tims

EMONA INSTRUMENTS
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Telecommunications, Signals & Systems
COURSE CURRICULUM

4 SECTION OVERVIEW -

1. **EXPERIMENTS SUMMARY**
2. **CURRICULUM : UNDERGRAD/POST**
3. **TIMS EQUIPMENT SUMMARY**
4. **WHITE PAPER : TIMS and 5G**

University Level Experiments in

• Wireless Communications • IoT • 3G • 4G • 5G • SDR
• Wi-Fi • Spread Spectrum • Signals & Systems • Fiber Optics

TIMS IMPLEMENTS ALL OF THIS AND MORE

Select your curriculum from the experiment list below.

EXPERIMENT SUMMARY

TIMS DOCUMENTED EXPERIMENTS:

❒ Adaptive Delta Modulation
❒ AM - Amplitude Modulation
❒ Amplifier Overload
❒ Armstrong's Phase Modulator
❒ ASK - Modulation & Demodulation

❒ Baseline Wander and Line Coding
❒ BER Instrumentation & measurement
NEW ❒ **Binary signal detection in Gaussian noise**
❒ Bit Clock Regeneration
❒ Block Coding and Decoding
❒ Block Coding Gain
❒ Block Coding - error correcting
NEW ❒ **π/2-BPSK used in 5G mobile**
❒ BPSK - Introduction
❒ BPSK and BER
❒ Broadcasting - AM and FM

❒ Carrier Acquisition - PLL
❒ CDMA - 2 Channel
❒ CDMA - Introduction
❒ CDMA - Multichannel
❒ CDMA - Processing Gain
❒ CDMA at Carrier Frequencies
❒ Complex Analog Messages
❒ Convolutional Coding
❒ Costas Loop

❒ Delta Demodulation
❒ Delta Modulation
❒ Delta-sigma Modulation
❒ Digital Signal Recovery
❒ Digital Noise in Baseband & Block Coded Channels
❒ DPSK and BER
❒ DPSK and Carrier Acquisition
❒ DSP Intro and Applications
❒ DSBSC - Generation & Demodulation
❒ DSSS - Spread Spectrum

❒ Envelopes and Envelope Detection
❒ Equalization for ISI
❒ Eye Patterns & BER

❒ Fading, Multi-path Channel
❒ FDM - Frequency Division Multiplex
❒ FHSS: Fast & Slow Hopping
❒ FHSS and Bit Error Rate Performance
❒ FHSS: Hybrid DSSS/FHSS System

❒ Fiber Optic Transmission, Splitting and Combining
❒ Fiber Optic - Bidirectional Transmission
❒ Fiber Optic - WDM Transmission

❒ FM - Demodulation by PLL
❒ FM - Demodulation by Zero Crossing Counting
❒ FM - Deviation Multiplication
❒ FM, Wideband - Generation by VCO
❒ FM - Synchronous Demodulation
❒ FM and Bessel Zeros
❒ Frequency Synthesis with the PLL
❒ FSK - Generation & Envelope Demodulation
NEW ❒ **BFSK - coherent signalling & BER**
NEW ❒ **BFSK - non-coherent signalling & BER**
❒ GFSK - Gaussian FSK

NEW ❒ **IoT - ASK+DSSS Physical Layer**
NEW ❒ **IoT - Chirp Spread Spectrum Application**
NEW ❒ **IoT - Ultra Wide Band Application**

❒ ISB - Independent Sideband
❒ ISI: PAM & ASK in band-limited ch

❒ Line-Coding & Decoding

❒ Matched Filter Detection
❒ MSK, OQPSK, π/4-QPSK, π/4-DQPSK
❒ Modeling Equations
❒ Modem: Binary Data via Voiceband
❒ Modem: Multi-Level Data via Voiceband
❒ Modem: Data Rates & Voiceband Modems
❒ Multi-channel Digital Fiber Link
❒ Multi-level QAM & PSK
NEW ❒ **Multi-path - Time-invariant fading channel characteristics**
NEW ❒ **Multi-path - ISI rejection in DS SS**

❒ Noisy Channel
❒ Noise Generation - Binary Sequences

❒ OFDM Principles - Introduction
NEW ❒ **OFDM, Cyclic Prefix & PAPR**
NEW ❒ **OFDM & Channel Equalisation with BER Measurement**
NEW ❒ **OFDM in band limited, multipath, time-invariant channel with BER measurements**
NEW ❒ **OFDM - IDFT, Complex Exponent & Complex Quad Signals**

❒ PAM & TDM
❒ Parseval's Theorem: Harmonic & Non-harmonic Signals
❒ PCM & Bit Clock Regeneration
❒ PCM Encoding &Decoding
❒ PCM TDM
❒ PCM-TDM 'T1' Implementation
❒ PDM - Phase Division Multiplex
❒ PLL - Phase Lock Loop
❒ Power Measurements
❒ PPM - Pulse Position Modulation
❒ PRBS Messages & Sequence Synchronization
❒ Product Demodulation
❒ Pulse Shaping - Introduction
❒ Pulse shaping for band-limited channels
❒ PWM - Pulse Width Modulation

