# Design and Characterization of a Low Cost ISM-Band Sub Carrier Multiplexed Broadband Digital Microwave Radio Link

Nikholas Toledo, Christopher Gerald Santos, Alvin Manlapat, Bienvenido Galang Jr., Azaleah Amina Chio, Ian Wong, Rolando Guevarra and Dr. Delfin Jay Sabido IX

Advanced Science & Technology Institute, Department of Science and Technology, A.S.T.I. Bldg., C.P. Garcia Ave., University of the Philippines Technopark, Diliman, Quezon City, 1101 Philippines

*Abstract* — **This paper describes the design, construction and characterization of a subcarrier multiplexed broadband digital microwave radio link with Viterbi error control coding. The design and construction of the RF and microwave devices are described and analyzed. A key point of the research is that low cost materials could be used to implement a broadband wireless link. The effect of error control coding on the system is analyzed and bit error rate measurements were performed. Adjacent channel interference (ACI) measurements were also performed to assess the performance of the link in the presence of an adjacent carrier.**

## I. Introduction

The major advantage of a wireless infrastructure is that it provides services to locations where direct cable installation is impractical because of distance or location. For example, the Philippines, being an archipelago, has always had difficulties in building an extensive wired communications infrastructure. It is therefore more suitable to establish a wireless infrastructure that is capable of bringing communications services to areas unreachable by cable [1]. Other advantages of the wireless approach are the ability for rapid deployment, mobility and accessibility [1], [2].

In order to achieve the high bit rates and multiple accesses required for broadband, several techniques have been proposed like TDMA, FDMA, and CDMA (for examples, see [3], [4]). Subcarrier Multiplexing (SCM) will be shown as a cost-effective and viable alternative wireless link for broadband service. The researchers earlier demonstrated an analog SCM microwave link for a two-channel video transmission. It was shown that SCM is relatively simple and can be built with low-cost, off-the-shelf components [5]. The system was then modified to include a data transmission channel. The authors have chosen to focus on the RF circuit design and the effects of error control coding (ECC) and adjacent channel interference (ACI) on the overall system performance.

The novelty of this project lies in the design and characterization of a working ISM band radio link using low-cost materials. This paper hopes to encourage other communications research agencies that have veered away from microwave research because of the cost of designing traditional microwave systems which are normally built on alumina and high–K materials. This paper also presents a practical working wireless system integrated from principles of microwave circuit design [6]-[9], digital modulation [3], [10] and error control coding [11], [12].

This paper shall initially discuss the design and development of each module of the system. After which, the system integration results are presented, and the results of the bit error rate tests are shown. Finally, the ongoing improvements to the current system are presented.

## II. SYSTEM DESIGN AND DEVELOPMENT

Shown in Fig. 1 is the block diagram of the wireless digital microwave radio link test setup used by the researchers. The SCM system has a center frequency of 2.375 GHz, a bandwidth of 104 MHz, and a transmit power of less than 1W. It is composed of the RF subsystem, baseband modulation-demodulation subsystem, and the error control subsystem.

### *A. RF Subsystem*

In the transmitter, a 70 MHz Binary Phase Shift Keying (BPSK) signal is upconverted to 2.439 GHz. This is then selectively amplified using a cascaded 22 dB broadband amplifier circuit, a $5^{th}$ order hairpin resonator filter and a power amplifier. The amplifier chips both amplify the signal and compensate for the large filter insertion loss as the circuit was built on cheap FR4 laminate.

The transmitted signal is then sent to a splash feed antenna [8] and a dish reflector. A similar dish antenna for the receiver is placed 3m away. A 40 dB attenuator is added immediately after the receiver dish to simulate a 300 m transmission assuming the link is governed only by the Friis free-space transmission loss.

At the receiver, the signal is amplified by a low noise amplifier (LNA) cascaded with an amplifier filter

Acknowledgement is due to the Department of Science and Technology- Grant In Aid (DOST-GIA) program for partially funding this project and to the Communications Engineering Laboratory of the University of the Philippines' Department of Electrical and Electronics Engineering for lending some of their equipment.

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

board similar to that of the transmitter's. The microwave signal is then downconverted to the 70 MHz IF, filtered using a 5th order Butterworth band pass filter and amplified using an MMIC chip. A directional bridge was used to sample the signal prior to demodulation. The test signal is split into two and analyzed using a Spectrum Analyzer and a Vector Signal Analyzer.

*B. Baseband*

The modulation scheme used is BPSK whose baseband signal is expressed by:

$$S(t) = g(t)cos\left[2pf_c t + 2ð\,\frac{m-1}{M}\right], 0 \le m \le M, 0 \le t \le T \quad (1)$$

where $g(t)$ is the pulse shape of the signal and $M=2$ for BPSK. The advantage of using BPSK is that it has a constant envelope, which eliminates the need for an equalizer whose complexity and cost increases as you increase the data rate [13]. However, it has the disadvantage of consuming more bandwidth due to spectral regrowth [14].

