Implementation and Performance Evaluation of Cooperative Wireless Communications with Beamforming and Software-Defined Radio Techniques

Dr. Liang Hong, Tennessee State University

Dr. Liang Hong received the B.S. and the M.S. degrees in Electrical Engineering from Southeast University, Nanjing, China in 1994 and 1997, respectively, and the Ph.D. degree in Electrical Engineering from University of Missouri, Columbia, Missouri in 2002. Since August 2003, he has been with the Department of Electrical & Computer Engineering at Tennessee State University where he is now Full Professor. His research interests include cognitive radio, security of communication systems, networked control system, wireless sensor networks, wireless multimedia communications and networks, and engineering education.

Prof. Shiwen Mao, Auburn University

Shiwen Mao received Ph.D. in electrical and computer engineering from Polytechnic University, Brooklyn, NY in 2004. He was the McWane Associate Professor in the Department of Electrical and Computer Engineering from 2012 to 2015, and is the Samuel Ginn Endowed Professor and Director of the Wireless Engineering Research and Education Center (WEREC) since 2015 at Auburn University, Auburn, AL. His research interests include wireless networks and multimedia communications. He is a Distinguished Lecturer of the IEEE Vehicular Technology Society in the Class of 2014, and the Vice Chair—Letters and Member Communications of IEEE Communications Socie-ty Multimedia Communications Technical Committee. He is on the Editorial Board of IEEE Transactions on Multimedia, IEEE Internet of Things Journal, IEEE Communications Surveys and Tutorials, and IEEE Multimedia, among others, and was Associate Editor of IEEE Transactions on Wireless Communications from 2010 to 2015. He serves as Steering Committee Member for IEEE ICME and AdhocNets, Area TPC Chair of IEEE INFOCOM 2017 & 2016, and Technical Program Vice Chair for Information Systems of IEEE INFOCOM 2015, symposium co-chairs for many conferences, including IEEE ICC, IEEE GLOBECOM, WCNC, ICCCN, et al. He received the 2015 IEEE ComSoc TC-CSR Distinguished Service Award, the 2013 IEEE ComSoc MMTC Outstanding Leadership Award, and the NSF CAREER Award in 2010. He is a co-recipient of the IEEE GLOBECOM 2015 Best Paper Award, the IEEE WCNC 2015 Best Paper Award, the IEEE ICC 2013 Best Paper Award, and the 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems.

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Liang Hong[1] Shiwen Mao[2]

[1] Department of Electrical and Computer Engineering, Tennessee State University, 3500 John A Merritt Blvd, Nashville TN, 37209, lhong@tnstate.edu

[2] Department of Electrical and Computer Engineering, Auburn University, 200 Broun Hall, Auburn University, Auburn AL, 36849, smao@ieee.org

Abstract: Software-defined radio (SDR) and transmit beamforming are two key techniques for next-generation wireless communications. In order to blaze a path to introduce these high demand advanced techniques to future entry-level communication engineers, an educational module was developed with well-defined objectives, learning outcomes, and assessment rubrics. This module is developed with the insights of benefits and challenges obtained from a Research Experience for Undergraduate project. Through this module, the students will not only gain valuable knowledge of the state-of-art beamforming technique, SDR concepts, and the universal software radio peripheral (USRP) platform, but also improve their creative thinking ability, hands-on and programming skills. Additional benefits include increased students' interests in communication engineering, higher retention rate and more minority students pursuing graduate degrees.

Background and motivation

With the significant growth in the number of users using various types of portable devices on diverse real and non-real time, high and low data rate applications, future wireless communication systems are expected to operate under the strict constraint of limited spectrum to provide ubiquitous communications in a heterogeneous environment composed of sophisticated digital communication systems, infrastructures, and services [1].

To meet the future wireless communications requirements, software-defined radio (SDR) and transmit beamforming have been proposed to be the key techniques [2] that future graduating communication engineers should be capable of designing and implementing. SDR is a flexible and cost efficient platform where some or all of the radio's operating functions (physical layer processing) are implemented through modifiable software or firmware operating on a computer, embedded system, or programmable processing devices such as field programmable gate arrays (FPGA), digital signal processors (DSP), general purpose processors (GPP), or programmable System on Chip (SoC) [3]. SDR can cope with the broad range of wireless standards, frequency bands, and user requirements by changing its software implemented functionalities on-the-fly [4]. Transmit beamforming, a promising multiple antenna technique for high frequency and power efficiency by steering its antennas' transmissions towards the direction of the intended receiver, enables increased coverage range, increased data rate, or decreased net transmit power for a fixed and desired received power [5]. However, in many scenarios, such as cellular phone, nodes in a wireless sensor network, and Internet-of-Things (IoT) applications, a transmitter may only be equipped with a single omni-directional antenna, and hence, it may not be able to implement beamforming on its own. Cooperative beamforming is a practical implementation of transmit beamforming for size and/or cost constrained devices. In cooperative transmit beamforming, a number of distributed transmit devices, each equipped with single antenna, cooperatively organize themselves into a virtual antenna array and focus their transmissions in the direction of the intended receiver, such that, after propagation, the signals combine constructively at the desired receiver [6].

