Summer 2011

Simulink as a tool for modelling communication systems

Chaitri Avinash Aroskar

SIMULINK AS A TOOL FOR MODELLING COMMUNICATION SYSTEMS

by

CHAITRI AVINASH AROSKAR

A THESIS

Presented to the faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In partial fulfillment of the requirements for the degree

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

2011

Approved by

Dr. Yahong Rosa Zheng, Advisor
Dr. Kurt Kosbar
Dr. Sahra Sedigh Sarvestani

PUBLICATION THESIS OPTION

This thesis consists of the following two articles that have been submitted for publication as follows:

Pages 1 - 17 are "Design of Simulink Projects for an Undergraduate Communications Course" presented at the ASEE Annual Conference & Exposition, Vancouver, Canada, June 2011.

Pages 18 - 34 are "Cross-Layer Approaches to Wireless Communications and Networking," presented at the ISC Research Symposium, Rolla, Missouri, April 2010.

ABSTRACT

Simulink is a graphical tool provided by MathWorks to enable model-based design and simulation. This thesis consists of two papers which take advantage of Simulink features in order to model communication systems.

The first paper employs Simulink to create projects to supplement a purely lecture oriented course: Communication Systems I. The projects cover Linear systems, Analog modulation and Digital modulation concepts in a set of six projects. These projects have been designed based on Gagne's nine events of instruction to enhance their impact on students' learning process. The paper also outlines the advantages of this approach over the conventional programming or hardware based laboratories used in some universities.

The second paper describes enhancements made to an existing Bluetooth communication model in Simulink. The original model is corrected by changing the original BER meter and then modified by incorporating Rayleigh fading channels and multiple slaves. The effect of fading on the Bluetooth communication protocol is studied with ease.

ACKNOWLEDGEMENTS

"You are what your deep driving desire is,

As your desire is, so is your will,

As your will is, so is your deed,

As your deed is, so is your destiny."

- Brihadaranyaka Upanishad IV 4.5

This quotation summarizes the attitudes of both, me and my advisor, Dr. Zheng. We share the belief that a strong desire and dedication to achieve one's goal are often the sole factors affecting the outcome, and in the long term one's destiny. I express my sincere thanks to Dr.Zheng, as her guidance and motivation have been an indispensable part of my research work.

I'd also like to thank Dr. Kosbar and Dr. Sedigh Sarvestani for serving as my committee members and for their thoughtful insights. The courses I took with them have also proven helpful towards my research. The staff and faculty at Missouri University of Science and Technology, has been fabulous and I acknowledge the fact that many of them have contributed to this research thesis directly or indirectly. This work is supported by the NSF CAREER grant #ECCS-0846486 and Intelligent Systems Center. Also, I appreciate my friends and lab mates who have been supportive of me and have helped me along my Masters journey.

Finally, my deepest gratitude to my parents, who have taught me the courage and perseverance necessary to pursue my dreams. They have been my pillars of strength throughout my life and I owe all my achievements to them.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure Page

PAPER I

PAPER II

LIST OF TABLES

PAPER I

I. Design of Simulink Projects for an Undergraduate Communications Course

Abstract

This paper describes a set of six Simulink based laboratory projects designed for a junior level undergraduate communications course. The course is traditionally a lecture course with no laboratory component. The authors aim to add a laboratory component to the course to help students to better understand and analyze the theory taught in lectures. The laboratory component is structured by following effective teaching strategies which aids reinforcement and retention of information.

1. Background and Motivation

An introductory communications course is the essential foundation to learn advanced communications topics. At Missouri University of Science and Technology, the Electrical and Computer Engineering (ECE) department offers a junior level undergraduate course: Communication Systems I. The course is presently a three hour lecture course with no laboratory component. As a first course in the communication series, it covers a review of linear systems and introduces analog communication systems as well as digital baseband communication systems. The course, first reviews important concepts of Fourier series, Fourier transforms, power spectral density and linear systems which students have learnt in their preliminary courses. Next, the students are introduced to basic analog modulation techniques of Amplitude Modulation (AM), Frequency Modulation (FM) and Phase Modulation (PM) along with feedback demodulators. They are also taught pulse modulation, digital signaling and multiplexing. Then, they are introduced to digital baseband transmission which covers the topics of line codes, pulse shaping, Inter-Symbol Interference (ISI), Zero Forcing (ZF) Equalizer and synchronization. This course structure is meant to provide students with a solid foundation for advanced courses such as Communication Systems II, Communication Circuits, and Wireless Communications.

The lecture approach to teaching communication courses can be intimidating for many students because of the heavy theoretical and mathematical content, compounded by the lack of visual aids. The students find the aforementioned concepts difficult to grasp with block diagrams alone. The complexity increases as the course progresses and the authors wanted to help students cope with the complex theory without reducing the standard of the course content. Empirical studies advocate the need for innovative techniques to help students grasp the course material[1,2,3]. A number of course developments implement MATLAB based projects to simulate theoretical concepts[4,5,6,7]. Although the textbook[8] provides MATLAB examples and exercises in the form of script files, previous offerings of the course have found that the lecture-only format does not lend itself to teaching simulation. Besides, more than 50% of the students are not ready for the extensive MATLAB required by this approach.

The authors hence decided to supplement the traditional lectures with hands on simulation experience using a model based Simulink approach. Simulink is a graphical environment provided by MathWorks to enable model-based design and simulation. It provides an extensive set of pre-defined blocks for modeling continuous-time or discrete-time systems or a hybrid of the two. It is an easy tool for beginners since, once the user has conceived a system, it can be built into a model by a simple drag, drop and connecting of blocks and wires. The models can be organized into modules in a hierarchical manner and display blocks can be used to visualize the results as the simulation runs. The model can be simulated for different parameters and users can learn from a 'what if' approach to such simulation. Simulink is integrated with the MATLAB environment and so the user may also utilize MATLAB features to define inputs, store results for analysis or post processing, or perform functions within a model. Overall, Simulink permits students to bring static representations of communication systems in textbooks to life. Thus, Simulink was chosen as a tool which could be used to make theory tangible.

Thanks to its attractive features, Simulink has been identified as an ideal tool for laboratory projects and has hence been adopted for teaching a variety of courses by many instructors[9,10,11,12,13,14]. For example, in[13,14] digital communication theory is taught by using Simulink exercises. However, none have attempted to introduce Simulink for teaching analog communication theory in core level communication courses, where students do not necessarily have a strong programming capability. The benefits of such a laboratory course are twofold. Firstly, students learn simulation, which is widely used by engineers in the industry to verify and validate system designs. Secondly, these laboratory projects have been designed following the Gagne's nine events of instruction[15] which leads to an enhanced learning environment. Also, when compared to hardware based labs, such as with EMONA TIMS[16], Mobile Studio[17] and Ettus USRP[18], Simulink has the advantage of lower cost and ease of maintenance.

2. Simulink Laboratory Projects for Communication Systems Course

Six Simulink laboratory projects are constructed to teach Simulink skills in parallel with the theory. Table 1 enumerates topics covered in the six labs and the Simulink skills gained therein. The first two projects relate to the review of frequency domain analysis and linear system concepts to reinforce previously learnt basics. At this stage, students are introduced to the primary skill of building a model and creating subsystems and masks. The next two projects deal with analog communication systems. Here we introduce students to design techniques such as creating libraries and using model referencing. The last two projects are on digital baseband communication systems. The fifth lab also introduces the Stateflow tool of Simulink to implement complex control logic in Simulink and the sixth lab introduces integration of models with MATLAB scripts as a formative step towards more advanced implementations in Simulink. The projects have been designed with a gradually increasing complexity to provide the necessary confidence boost to students for subsequent projects.

