AN SDR BASED WIRELESS LABORATORY: INTRODUCING MULTI - DIMENSIONAL SIGNAL ANALYSIS [§]

Sabih Guzelgoz[†], Ahmed Hesham[†], Omar Zakaria[†], Huseyin Arslan[†]
[†]Department of Electrical Engineering, University of South Florida
4202 E. Fowler Avenue, ENB118 Tampa, FL, 33620
E-mails:{sguzelgo, ahesham, ohashimz}@mail.usf.edu, arslan@eng.usf.edu

ABSTRACT

In this article, a novel Software-Defined Radio (SDR) based wireless communication systems laboratory is introduced. The laboratory teaches students how to design, test, and simulate SDR based wireless systems using modern instrumentation and computer aided design software. The laboratory mainly discusses signal characteristics in multiple domains such as time, spectrum, modulation, and code leading to the concept of multi-dimensional signal analysis. Multi-dimensional signal analysis is very important to understand challenges and trade-offs introduced by emerging wireless technologies. Learning multi-dimensional signal analysis helps students grasp difficult wireless concepts in laboratory environment.

1. INTRODUCTION

Wireless technologies and services have evolved significantly over the last couple of decades, from simple paging to real-time voice communication and recently to very high rate data communication. Recently, software-defined radio (SDR) gained significant interest in the wireless communication community since it provides flexible radio functionality and avoids the use of application specific fixed analog circuits and components [1].

With this ever growing wireless communication technologies and standards along with the introduction of SDR concept, there is a strong desire to develop a flexible wireless laboratory platform. Laboratory benches that are equipped with SDR capable transmitters and receivers can address this goal. In this paper, we introduce a state of the art wireless communication systems laboratory that enables students to understand the SDR concepts from different perspectives. Understanding the basic theories, software simulation of the systems, hardware test and modeling, system measurement and testing, software and hardware interactions and co-simulations are the objective of this laboratory. From the perspective of students, this course acts like a bridge between courses on RF circuits and devices, and courses on wireless systems and networking.

This laboratory course is the outcome of some of the research activities developed in the Electrical Engineering Department at the University of South Florida (USF) [2, 3]. In the laboratory course, the provided test-beds integrate Vector Signal Generator (VSG), Vector Signal Analyzer (VSA), and RF hardware with CAD tools including Matlab, and Signal Studio. The test-bed setups are very flexible and allow generation of various signal waveforms, measurements and modeling of the RF and baseband circuitry under different stimulus conditions, modeling of wireless radio channel effects and RF impairments, and optimization of the transceiver structures and baseband algorithms.

This paper discusses the fundamental structure of the laboratory course followed by the overview of the experiments. Then, multi-dimensional signal analysis concept being the core of the laboratory course is introduced and discussed in detail through hands-on laboratory based experiments.

2. MODEL OF THE LABORATORY COURSE

Fig. 1 shows the laboratory bench set-up along with the integration of various components and instruments. The three important elements of the model (computer simulations and software, test & measurement instruments, and hardware) are shown in different rows. The top row shows the simulation world where the students can simulate and test various wireless communication systems prior to implementing a real-world application. The next row is related to the use of test and measurement equipment which connect the simulation world with the realistic hardware. Test and measurement instruments are important elements of the wireless communication systems laboratory. The figure shows some of the important test and measurement equipment, i.e. Vector Signal Generator (VSG), Vector Signal Analyzer (VSA), and Spectrum Analyzer (SA). The modern versions of spectrum analyzers with capabilities of providing I/Q samples through wide bandwidth digitizer such as Agilent PSA (E4440A), can also be used as signal analyzer or the other way around. Therefore, a signal

---

[§] This paper is supported in part by National Science Foundation (NSF) under CCLI program and by Agilent Technologies.

analyzer will be sufficient to study temporal, spectral, and waveform characteristics of the received signal. The VSG can generate custom and standard waveforms from various sources. For instance, a baseband signal can be developed using Matlab (or Agilent's Signal Studio software or Advanced Design System (ADS) simulator), and then downloaded to the VSG to create a real-time signal. Real-time signal generation is important in order to feed the signal into the real hardware. Signal generators can also be used to generate signals with noise and other impairments to test the receiver's ability to demodulate the signal under more realistic conditions. Similarly, signals with fading and interference can be easily generated.

3. LABORATORY EXPERIMENTS

The laboratory course is composed of eight mandatory, one optional experiments and a final project.