Despite the compelling needs of SDR and beamforming expertise in the wireless industry, few schools are offering undergraduate courses on these high demand advanced topics. Typical undergraduate communication systems course mainly focuses on the theories of basic analog and digital modulation techniques. The students learn from equations and block diagrams and practice with theory-based homework questions and a few computer simulations through Matlab. In recent years, several efforts have been taken to integrate hands-on projects and experiential experiences of advanced topics, such as SDR, into undergraduate Electrical Engineering education. Mao *et al* offered SDR based senior design projects and SDR-related experiments for analog and digital modulated systems [7, 8]. Blass *et al* presented a student project that implemented a global positioning system repeater using SDR [9]. Bonior *et al* used SDR as an enabler to encourage undergraduate students to consider graduate level studies [10]. Jiang and Mao attempted to implement SDR based courses in minority institution [11]. Wu *et al* developed an affordable, evolvable, and expandable laboratory suite to allow different institutions to offer laboratories in communications and networking courses [12]. However, to the best of our knowledge, there is no existing work that introduces cooperative transmit beamforming, the key technique in next-generation communication systems, with SDR to undergraduate electrical engineering students.

To bridge the gap between the undergraduate communication systems education and the industrial demands of entry-level electrical engineers with SDR and beamforming expertise, an educational module has been developed for Communication Systems course. This module is developed based on a Research Experience for Undergraduate (REU) project that focused on implementation and performance evaluation of cooperative wireless communications with beamforming and SDR technique. Since it has been reported extensively in the literature of engineering education that the undergraduate students will benefit from the involvement of hands-on and research activities [13], the active and creative pedagogy is used in the development. It is expected that when hands-on and research experiences are incorporated into conventional lecture and/or laboratory courses, students will be motivated to learn because students usually react favorably to having curricular content that is not presented in textbook [14].

The rest of the paper is organized in the following manner: First, the theoretical background of cooperative beamforming and the software defined radio platform is introduced. Then a REU project that implemented and evaluated a cooperative wireless communication system with SDR and beamforming techniques is described. After that, a course module with hands-on project for communication systems course that integrates hands-on and research activities is explained. The learning outcome and assessment rubrics are also presented in this Section. Finally, conclusions are drawn.

Cooperative transmit beamforming

Beamforming with antenna arrays is a well-studied multiple input multiple output (MIMO) technique. It provides space-division multiple access which enables significant increase in communication rate [15]. Cooperative transmit beamforming is a practical implementation of beamforming technique for next generation wireless networks. It applies distributed transmission technique in which randomly distributed nodes in a network cluster form a “virtual antenna array” and calibrate their transmissions to a faraway destination. Under this scheme the individually transmitted signals add up coherently at the intended receiver to enhance communication range and/or power efficiency. The destination receives highly reliable data without each node exceeding its power, size, and/or cost constraint. Figure 1 shows the system model of a cooperative transmit beamformer.

