF9902.PCBA evaluation boards were obtained from RF Micro Devices.
These are printed circuit boards with the integrated circuits, external components, and connectors
for power supply, data input/output, and RF signal input/output. The schematic of the evaluation
board is the same as the design already selected, shown in Appendix A.

Two monopole antennas were constructed, each one made by stripping a length of
shielding and dielectric off of a 50 Ω semi-rigid cable, bending the center conductor at a 90 degree
angle to the remainder of the cable, and soldering the base of the cable to a 20 cm by 13 cm
section of copper plated fiberglass. The center conductor was cut a little longer than a quarter
wavelength. The antennas were then connected to a network analyzer (machine J of equipment
list in Appendix D). The center conductor of each antenna was then carefully trimmed to
minimize the voltage standing wave ratio (VSWR). This minimization located the exact quarter
electrical wavelength for the antenna. The final length of the center conductors was around 7.5 cm. A diagram of the constructed monopole is shown in Figure 2.

![Diagram of the constructed monopole](image)

**Figure 1. Construction of Monopole Antenna**

The VSWR, characteristic impedance, and directional antenna gain characteristics were measured for the antennas with the network analyzer. The plots are given in Appendix C, along with a summary of the impedances and VSWR at 914 MHz. While this is not the design frequency of 916 MHz, the plots show that the approximation is fairly accurate for all the antenna characteristics. The directional gain of the antennas were measured at a distance of two feet, which is approximately twice the wavelength at 916 MHz. This is within the $\lambda_0$ to $5\lambda_0$ near-field to far-field transition region, although less than the commonly used $3\lambda_0$ point (2:557). With the limited space around the equipment, two feet was the best that could be done without getting detrimental effects from scatter and multipath in the laboratory. The directional antenna gain
characteristics were assumed to be far-field measurements. The values of $G_T$ and $G_R$ were calculated in Appendix B.2 using the Friis transmission equation.

The evaluation boards were first set up for an operational demonstration by connecting the RF ports to the antennas and assembling equipment as shown in Figure 2. Equipment specifications are listed in Appendix D. The VCC connections of the boards were connected to +4.0V DC power supplies (A and F), and the GND connections were grounded. A function generator (B) was connected to the digital input of the transmitter via a terminated 50 Ω SMA cable. The generator was set to output a 250 KHz TTL level square wave (+4V, 0V), to mimic a series of logic ones and zeroes at a data rate of 500 Kbit/s. The power control pin of the transmitter was connected to an adjustable DC power supply (C). The data output of the receiver was connected to an oscilloscope (G) set to a time scale of 2 microseconds per division. A signal generator (E) was connected to the local oscillator port of the receiver via a 50 Ω SMA cable. The signal generator was set to output a -3 dBm sine wave at 936.3 MHz. A spectrum analyzer (H) was set up on the bench with a center frequency of 916.3 MHz and a span of 5 MHz. A loop antenna was connected to observe the RF signal from the transmitter.
When the power and signals were turned on, a square wave was appeared on the oscilloscope with the same period as the function generator. This showed that the “data” was being accurately transmitted between the transmitter and receiver. The spectrum of the FSK modulated carrier was visible on the spectrum analyzer. The amplitude of the square wave was then adjusted to (+2.90 V, 0 V) for optimum frequency separation (for white gaussian noise), $1/T_b = 500$ KHz ($7:107$). The antennas in this setup were separated by approximately five feet.

Limited available space on the bench prevented the large antenna separations necessary to measure the maximum range. To simulate the response for large separation distances, an adjustable attenuator (D) was used to identify the lowest signal power level at the receiver associated with a noticeable BER. Since this design did not involve the clock recovery and data
transmission control sections of the system, the BER of the system was not directly measurable. The BER was estimated by observing the output in an oscilloscope. Due to the strobing of the oscilloscope, it was decided that a 1% BER would be barely noticeable by viewing the display for a few seconds. Therefore, when bit errors were noticed on the oscilloscope display, the BER was estimated to be 1% (1x10^{-2}). This value was then "interpolated" using the noncoherent BER formula to find the corresponding signal power level for a BER of 1x10^{-6}.