Table 1. Simulink Laboratory Projects

Lab	Topics covered	Simulink skill
I	Frequency Domain Analysis	Building a Model
II	Linear Systems	Subsystems & Masks
III	Amplitude Modulation	Library Building
IV	Frequency & Phase Modulation	Model Referencing
V	Pulse Code Modulation & Line Codes	Using Stateflow
VI	Zero Forcing Equalizer	Interacting with MATLAB

In this paper we discuss two of the laboratory projects. Firstly, we discuss Lab III (AM lab) and how it implements the features of Simulink outlined earlier. This lab is split into two parts, one to implement the modulation techniques and one to implement the demodulation techniques. Typically, the equation for an AM signal is given by,

$$x_c(t) = A_c \, [\, A + a \, m(t) \,] \cos(2 \, \pi \, f_c \, t) \tag{1}$$

where, A_c is the amplitude of the unmodulated carrier wave $A_c\cos(2 \, \pi \, f_c \, t)$, m(t) is the message signal, a is the modulation index and A is the DC bias. The inclusion of a DC bias results in the carrier component to be included in the AM signal. Further, the Double Sideband (DSB) modulation and Single Sideband (SSB) modulation are variations of AM itself. DSB can be achieved by simply multiplying the carrier with the message signal.

$$x_c(t) = A_c \, m(t) \cos(2 \, \pi \, f_c \, t) \tag{2}$$

The SSB signal can be generated from the DSB output by the method of sideband filtering. The illustration in Fig.1 shows a complete model of the modulation half of the lab. It includes a scope for visual comparison of the modulation techniques. As can be seen from the figure the model is a direct translation of the equations into an intuitive assembly of blocks. All the blocks have been taken from the variety of block libraries available in Simulink.

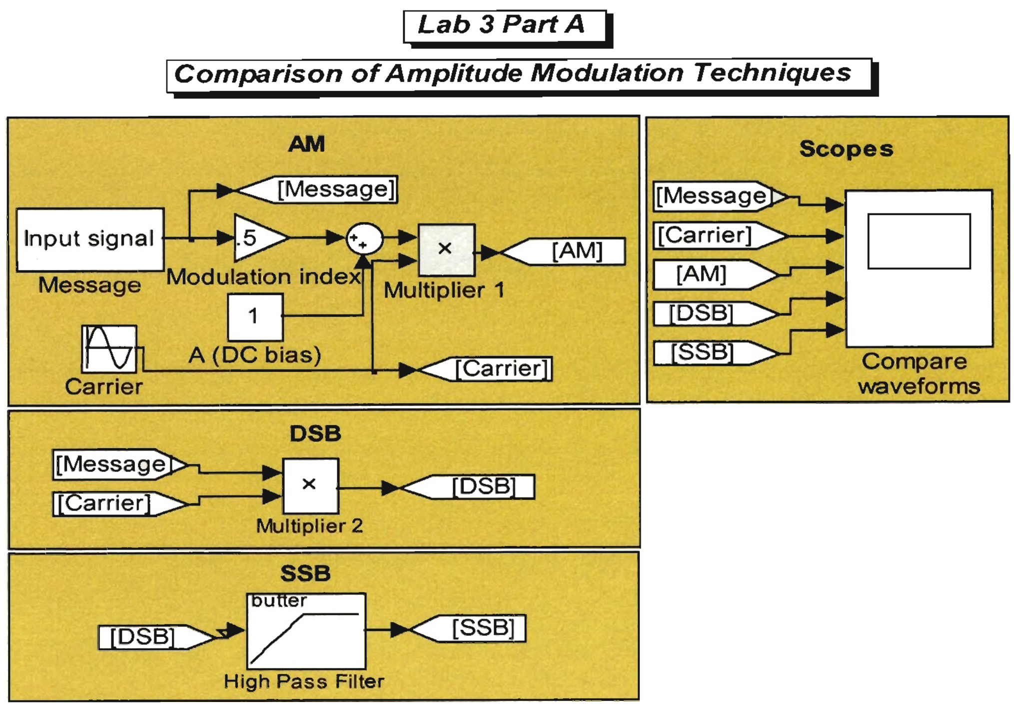

Fig. 1 Intuitive assembly of blocks for amplitude modulation lab

The above model can be better organized by making subsystems for the individual modulation techniques and then combining them to form an AM techniques subsystem.

This is an example of a two level hierarchy being designed in a bottom-up manner. Similarly, a top-down design is possible by making empty subsystems and entering constituent blocks into them individually. Fig.2 shows the final hierarchical model. The amplitude modulator can now be stored in a library to be used for other model designs, for example in the other half of this lab, AM demodulation techniques. In Fig.3 we see the compact design of the AM demodulation techniques is made possible by the hierarchical design feature of Simulink.

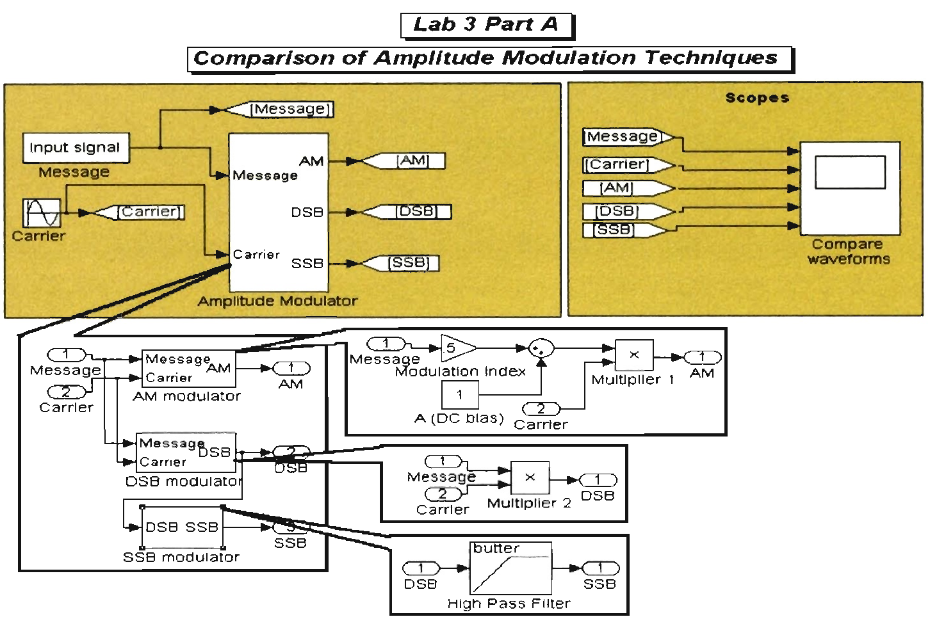

Fig. 2 Hierarchical design of amplitude modulation lab

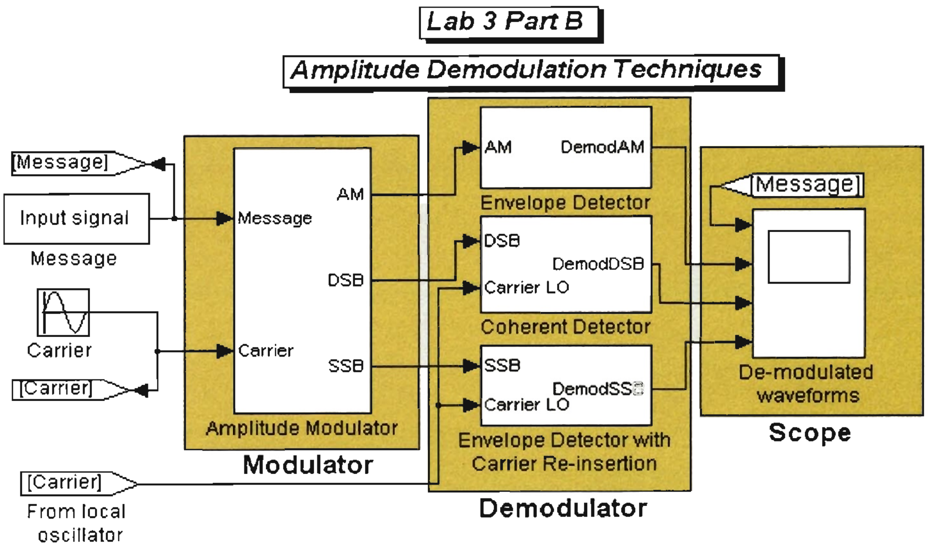

Fig. 3 Modularized AM demodulation lab

By playing around with different parameters and settings, the students can satiate their curiosity about what happens when a certain parameter in an equation is changed or a block from a block diagram is omitted. Such an interactive interface allows the students to learn from a 'what if' approach. One of the post-lab questions asks students to vary the modulation index in order to observe over-modulation and check if correct demodulation is possible.

