# Course Description

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| **Course name** | **#058 - Modern Digital Modulation Techniques for Wireless, Satellite, and Wireline Communications - 5G and Beyond** |
| **Duration** | 5 **days** |
| **Format** | **Public Classroom and Inhouse Event. Not Suitable Online** |

**Overview**

Professor Irving Kalet, Ariel University, Israel, and Columbia University, New York, USA, is teaching this advanced five-day course.

The goal of this course is to introduce the participant to those digital modulation methods and multiple access techniques presently in use in mobile wireless (e.g.,5G-NR), broadband wireless(e.g.,Wi-Fi6), cable, satellite, deep-space and wireline (and power-line) communications, as well as to those techniques, which are being considered for future or next generation systems, e.g., 6G, and Wi-Fi 7.

Modern digital modulation and multiple access techniques are basic building blocks of the physical (or radio) interface of all digital communication systems. We will describe many of these techniques during the course including those methods, which are being used in the newest systems including the Fifth Generation (5G-NR) cellular system, as well as ideas for modulations for 6G.

We will devote much time to OFDM -based systems including OFDM, OFDMA, S-OFDMA, and SC-FDMA, which are integral parts of 5G-NR, 4G-LTE and the IEEE 802.11 (Wi-Fi) systems.

We will place special emphasis on the new modulation standard for the physical interface of 5G-NR. This OFDM standard is based on scalable subcarrier spacing.

We will also discuss other modulations, such as "Faster Than Nyquist" (FTN) signaling, which are considered for advanced wireless systems. Many of the modulations have been combined with MIMO, Massive MIMO, and BLAST, to improve spectral efficiency.

We will also describe the use of constant-envelope CPM modulations (e.g., GMSK), especially for present and future broadband wireless communications and space communications. All of the modulations have been, and will be, utilized in mobile and broadband wireless systems, as well as in xDSL systems, to greatly improve both bandwidth and power efficiency.

We will also devote time to a discussion of one of the most important topics in communications, Shannon Information Theory.

**Technical Focus**

Larger We will discuss the modern digital modulation techniques and multiple access techniques of the physical (or radio) interface of all digital communication systems

Techniques such as OFDM, OFDMA, SOFDMA, SC-FDMA, DMT, MIMO, Massive MIMO, BLAST, CPM modulations (e.g., GMSK), and adaptive modulation and coding methods will be discussed. These techniques are used in broadband wireless communications, e.g., 5G-NR (based on $2^n$ OFDM

numerology), 4G-LTE and Wi-Fi 6 (IEEE802.11) and Wi-Fi 7. These methods are also in use in wireline systems such as ADSL and DOCSIS, as well as space and satellite communications. We will place special emphasis on the CP-OFDM modulation, which is the standard for 5G-NR.

Recently there have been a number of new modulation proposals, e.g., "Faster-Than-Nyquist" (FTN) signaling, index modulation and Orthogonal Time Frequency Space (OTFS) modulation. We will describe these concepts and techniques.

We will discuss Continuous Phase Modulations (CPM), e.g., GMSK used in Bluetooth and space communications. CPM modulation is also a possible candidate for 6G modulations.

We will also describe some of the important results of Shannon Information Theory, which are the basis for almost all communications.

**Course Content**

We will describe the digital modulation techniques used in present major wireless and wireline communication systems and for those systems being planned, for the future. During the course we will discuss the latest versions of wireless systems including Fifth Generation (5G) cellular systems and the latest Wi-Fi systems. These systems use the latest modulation concepts and technologies. The 5G systems utilize many of the concepts to be discussed in the course. We will also discuss new ideas for 6G systems.

We begin the course with a discussion of the characteristics of major communications channels with special emphasis on the fading channel of wireless communications. We continue with a description of the classic modulations, e.g., Nyquist signaling, QPSK, QAM (and Offset QAM), CPM and GMSK, and the optimum receivers for these modulations. We will place special emphasis on OFDM and its related multiple access techniques, e.g., OFDMA, SOFDMA, SC-FDMA. This discussion will include a description of the radio interfaces of 5G-NR, 4G-LTE, and IEEE802.11 (Wi-Fi). We will also discuss some of the new OFDM-based proposals for 6G as well as other proposals for new modulations for future 6G systems, including "Faster-than-Nyquist" (FTN) signaling, and the OTFS (Orthogonal Time Frequency and Space) modulation.

We will cover the space, time and frequency diversity techniques used in new wireless systems with special emphasis on MIMO, BLAST and Massive MIMO techniques. Massive MIMO is one of the major elements of the standards for 5G-NR systems.