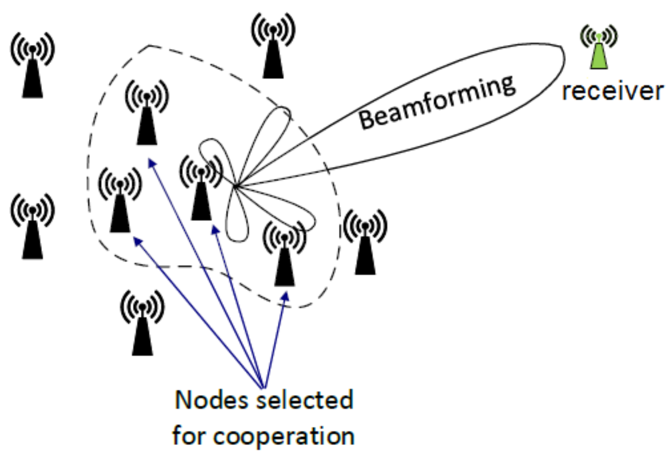


Figure 1. System model of a cooperative transmit beamformer

In order to obtain the large potential benefit offered by cooperative transmit beamforming, the key challenge is that the transmitted signals from each transmitter must be precisely synchronized so that they can be aligned in phase at the intended receiver. However, a distinguishing feature for cooperative transmit beamformer is that each transmitting device has its own local oscillator (LO) and there is no regular and precisely known location of the transmitting and receiving devices. The carrier frequency of each transmitter is typically generated by multiplying the frequency of the LO up to a fixed nominal frequency. But due to manufacturing tolerances and temperature variations, even when two oscillators are set to the same nominal frequency, the carrier frequencies would in general have a non-zero frequency offset with respect to each other and exhibit variations on the order of 10–100 parts per million (ppm) with respect to the nominal. Moreover, all oscillators undergo frequency drifts over time. If uncorrected, these frequency variations among transmitters are catastrophic for transmit beamforming since the phases of the signals may drift out of alignment over the duration of the transmission and may even result in destructive combination at the destination. Furthermore, when there is no precise location information of the transmitting and receiving devices, it is impossible to determine the phases that the cooperative transmitters must employ in order to direct energy towards the destination [16].

Decentralized, feedback-based synchronization architecture could be used to tackle all of the preceding uncertainties [16]. In this scheme, each transmitter adapts its frequency and phase independently based on the feedback packet broadcasted by the receiver. In each feedback packet, only one bit information is included to indicate the change in the received signal strength. After receiving the feedback packet, each transmitter conducts two independent and concurrent processes to synchronize its frequency to the receiver's frequency and steer the beam. In frequency synchronization process, an extended Kalman filter is applied on the preamble and header symbols of the feedback packet to track the LO's frequency offset between the transmitter and the receiver. In beam steering process, the one bit information in the payload of feedback packet is used to adjust the phase relationship between the transmitters so that the transmitted signals add up coherently at the intended receiver. The randomized ascent algorithm could be used for phase adjustment as follows: [17], each transmit device adds a random phase perturbation to its current phase before each transmission; if the one bit feedback indicator shows that the received signal strength is higher, the transmit devices keep their phase perturbation and go on to the next time slot. If the received signal strength is lower, the transmit devices return their phase to the one of the previous time slot before going on to the next time slot. There are three advantages of this synchronization scheme [16]: first, it allows the system scale to large number of cooperative transmitters; second, the scheme is easy to implement and has low overhead; third, the same feedback packets can be used for both frequency synchronization and beam steering. Figure 2 shows the block diagram used in each transmit node and the receiving node.

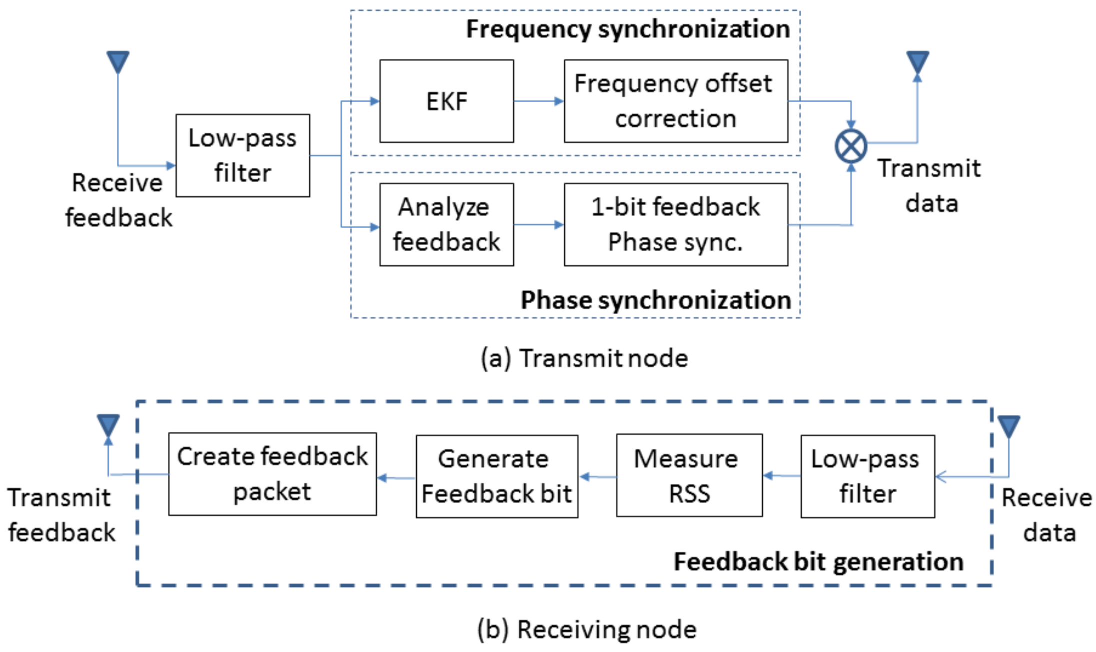


Figure 2. Block diagram used in each transmit node and the receiving node

Software defined radio development environment

In recent years, considerable advances have been made in the availability of software radio platforms, such as Ettus Research's Universal Software Radio Peripheral (USRP), BeeCube's