The RF9901 transmitter was connected to the input of the attenuator and an RF power meter (I) was connected to the output of the attenuator. The power level at the output of the attenuator was measured with the attenuator programmed for no attenuation. Next, the attenuator was set for 50 dB and was connected between the RF output of the transmitter and the RF input of the receiver. The attenuation was then raised until bit errors in the square wave pattern became noticeable on the oscilloscope. The calculations in Appendix B.3 show the estimate of range corresponding to this attenuation, using the measured gain characteristics for the constructed antennas.
One final set of measurements was taken to determine the output power as a function of the power control voltage. With this data, the transmitter can be operated at any output power level by fixing the power control voltage to a certain value. This data and associated scatter plot are in Appendix C.5.

4.0 PRESENTATION OF RESULTS

The system design formulated here uses the RF Micro Devices RF9901 FSK transmitter and RF9902 FSK receiver along with two quarter wavelength monopole antennas as the RF and modulation/demodulation portions of a low-cost, one-way, wireless digital communication system. The RF9901 and RF9902 are $1.95 each in quantities of 10,000, and require few external components, resulting in a very low cost system. The system design phase resulted in an expected range of 910 meters for operation with a BER of less than $1 \times 10^{-6}$, which is much more than the design requirement of 30 meters. The system testing phase resulted in an estimated range of 101
meters for operation with a BER of less than $1 \times 10^{-6}$, which was much less than expected, but still well within the design requirement. The discrepancy between expected and measured range corresponded to a power loss of around 19.1 dB.

5.0 CONCLUSION

This project yielded a design that did not perform as well as expected, but far exceeded the design requirements. The discrepancy between the expected performance and the measured performance remains unaccounted for. The discrepancy could be due to a combination of factors, including the difference between the noncoherent FSK demodulation performed by the RF9902 and the ideal demodulation assumed in the formula for bit error rate, an impedance mismatch, or maladjusted hardware. The test results did show, however, that the system can be used to transmit 500 Kbit/s quite reliably over a hundred meters in an ideal environment. This is enough to transmit digitized compact disc quality audio to a limited area. It could also be used for the transmission of digitized black-and-white video from security cameras, or any of a number of lower data rate applications.

The range of this system could be improved considerably by the addition of a low noise amplifier and noise imaging filter at the receiver input. This adds some extra cost, which would have to be examined as a cost benefit analysis for the system. Also, it is possible that the system can be made to operate at the expected performance level by further testing and analysis of the hardware.

There is much potential for future research on this topic, as the local oscillator, clock recovery, data control (start and stop sequences), and error coding circuits have not yet been
designed. Also, channel switching or sharing could be implemented to facilitate several different transmitters operating at once.

This project establishes the basic building block for a practical and versatile one-way, low-cost, wireless digital communication system. This lays the foundation for the continued work on the different aspects of the system. The finished system should be a useful tool in assisting humankind in the efficient management of information.
REFERENCES


BIBLIOGRAPHY


NOTE: VCC is connected to +4.0 VDC
APPENDIX B: CALCULATIONS
B.1 Calculation of the Expected Maximum Reliable Range

The first part of the calculation section involved calculating the expected maximum distance between the antenna of the transmitter and the antenna of the receiver for operation within specifications. This was done by finding the noise power at the receiver input and the signal power at the receiver input as a function of distance, and using these to calculate the signal to noise ratio, which was used to find the BER as a function of distance. Using the specified value of BER, the expected range was then found.