The second lab discussed in this paper is the final lab project on ZF equalizer. The objective of this project is to let students implement a multi-tap ZF equalizer and to learn to incorporate MATLAB scripts into Simulink to make the models more attractive. The MATLAB required here is not as extensive as required for building the complete models using MATLAB programming.

An N-tap ZF equalizer is a filter designed to accept a channel output response affected by ISI and produce an output pulse of value one with $\frac{(N-1)}{2}$ zero values samples on either side. Let the channel coefficients constitute the matrix P_c and the desired equalizer output constitute the matrix P_{eq}. The equalizer coefficient matrix C can be found as:

$$C = [P_c]^{-1} [P_{eq}] \tag{3}$$

As a pre-lab task students are asked to find the equalizer weights when given the channel coefficients as [-0.05 0.2 1 0.3 -0.07] and [-0.05 0.2 -0.1 0.3 -0.07].

An eye diagram is a good visual representation of the system performance. It is constructed by plotting segments of a digitally modulated baseband signal, typically two symbol periods in length, so that the segments overlap. The optimal sampling time for a receiver is when the eye is most open. A ZF equalizer's performance can be gauged using an eye diagram since an eye will be more closed due to presence of ISI and the ZF equalizer's job is to minimize ISI and maximize the eye opening. Thus, this lab uses eye diagrams to view results.

In the specimen solution discussed here, we modulate a string of binary data using Binary Phase Shift Keying (BPSK) modulation and then pass it through the specified channel and Additive White Gaussian Noise (AWGN). The received signal is equalized by finding the equalizer weights for a three-tap ZF equalizer and implementing them. The result of equalization is observed using an eye diagram. By implementing this lab students are able to verify their answers obtained in the pre-lab task. The complete Simulink model for this lab is given in Fig.4.

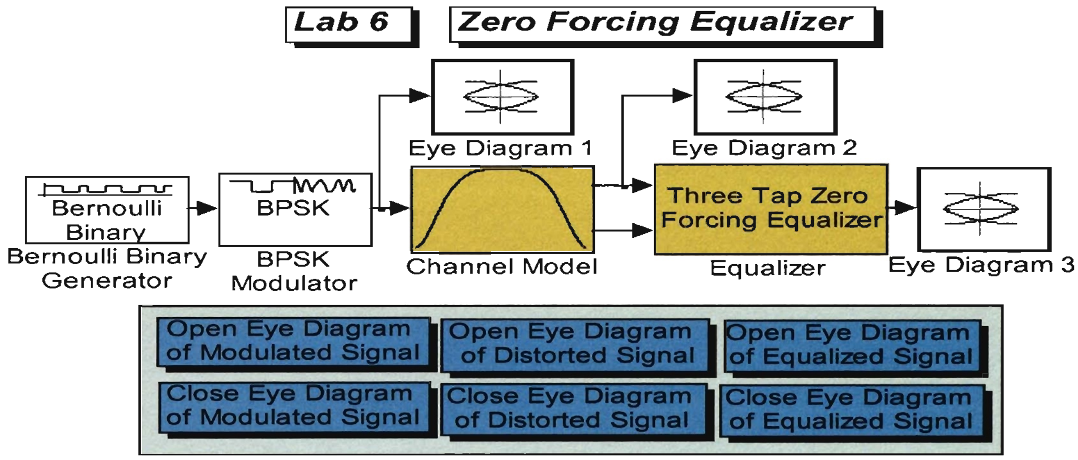

Fig. 4 Top level template for ZF equalizer lab

In this model, the binary stream and the BPSK modulator and demodulator blocks are taken from Simulink's Communications blockset library. The channel and ZF equalizer are user defined subsystems. The channel is constructed using a filter with the given channel coefficients followed by an AWGN block while the ZF equalizer is constructed using a MATLAB function block followed by the equalizing filter. The computation of the equalizer coefficients is done using a MATLAB function block and then the result is passed to the equalizing filter. The implementation of both the subsystems is seen in Fig.5.

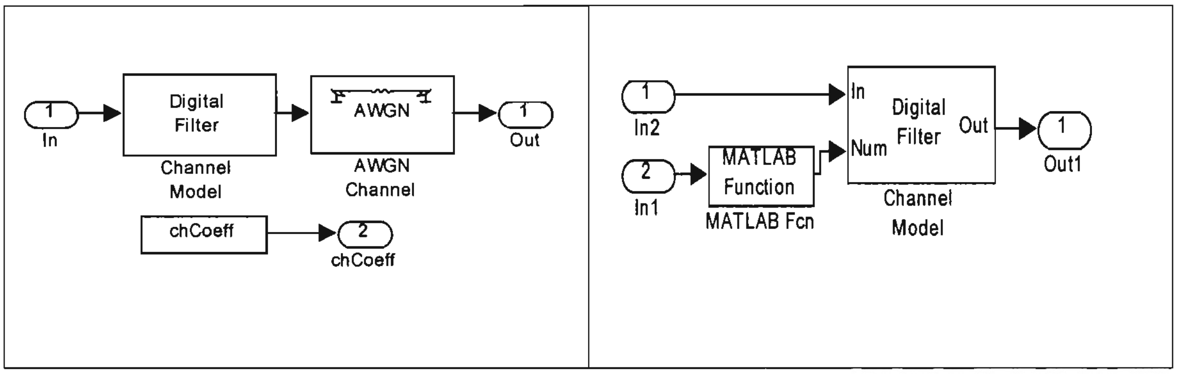

Fig. 5 Channel and ZF equalizer subsystems

Fig. 6 depicts eye diagrams for the distorted signal before and after the equalization stage. The AWGN distortion effect has been kept to a minimal value. As can be seen from the eye diagrams, for the first set of channel coefficients, a three tap equalizer can improve the performance against ISI whereas for the other set of channel coefficients, the degradation caused by ISI is so severe that the eye closes and the equalizer fails to rectify it. By increasing the number of taps, students can see that a better performance can be achieved even for the second set of channel coefficients. An extension of this lab involves studying the effect of using pulse shaping filters along with ZF equalizer to combat ISI.

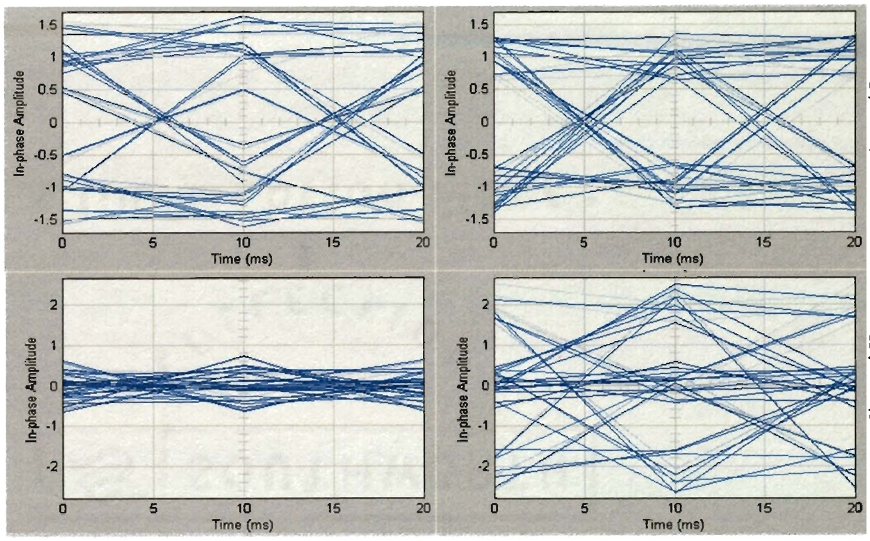

Fig. 6 Eye diagrams for two sets of channel coefficients

The scope buttons at the bottom are designed to open or close the scopes during simulation. They all are masked subsystems, which is a Simulink skill introduced in the second lab. The button functionality is implemented by using a MATLAB script. As can be seen this skill is essential for introducing additional functionalities to the model.