Other important subjects to be covered are Alamouti space-time coding, iterative techniques, and adaptive modulation and coding. We will also discuss the very important limits on communications based on Shannon's information theory. These limits are the basis for coding, OFDM, MIMO and other important results. Coding techniques including convolutional coding, turbo-coding, and LDPC codes will be described.

We will place special emphasis on constant envelope (CPM) modulations, e.g., GMSK and MSK, which are important modulations for wireless and space communications, and may find increased use in the future, e.g., 6G. And finally, we finish the course with a description of CDMA, a major multiple access technique, which was used in Second and Third Generation Cellular Systems.

**After participating in this course, you will:**

- Understand the modulations and multiple access techniques in use in modern mobile wireless (including satellite communications), broadband access and wireline communications, especially 4G-LTE, 5G-NR and Wi-Fi.
- Understand the OFDM, OFDMA, Scalable OFDMA (SOFDMA), SC-FDMA modulations and multiple access methods, as well as their implementation based on DMT
- Understand the performance of classic modulations such as QPSK and QAM, as well as the CPM modulations, e.g., GMSK
- Understand the space, time and frequency diversity techniques of wireless communications e.g., MIMO, Massive MIMO, BLAST, and Alamouti Coding
- Be familiar with the radio (or physical) interfaces of the 5G-NR, 4G-LTE and IEEE802.11 (Wi-Fi 6 and 7) systems
- Understand the challenges faced by the planners of the Sixth Generation (6G) systems and the possible solutions to these challenges
- Understand some old ideas like Offset QAM and "Faster-than-Nyquist" Signaling, which may be used in new 6G systems.

**Who should attend?**

The course is aimed at engineers, scientists and algorithm developers who are interested in digital modulation and multiple access techniques for modern wireless and wireline communications.

The course should be of interest to those people who want to know about the OFDM (and OFDM-based modulations), MIMO and Massive MIMO techniques in use in 4G and 5G-NR.

The course should also be of interest to those who want to know more about constant envelope modulation techniques, e.g. GMSK.

# Course Daily Schedule

**Day 1**
**Rayleigh Fading Channel and Baseband Nyquist Signaling**

The course begins with a description of the channel models for mobile wireless and wireline systems. This is followed by discussions of Nyquist baseband signaling, as well as ISI and linear equalization.

- "A Bit of History"
- Discussion of the Challenges Facing the Sixth Generation (6G)
- Introduction to Analog and Digital Communications
- System Model-The Channel
- The Multipath Channel (Rayleigh, Delay Spread and Frequency-Selective Fading)
- Introduction to Diversity Techniques-Antenna Diversity and Coding
- Twisted-Pair Channel

Brief Review of Fourier Transform, Power Spectral Density, White Noise

**Nyquist Signaling**

- ISI, Optimum Filtering, Square-Root Nyquist Filtering, Linear Equalization
- Partial Response Signals-Why the MLSE and the Viterbi Algorithm?
- What is "faster-than-Nyquist" Signaling?

**Day 2**
**Signal Space, Optimum Detection**

The concept of signal space is used to define the classical modulation techniques and derive the optimum detectors.

**Signal Space, Optimum Detection**

- Signal Space
- BPSK, QPSK, MPSK, QAM, BFSK and MFSK-Definitions
- Optimum Detection of Binary Signals and Probability of Error
- Matched Filter

**The Rayleigh Fading Channel and Antenna Diversity-BLAST, MIMO**

An in-depth discussion of the performance of modulations, transmitted over Rayleigh fading channels, followed by a discussion of the concept of space diversity (BLAST, MIMO and Massive MIMO), which is used to greatly improve spectral efficiency.

- Detectability Performance of BPSK over Rayleigh Fading Channel (SISO)
- Classic Antenna Diversity (SIMO)
- Space Diversity
- MIMO
- BLAST
- Massive MIMO-What is it? What can be gained?

**Day 3**
**MSK-type Signals**

QPSK, SQPSK, and MSK are essentially constant envelope modulations, which are used in many satellite and wireless systems.

- QPSK, SQPSK, pi/4 - QPSK, EDGE "8PSK", π/2-BPSK
- MSK-type (MSK, SFSK) Signals
- Adjacent Channel Interference (ACI)

**M-ary Signals**

M-ary signals are used in many systems, e.g., analog modems, ADSL, VDSL, microwave radio, and are the basic modulation of almost all OFDM systems.

- Optimum Detection of M-ary Signals
- MPSK
- Quadrature Amplitude Modulation (QAM)-Nyquist Signaling
- Offset QAM-OQAM- 6G Modulation Proposals
- MFSK

**Shannon Information Theory**

Shannon information theory is the basis behind much of what we do in communications including, coding, analog modems, ADSL, multitone modulation (DMT), OFDM, and adaptive modulation and coding. OFDM (DMT) is the modulation for 5G-NR, 4G-LTE, IEEE 802.11 (Wi-Fi 6 and 7), as well as ADSL and VDSL. We present an in-depth discussion of multitone modulation, DMT, OFDM, OFDMA,

Scalable OFDMA and SC-FDMA. Then we will discuss the Radio Interfaces of 5G-NR, 4G-LTE and IEEE802.11., which are all based on OFDM.