B.1.1 Calculation of Noise Bandwidth

Calculation of noise bandwidth involves finding a rectangular frequency spectrum equivalent for the IF filter. This calculation makes use of the following equation (2.207):

\[ A_m^2 B = \int_0^\infty |H(jw)|^2 \, df \]

where:
- \( H(jw) \) = network transfer function
- \( A_m^2 \) = the maximum absolute value of \( H(jw) \)
- \( B \) = noise equivalent bandwidth

These values were found by examining the IF filter circuit in the receiver (Appendix A). The filter network is terminated internally with 500 \( \Omega \). The network was analyzed in Mathcad 6.0. The value of \( A_m^2 \) was found to be 0.486. The integral was evaluated numerically to 1 GHz (the 3 dB point of the filter is a little over 20 MHz) and was found to be 2.278\texttimes10^6.

\[ BW = \text{integral} / A_m^2 = 4.69 \text{ MHz} \]

B.1.2 Calculation of Noise Power at the Receiver Input

This calculation was made using the following equations (1.767). The result is the noise power as seen at the input of the receiver due to the internal noise of the receiver. Since both the signal and noise are amplified by the same amount in the receiver, the gain can be ignored.

\[ P_{\text{internalNoise@input}} = k \cdot T_e B \text{ Watts} \]

\[ T_e = T_o(F - 1) \]

where:
- \( T_o \) = room temperature in Kelvin = 290 K
- \( k \) = Boltzmann's constant = 1.38\texttimes10^{-23} \text{ J/K}
- \( T_e \) = Effective noise temperature
- \( F \) = noise figure = 8 (from RFMD specifications)
- \( B \) = system bandwidth = 4.69 MHz
\[ P_{\text{int}} (\text{referenced to } 1\text{mW}) \text{ dBm} = 10 \log_{10} (kT_b) + 10 \log_{10} (B) + 10 \log_{10} (1000) \text{ (W to mW conversion factor)} \]
\[ = -98.80 \text{ dBm} \]

B.1.3 Calculation of Maximum Legal Signal Power

The FCC guidelines in Part 15 of the US CFR Title 47 for 1996 specify that intentionally radiating devices in the Industrial-Scientific-Medical (ISM) band must have a fundamental signal field strength of less than 50mV/m at a distance of 3m. Using the transmitting antenna gain, we can find the maximum legal average signal power by using an equation from (3.554):

\[ |E| = \frac{1}{d} \sqrt{60 \cdot P_T \cdot G_T} \text{ V/m} \]

where:
\( d = 3\text{m} \)
\( G_T = 1.5\text{W/W} \)
\( \text{mag}(E) = 50\text{mV/m} \)

\[ P_T = -6.02\text{dBm} \]

B.1.4 Expected Monopole Gain

The expected directional gain of each monopole antenna was calculated using the ideal directional gain and an expected efficiency of 50%. The values used are from Wolff (4:13,74).

\[ G = \eta \cdot D \]

where:
\( G = \text{antenna gain over isotropic} \)
\( D = \text{directivity} = 3 \text{ (for ideal monopole)} \)
\( \eta = \text{efficiency} = 50\% \text{ expected} \)

\[ G = 10 \log_{10} (3/2) = 1.76 \text{ dB} \]

B.1.5 Calculation of Signal Power at the Receiver Input

This calculation was made using the Friis transmission equation (1.765):

\[ P_R = \left( \frac{\lambda}{4 \cdot \pi \cdot R} \right)^2 \cdot G_T \cdot G_R \cdot P_T \]

where:
\( G_R = G_T = 1.76 \text{ dB} \)
\( \lambda = c/f = 3E8 \text{ m/s} / 916 \text{ MHz} = 0.328 \text{ m} \)
PT = -7dBm (subtracting 1dB from the legal limit for tolerance)

\[ P_R = 20 \log_{10} \left( \frac{\lambda}{4\pi} \right) + 1.76 + 1.76 + (-7 \text{ dBm}) + 20 \log_{10} (1/R) \]

\[ = -35.16 \text{ dBm} + 20 \log_{10} (1/R) \]

B.1.6 Calculation of Signal to Noise Ratio at Receiver Input

This calculation yields the SNR at the receiver input. This is also the SNR at the detector because the gain of the receiver applies to both signal and noise.

\[ \text{SNR}_i = P_R - P_{\text{noise}} = -35.16 + 20 \log_{10} (1/R) - (-100.52 \text{ dBm}) \]

\[ = 65.65 \text{ dB} + 20 \log_{10} (1/R) \]