The baseband processing system is a simple BPSK modem wherein a Vector Signal Generator (VSG) and mixer act as modulator and demodulator, respectively. The IF LO was tapped from the VSG to simulate a carrier recovery circuit. The demodulated signal is then low-pass filtered. High-speed comparators convert the bipolar signal into TTL levels.

*C. Error Control subsystem*

Convolutional codes have been proven to be most suitable for random errors in radio channels normally attributed to Additive White Gaussian Noise (AWGN). The most widely used convolutional decoding algorithm is the Viterbi decoder. Terrestrial radio channels, however, have impairments other than AWGN such as multipath fading and atmospheric noise, which make errors bursty in nature. Viterbi decoding is still useful for these types of errors, but it is not the optimal method [15]. The researchers initially implemented the Viterbi decoding algorithm for this system, but will eventually explore more optimal coding schemes.

A Viterbi codec (code rate of ½ and constraint length of 3) was implemented in a commercial field-programmable gate array (FPGA) [16].

## III. SYSTEM CHARACTERIZATION AND RESULTS

*A. Component Characteristics*

The following circuit components were designed and implemented using low cost, off-the shelf components.

1. Low Noise Amplifier (LNA)

The LNA module is designed around an HBFP 0420 NPN silicon transistor. The LNA is designed to have an optimum noise figure (NF) of 1.25 dB and a theoretical gain of 14 dB. The constructed LNA has a measured NF of 1.68 dB and a gain of 12.8 dB at 2.375 GHz. The difference between the theoretical and actual noise figure and gain is due to the tradeoff in the VSWR requirement [17].

2. Hairpin Filter

Using [6] and Agilent ADS [18], empirical data for a range of resonator spacing was obtained to record the coupling coefficient and loaded Q, which is then used to synthesize the hairpin filter. A 3 dB bandwidth of 135 MHz was achieved at the center frequency and 60 dB attenuation was achieved 240 MHz relative to the center. This translates to approximately 5.7% bandwidth and a quality factor of 17.4. The 10 dB insertion loss was compensated using a monolithic amplifier.

3. Wilkinson Power Combiner

The Wilkinson power combiner is designed at 2.2 GHz using low-cost FR4 laminate and SMA connectors. The power combiner exhibited very low excess loss (0.23 dB). The implemented design is comparable in performance to commercially available power combiners [19].

*B. Bit Error Rate (BER) Testing*

A bit error rate test of the microwave radio link was performed on both the IF and RF link to assess its performance. The link was first tested without error control coding. The transmitter module of a digital transmission analyzer is used to generate a pseudo-random binary sequence with a length of $2^{23}$-1. It is connected to the input of the VSG. The IF signal (VSG output) is then sent to a noise interference test set, which is used to control the $E_b/N_o$. The noise bandwidth is set at 17.3 MHz while the signal filter is set at 70±5 MHz. The output is sent to the BPSK demodulator which is then connected to the digital transmission analyzer's receiver module. This BER vs $E_b/N_o$ test setup is based on [20]. Fig. 2 shows the BER vs $E_b/N_o$ for the IF.

The theoretical curve for BPSK is given by the equation below.

$$P_b = Q\left(\sqrt{2 \times \left(\frac{E_b}{N_o}\right)}\right) \quad (2)$$

This equation was derived from a linear channel model that is acted on by AWGN [15]. The deviation of the BER curve without coding is due to the nonlinear devices used in the system like mixers and amplifiers.

The small implementation margin is a reflection of how good the system's performance is [20].

A similar setup is implemented in the RF link. Fig. 3 shows the BER vs $E_b/N_o$ for the RF. It could be verified from [5] that the current system showed a 3 dB gain from the original system. This could be attributed to the improvement in the RF circuit design. The IF-to-RF upconversion (as seen from Fig. 2 and 3) has a penalty of about 3.55 dB at BER = $10^{-10}$. This is close to the 3 dB estimate of [20].

The performance of the ½ rate Viterbi coder-decoder is also tested using the test setup described above. The resulting BER curves are recorded in both Fig. 2 and 3. The coding gain was obtained by subtracting the $E_b/N_o$ of the measured RF without coding curves to those with coding.