**Introduction to Shannon Information Theory**

- Channel Capacity for Ideal and General Gaussian Channels

**Multitone-DMT**

- Discrete Multitone (DMT) - Implementation
- The Twisted Pair Channel
- Multitone (DMT) over the Twisted Pair Channel (ADSL and VDSL)

**OFDM-Orthogonal Frequency Division Multiplexing**

- OFDM - for Broadband Wireless Communications
- Adaptive Modulation and Coding Techniques
- OFDMA as a Multiple Access Technique
- Scalable OFDMA
- SC-FDMA (Single-Carrier FDMA-4G-LTE)
- OFDM-MIMO

**Physical Interfaces of IEEE 802.11 (Wi-Fi 6 and 7), 4G-LTE and 5G-NR (including $2^n$ numerology)**

- Wi—Fi 6 and 7
- 3G-LTE, 4G-LTE,5G-NR
- 6G (?)

**Day 4**
**Trellis Coding, Convolutional Coding and The Viterbi Algorithm**

We continue with a description of trellis coded modulation concepts and convolutional coding, including a discussion of the Viterbi Algorithm. We also include the topic of interleaving for improving the performance of modulations on Rayleigh fading channels.

- The Viterbi Algorithm (VA)
- Ungerboeck Trellis Coding
- The VA Equalizer
- Interleaving for Rayleigh Fading
- Performance on the Rayleigh Fading Channel
- Convolutional Coding

**"Faster-Than-Nyquist (FTN) Signaling" and Other Modulation Proposals for 6G**

- What is FTN?
- What is its performance?
- Index Modulation and OTFS

**Turbo-Coding-Introduction**

A topic of increasing importance is the turbo-coding (iterative decoding) concept and its use in areas such as antenna diversity, equalization and OFDM.

- Turbo Coding
- Iterative Decoding Techniques
- Turbo-Equalization
- Introduction to LDPC Codes

**Capacity of Rayleigh Fading Channels**

Shannon's work has been updated to include bounds on the performance of Rayleigh fading channels. This work led to the concept of MIMO and space-time (Alamouti) coding.

- Bounds on Communications for Fading Channels
- OFDM-MIMO-Coding
- Space-Time Coding
- Alamouti Coding
- Multi-User Diversity Techniques

**Day 5**
**Continuous Phase Modulations (CPM)**

CPM signals (e.g., GMSK) are constant envelope, bandwidth efficient modulations, suitable for use with nonlinear power efficient, transmitting power amplifiers. These modulations are used in GSM and deep space communications, as well as Bluetooth.

- Continuous Phase Modulation (CPM)
- Gaussian MSK (GMSK)
- Tamed FM (TFM)
- Generalized TFM (GTFM)
- Constant Envelope OFDM
- Adjacent Channel Crosstalk in CPM Signals

**Non-Coherent Detection**

- DPSK
- FM Detection of CPM Signals-Bluetooth, DECT

**CDMA and WCDMA**

We continue with a discussion of CDMA and WCDMA and describe the radio interfaces of the IMT-2000 WCDMA system, as well as the physical interface of IS-95.

- The RAKE Receiver
- Pseudo-Random Sequences
- Power Control
- Intra and Inter-Cell Interference and Capacity
- IS-95 Physical Interface
- IMT-2000 WCDMA Physical Interface: Walsh and OVSF Functions

**Summary and the Future**

# Instructor Biography

**Professor Irving Kalet** has been teaching and working in the area of digital communications in both Israel and the United States for more than forty-five years.

He lives in Israel, where he teaches at the Ariel University. He has also been teaching as an Adjunct Professor in the Department of Electrical Engineering at Columbia University in New York, since 2004. He has worked on modulation techniques, in mobile wireless communications and digital transmission over the twisted-pair cable (HDSL, ADSL, and the 56 Kbps modem) at Bell Laboratories and in satellite communications at MIT Lincoln Laboratories.

Professor Kalet has published many papers in digital communications and is the author of the chapter on Multitone Modulation in Sublet and Wavelet Transforms - Design and Applications, Kluwer Academic Publishers-1995. He is presently working in the areas of digital modulation techniques, constant envelope techniques and multiple access techniques for wireline and wireless communication systems.

Professor Kalet has been a member of the Continuing Education Institute-Europe Faculty since 1988.