A brief description of the mandatory experiments is given below:

1. An introduction to basic digital baseband communication through Matlab simulation: The objective of this experiment is to familiarize students with the following terms: Bit-error-rate (BER) and signal-to-noise-ratio (SNR) relationship, power spectrum, time domain representation (power versus time), constellation, polar, and eye diagrams.
2. Understanding test equipment: The objective of this experiment is to teach students how to use VSG/VSA in order to generate and analyze digital waveforms.
3. Introduction to wireless RF front end: The objective of this experiment is to teach students the functionality and characteristics of several hardware components such as Voltage-Controlled Oscillator (VCO), bandpass filters, mixer, and Low-Noise Amplifier (LNA).
4. Modulation domain analysis: The objective of this experiment is to study modulation domain analysis by examining various modulation schemes.
5. Filter effect in communication systems: This experiment studies the impact of different pulse shaping filters.
6. Introduction to code and joint time-frequency domain analysis: The purpose of this experiment is to teach students the necessary tools to analyze cyclostationary signals such as CDMA, Bluetooth and WLAN.
7. Synchronization in wireless systems: The objective of this experiment is to understand basic synchronization process at the receiver side.
8. Channel impact in wireless communication: The objective of this experiment is to introduce some of the fundamental wireless channel effects.

In addition to the eight mandatory experiments, three optional experiments are offered as follows:

- Nonlinearities in the RF front end
- Main features of OFDM signals
- Effect of interference on communication systems

Students are required to select one of these optional experiments regarding their field of interest. All mandatory and optional experiments should be completed before the project. Student projects are discussed in section V.

It is essential to understand the basics of multi-dimensional waveform analysis since it forms the core objective of each experiment. This concept is introduced and discussed in detail in the subsequent sections.

4. MULTI-DIMENSIONAL SIGNAL ANALYSIS

Different analysis domains are introduced and integrated to fully characterize the multi-attributes of wireless signals. Examples of these domains are time, frequency, joint time-frequency, modulation, and code domains.

We first discuss time, frequency and joint time-frequency analysis of a signal. Then, code domain analysis which is very useful in characterizing communication systems that employ code division multiple access techniques is introduced. Afterwards, modulation domain analysis is studied by investigating some of the important performance measures.

4.1. Time, Frequency, and Joint Time-Frequency Domain Analysis

Time and Frequency Domains: These are the most popular analysis domains where many of the signal attributes can be extracted. Time and frequency domain analysis are intensely studied throughout the laboratory experiments. However, joint time-frequency analysis (TFA) is a better tool to describe the dynamic non-stationary signals.

Joint Time-Frequency Analysis (TFA): In order to reveal the temporal spectral components of the signals, joint time-frequency analysis should be performed. TFA combines time and frequency domain analysis which is especially useful to understand the characteristics of non-stationary and multi-component signals. Many TFA methods exist in the literature [4, 5]. One of the most well-known TFA methods is Short Time Fourier Transform (STFT). In one of the experiment, namely the multi-dimensional signal analysis experiment, TFA was introduced to the students as a possible analysis domain. In order to study TFA, VSA spectrogram (the square magnitude of STFT) was used to capture a WLAN and a Bluetooth signal. The capture range was 80 MHz, and the frequency resolution was 1 MHz. Fig. 2 shows the spectrogram of the hopping Bluetooth signal which occupies about 1MHz of bandwidth per hop. Due to the limitation of the equipment, some important parameters such as window type and size, as well as the overlapping between windows can not be controlled. Therefore, students were required, in an optional step of this experiment, to capture the signal and process it in Matlab environment to have a full control on these parameters. A more resolvable spectrogram contour is thus obtained for the hopping Bluetooth signal. Hence different signal parameters (such as gap duration, signal bandwidth, hop duration, and center frequencies) can be evaluated as shown in Fig. 2.