A rough estimate of the theoretical coding gain of the Viterbi decoder with BPSK modulation in an AWGN channel using asymptotic coding gain is given by [12]

$$\tilde{a} = 10log_{10}\left(d_{free} R\right) \quad \text{dB} \qquad (3)$$

The error control block parameters are $R=½$ and $d_{free} = 5$ resulting in a theoretical coding gain of 4 dB. The maximum coding gain is 4.4779 dB at BER=$10^{-6.5779}$ (see Fig. 4). The graph presented in Figure 4 is very close to the theoretical value of the coding gain because other channel impairments may not be observable with this setup due to the close proximity of the antennas. The graph shows that coding gain increases as the BER increases. At very low BER, there is less occurrence of error and therefore smaller coding gain is observed. At some point though, further increase in the BER may trigger the occurrence of burst errors causing the Viterbi error control block to degrade in performance [15].

### *C. Adjacent Channel Interference Measurements*

A second BPSK modulated PRBS signal with internal PRBS frequency of 5.0 MHz is injected in the radio link along with the 70 MHz digital signal. The second signal's center frequency is set at 74.7 MHz. It can be verified from the spectrum analyzer that the main spectral lobes of both signals barely touch each other; thus, simulating a zero guard band condition. This set up is used to analyze the adjacent channel interference between subcarrier channels within an SCM radio link. Both signals have the same IF power. The noise interference test set's filter bandwidth is increased 40 MHz (70±20 MHz setting activated) so that the $E_b/N_o$ can be controlled for both channels. The difference between the single channel and two channel BER curves is the measure of the power penalty due to adjacent channel interference.

The power penalty can be attributed to the fact that BPSK modulation exhibits phase inversion that causes its spectrum to spread and interfere with the adjacent channels [14]. It can be observed from Figure 5 that the power penalty increases as the required BER is decreased. This is expected since a higher $E_b/N_o$ is necessary for the receiver-demodulator to increase its probability of successfully regenerating the correct bit sequence in the presence of an interfering channel. An approximate RF power penalty of 1.65 dB was obtained at BER = $10^{-5}$.

It has been shown that the presence of another channel creates a power penalty requirement to the channel of interest. A similar study has been done in lightwave WDM systems and similar results were observed [21]. The required guard band can be found by moving the 2nd signal's center frequency until the power penalty approaches tolerable levels. Better performance can be achieved by using pulse-shaping filters.

## IV. ONGOING IMPROVEMENTS

An RF transceiver for a 4-channel SCM link will be operational by June 2001. Two video channels (channels 3 and 6) and two data channels (E1 rate at 70 and 140 MHz) will be transmitted over a 2.4 GHz radio link at a minimum forecasted distance of 3 km.

A DSP-based π/4 DQPSK baseband modem is also currently being developed to evaluate its performance at the 2.4 GHz SCM radio link.

More powerful error control codes like the Reed-Solomon-Viterbi concatenated code and the Turbo codes are also being investigated.

## V. CONCLUSION

This project was able to verify that the subcarrier multiplexing technique is possible in the transmission of digital broadband signals over a 2.375 GHz wireless link using low-cost materials. The project demonstrates a very promising technique of distributing broadband signals especially in areas that do not have a wired infrastructure. The SCM system was shown to be robust in terms of BER measurements and adjacent channel interference. The Viterbi coder was also shown to provide an additional 4 dB gain in the link. The SCM 2.4 GHz link's power penalty due to ACI was measured to be 1.65 dB at a BER of $10^{-5}$.

## REFERENCES


[1] W. Honcharenko, J. Kruys, D. Lee, and N. Shah, "Broadband Wireless Access," *IEEE Communications Magazine*, pp. 20-26, Jan. 1997.

[2] S. Ohmori, Y. Yamao, and N. Nakajima, "The Future Generations of Mobile Communications Based on Broadband Access Technologies," *IEEE Communications Magazine*, pp. 134-142, Dec. 2000.