B.1.7 Calculation of Eb/N0

This calculation converted the SNRi to signal energy-per-bit / noise power spectral density ratio (Eb/N0), which was then used to calculate the BER. The SNRi to Eb/N0 conversion was done by multiplying the SNRi by the bit duration and bandwidth, since the signal power multiplied by the bit duration yields energy per bit and the noise power divided by noise bandwidth yields the noise power spectral density.

\[ \frac{E_b}{N_0} = z = \text{SNR}_i B T_b \]

where:
- \( B \) = noise bandwidth = 4.69 MHz
- \( T_b = 2 \times 10^{-6} \) s

\[ z = 63.65 \text{ dB} + 20 \log_{10} (1/R) + 10 \log_{10} (B T_b) \]

\[ = 73.38 \text{ dB} + 20 \log_{10} (1/R) \]

B.1.8 Calculation of Expected Reliable Range

Next, the \( \frac{E_b}{N_0} \) is used with the bit error probability formula for ideal noncoherent FSK modulation (1.489). Plugging in the desired bit error probability gives the expected reliable range.

\[ P_e = 0.5e^{-z^2} \]

where:
- \( P_e = 1 \times 10^{-6} \)

\[ z \text{ dB} = 10 \log_{10} (-2 \ln(2P_e)) \]

\[ 68.14 \text{ dB} + 20 \log_{10}(1/R) = 14.19 \text{ dB} \]

\[ 20 \log_{10} (1/R) = -59.19 \text{ dB} \]

\[ R = 910 \text{ meters} \]
B.2 Calculation of Far-Field Directional Antenna Gain

The Friis transmission equation was used to find the $G_T$ and $G_R$, which are assumed to be equal for the similarly fashioned antennas.

$$P_R = \left(\frac{\lambda}{4 \cdot \pi \cdot R}\right)^2 \cdot G_T G_R P_T$$

where:

$P_R/P_T = -25.42 \text{ dB}$

$G_T = G_R$

$R = 2 \text{ ft.} = 0.610 \text{ m}$

$\lambda = 0.328 \text{ m}$

$$2 \cdot G_{\text{dir}} = -25.42 \text{ dB} + 20 \log_{10} \left(4\pi R/\lambda\right)$$

$G_{\text{dir}} = 0.972 \text{ dB}$

B.3 Calculation of Measured Reliable Range

This is the effective distance of separation for the current hardware where the BER is estimated to be $1 \times 10^{-6}$ (0.0001%). This is found by using the Friis transmission equation and the measured antenna gain values to calculate loss as a function of separation distance. Then, the actual signal power received through the attenuator at an estimated BER of 1% was added to a loss term representing the conversion from the estimated observed BER to the specification. These two values were equated, yielding an effective separation distance.

$$P_R = \left(\frac{\lambda}{4 \cdot \pi \cdot R}\right)^2 \cdot G_T G_R P_T$$

where:

$G_T = G_R = 0.972 \text{ dB}$

$\lambda = c/f = 3 \times 10^8 \text{ m/s} / 916 \text{ MHz} = 0.328 \text{ m}$

$P_T = -7 \text{ dBm} \text{ (subtracting 1 dB from the legal limit for tolerance)}$

$$P_R = 20 \log_{10} \left(\lambda/4\pi\right) + 0.972 + 0.972 + (-7 \text{ dBm}) + 20 \log_{10} \left(1/R\right)$$

$$= -36.74 \text{ dBm} + 20 \log_{10} \left(1/R\right)$$

$P_R = \text{ power received through attenuator for noticable bit errors} = -82.11 \text{ dBm}$
Next, extra attenuation was added to account for the difference between the estimated BER of $1 \times 10^{-2}$ and the desired $1 \times 10^{-6}$. This extra attenuation assumes the BER behaves as the ideal noncoherent FSK demodulation.

\[
\begin{align*}
\text{BER} &= 1 \times 10^{-2} = 0.5 e^{z/2} \Rightarrow z = 8.93 \text{ dB} \\
\text{BER} &= 1 \times 10^{-6} = 0.5 e^{z/2} \Rightarrow z = 14.19 \text{ dB}
\end{align*}
\]