Berkeley Emulation Engine (BEE) (both Ettus Research and BeeCube were part of National Instruments Corporation now), Rice University's Wireless Open-Access Research Platform (WARP), Microsoft Research's Software Radio Platform for Academic Use (SORA), and Datasoft's Typhoon SDR Development Platform. Due to the highest versatility for lowest cost, USRP N200 kit [18] and SBX daughterboard [18] that provides 400 MHz-4400 MHz accessible frequency range were selected for the REU project and the educational module presented in the following two sections. The main component of the USRP N200 kit is a motherboard that consists of a Xilinx Spartan FPGA for all the physical layer functions such as filtering, modulation/demodulation and other baseband signal processing, 100 MS/s dual analog-to-digital converters (ADC) and 400 MS/s dual digital-to-analog converters (DAC) for digitization and reconstruction, and two digital up/down converters with programmable interpolation rates for translating passband and baseband signals into intermediate frequency (IF) band. The daughterboard that includes antenna circuitry, amplifiers, filters, and local oscillators is attached to the motherboard to serve as RF frontend for signals transceiving. When coupled with GNU Radio [19], a hardware independent open source software toolkit installed on a host PC, a complete software radio development environment is created. Up to 50 MS/s data to and from the host applications can be streamed between a USRP N200 and the host PC via a Gigabit Ethernet interface. Figure 3 shows the block diagram of the GNU Radio/USRP based software defined radio development environment and a USRP N200 with SBX Daughterboard.

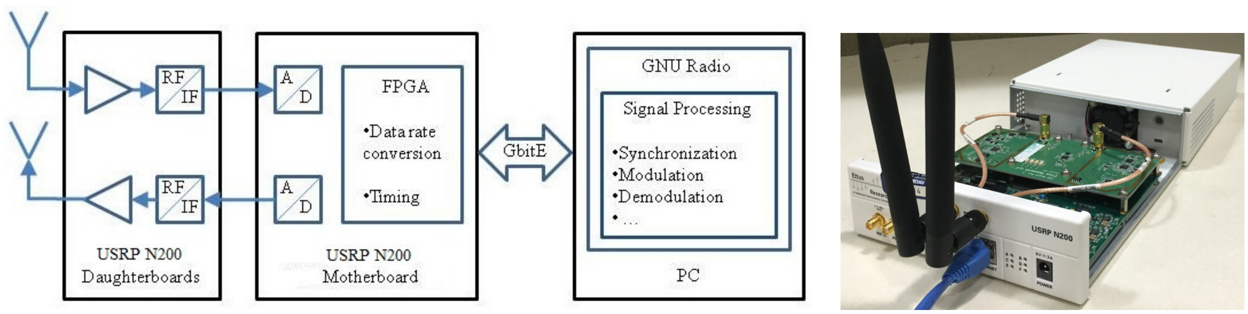


Figure 3. Block diagram of the SDR development environment and a USRP N200 with SBX Daughterboard

The relatively easy programming, well-maintained documentation, large developer community, and popularity in industry and academia shortens the GNU radio learning curve and makes it suitable for integrating in undergraduate communications courses. Moreover, the hardware independent and open-source feature of GNU Radio reduces the cost of the lab, increases the inter-operability of the developed software radio applications, and lowers the adoption barrier of the developed educational module at other universities.

REU project: Implementation and performance evaluation of cooperative wireless communications with beamforming and software defined radio techniques

In order to get insight of the benefits and challenges of introducing the advanced topics (cooperative transmit beamforming and software defined radio) to undergraduate electrical engineering major students with hands-on and research integrated pedagogy, a REU project is conducted. A junior African American student with Electrical Engineering major is recruited to implement and evaluate the performance of cooperative transmit beamforming using GNU Radio/USRP N200.

SDR applications created with GNU Radio are built with two main structural entities – signal processing blocks and flow graphs. Blocks are used to perform physical layer functions and other baseband signal processing such as frequency synchronization, beam steering, and feedback packet generation that are needed for cooperative transmit beamforming. The blocks have certain number of input and output ports. A number of blocks for basic physical layer functions, such as different modulation/demodulation techniques, various filters, USRP, signal indicators and widgets, are built-in blocks of GNU Radio. New functions such as those needed for cooperative transmit beamforming must be created as out-of-tree modules to extend GNU Radio. When the blocks are appropriately connected, a flow graph is made. Typically, signal processing blocks are written with C++ programming language and Python commands are used to create flow graph. The flow graph can also be created with GNU Radio Companion (GRC), a graphical user interface for GNU Radio. GRC allows building flow graphs by simply connecting visually-presented blocks. Since GRC is highly intuitive interface suitable for GNU Radio beginners, it is used in this REU project.