❒ Random Variables & AWGN
NEW ❒ **Radar signals:**
Constant-frequency pulse
Linear-frequency modulated pulse
Coherent train of LFM pulses
Phase-coded pulse
Coherent train of identical Unmodulated pulses
Stepped-frequency pulse

NEW ❒ **16-QAM - as used in 4G and 5G LTE**
NEW ❒ **16-QAM - LTE BER measurement**
❒ QAM - Generation &Demodulation
❒ QAM and 4-PSK
❒ QASK - Modulation & Demodulation
❒ QPSK - Modulation & Demodulation
NEW ❒ **QPSK - BER of Coherent QPSK in distortionless channel**
❒ Sampling & Reconstruction

❒ Sampling with Sample-&-Hold
❒ Signal Analysis: relationship between time and frequency domains
NEW ❒ **SDR - Intro to GNURadio**
NEW ❒ **SDR - Exploring sampling & resampling**
NEW ❒ **SDR - Software Defined Radio in TX**
NEW ❒ **SDR - Software Defined Radio in RX**
❒ Signal Constellations 4/8/16QAM and 4/8/16PSK
❒ SNR in AM Demodulated Signals
❒ SNR performance of SSB and DSBSC
❒ SONET - TDM and Byte Interleave Mux
❒ SONET Data Frame
❒ SONET transmission via an optical link
❒ Spread Spectrum Principles
❒ Spread Spectrum: Direct Sequence, Frequency Hop, Time Hop Hybrid FH-DS, FH-CDMA,
❒ Speech in Telecommunications
❒ SSB Generation and Demodulation
❒ SSB Linear Amplifier Measurements
❒ Superheterodyne
❒ System fault finding

❒ TCM - Coding Gain
❒ TCM - Trellis Coding
❒ TDM
❒ Timing jitter in Band Limited Channels
NEW ❒ **Turbo coding**
❒ UWB - Pulse Shapes & Spectra
❒ UWB - with BER
❒ UWB - Multiband Modulation
❒ UWB - Multiple Access Orthogonal Pulse Modulation with MHP
❒ UWB - OOK, PPM, BPM & OPM

❒ Wave Analyzer - Spectrum Analysis
❒ Weaver's SSB Mod and Demodulator

SIGNALS & SYSTEMS EXPERIMENTS MANUALS:

❒ Special Signals - characteristics and applications
❒ Modeling Linear and Non-linear Systems
❒ Unraveling Convolution
❒ Integration, correlation & matched filters
❒ Exploring complex numbers and exponentials
❒ Comparing Responses in the Time and Frequency Domains
❒ A Fourier Series Analyzer
❒ Spectrum Analysis of Various Signals
❒ Poles and Zeros in the Laplace Domain
❒ Sampling and Aliasing
❒ Analog-Digital Conversion
❒ Discrete-Time Filters - Finite Impulse Response
❒ Poles and Zeros in the z plane: Discrete-time Filters
❒ Discrete-time Filters - Practical

STUDENT PROJECT CAPABILITIES:

❒ Building electronic circuits with the **TIMS-820 Wire-wrapping Project Module**
❒ Solderless breadboarding of electronic circuits with the **TIMS-840 Experimenter**
❒ Programming DSP implementations with the **TIMS-DSP-6713 Module**

NOTE: This list is constantly expanding as new modules are released and new experiments are written.

CURRICULUM FOR UNDERGRADUATE & POSTGRAD COURSES

Undergraduate Courses

Subject:

Analog & Digital Signal Processing I:

BLOCK1: Classification of signals

suggested experiments:

Special signals - characteristics and applications
SS1-02, TIMS Signals & Systems V2 Experiment Manual

Characteristics and parameters of signals

suggested experiments:

Power measurements
A1-12, Volume A1 Fundamental Analog Experiments

Unravelling convolution
SS1-04, TIMS Signals & Systems V2 Experiment Manual

Integration, correlation & matched filters
SS1-05, TIMS Signals & Systems V2 Experiment Manual

BLOCK2: Fourier series representation of continuous - time periodic signals

suggested experiments:

Exploring complex numbers and complex exponentials
SS1-06, TIMS Signals & Systems V2 Experiment Manual

Complex exponentials, complex quadrature signals
D10-02B, Volume D10 OFDM Experiments

Build a Fourier series analyzer
SS1-07, TIMS Signals & Systems V2 Experiment Manual

Spectrum analysis of various signal types
SS1-08, TIMS Signals & Systems V2 Experiment Manual

Fourier transform

suggested experiments:

Parseval's theorem - relationship between time & frequency domain
S1-12, TIMS Signals & Systems Experiment Manual

Comparing responses in the time and frequency domain
S1-04, TIMS Signals & Systems Experiment Manual

The discrete-time Fourier transform

suggested experiments:

IDFT
D10-02B, Volume D10 OFDM Experiments

Laplace transform

suggested experiments:

Poles and zeros in the Laplace domain
SS1-09, TIMS Signals & Systems V2 Experiment Manual

CURRICULUM : UNDERGRAD/POST

BLOCK3: Systems

suggested experiments:

Systems: linear and non-linear
SS1-03, TIMS Signals & Systems V2 Experiment Manual

BLOCK4: Sampling & A/D conversion

suggested experiments:

The sampling theorem
A1-11, Volume A1 Fundamental Analog Experiments

Sampling and aliasing
SS1-10, TIMS Signals & Systems V2 Experiment Manual

Getting started with analog-digital conversion
SS1-11, TIMS Signals & Systems V2 Experiment Manual

Sampling with SAMPLE & HOLD
D1-10, Volume D1 Fundamental Digital Experiments

PCM encoding
D1-11, Volume D1 Fundamental Digital Experiments

PCM decoding
D1-12, Volume D1 Fundamental Digital Experiments

Delta modulation
D1-13, Volume D1 Fundamental Digital Experiments

Delta demodulation
D1-14, Volume D1 Fundamental Digital Experiments

Adaptive delta modulation
D1-15, Volume D1 Fundamental Digital Experiments

Delta-sigma modulation
D1-16, Volume D1 Fundamental Digital Experiments

BLOCK5: Analog modulation

suggested experiments:

DSBSC generation
A1-03, Volume A1 Fundamental Analog Experiments

Amplitude modulation
A1-04, Volume A1 Fundamental Analog Experiments

Envelopes
A1-05, Volume A1 Fundamental Analog Experiments

Envelope recovery
A1-06, Volume A1 Fundamental Analog Experiments

SSB generation - the phasing method
A1-07, Volume A1 Fundamental Analog Experiments

Product demodulation - synch. & asynchronous
A1-08, Volume A1 Fundamental Analog Experiments

SSB demodulation - the phasing method
A1-09, Volume A1 Fundamental Analog Experiments

Amplitude modulation - method 2
A2-01, Volume A2 Further & Advanced Analog Experiments

Carrier acquisition and the PLL
A2-02, Volume A2 Further & Advanced Analog Experiments

Introduction to FM using a VCO
A2-10, Volume A2 Further & Advanced Analog Experiments

Analysis of the FM spectrum
A2-09, Volume A2 Further & Advanced Analog Experiments

FM and the synchronous demodulator
A2-11, Volume A2 Further & Advanced Analog Experiments

Armstrong's phase modulator
A2-12, Volume A2 Further & Advanced Analog Experiments

FM deviation multiplication
A2-13, Volume A2 Further & Advanced Analog Experiments

FM and Bessel zeros
A2-14, Volume A2 Further & Advanced Analog Experiments

FM demodulation with the PLL
A2-15, Volume A2 Further & Advanced Analog Experiments

The Costas loop
A2-16, Volume A2 Further & Advanced Analog Experiments

Analog & Digital Signal Processing II:

BLOCK1: The z-Transform

suggested experiments:

Using poles and zeros in the z plane: discrete-time filters
S1-11, TIMS Signals & Systems Experiment Manual

Poles and zeros in the z plane with IIR systems
SS1-13, TIMS Signals & Systems V2 Experiment Manual

BLOCK2: The discrete time structures

suggested experiments:

Discrete-time filters - Finite Impulse Response
S1-10, TIMS Signals & Systems Experiment Manual

Discrete-time filters - practical applications
S1-12, TIMS Signals & Systems Experiment Manual

The discrete time structures: FIR

SS1-12, TIMS Signals & Systems V2 Experiment Manual

Poles and zeros in the z plane with IIR systems

SS1-13, TIMS Signals & Systems V2 Experiment Manual

Digital Communications I:

BLOCK1: Linear modulations

suggested experiments:

Line coding

D1-05, Volume D1 Fundamental Digital Experiments

ASK - amplitude shift keying

D1-06, Volume D1 Fundamental Digital Experiments

FSK - frequency shift keying

D1-07, Volume D1 Fundamental Digital Experiments

FSK - asynchronous single branch detection

D1-17, Volume D1 Fundamental Digital Experiments

PPM and PWM

D2-11, Volume D2 Further and Advanced Digital Experiments

Base-line wander and line coding

D3-04, Volume D3 Advanced Digital Experiments

BLOCK2: Noise in communication systems and band limited channel

suggested experiments:

Random signal analysis AWGN and erfc

S1-14, TIMS Signals & Systems Experiment Manual

Eye patterns

D1-02, Volume D1 Fundamental Digital Experiments

The noisy channel model

D1-03, Volume D1 Fundamental Digital Experiments

ISI: PAM & ASK over band-limited channels

D3-01, Volume D3 Advanced Digital Experiments

Equalisation for ISI

D3-02, Volume D3 Advanced Digital Experiments

Pulse shaping for band limited channels

D3-03, Volume D3 Advanced Digital Experiments

Additive noise in digital baseband channel

D3-07, Volume D3 Advanced Digital Experiments

Additive noise in block coded channel

D3-08, Volume D3 Advanced Digital Experiments

Timing jitter in band limited channels

D3-05, Volume D3 Advanced Digital Experiments

BLOCK3: Receivers for digital communications

suggested experiments:

Detection with the DECISION MAKER

D1-04, Volume D1 Fundamental Digital Experiments

BER measurement in the noisy channel

D2-01, Volume D2 Further and Advanced Digital Experiments

BER instrumentation macro model

D2-02, Volume D2 Further and Advanced Digital Experiments

BER measurement of unipolar NRZ signals in a baseband distortion less channel

D4-01, Volume D4 Further and Advanced Digital Experiments

BER measurement of bipolar NRZ signals in a baseband distortion less channel

D4-02, Volume D4 Further and Advanced Digital Experiments

BLOCK4: Channel coding

suggested experiments:

Block coding & decoding

D2-07, Volume D2 Further and Advanced Digital Experiments

Block coding and coding gain

D2-08, Volume D2 Further and Advanced Digital Experiments

Digital Communications II:

BLOCK1: Digital modulations

suggested experiments:

BPSK - binary phase shift keying

D1-08, Volume D1 Fundamental Digital Experiments

DBPSK - carrier acquisition and BER

D2-04, Volume D2 Further and Advanced Digital Experiments

QAM and 4-PSK

D2-12, Volume D2 Further and Advanced Digital Experiments

Multi-level QAM & PSK

D2-13, Volume D2 Further and Advanced Digital Experiments

Signal constellations

D1-09, Volume D1 Fundamental Digital Experiments

MSK in a pass band channel, with BER vs SNR

D4-04, Volume D4 Further and Advanced Digital Experiments

OQPSK in a pass band channel, with BER vs SNR

D4-05, Volume D4 Further and Advanced Digital Experiments

PI/4-DQPSK, PI/4-QPSK, OQPSK & MKS: spectra and constellations

D4-06, Volume D4 Further and Advanced Digital Experiments

GFSK - Gaussian minimum shift keying

D3-18, Volume D3 Advanced Digital Experiments

BLOCK2: PN sequences and multiple access techniques

suggested experiments:

PRBS generation

D1-01, Volume D1 Fundamental Digital Experiments

PCM TDM

D2-06, Volume D2 Further and Advanced Digital Experiments

Introduction to OFDM principles

D3-06, Volume D3 Advanced Digital Experiments

Spread spectrum - DSSS and CDMA

D2-14, Volume D2 Further and Advanced Digital Experiments

Introduction to FHSS using FSK

D3-09, Volume D3 Advanced Digital Experiments

FHSS: fast and slow hopping

D3-10, Volume D3 Advanced Digital Experiments

FHSS and bit error rate performance

D3-11, Volume D3 Advanced Digital Experiments

FHSS: hop pattern diversity correlation

D3-12, Volume D3 Advanced Digital Experiments

Multiple-access UWB using orthogonal pulse modulation with modified Hermite pulses (MHP)

D4-10, Volume D4 Further and Advanced Digital Experiments

UWB - multiple-access techniques: TDMA, DS-CDMA, OPM-MA

D4-13, Volume D4 Further and Advanced Digital Experiments

BLOCK3: Channel coding

suggested experiments:

Convolutional coding

D2-09, Volume D2 Further and Advanced Digital Experiments

TCM - trellis coding

D2-10, Volume D2 Further and Advanced Digital Experiments

BLOCK4: Short range communication systems

suggested experiments:

Introduction to UWB pulse shape and spectra

D4-08, Volume D4 Further and Advanced Digital Experiments

UWB modulation & detection: OOK, PPM, BPM & OPM

D4-09, Volume D4 Further and Advanced Digital Experiments

Multiband UWB modulation

D4-11, Volume D4 Further and Advanced Digital Experiments

Postgraduate Courses

Subject:

Mobile Communications I:

BLOCK1: Digital modulations

suggested experiments:

BER measurement of noncoherent BFSK signaling in an ideal distortion less channel

D7-01, Volume D7 Advanced BER Experiments

BER measurement of coherent BFSK signaling in an ideal distortion less channel

D7-02, Volume D7 Advanced BER Experiments

BER measurement of DBPSK signaling in an ideal distortion less channel

D7-03, Volume D7 Advanced BER Experiments

BER measurement of QPSK signaling in an ideal distortion less channel

D7-04, Volume D7 Advanced BER Experiments

BLOCK2: Spread spectrum systems

suggested experiments:

Spread spectrum - Analysis of direct sequence spread spectrum system

D5-01, Volume D5 Basic Spread Spectrum Techniques

Spread spectrum - Analysis of frequency hop spread spectrum system

D5-02, Volume D5 Basic Spread Spectrum Techniques

Spread spectrum - Analysis of time hop spread spectrum system

D5-03, Volume D5 Basic Spread Spectrum Techniques

Spread spectrum - Analysis of hybrid FH-DS spread spectrum system

D5-04, Volume D5 Basic Spread Spectrum Techniques

DS SS baseband system - processing gain measurement

D6-02, Volume D6 Advanced Spread Spectrum Experiments

BLOCK3: Multiple access systems

suggested experiments:

CDMA - DSSS 3 channel basic system

D6-01, Volume D6 Advanced Spread Spectrum Experiments

FH-CDMA/BFSK

D6-03, Volume D6 Advanced Spread Spectrum Experiments

The SONET PCM data frame

D3-13, Volume D3 Advanced Digital Experiments

SONET STS-1 demultiplexing

D3-14, Volume D3 Advanced Digital Experiments

SONET STS-1 transmission via optical link with bit clock recovery

D3-15, Volume D3 Advanced Digital Experiments

SONET STS-3 multiplexing
D3-16, Volume D3 Advanced Digital Experiments

Mobile Communications II:

BLOCK1: OFDM

suggested experiments:

Introduction to OFDM principles using discrete TIMS modules
D10-01, Volume D10 OFDM Experiments

OFDM - Theory
D10-02A, Volume D10 OFDM Experiments

OFDM - Experiments
D10-02B, Volume D10 OFDM Experiments

BLOCK2: Fading channels

suggested experiments:

Time-invariant fading channel characteristics
D8-01, Multipath Experiments

ISI rejection in DS SS
D8-02, Multipath Experiments

BLOCK3: High frequency systems

suggested experiments:

UWB - detailed experiments in UWB communications systems
D4-12, Volume D4 Further and Advanced Digital Experiments

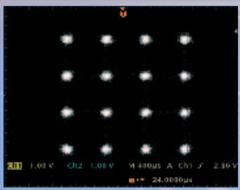
UWB - BER using BPM and OOK signaling
D4-14, Volume D4 Further and Advanced Digital Experiments

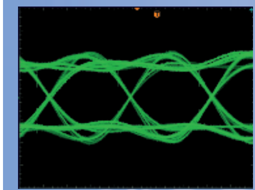
UWB - processing gain and UWB operating bellow the noise level
D4-15, Volume D4 Further and Advanced Digital Experiments

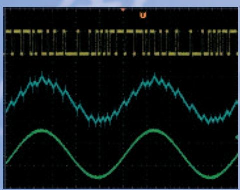
Radar signals
D9-01, Volume D9 RADAR Signals Experiments

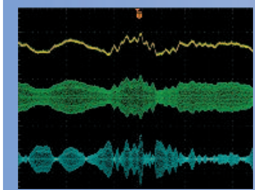
THE BEST LAB SOLUTION

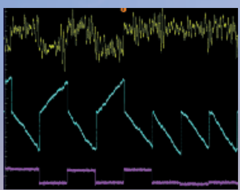
ACTUAL TIMS WAVEFORMS

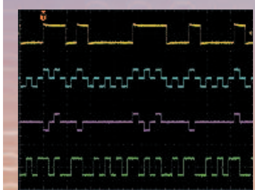

16-QAM

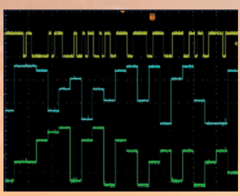

Eye Patterns

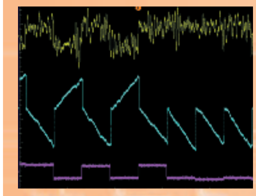

Delta Modulation


Speech AM & DSB

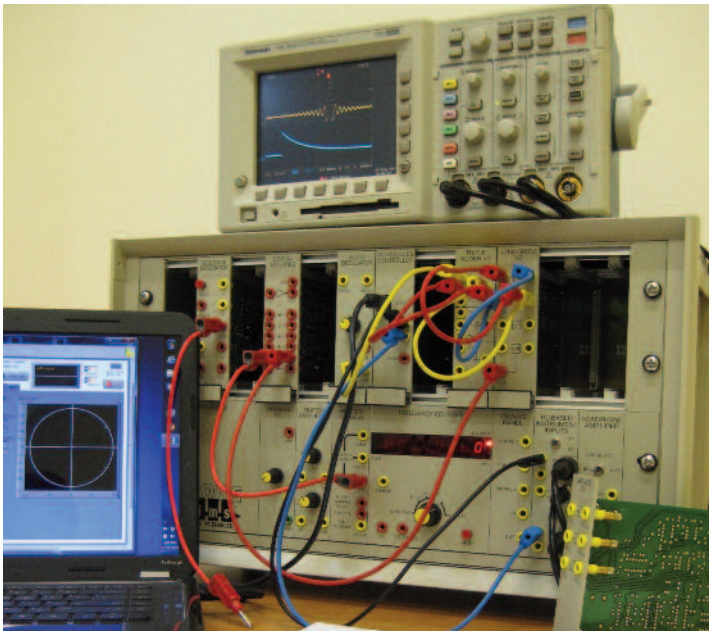

Integrate & Dump


Line Code Encodes


Multi-Level I & Q Signals


Matched Filter

TIMS is laboratory hardware & software for analog & digital communications experiments.