3. Pedagogical Consideration

Effective teaching and learning models demand an organized approach to the classroom teaching[15,19,20]. In 1977, Gagne provided an instructional model with focused learning outcomes[15]. The Gagne's nine levels of instruction are enumerated in Table 2 along with their corresponding learning outcomes. The six Simulink projects are created and will be implemented in the classroom following Gagne's model. Overall, conforming to this model of instruction facilitates a pedagogically rich learning environment.

Table 2. Gagne's nine events of instruction

Event	Instructional event	Learning outcome
1	Gaining Attention	Reception
2	Informing Learners of the Objective	Expectancy
3	Stimulating Recall of Prior Knowledge	Retrieval to Working Memory
4	Presenting a Stimulus	Clear Perception
5	Providing Learning Guidance	Semantic Encoding
6	Eliciting Performance	Responding
7	Providing Feedback	Reinforcement
8	Assessing Performance	Reinforcement
9	Enhancing Retention	Cueing Retrieval

Gaining attention: A brief introduction to Simulink and its benefits along with attractive demos capture the attention of the students. A demo exhibits the potential of the new technique and hence makes the students want to focus and concentrate on the matter that is to follow.

Informing learners of the objectives: Learning objectives are clearly specified at the beginning of each project instruction. For example, the AM lab outlines learning objectives as simulating amplitude modulation techniques and learning to build libraries in Simulink.

Stimulating recall of prior knowledge: Lectures on theoretical concepts are given prior to each project. Pre-lab reading and questions are also assigned and they are required to be submitted at the beginning of each project. Also, each lab includes practice of Simulink skills learnt in previous lab projects.

Presenting a stimulus: The objectives outlined in every project instruction, coupled with clear step by step procedures provide students with a direction and the necessary stimulus to perform the task.

Providing learning guidance: Every project instruction begins with an example of the Simulink skill to be learnt. Sample outputs and theoretical results are provided to students for comparison with the Simulink generated results. The use of a Teaching Assistant (TA) to assist in lab sessions and outside the classroom Learning Enhancement Across Disciplines (LEAD) program reduces student to instructor ratio and improves student-teacher interaction.

Eliciting performance: Desired performance is elicited by designing a grading policy which requires projects to be performed in teams of two where individual members have different roles. Peer rating is used to assign individual grades. Bonus points are awarded for outstanding performance.

Providing feedback and Assessing Performance: In each lab session, students can try varying block parameters and simulate the system to get an immediate feedback on their understanding of the concept. Moreover mistakes made in a simulation will give instantaneous feedback. The post-lab questions after each session provide a feedback on their progress towards the learning objectives of the course. The lab reports are promptly graded and returned to the students along with lab-critiques which address various factors associated with understanding the material. Thus, the students receive an elaborate and informative feedback on their performance.

Enhancing retention: Each project utilizes some basic concept learnt in an earlier project or lecture. For example, the ZF equalizer lab uses the subsystem and masking skill learnt in the AM lab. This repeated use of prior knowledge to build projects helps students retain information.

4. Evaluation

These laboratory projects are ready to be tested and will be implemented in class during Spring2011. Planned assessment tools are entry, mid-term and exit surveys, to understand how the students are coping with the introduction of a lab component. Also, students are asked to list the difficulties faced by them during the projects, in their lab reports, thus providing regular feedback on individual projects. Data will be collected and analyzed to ascertain the effectiveness of this approach. It will be compared to the data from previous lecture only offerings of the course. The projects will be further refined over upcoming semesters by incorporating feedback obtained from the students. We anticipate these Simulink projects to transform the dry theory into vivid illustrations and thus increase retention and stimulate students' interest.

5. Summary

In summary, this paper introduces the benefits of Simulink to teaching a communications course. Six Simulink laboratory projects are discussed in brief. Also, the implementation of effective teaching methods with this laboratory course is explained. Therefore, a twofold benefit of ingrained fundamentals and an enhanced simulation skill set is achieved with the proposed course.

6. Acknowledgements

This work is supported by the NSF CAREER grant #ECCS-0846486.

7. References

[1] B.Keys, "The Management of Learning Grid for Management Development," *Academy of Management Review*, pp. 289-297, April 1977

[2] R. Saint-Nom, "Advertise Your A/D Converter, a SP Teaching Strategy," *Proceedings ICASSP 2010*, pp. 2930-2933, March 2010.

[3] B. Erwin, M. Cyr and C. Rogers, "LEGO Engineer and RoboLab: Teaching Engineering with LabVIEW from Kindergarten to Graduate School," *International Journal of Engineering Education Vol.16 No.3*, TEMPUS Publications, Great Britain, pp. 181-192, 2000.

[4] Y. Zhang, "The Application of MATLAB to Teaching Communication Systems," *Proceedings 2009 ASEE Annual Conference & Exposition*, June 2009.

[5] M. Ostendorf, J. Bowen and A. Margolis, "Freshman Design: A Signal-Processing Approach," *Proceedings ICASSP 2009*, pp. 2325-2328, April 2009.

[6] C.T. Merkel, " A MATLAB-Based Teaching Tool for Digital Logic," *Proceedings 2004 ASEE Annual Conference & Exposition*, June 2004.

[7] S. Wentworth, D. Silage, M. Baginski, "Individualized Matlab Projects in Undergraduate Electromagnetics," *Proceedings 2010 ASEE Annual Conference & Exposition*, June 2010.

[8] R.E. Ziemer and W.H. Tranter, *Principles of Communication*, Wiley, 2009.

[9] J. Turner and J.P. Hoffbeck, "Putting Theory into Practice with Simulink," *Proceedings 2005 ASEE Annual Conference & Exposition*, June 2005.

[10] J. Klegka and T.E. O'Donovan, "Using Simulink as a Design Tool," *Proceedings 2002 ASEE Annual Conference & Exposition*, June 2002.

[11] K. Ossman, "Teaching State Variable Feedback to Technology Students Using MATLAB and Simulink," *Proceedings 2002 ASEE Annual Conference & Exposition*, June 2002.

[12] J.S. Dalton, D.S. Stutts and R.L. Montgomery, " Mini-Lab Projects in the Undergraduate Classical Controls Course," *Proceedings 2003 ASEE Annual Conference & Exposition*, June 2003.

[13] M. Rice, "*Teaching Digital Communication Theory with Simulink at Brigham Young University*," Matlab Digest: Academic Edition, vol. 3, no. 2, April 2009.

[14] E. Perrins, Lab exercises for EECS 700: Implementation of Digital Communication Systems, URL (retrieved on 12.21.2010): http://people.eecs.ku.edu/~esp/class/F08_700/lab/

[15] R.M. Gagne, *The Conditions of Learning and Theory of Instruction,* Holt, Rinehart and Winston Inc., New York, 1985.

[16] B. Maitipe, Modern communications lab for ECE 5765, URL (retrieved on 12.21.2010): http://www.d.umn.edu/~maiti012/

[17] Rensselaer Polytechnic Institute, Mobile Studio URL (retrieved on 12.21.2010): http://mobilestudio.rpi.edu/Project.aspx

[18] Ettus Research LLC Website URL (retrieved on 12.21.2010): http://www.ettus.com

[19] A.W. Chickering and Z.F. Gamson, "Seven Principles for Good Practice in Undergraduate Education," *American Association for Higher Education Bulletin*, March 1987.

[20] R.E. Slavin, "A Model of Effective Instruction," *The Educational Forum Vol.59*, pp.166-176, 1995.

PAPER

II. CROSS-LAYER APPROACHES TO WIRELESS COMMUNICATIONS AND NETWORKING

Chaitri Aroskar
caa279@mst.edu

Y.R.Zheng
zhengyr@mst.edu

ABSTRACT

The main goal of this paper is to present a tool for modeling communication network architectures. With the advent of Cross-layer design techniques for wireless networks, the conventional modeling tools prove inadequate. Here we use Simulink Matlab to simulate the physical layer and baseband layer of Bluetooth as an example. The use of the same tools can be extended to simulate the physical and link layers of any network standard.