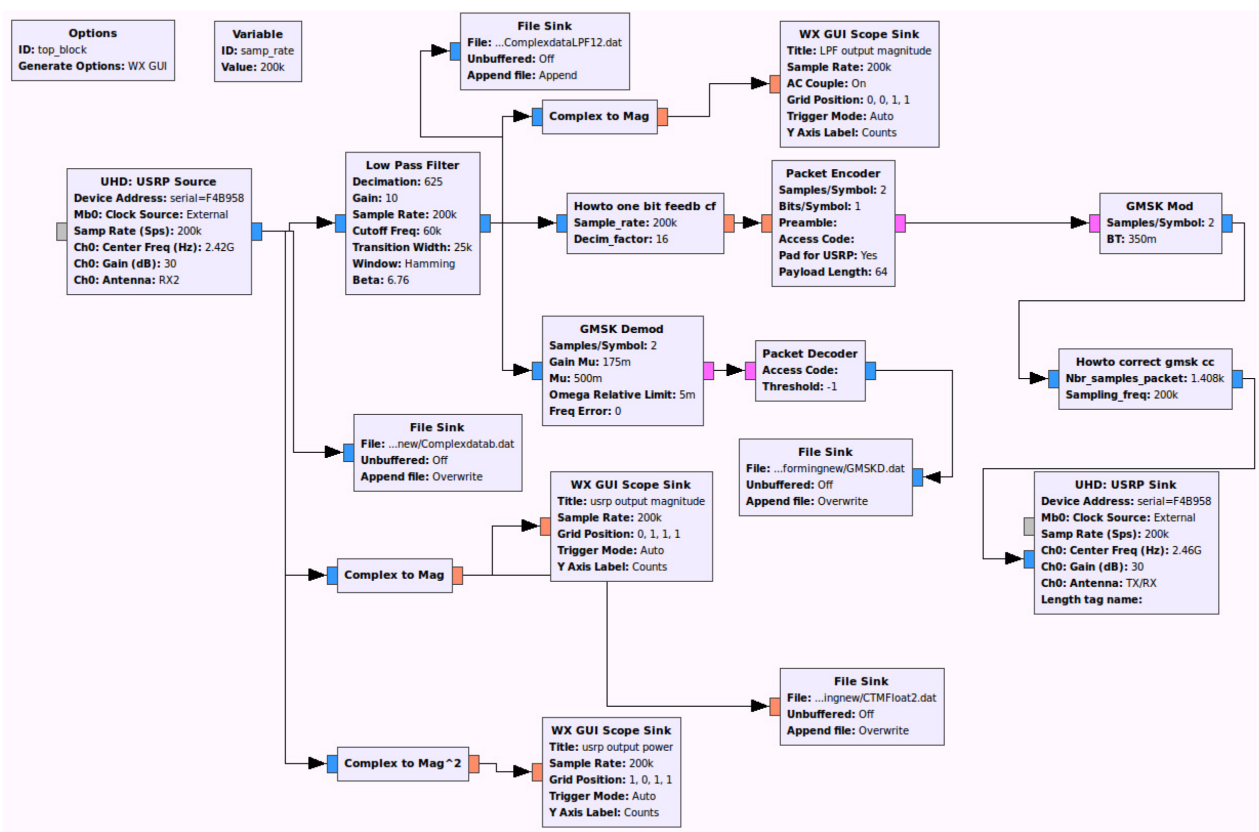


Figure 4. GNU Radio flow graph for the receiver

In this REU project, out-of-tree modules were created first for new functions used for frequency synchronization, beam steering, and feedback packet generation. Then flow graph were created to implement a cooperative wireless communication system with cooperative transmit beamforming. The implementation is based on the publicly available software package [20]. However, this package is implemented with the obsolete release (3.5.0rc0) of GNU Radio. Comparing with 3.5.0rc0 release, the recent release (3.7) of GNU Radio has significant changes in out-of-tree module creation, including changes in code structure, blocks, namespace, gnuradio-runtime, the 'include' directories, classes, structs, typedefs, etc. Therefore, most of the implementation was re-written by the REU student with assistance from a graduate student and a faculty member. Figures 4 and 5 show the GNU Radio flow graphs for the receiver and one of the cooperative transmitters, respectively.