4.2. Code Domain Analysis

Detailed analysis of signals has become essential especially with recently emerging technologies. It has become evident that the analysis of the signals should not be limited to only frequency and time, but should be expanded to other domains such as code, space, modulation and so on [6]. For instance, CDMA is a spread spectrum technology which employs special coding scheme for multiple accessing. Therefore, analysis of the CDMA signals in code domain can provide very valuable information which can not be extracted from other domains. Code Domain Power analysis provides the signal power projected on a code-space normalized to the total signal power. This is useful for composite signal analysis. The analyzed coded waveform is correlated with different codes to determine the correlation coefficients for each code. Once different channels are separated, the power in each code channel is determined. Fig. 3 shows two CDMA signals with different number of active codes. Observing the code domain power plot, the number of codes is 9 for Fig. 3(a) and 4 for Fig. 3(b). The time and frequency plots of the CDMA signal are also presented. Different signal parameters such as spectrum bandwidth, out-of band emission, average power, carrier to noise ratio, and time-signal dynamic range can be extracted from the plots. Dynamic range of a CDMA signal depends on the number of codes used in the transmission, and it is expected to become larger as the number of codes is increased.

Since composite polar diagram shows all possible symbol transitions for all active codes in the same plot, it may not provide sufficient information about the symbol transitions for a particular code. However, it gives an indication about the constellation diagram and the possible transitions in the composite signal.

4.3. Modulation Domain Analysis

Modulation domain analysis allows detecting and recovering the data bits. It also provides powerful tools to identify and quantify impairments to the I-Q waveforms. EVM, constellation, I-Q polar, and eye diagrams are some of the critical measures in modulation domain analysis. Integrating all these measures in one display enable students to better understand the effects of modulation type, filter parameters, signal power, etc. Some of these measures are described below:

- EVM: It is used to measure the transceiver performance by computing the magnitude of the difference vector between estimated and received constellation points at the receiver side.
- Constellation diagram: It displays the digitally modulated symbols on complex plane.
- I-Q polar diagram: It displays the constellation points with possible transitions between states by oversampling the complex symbols.
- Eye diagram: It is used to plot the signal in an overlapped way so that different parameters can be measured such as timing error, noise margin, distortion, etc.

Agilent VSG and VSA were used to generate and analyze wave forms in real time. The individual and/or joint modification of the modulation and filter parameters such as modulation type and order, symbol rate, transmitted power, transmitter and receiver filter types, and roll-off factor followed by the interpretation of the modulation domain measures help students understand the effect of each parameter on the communication system. Signal parameters and modulation schemes used in the laboratory are shown in Table I.

TABLE I
GENERATED SIGNAL TYPES AND THEIR TRANSMISSION PARAMETERS

Signal Type	Symbol Rate (ksps)	Pulse Shaping Filter / Roll off Factor	Modulation Type
NADC	24.3	Root raised cosine(RRC) / 1	QPSK, OQSPK, 8PSK, 16QAM , $\pi / 4$ DQPSK
GSM	270.8	Gaussian / 0.3	MSK

Examining different modulation schemes

- *Quadrature Phase Shift Keying (QPSK)*

Having the spectrum, constellation, IQ polar, and eye diagrams integrated in one screen helps students understand QPSK waveform properties more easily as shown in Fig. 4(a). Although QPSK is a phase modulation, its envelope is not constant due to abrupt phase changes, especially for a possible 180° phase transition, and non-ideal characteristics of pulse shaping filter. Constant envelope is very desirable when the operation of nonlinear RF devices is considered whose characteristics are highly dependent on the input power. This leads to the development of modulation types which exhibit better peak-to-average-power ratio (PAPR) characteristics such as Offset-QPSK, OQSPK, GMSK, and $\pi/4$ DQPSK.

- *Offset-QPSK (OQPSK)*

OQPSK is a slight variation of QPSK. OQPSK avoids 180º phase transition caused by a possible simultaneous change of I and Q components. By offsetting the timing of the odd and even bits by one bit-period the phase-shift is limited to no more than 90° at a time as shown in polar diagram in Fig. 4(b). Half symbol-period timing offset can be seen in the eye diagram for I and Q components. Notice that, because of the offset between I and Q symbol timings, two sampling clocks are necessary resulting in eight constellation points as shown in the constellation and polar diagrams. Because of the limited phase transitions, the envelope of OQPSK has lower dynamic range compared to QPSK.