TIMS, Telecommunications Instructional Modeling System, is laboratory teaching equipment for EE and EET students in wireless, telecommunications and signal processing courses.

TIMS is a hardware engineering modelling system that can implement **practically any form of modulation or coding** - keeping pace with the rapid development of telecommunications theory.

• OPEN ENDED & EXPANDABLE ARCHITECTURE

TIMS can implement from basic to advanced communications experiments.

• SELF CONTAINED

TIMS is self contained includes in-built PC-based multi-instrument.

• PC-INTERFACE - INSTRUMENTATION

Oscilloscope, spectrum and meter display plus LabVIEW™ & MATLAB™ interfaces.

• STUDENT PROJECTS

TIMS is the ideal system to allow students to conveniently develop, build and analyse the performance of their thesis projects.

TIMS is a 'hands-on' lab system where engineering students learn mathematics "by-doing" through practical experience.

TIMS LAB EQUIPMENT

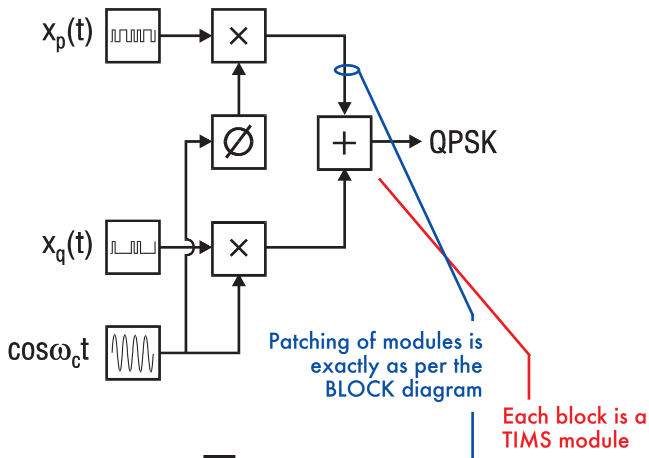
TELECOMS BLOCK DIAGRAMS COME TO LIFE

START WITH MATH OR THEORY . . . . .

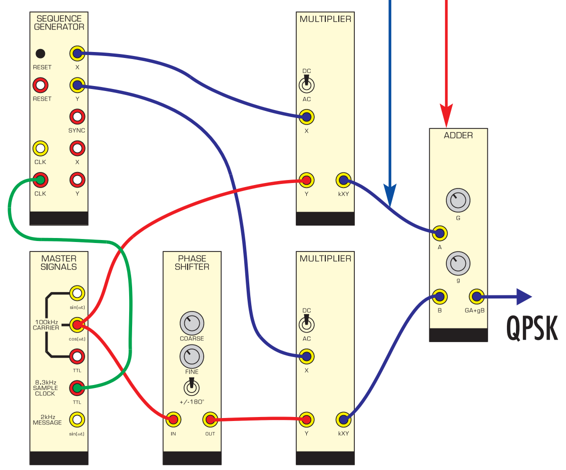
$$x_p\,(t).cos\;\omega_c\,t + x_q\,(t).sin\;\omega_c\,t = QPSK$$

where $x_p\,(t)$ and $x_q\,(t)$ are alternate elements of a digital sequence.

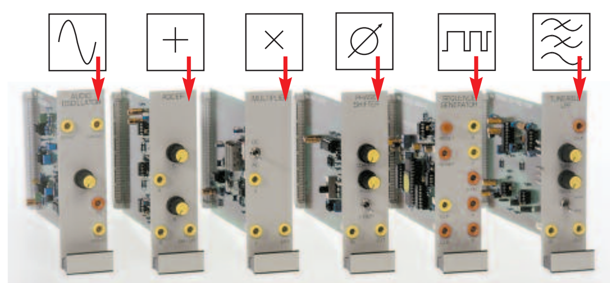
REPRESENT IT AS A BLOCK DIAGRAM



STUDENTS BUILD IT USING TIMS MODULES



ONE MODULE FOR EACH BLOCK



60+ Functional blocks to choose from

Emona TIMS White Paper

5G - Modelling the Future Using TIMS

By

Martin Rakus

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WHITE PAPER : TIMS and 5G

5G - Modelling the Future Using TIMS

Martin Rakus

***Abstract*—The presented paper describes an implementation of modelling approach in contemporary education of IT technology. Modelling is performed using TIMS - Telecommunications Instructional Modelling System, developed by EMONA, AU. It describes one example of possible TIMS application in education of telecommunications. Many more other examples (together with direct quantitative parallel of math and theory) can be found in [1].**

***Keywords* — 5G, OFDM, TIMS, digital modulation.**

I. Introduction

In the recent years it is possible to observe a decreasing interest of students to enrol in technical university programs. Information technologies and telecommunications namely are not an exception. One way how to address this problem could be a real hands-on student's experiments implementation to backup the lectured theory. It is a commonly known fact that one appropriate picture can replace "thousands" of words. This especially holds for technical sciences. This well known phenomenon of visual and practical experience was many times proven and published, e.g. in [2]. The paper is organized as follows. In section II. a brief introduction to 4G and 5G technology is given. Section III. describes a possible TIMS implementations in modelling various aspects of 4G/5G physical layer. Section IV. concludes the paper.