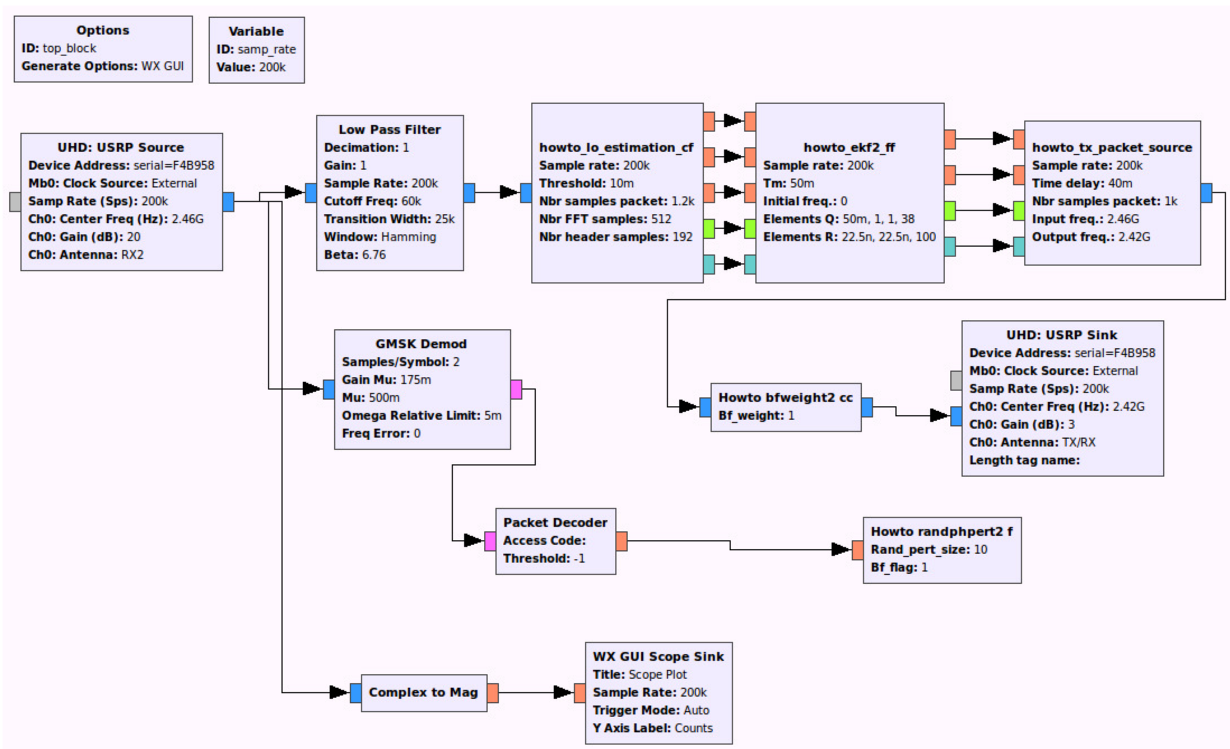


Figure 5. GNU Radio flow graph for one of the cooperative transmitters

To evaluate the system performance, two transmitters form a transmit beamformer cooperatively to stream data to the receiver. Both transmitters and the receiver are put in an indoor environment with research laboratory setting. The distance from one transmitter to the receiver is about 1.5 meters. The distance from the other transmitter to the receiver is about 3 meters. Figure 6 shows the set-up for performance evaluation.

In testing, the receiver sends feedback packets to the transmitters at a carrier frequency of 2.46 GHz and the data is transmitted at a carrier frequency of 2.42 GHz. The feedback rate is 20 Hz. The random phase perturbations are either $+10^{\circ}$ or -10°. GMSK is used as modulation for both data streaming and one-bit feedback. The host PC is installed with Linux (Ubuntu 14.04 LTS) operating system. The amplitude of the received signal is investigated. Figure 7 compares the received signal amplitude when there is only one transmitter (therefore no beamforming) and when there are two transmitters forming the cooperative beamforming. It is clear that the received signal amplitude is significantly increased when the beamformer is formed, implying that the communication quality is significantly enhanced with cooperative beamforming technique.