- *Gaussian Minimum shift Keying (GMSK)*

MSK is same as OQPSK where Q component is delayed by half symbol period relative to I component. However, MSK is an enhancement to OQPSK in a way that it uses half-cycle pulse shaping filter instead of RRC to reduce the undesired effect of abrupt phase transitions. GMSK is very similar to MSK; however, pulses are shaped with a Gaussian filter to enhance bandwidth efficiency of the transmission at the expense of some inter symbol interference (ISI). Bandwidth efficiency and the extent of ISI are determined by bandwidth-time product (BT) which also implies the length of the Gaussian filter. Small values of BT lead to narrower bandwidth and more ISI, whereas large values lead to wider bandwidth and less ISI. This tradeoff between the extent of ISI and the bandwidth efficiency requires a very careful selection of BT value. Constant envelope is one of the most desirable features of GMSK considering the operational characteristics of the nonlinear RF devices

- *8-Phase Shift Keying (8-PSK)*

8-PSK is a type of phase shift keying modulation. The number of constellation points is 8 corresponding to 3 bits per symbol. Having smaller phase transitions among symbols is one of the superiorities of 8-PSK over QPSK; however, it is more susceptible to bit errors for the same average power since the minimum symbol distance is smaller. Fig. 4(d) shows the analysis of an 8-PSK signal. Notice that the eye diagram represents the four levels in each of I and Q components. Again, since there is no limitation on the transitions between symbols the signal envelope is not constant.

- *$\pi/4$ Differential-QPSK ($\pi/4$ DQPSK)*

DQPSK is a variation of QPSK modulation in a way that it uses two identical QPSK constellations which are rotated by 45° (radians, hence the name) with respect to one another. Symbol phases are alternately selected from one QPSK constellations and then the other, resulting in eight phases as shown in the constellation diagram in Fig. 4(e). Five possible amplitude levels in both I and Q components can be observed in the constellation and the eye diagrams. DQPSK has some advantages over QPSK and OQPSK [7]. It can be detected using differential detector that has lower complexity compared to coherent receiver used in the case of QPSK and OQPSK. This is especially important considering the fast fading channels where the coherent detection results in higher BER than differential detection [8]. Furthermore, unlike QPSK, the transitions between symbols in the DQPSK constellation do not pass through the origin which result in lower dynamic range of the signal envelope and hence better spectral characteristics.

- *16-Quadrature Amplitude Modulation (16QAM)*

QAM is a special type of amplitude modulation where both phase and amplitude of the symbols are changed.

In M-ary QAM, M is the modulation order and indicates the number of symbol points on the constellation diagram. For instance, there are 16 symbol points on the constellation diagram of 16-QAM as can be seen in Fig. 4(f). The polar diagram looks messy since there is no restriction on transition of the signal, i.e. the transition between any two symbols is possible. As expected, the eye diagram of both I and Q components have 4 levels representing 4 possible amplitude levels on the constellation diagram.

5. STUDENT ASSESSMENT AND PROJECTS

Assessment of the students is based upon pre-laboratory assignments, post-laboratory reports, quizzes, final exam, and projects. Projects are the most important part of the student assessment process. Students are required to successfully demonstrate their project at the laboratory with the provided equipment, hardware and software tools in front of their classmates. It is worth mentioning that SDR related projects are encouraged. Some of the projects are given as follows:

- Spectrum sensing and sharing
- Vertical hand-off

- Cognitive radio solution to ISM band congestion
- RSSI for the indoor channels

6. CONCLUSION

This paper introduces an SDR-based wireless laboratory course which was developed in spring 2008 in the Electrical Engineering Department at the University of South Florida. The laboratory aims at teaching basic and advanced wireless communication concepts through hands-on experiments using advanced wireless platforms. After familiarizing students with hardware components, sophisticated experiments were carried out. Main objective of the laboratory was to introduce SDR-based multi-dimensional signal analysis. Various domain analyses such as time, frequency, joint time-frequency, code, and modulation were discussed in detail. The laboratory was structured in a way that it is composed of complementary experiments serving the above-mentioned goal. Students were also encouraged to be creative and conduct self-dependent projects based on what they learned from the experiments. In order to evaluate students' performance, pre-laboratory assignments, post-laboratory reports, quizzes, final exam, and projects were considered. The initial evaluation of this laboratory provides positive feedback with different students' perceptions based on their style, prior knowledge, and skills.

ACKNOWLEDGMENT

This laboratory course is supported in part by National Science Foundation (NSF) under CCLI program and by Agilent Technologies.

REFERENCES

[1] J. Mitola III, "The Software Radio Architecture," *IEEE Commun. Mag*., vol. 33, no. 5, May 1995, pp. 26 38.