1. INTRODUCTION

The methodology of layered protocol design for communication networks has dominated research of the communications community for the past few decades. The layered design outlines the different layers of networking protocols and their relationship with each other. The traditional approach of designing a network stack has always been to treat the different layers as separate entities. Each layer performs specific operations to achieve an operational network stack with acceptable performance. The TCP/IP [1] is a 5 layered model followed popularly in the communications industry.

However the technical challenges of wireless networks cannot be met with a layered design approach. Cross-layer protocol interactions, when used appropriately, can lead to increased network efficiency and better QoS support [2]. A Cross-Layer Design

(CLD) is particularly important for any network using wireless technologies, since the state of the physical medium can significantly vary over time. Adaptation of the application should be possible based on the underlying channel and network characteristics [2]. A protocol design which does not follow a reference layered communication architecture is considered a CLD with respect to the particular layered architecture.

Recently the CLD approach has attracted great attention since it has made possible many exciting emerging technologies which would not have not have been possible with the traditional layered protocol structure. The increasing interest stems from its potential to provide significant increase in end to end throughput, scalable network performances and satisfactory quality of service [3].

The influence of layered protocol approach has resulted in a significant gap between Simulink and NS2 which are used for PHY-layer and MAC-layer simulations respectively. This makes cross layer research difficult. Our final goal is to develop a tool that would link the two and enable simulation and performance evaluation of cross layer designs.

Although CLD can involve cooperation and state information sharing between all layers, however we opted to focus on joint design of Physical, MAC and Network layers.

We chose an existing Bluetooth model in Simulink Matlab which simulates the physical and baseband layers of the Bluetooth standard. In Section 2, we give a brief overview of those parts of the Bluetooth standard which are relevant to our simulation model. In Section 3, we discuss the original model. In Section 4, we describe our modeling approach with the original model as a basis. Section 5 describes the evaluation and analysis of simulation results thus obtained. Concluding remarks are offered in Section 6.

2. BLUETOOTH STANDARD

The Bluetooth specification [4], [5] specifies the architecture as consisting of physical layer (PHY), Baseband layer (BB), Link Manager Layer (LM) and Logical Link and Adaptation Protocol (L2CAP) and a Host Controller Interface (HCI).

Bluetooth supports both voice and data transmission. Bluetooth voice transmission is called Synchronous Connection Oriented (SCO) and data transmission is called Asynchronous Connection Less (ACL). This paper presents the simulation results for DM1 (Data Medium rate) packets of ACL transmission.

2.1. Physical Layer

The PHY of Bluetooth operates in the 2.4GHz ISM band. It uses Frequency Hopping Spread Spectrum (FHSS) technique to combat interference from other communication systems operating in the same frequency range. The physical channel is divided into slots of 625μs, each with a new hop frequency. The data undergoes Gaussian Frequency Shift Keying (GFSK) modulation.

2.2. Baseband Layer

The BB provides a point to point or point to multi-point connection between Bluetooth enabled devices. Up to one master and seven slaves can be sharing a single physical channel forming what is referred to as a piconet. The BB protocol provides the basic Automatic Repeat request (ARQ) protocol [1]. The link controller in the BB is responsible for the encoding and decoding of packets from the data payload and parameters related to the physical channel, logical transport and logical link.

2.3. Link Manager and L2CAP Layers

The LM controls and negotiates all aspects of link setup between devices. The L2CAP provides services to higher level applications.

2.4. Data Transmission

Data transmission differs from voice transmission in one essential fact that no errors are allowed. If an error is detected the packet is required to be retransmitted. In Bluetooth, packets are sent repeatedly by the transmitter until an acknowledgement is received from the receiver notifying that the packet was received error free. The incoming packets are tested for Cyclic Redundancy Check (CRC) [6] to determine correct reception. This is the Automatic Repeat request (ARQ) technique.

There are a variety of ACL packet types available for transmission. Depending on whether the data is Forward Error Correction (FEC) encoded or not the packets can be segregated into data-medium (DM) rate and data-high (DH) rate respectively. The DM1 packet carries information only in a single time slot. The payload can be between 1 to 18 bytes of data plus 16 bits of CRC. The data and the CRC bits of this packet are 2/3 FEC encoded. The DH1 packet is similar to the DM1 packet except that it does not undergo FEC. Thus it can carry 1 to 28 bytes of information plus 16 bits of CRC. Similarly the DM3, DH3 and DM5, DH5 packets occupy 3 and 5 slots respectively and carry more data than the basic single slot packets.

The DM1 packets incorporate FEC in conjunction with CRC to enable the receiver to correct errors in the received packet. The purpose of FEC is to reduce the frequency of retransmissions by correcting the recurring error patterns. Only when an error pattern which cannot be corrected is received does the receiver request for retransmission. The receiver sends acknowledgements back to the transmitter by setting the ARQN status bit in the header info of the return packet. ARQN=1 signifies successful transmission and ARQN=0 signifies unsuccessful transmission.

2.5. Piconet Concept

Piconet by definition is a collection of devices occupying a shared physical channel where one of the devices is the piconet master and the remaining devices are connected to it. Devices in a piconet use a specific frequency hopping pattern, which is algorithmically determined by fields in the device address and the clock of the master.

There is a physical link between each slave and the master. Physical links are not formed directly between the slaves in a piconet. The physical link between a master and a slave device is active if a default ACL logical transport exists between the devices. Upto 7 active slaves and upto 255 parked (inactive) slaves can be accommodated in a single piconet. There is only one single master in one piconet. The master polls the slaves on a per slot basis [4].

3. ORIGINAL BLUETOOTH MODEL

The Simulink Matlab Bluetooth model simulates a full duplex communication link with an acknowledgement scheme. It consists of one master device and one slave device. Each has a pair of transmitter and receiver. Figure 1 shows the overall model.