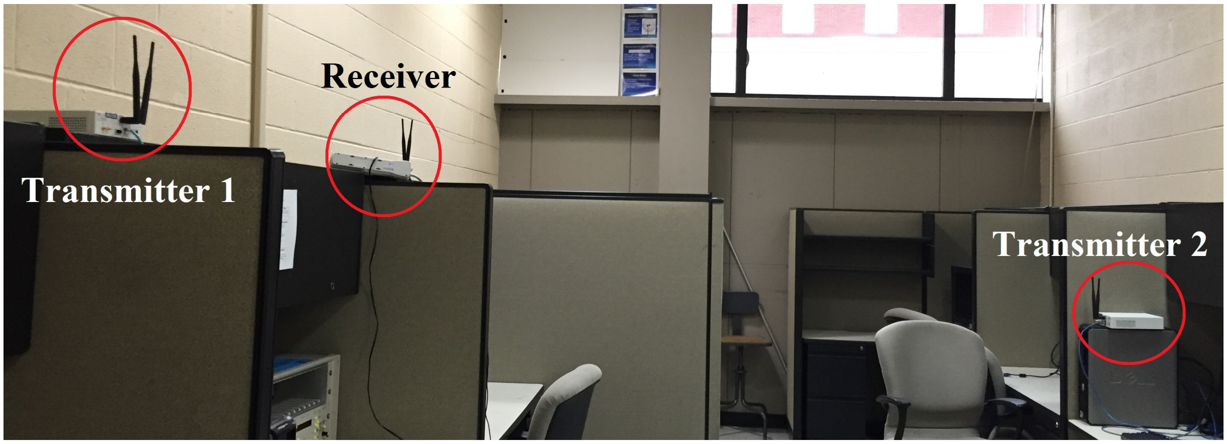
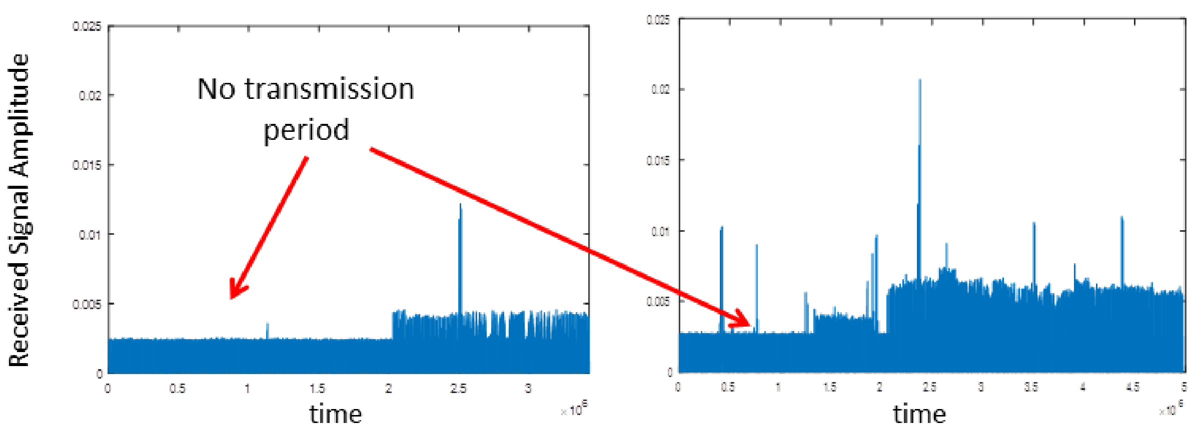


Figure 6. Set-up for performance evaluation



(a) One transmitter (no beamforming) (b) two transmitters form beamforming

Figure 7. Comparison of the received signal amplitude with/without cooperative beamforming

The feedback from the REU student is very positive and encouraging. His interest in communication engineering is significantly increased. His knowledge obtained from communication systems course is consolidated. His skills in research, information acquiring, and professional communication is enhanced. He will finish the undergraduate education and pursue graduate degree in the future.

Development of hands-on and research integrated educational module to introduce advanced communication topics

Motivated by the positive feedback from the REU project and the well-known benefits of integrating research and hands-on experience to the undergraduate coursework, such as increasing student interest in engineering, improving the recruitment of underrepresented minorities and retaining engineering students, an educational module that introduces two advanced topics, cooperative transmit beamforming and SDR, is developed. The final goal is to develop a laboratory course with more modules for different basic and advanced topics. This laboratory course will serve as a compliment for the current lecture based communication systems course.

The four-fold objectives of the developed module are: 1) introduce the fundamentals of cooperative transmit beamforming and SDR; 2) allow hands-on experience on advanced topics through implementing and evaluating a cooperative communication system using the SDR application developed in REU project; 3) enhance communication skills through professional format report and presentation; and 4) encourage research through open-end problems by extending the SDR application developed in REU project. The learning outcomes of this module include enhanced interest in communication engineering; better understanding of contemporary communications techniques; improved programming, communication and research skills; and increased persistence in pursuing advanced degrees.