[3] K. Feher, *Wireless Digital Communications*. New Jersey: Prentice Hall, 1995.
[4] G. W. Wornell, "Spread-Signature CDMA-Efficient Multi-User Communications in the Presence of Fading," *IEEE Trans. Info. Theory*, vol. 41, no. 5, pp. 1418-38, Sept. 1995.
[5] R. Guevarra and D. J. Sabido IX. "Design and Characterization of a Broadband Subcarrier Multiplexed 2.375 GHz Wireless Link," presented at *Asian Mobile Computing Conf.*, Penang, Malaysia, Nov. 2000.
[6] G. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*. Boston, MA: Artech House, 1980.
[7] ARRL, Ed., *The ARRL UHF/Microwave Experimenter's Manual*. CT: ARRL, 1990.
[8] ARRL, Ed. *The ARRL UHF/Microwave Projects Manual*. CT: ARRL, 1994.
[9] G. Gonzalez, *Microwave Transistor Amplifiers: Analysis and Design*, 2nd ed. NJ: Prentice-Hall, 1996.
[10] J. Y. C. Cheah, *Practical Wireless Data Modem Design*. Boston, MA: Artech House, 1999.
[11] S. B. Wicker, *Error Control Systems for Digital Communication and Storage*. N.J.: Prentice Hall, 1995.
[12] R. Johannesson and K. S. Zigangirov, *Fundamentals of Convolutional Coding*. NY: IEEE, Inc, 1999.
[13] J. Lu, T. T. Tjhung, F. Adachi and C. L. Huang, "BER Performance of OFDM-MDPSK System in Frequency-Selective Rician Fading with Diversity Reception," *IEEE Trans. Vehic. Technol*. vol. 49, no. 4, pp. 1216-1225, Jul. 2000.
[14] L. E. Larson, Ed., *RF and Microwave Circuit Design for Wireless Communications*, Boston, MA: Artech House, 1996.
[15] S. G. Wilson, *Digital Modulation and Coding*. N.J.: Prentice-Hall, 1996.
[16] A. A. Chio and M. M. Tabangcura. "A Comparizon of Implementing a Convolutional Error-Correcting Coder-Decoder as an ASIC and an FPGA." presented at *HDLCon*, Sta. Clara, California, 2001.
[17] N. G. Toledo, "Design of an X-band Low Noise Amplifier." presented at *1st National ECE Conference*, Manila, Philippines, 2000.
[18] *Advanced Design System*, Agilent Eesof EDA, 1999.
[19] R. Guevarra, "Design and Construction of a Broadband Wilkinson Power Divider/Combiner," presented at *1st National ECE Conference*, Manila, Philippines, 2000.
[20] Hewlett-Packard, *Digital Radio Theory and Measurements*. Application Note 355A.
[21] K.P. Ho and S.K. Liaw, "Demultiplexer Crosstalk Rejection Requirements for Hybrid WDM System with Analog and Digital Channels," *IEEE Photonics Technol. Lett.*, vol. 10, no. 5, pp. 737-739, May 1998.

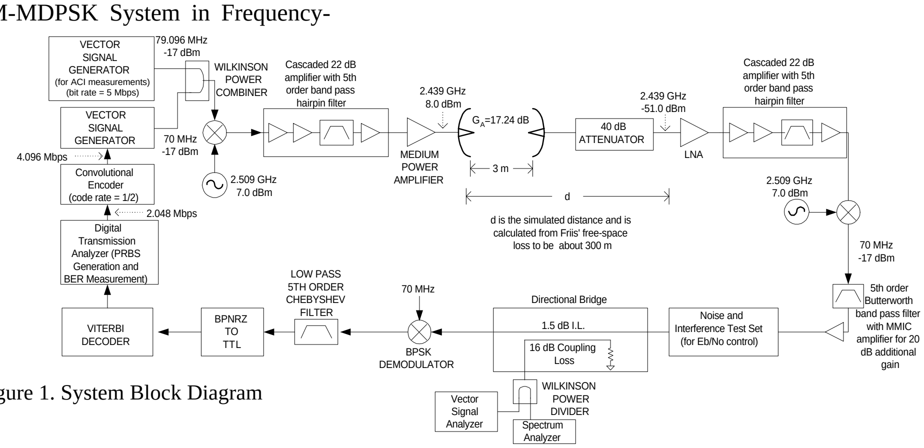


Figure 1. System Block Diagram

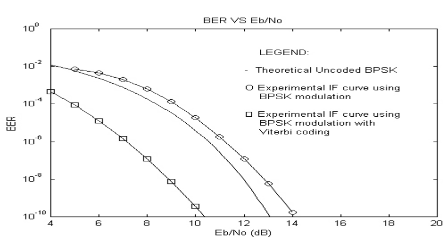


Figure 2. BER curve for IF back to back

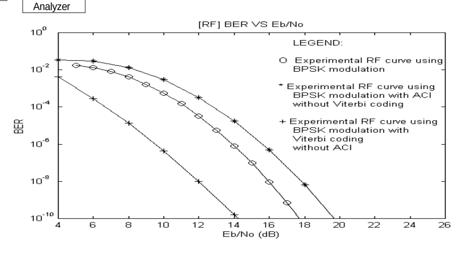


Figure 3. BER curve for RF back to back

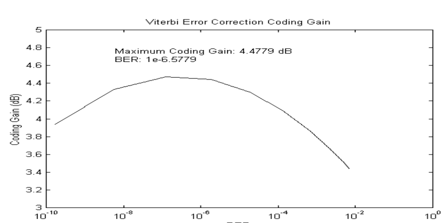


Figure 4. Viterbi Coding Gain

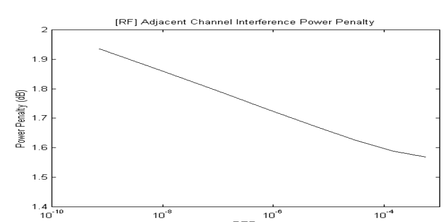


Figure 5. Adj. Channel Interference Power Penalty