[2] H. Arslan and D. Singh, "Wimax Transceiver Testing: PART-1 - Establish Test Procedures For WiMAX Transceivers," Microwaves & RF Magazine, July 2006, pp. 63-96 (also available online "http://www.mwrf.com/Articles/ArticleID/13004/13004.html").

[3] A. Webster, J. Liu, H. Arslan, L. Dunleavy, and J. Paviol, "Measurement-based Modeling of a 5 GHz WLAN Transmitter", *in Proc. IEEE RAWCON*, Sep. 2004.

[4] A. Hesham and H. Arslan, "Multidimensional Signal Analysis and Measurements for Cognitive Radio Systems*," Proc. IEEE RWS*, Jan 2008.

[5] F. Hlawatsch and G. F. Boudreaux-Bartels, "Linear and quadratic time-frequency signal representations," *IEEE Signal Processing Mag*
vol. 9, no. 2, pp. 21–67, Apr. 1992.

[6] H. Arslan, "Testing and Measurement of Cognitive Radio and Software Defined Radio Systems," *SDR Forum 2007*

[7] S. Chennakeshu and G. J. Salnier, "Differential Detection $\pi/4$-Shifted-DQPSK for Digital Cellular Radio," *IEEE Trans. on Vehicular Technology*, vol. 42, no. 1, Feb. 1993

[8] Y. Akaiwa and Y. Nagata, "Highly Efficient Digital Mobile Communications with a linear modulation method," IEEE J. Select Areas Commun., vol. SAC-5, pp-890-895, June 1987

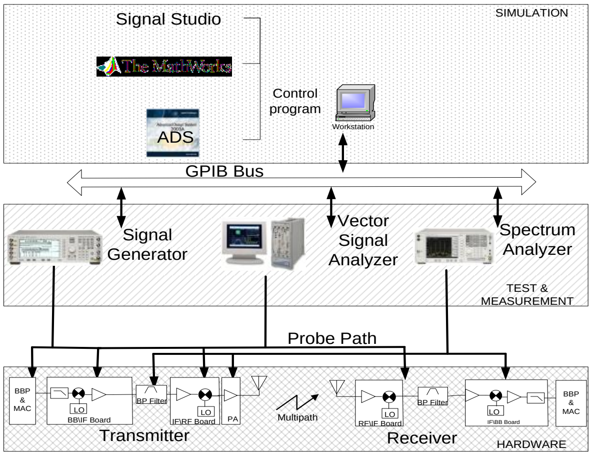


Fig. 1. Pictorial representation of the model used for the wireless communication systems lab