To accomplish the objectives, the educational module is developed with four components: "Theory and Fundamentals", "Hands-on Experiences", "Report and Presentation", and "Open-end Research Problems". The first three parts can serve as pre-lab, lab, and post-lab activities. The last part can serve as extended works. In "Theory and Fundamentals", the basic concepts of cooperative transmit beamforming and SDR are provided. The "Hands-on Experiences" section provides video demonstrating GNU Radio structure, GRC based flow graph generation, and step-by-step instruction on how to implement the SDR application for one transmitter. The implementation of SDR application for receiver is left for students to figure out with the given block diagram shown in Figure 2. One key challenge observed from the REU project is the creation of out-of-tree modules. Taking into account the time limit that the students could commit to the hands-on experience, all out-of-tree modules will be provided to students. Therefore, only flow graphs are needed to be created by the students for transmitters and the receiver. Students can stop, accelerate and replay the video anytime in the process. In "Report and Presentation", students analyze the experiment results, prepare a lab report following the professional format, and take a video to present their working processes and their result demonstration. The video can be posted on social media such as YouTube so that external expert can review and help disseminate this educational module. Highly motivated and interested students can continue to work on open-end research problems, such as finding the optimum feedback rate, the impact of different modulation schemes on system performance, and streaming of video through cooperative communications. These research problems allow students to work on a real-world question by using their creativity as well as the learned techniques and skills.

Taking into account that rubric based assessment gives a quantitative judgment of student knowledge, requires little extra work in the grading process, requires no additional training for faculty to use, and avoids complete reliance on students' self-reporting through surveys [21], rubrics were developed to quantify students' achievements on the above summarized educational outcomes. Table 1 gives the outcome indicators and the levels of achievements for SDR based cooperative beamforming laboratory. For each instructional outcome, four levels of achievements were designated. A score of 1 to 4 was given based on their hands-on performance, lab report, and presentation.

Table 1 – Rubrics for assessing students' performance

Outcome Indicator	4	3	2	1
Students were able to (1) understand the fundamentals of cooperative beamforming and SDR and (2) develop flow graph for both transmitter and receiver	Both SDR applications were developed correctly and independently.	Both SDR applications were developed correctly but some assistance was needed.	Transmission application was developed correctly but receiving application was developed with lots of assistance.	The developed SDR applications had many major mistakes.
Students were able to connect USRP with host computer and conduct performance evaluation.	Both works were done correctly and independently.	Both works were done correctly but some assistance was needed.	Student could connect USRP with host computer and execute the SDR applications correctly but lots of assistance was needed for performance evaluation	Students did not attempt this.
Students were able to present their working processes and results analysis through lab report and presentation.	All works were done correctly.	The working processes and experiment results were presented but no analysis was given.	There were lots of mistakes in explaining the working processes and results analysis.	Students did not attempt this.

Three undergraduate student volunteers were recruited together with the REU student to test the developed module. The first three parts: "Theory and Fundamentals", "Hands-on Experiences", and "Report and Presentation" were given to the students. The students' achievements were assessed using the developed rubrics. Table 2 shows the preliminary assessment results. It is clear that the proposed educational module will be successful in teaching the advanced techniques. Moreover, the feedbacks received through the conversations with the student volunteers are all very positive and encouraging and similar to those received from the REU student.

Table 2 – Preliminary assessment results

Outcome Indicator	mean	median
Understand the fundamentals and develop flow graph	3.25	3.5
Set up the testing system and perform evaluation	3.25	3.5
Present results	3.75	4

More comprehensive evaluation of the developed module and rubrics will be conducted in the undergraduate Communication Systems course offered at Tennessee State University, an 1890 land grant university and one of the Historically Black Colleges and Universities. Half of the students enrolled in this class will be randomly selected to use this educational module. Selected students will use this lab to substitute one of the two TIMS (Telecommunications Instructional Modeling System) experiments that are currently included in the course. Comparison between the two student groups, one uses the developed educational module and the other one does not, will be conducted using the rubrics based assessment. The efficiency of the developed module on introducing contemporary and advanced topics and enhancing the understanding of basic modulation concepts will be used to revise the module for future use. Survey will also be conducted to study how integration of hands-on research and advanced topic for underrepresented students will increase minority retention and the number of minority students pursuing graduate degrees.

Conclusions

This paper presents our attempt to introduce two highly demanded emerging techniques, cooperative transmit beamforming and SDR, to undergraduate students. A hands-on research integrated educational module on these two topics was developed to supplement the lecture based Communication Systems course. This module is developed based on a REU project that implemented and evaluated a cooperative wireless communication system using beamforming and SDR technique. The module will be extended to a laboratory course. It is expected that the developed module will increase students' interests in communication engineering, consolidate their knowledge learned from course, and increase minority retention and the number of minority students pursuing graduate degrees after full implementation.

Acknowledgment

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