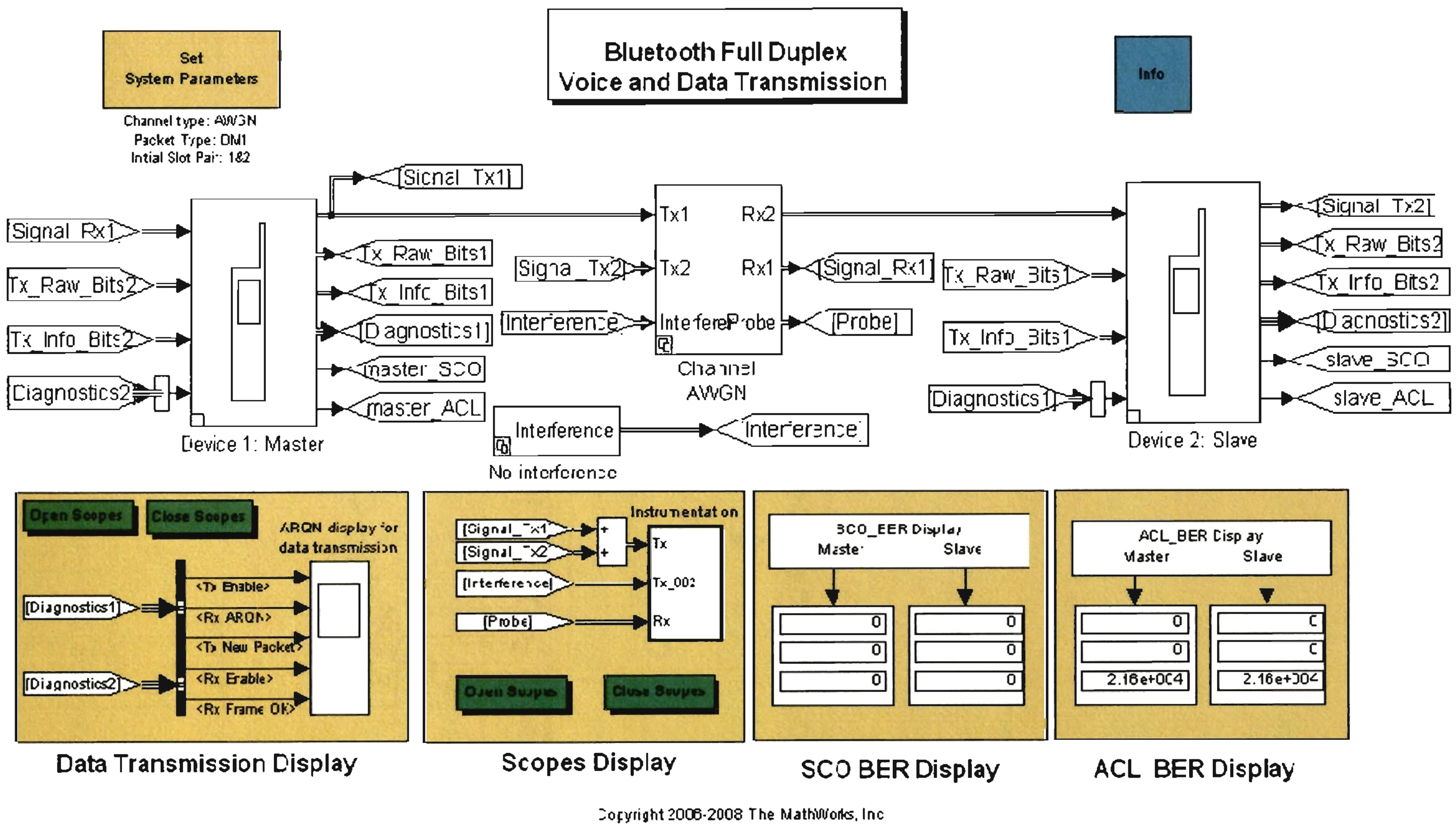

Fig. 1: Bluetooth Full Duplex Transmission Model

Simulink allows for the simulation of PHY and BB layers with the use of common blocks from the Simulink library. However the control logic elements such as the acknowledgement schemes of the logical link of BB cannot be developed using traditional blocks. This control logic is incorporated using Stateflow, which is a finite state machine design tool provided in Simulink [7]. It allows graphic design of states and the transitions between them. The state changes are event driven and are triggered by events in the physical layer.

The model includes a channel block which can be configured to have pure AWGN or AWGN along with interference from a nearby 802.11b device. We shall evaluate the results for the pure AWGN channel which would serve as a reference for further modifications. The model provides displays for Bit Error Rate (BER), channel spectrum, timing diagram and trigger signals, enabling thorough analysis of performance.

Figure 2 zooms in on the pair of transmitter and receiver in one of the devices. Figure 3 shows some of the displays available for visual aid.

For modeling purposes it has been assumed that a connection has already been established between the master and slave and the synchronization process is complete.

3.1. Channel Block

The channel consists of an AWGN block and a Free Space Path Loss (FSPL) block. The AWGN block induces AWGN based on the input signal strength and the FSPL block accounts for the path loss experienced by the signal with varying distance between the master and slave devices. If the channel is configured for presence of 802.11b interference, then a block for the same is also present.

3.2. Transmitter Section

It consists of a transmitter controller block which computes CRC bits from the transmitted data bits and appends them to the payload. There are 144 payload bits and 16 CRC bits constituting the final 160 bits. At the start of every slot the ARQN bit is checked. If the ARQN bit indicates successful transmission for the previous data packet it transmits a new packet, else it retransmits the previous packet. This control logic is constructed with Stateflow diagram. The next block performs FEC on the data. The final block frames the data and includes Header Error Correction (HEC) and then transmits the data onto the channel.

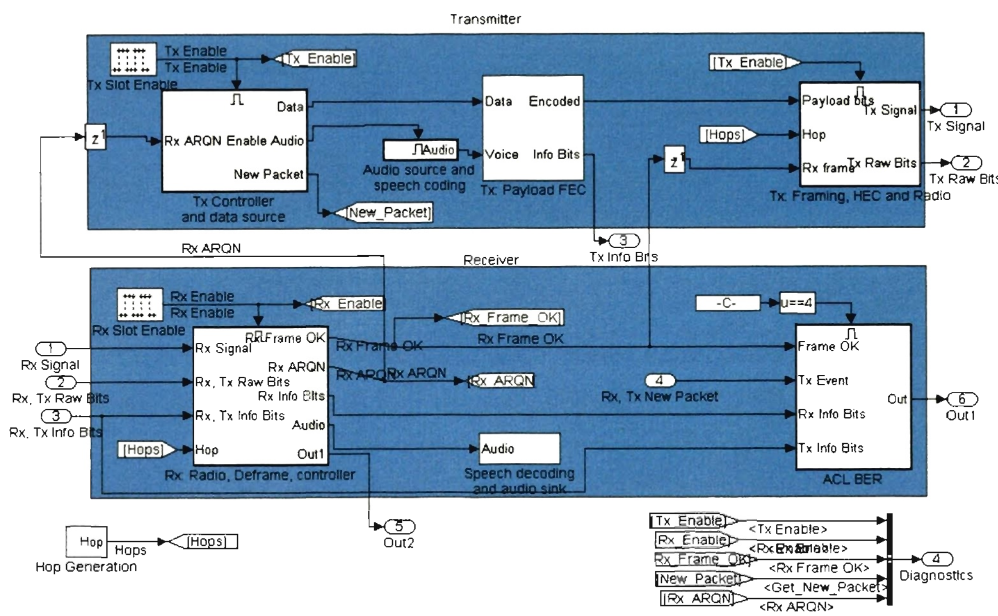

Fig. 2: Transmitter and Receiver modules inside a device

3.3. Receiver Section

The first block deframes the received packet and performs error checks on it. The packet is checked for data integrity. Verification of receiver address and HEC is conducted and FEC is carried out on the information bits. Then CRC is carried out to check for residual errors. The ARQN bit is set to zero incase errors still persist and the packet is rejected. This decision making is also performed with a Stateflow diagram. The BER and throughput are computed in the BER meter block.

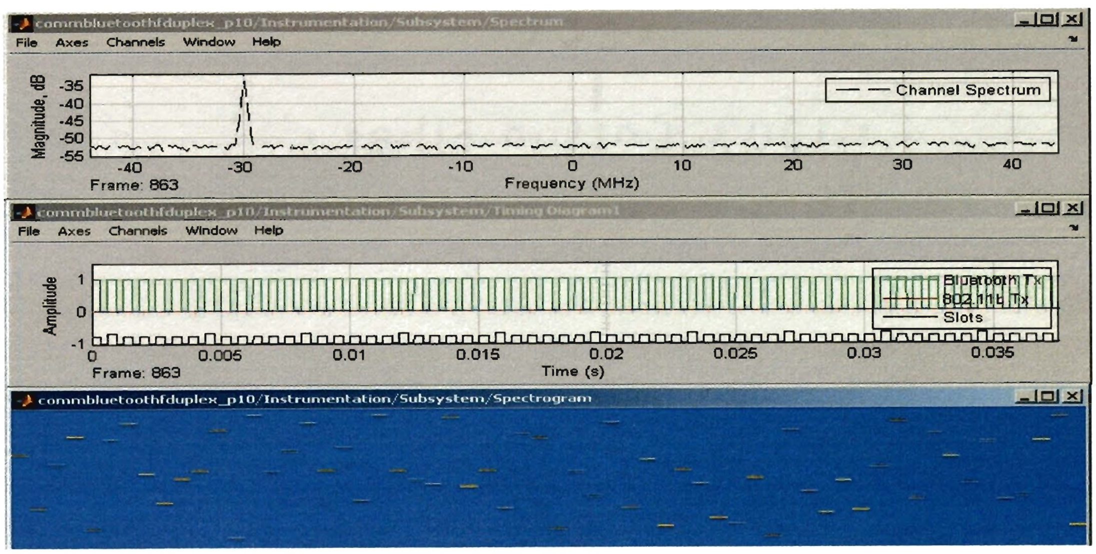

Fig. 3: Spectrum, Timing diagram and Spectrogram scopes of the model

4. MODIFIED BLUETOOTH MODEL

Each of the following sub-sections presents certain modifications made to the original model.

4.1. BER Meter

The original model had a BER meter which checked for errors only after the retransmission assured of a correct packet. Hence the BER meter was checking for any residual errors. This mostly would turn out to be close to zero with the exception of highly noisy links. Hence it did not reflect the true nature of the channel conditions. A modification was made to the model by incorporating a BER check which takes the retransmissions into account. Thus both the BER and the throughput values shall be a realistic estimate of the loss due to errors and consequent retransmissions.