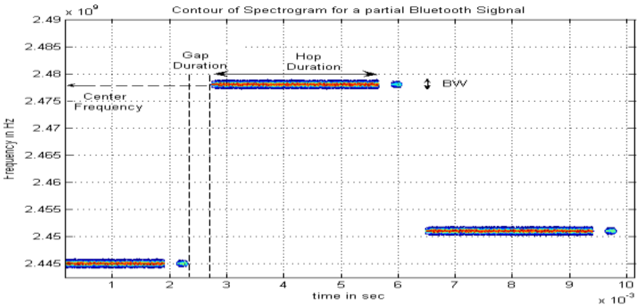
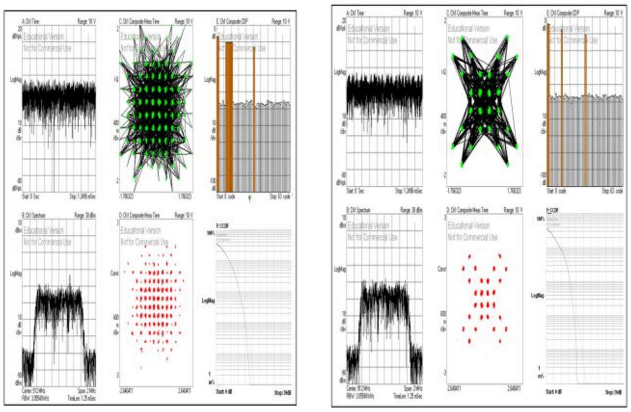
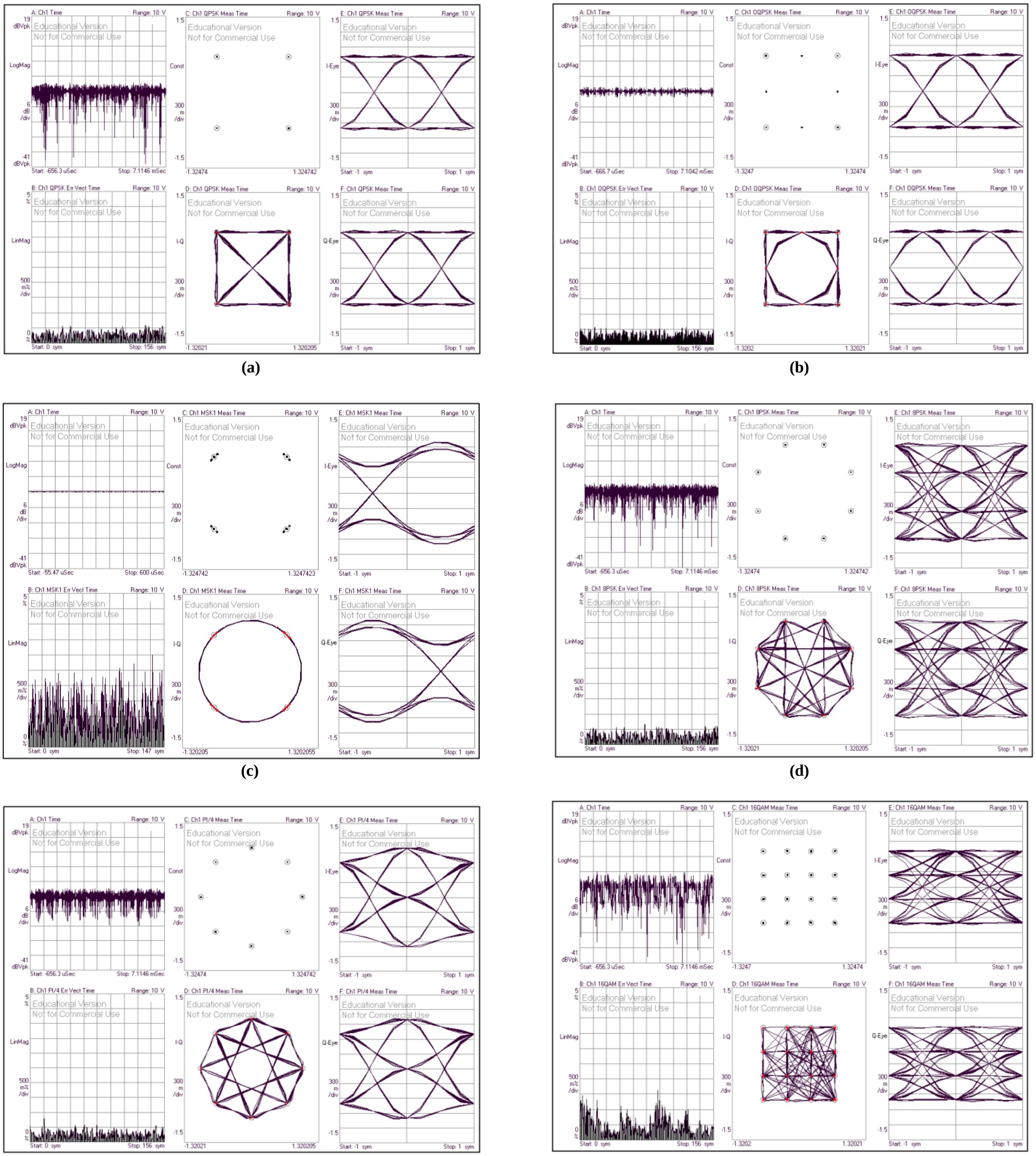


Fig. 2. Spectogram of a Bluetooth signal



(a) **(b)**

Fig. 3. Code domain analysis for forward link CDMA2000 signal for different number of active codes: (a) 9 active codes; (b) 4 active codes; each having six sub-figures (From top left to bottom right): Waveform envelope, Spectrum, Composite polar diagram and Constellation diagrams, Composite code domain power, and CCDF.



(a) (b)

(c) (d)

(e) (f)

Fig. 4. Demodulation analysis of captured waveforms: (a) QPSK; (b) OQPSK; (c) GMSK; (d) 8PSK; (e) $\pi / 4$ DQPSK; (f) 16QAM. For each modulation type, six subfigures are shown: (A) waveform envelope; (B) EVM; (C) Constellation diagram; (D) Polar Diagram; (E) Eye Diagram of I-component; (F) Eye Diagram of Q-component;