II. 5G - The Mobile Communication of the Future

Mobile communications became an integral part of our everyday life. Today we live in the era of evolving 4G of mobile communications bringing us much more variety of services and increased performance over the previous generations of mobile networks. The logical step after 4G is 5G. Vision characterisation of 5G outlined by Next Generation of Mobile Network Alliance is: "5G is an end-to-end ecosystem to enable a fully mobile and connected society. It empowers value creation towards customers and partners, through existing and emerging uses cases, delivered with consistent experience, and enabled by sustainable business models" [3]. 5G use case families and related examples are shown in Fig.1.

"The 5G system, which is shown in Fig. 2, will be built on “flexible” radio access nodes, distributed and centralized data centres allowing for flexible allocation of workloads. These nodes and data centres are connected via programmable transport networks. The transport networks are connected via backbone nodes that carry the information from the access nodes to the data centres where most of the data is stored and the network is managed" [4].

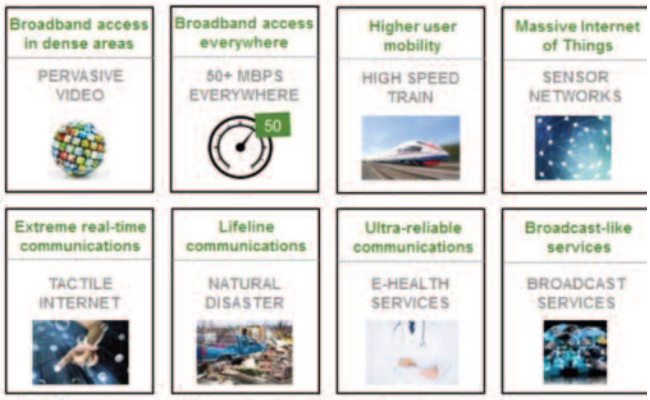

Fig. 1. 5G use case families and related examples. Source: www.ngmn.org

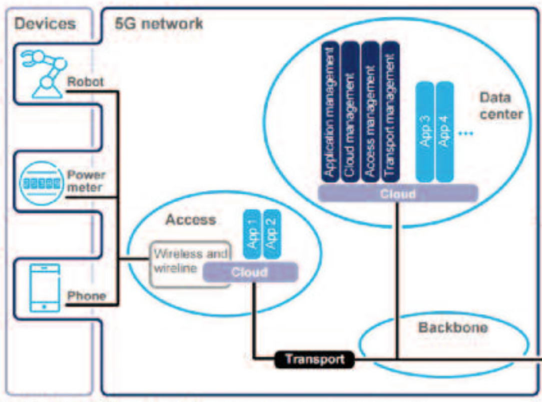

Fig. 2. The 5G system. Source: www.ericsson.com

"5G will expand upon the dual-connectivity framework that was first introduced for LTE to support simultaneous links and aggregations across 5G, 4G, 3G, and Wi-Fi in a multi-connectivity framework using multi-mode devices" [5]. The 5G multiconnectivity concept is shown in Fig.3.

Fig. 3. The 5G multiconnectivity concept. Source: www.qualcomm.com

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All of the demanding challenges stated above would not be possible without a new 5G radio technology. The unified 5G air interface is denoted 5G NR (New Radio). "It will not only significantly enhance mobile broadband, but will also enable new services such as mission-critical control and massive IoT. 5G NR adopts an optimized OFDM-based family of waveforms and multiple access, as well as a common, flexible framework that enables efficient service multiplexing and provides the forward compatibility required to future proof 5G" [5]. The 5G NR foundational design elements are shown in Fig.4.

Fig. 4. The 5G NR foundational design elements. Source: www.qualcomm.com

As was shown above the key technology for 5G (and also for 4G) enabling multiple access is (in some form) OFDM. When we compare the applied technology implementing the physical layer in all mobile generations (starting from the first) we can see, that the same basic building blocks (shown in Fig.5) creating the digital communication system (DCS) are used.

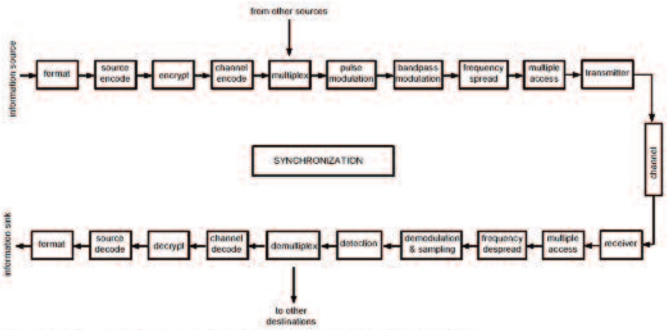


Fig. 5. Block diagram of digital communication system.