4.2. Increased Number of Slaves

The model originally included only one slave. The number of slaves was increased to three as seen in Fig.4. The master can choose which slave to transmit to and communicate with that slave for the length of the simulation. To allow for such a modification, a change was made in the way a packet is deframed. In the original model, at the receiver end, the packet's address field was not checked before performing further processing. This has been modified to the address field being checked first and only if the address is found to match that of the device can the processing of the data be carried out.

4.3. Rayleigh Fading Channel Incorporated

The channel for Bluetooth piconet environments is typically known to be slow and flat Rayleigh fading [8], [9]. A Rayleigh fading block was added along with the AWGN block as seen in Fig.5. The Doppler frequency is normalized and set to 4Hz which would translate to a speed of 0.5m/s which is typically jogging speed and could be the worst case scenario for a Bluetooth network.

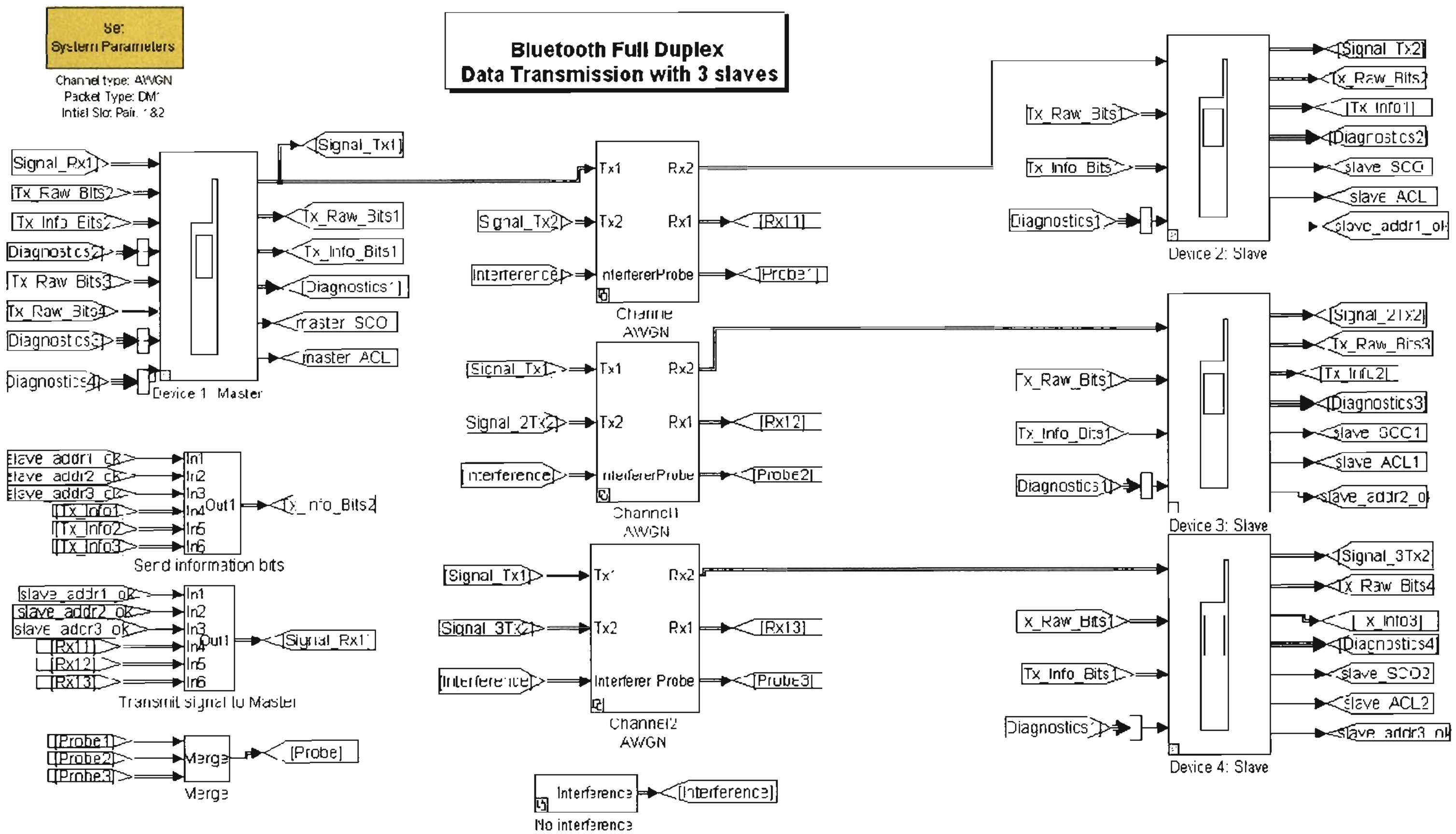

Fig. 4: Modified Bluetooth model with three slaves

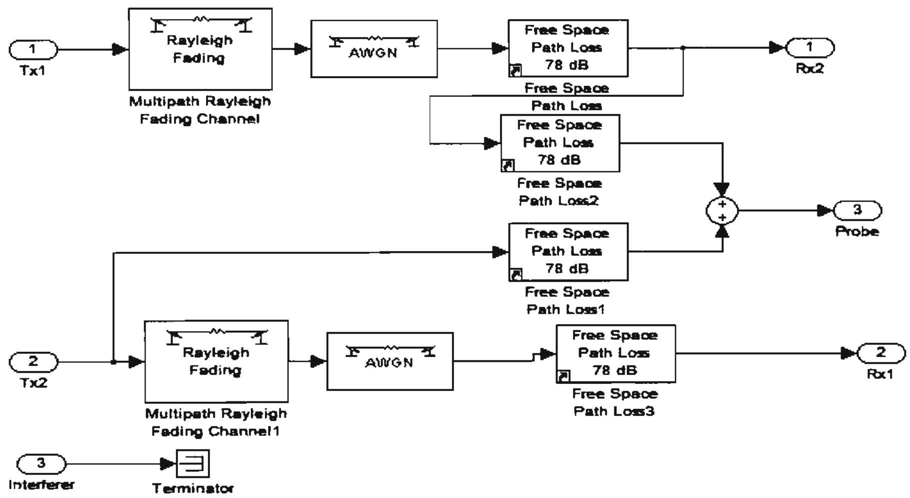

Fig. 5: Rayleigh fading incorporated along with AWGN channel

5. RESULTS AND ANALYSIS

The model was tested for DM1 packet transmission. In case of DM1 packets, the packets get accepted only if the Header Error Check (HEC), device address and CRC are correct. Otherwise the packet is ignored. This can happen in the case of a CRC fail or even in case of a duplicate packet.

The model was tested through a range of Signal to Noise (SNR) values in order to calculate throughput and BER in pure AWGN channel and then compared with Rayleigh fading channel. Essentially retransmission is a waste of bandwidth and reduces the throughput of the network. In data transmission, it is the throughput that needs to be observed more carefully than the BER. The throughput reduces if the packet needs to be retransmitted often.

The simulation environment was set with the following conditions:

(1) Eb/No: Ranging from 0 dB to 18 dB

(2) Simulation time : T = 27 seconds

(3) Maximum number of packets transmitted in either direction : 43200

(4) Normalized Doppler frequency : 4 Hz

Although the bit rate is as high as 1 Mbps, the maximum throughput of the DM1 packet is 128 kbps [7]. This can be calculated as 160 bits of information every other slot. That is 160/2 *625 μsec = 128 kbps. The throughput can be increased if the communication is carried with other data packets like DH1 which do not have FEC overhead, however, this would not be feasible in a noisy environment.

Figure 6 illustrates the BER plots of a Rayleigh fading channel compared against pure AWGN channel for the first slave and the master. Figure 7 illustrates the throughput for the master and slave for both the cases. Figure 8 illustrates the number of retransmissions at both the master and slave devices in both the type of channels.