Therefore, the extra attenuation is $14.19 - 8.93 = 5.26 \text{ dB}$

Setting the two equations equal to each other yields:

\[
-82.11 \text{ dBm} + 5.26 \text{ dB} = -36.74 \text{ dBm} + 20 \log_{10} (1/R)
\]

\[R = 101 \text{ meters}\]

**B.4 Power Difference Between Expected and Measured**

This is a measure of the power gain which would be required to be added to the system for the system to perform as calculated in B.2.

\[
\begin{align*}
R_1 &= 910 \text{ m} \\
R_2 &= 101 \text{ m}
\end{align*}
\]

\[
20 \log_{10} (1/R_1) - 20 \log_{10} (1/R_2) = -59.19 - (-40.09) = 19.09 \text{ dB gain required}
\]
APPENDIX C: MEASUREMENT DATA
C.2.1 Impedance Measurement of Antenna 2

\[ S_{11} \]
\[ Z \]
\[ \text{REF 1.0 Units} \]
\[ \frac{1}{\text{200.0 mUnits/}} \]
\[ 62.818 \Omega \quad \text{-16.592 } \Omega \]

\[ \text{hp} \]

\[ \text{MARKER 1} \]
\[ 914.05 \text{ MHz} \]

\[ \text{START 0.045000000 GHz} \]
\[ \text{STOP 1.000000000 GHz} \]
C.4 Summary of Antenna Measurement Data at 914 MHz

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Real Impedance</th>
<th>Complex Impedance</th>
<th>VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62.3 Ω</td>
<td>18.8 Ω</td>
<td>1.56</td>
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<tr>
<td>2</td>
<td>62.8 Ω</td>
<td>-16.6 Ω</td>
<td>1.49</td>
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</tbody>
</table>
C.5 Relationship of Output Power to Vpc on RF9901

Table 1: Raw Measurement Data

<table>
<thead>
<tr>
<th>VPC</th>
<th>RF Output Power</th>
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<tbody>
<tr>
<td>3.45</td>
<td>1.76</td>
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<tr>
<td>3.35</td>
<td>1.65</td>
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<tr>
<td>3.30</td>
<td>1.59</td>
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<tr>
<td>3.20</td>
<td>1.46</td>
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<tr>
<td>3.10</td>
<td>1.32</td>
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<td>3.00</td>
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<td>2.50</td>
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<td>2.25</td>
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<tr>
<td>1.75</td>
<td>-1.30</td>
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<td>1.50</td>
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<td>1.25</td>
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<td>1.00</td>
<td>-9.99</td>
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<tr>
<td>0.75</td>
<td>-25.37</td>
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<tr>
<td>0.50</td>
<td>-38.50</td>
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</table>

Figure 2: Graph of Measurement Data
## D. EQUIPMENT USED IN MEASUREMENTS

<table>
<thead>
<tr>
<th>Reference</th>
<th>Type of Equipment</th>
<th>Model Number</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>DC power supply</td>
<td>LA-200</td>
<td>Lambda</td>
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<tr>
<td>B</td>
<td>function generator</td>
<td>HP8516A</td>
<td>Hewlett Packard</td>
</tr>
<tr>
<td>C</td>
<td>adjustable DC power supply</td>
<td>PAB 25-ITR</td>
<td>Kikusui</td>
</tr>
<tr>
<td>D</td>
<td>adjustable attenuator set</td>
<td>HP8494B, HP8496B</td>
<td>Hewlett Packard</td>
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<tr>
<td>E</td>
<td>signal generator</td>
<td>HP83732A</td>
<td>Hewlett Packard</td>
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<td>F</td>
<td>DC power supply</td>
<td>LA-200</td>
<td>Lambda</td>
</tr>
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<td>Tektronix</td>
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<td>spectrum analyzer</td>
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<td>I</td>
<td>RF power meter</td>
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<td>Hewlett Packard</td>
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<td>J</td>
<td>network analyzer</td>
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<td>Hewlett Packard</td>
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