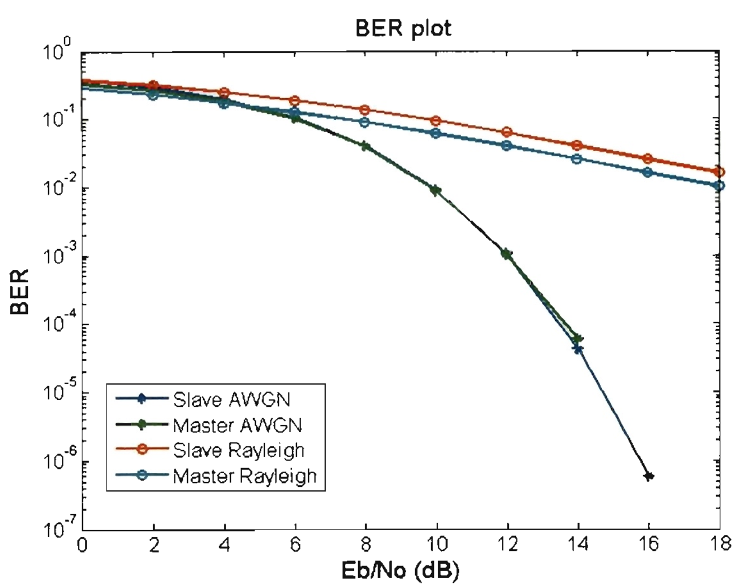

Fig. 6: BER plot

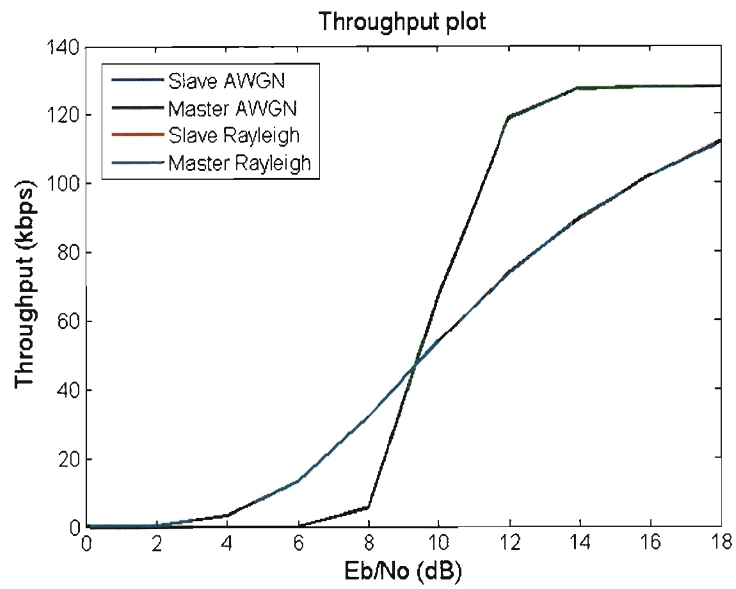

Fig. 7: Throughput plot

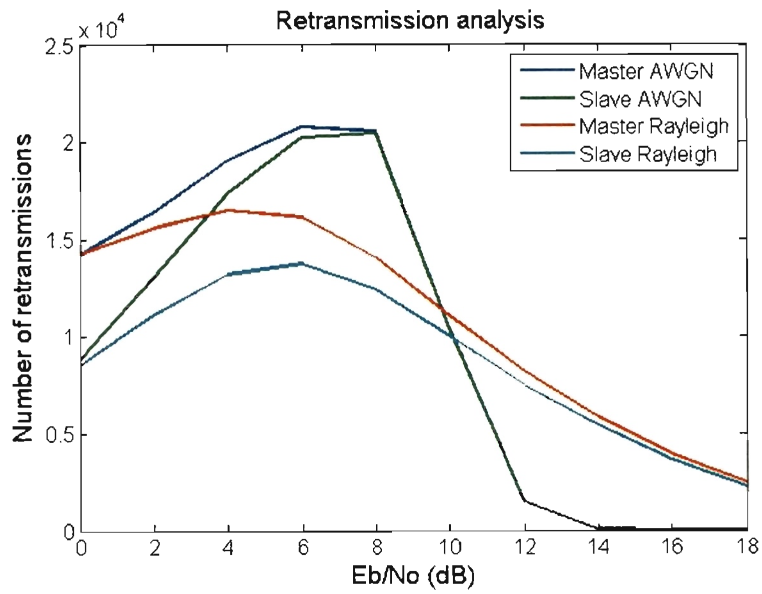

Fig. 8: Re-transmissions plot

The BER, throughput and re-transmission comparison of the other two slaves is given in a tabulated form in Table 1 and Table 2.

Table 1: Slave 2 performance measures

Eb/No	BER	Throughput(kbps)	Retransmissions
0	0.2904	0	8541
2	0.2320	0.3152	11086
4	0.1756	3.1382	13201
6	0.1266	13.2150	13739
8	0.0892	32.0240	12341
10	0.0609	53.6590	9964
12	0.0399	73.2980	7454
14	0.0255	89.7660	5393
16	0.0159	102.610	3622
18	0.0101	111.460	2287

The BER curve for the pure AWGN channel falls to zero by 18 dB of Eb/No while that for the Rayleigh fading channel is of the order of 10^{-2} at 18 dB of Eb/No.

In the case of throughput, the maximum throughput of 128 kbps is reached at 14 dB for pure AWGN channel while that for the Rayleigh fading channel is around 112 kbps.

The retransmissions plots explicitly show a sharp decrease in number of retransmissions with the increase in Eb/No. Although the retransmissions increase in the initial stages the operation is still correct. The initial noise floor is so high that the ARQN bit could also be received in error causing the transmitter to transmit a new packet although the original packet was found to be in error.

Table 2: Slave 3 performance measures

Eb/No	BER	Throughput(kbps)	Retransmissions
0	0.2899	0	8522
2	0.2318	0.3151	11179
4	0.1753	3.0424	13179
6	0.1283	13.0960	13869
8	0.0890	32.1360	12306
10	0.0608	53.8900	9952
12	0.0408	73.7190	7535
14	0.0258	89.9440	5404
16	0.0159	102.440	3646
18	0.0102	111.610	2294

6. CONCLUSIONS

Simulink proves to be an enabling platform to simulate the PHY and link layers of a protocol standard. The performance can be measured in terms of BER and throughput.

7. ACKNOWLEDGMENTS

The authors wish to thank Fei Ren for his help in understanding the original Simulink model. Also they wish to acknowledge the support of the Intelligent Systems Center for the research presented in this paper.

8. REFERENCES

[1] A. Tanenbaum, " *Computer Networks* ", Prentice Hall, 2003

[2] S. Shakkottai, T. Rappaport and P. C. Karlsson, 2003, "*Cross Layer Design for Wireless Networks* ", WNCG Technical Report TR-2003-04-00001, Department of Electrical and Computer Engineering, University of Texas at Austin.

[3] X. Lin, N. Shroff and R. Srikant, "*A Tutorial on Cross-Layer Optimization in Wireless Network*", IEEE Journal on Selected Areas in Communications, Special Issue on Non-Linear Optimization Of Communication Systems, Vol. 24, No. 8, August 2006

[4] *Bluetooth Specification*: www.bluetooth.com

[5] J Haartsen, Ericsson Radio Systems B.V, "*Bluetooth Radio System*", IEEE Personal Communications, Feb 2000

[6] B.Sklar, " *Digital Communications*" , Pearson Education, 2001

[7] "Bluetooth Control Logic Design with Stateflow", MATLAB digest, September 2002

[8] S. Galli, D.Famolari, T.Kodama, "Bluetooth : Channel Coding Considerations", 2004

[9] W.C. Jakes, "*Microwave Mobile Communications*", Piscataway, NJ: IEEE Press, 1994.

[10] T. Rappaport, "Wireless Communications: Principles and Practice", Prentice Hall, 2002.

VITA

Chaitri Avinash Aroskar was born on December 2, 1987 in India. Her major areas of interest are Wireless Communication and Signal Processing. She is a member of IEEE and WIE. During her study at the Missouri University of Science and Technology, she has served as the Vice President of the Council of Graduate Students and on the Executive Committee of the India Association. She earned her Bachelor of Engineering degree in Electronics from the University of Mumbai, India in 2009. She earned her Master of Science degree in Electrical Engineering from Missouri University of Science and Technology, USA in May 2011.