At this point an analogy with an alphabet can be used: as soon as you know the meaning of each single letter (a functionality and principle of each block in Fig.5) you can compose a complex words in a countless variety of ways (you can understand the principle of a new complex, emerging technologies). The same idea is applied in TIMS. TIMS enables to model a functionality of a single blocks shown in Fig.5. The modern communications systems (especially mobile ones) are far too complex to be modelled as a whole. It was proven by practical experience, that it is easier for students to comprehend functionality of complex system, when they start to understand the functionality and principles of each single block of which the complex system is composed. It is not possible to read a complex text without knowing an alphabet and TIMS enables to teach students telecommunication "alphabet" in a "hands-on" approach. It has to be stressed that TIMS is not a simulator. It is a modelling system using real signals. In the next section will be briefly shown how TIMS can reveal the essence of the currently used mobile technology as well as the new emerging mobile technology.

III. MODELLING 5G PHYSICAL LAYER USING TIMS

The upper blocks in Fig.5 : format, source encode, channel encode, multiplex, pulse modulation, band pass modulation, frequency spread and multiple access - denote signal transformation from the source to the transmitter. For wireless applications, the transmitter consists of a frequency-up conversion block, a high power amplifier, and an antenna. On the receiving side in Fig.5 the receiver consists of an antenna and low-noise amplifier. Frequency down-conversion is performed in the front end of the receiver and/or the demodulator. The bottom line of blocks in Fig.5 basically perform an inverse operations as the upper line of blocks.

In the following paragraphs a short demonstration of the possibility how to model the selected set of blocks in Fig.5 using TIMS with respect to mobile communication systems (with the focus on 5G/4G) will be given.

The input of the DCS is information, which is in case of Smartphone in analog form: voice, light, and tactile. In order to transfer such information through DCS it has to be first converted into digital form followed by some kind of source encoding. These operations can be modelled using TIMS PCM ENCODER/DECODER modules. An audio frequency input is digitised using A/D converter producing TTL-level PCM format. Three digitising schemes (selectable via front panel switch) are provided:

a) 7-bit linear
b) 4-bit linear
c) 4-bit commanded using A_4-Law or μ_4-Law

Frame synchronisation is implemented by both separate output synchronisation signal and also an embedded code within serial data stream. A variable frequency sinuous-type message is provided, which is always synchronised to the input bit clock. Two PCM encoder modules may be connected in parallel, with the appropriate control signal, to establish a two channel Time Division Multiplex system - which can mimic e.g. LTE TDD operation. More details can be found in PCM encoding/decoding experiments D1-11 and D1-12 described in [6].

In order to protect transmitted information against channel impairments some form of channel coding has to be applied. The modern channel coding is a rather complex issue. To get acknowledge with coding theory, students can start with simple experiments such are: Block coding & decoding D2-7 and Block coding & coding gain D2-8 described in [7]. Experiments start with simple parity (even/odd) error detection and continues with Hamming single error correction linear block code. Depending on the installed EPROM chip also binary cyclic code can be used. These experiments are performed using TIMS BLOCK CODE ENCODER/DECODER modules. A more complex coding scheme using convolutional codes applied e.g. in GSM is described in the experiment D2-9 Convolutional coding [7]. Encoding is provided by TIMS CONVOLUTIONAL ENCODER module. Decoding is performed in TIMS-DSP-6713 module using an appropriate software. Trellis Coded Modulation using soft-decision Viterbi decoding algorithm can be also modelled using TIMS-DSP-6713 module with appropriate software. To keep in track with technological changes in mobile communications industry an experiment modelling turbo-coding was developed. As an example UMTS turbo code was implemented in TIMS-DSP-6713 module, for encoder see Fig.6.

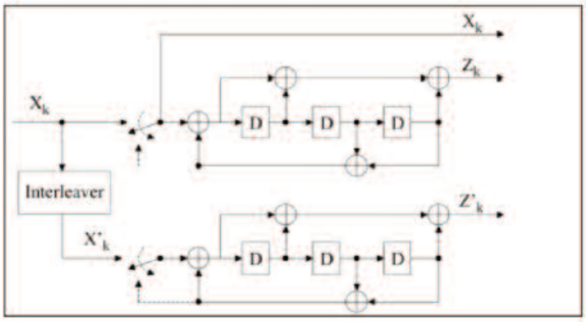


Fig. 6. UMTS turbo encoder (taken from Valenti and Sun).

The heart of the LTE and developing 5G radio access technology is OFDM. The necessary prerequisite to fully comprehend DFT based OFDM processing is to have a firm background of complex numbers. To visualize terms like: complex numbers, complex exponential, etc. TIMS has developed a standalone software enabling to visualise complex numbers called: EQ vector Visualiser, see Fig.7.

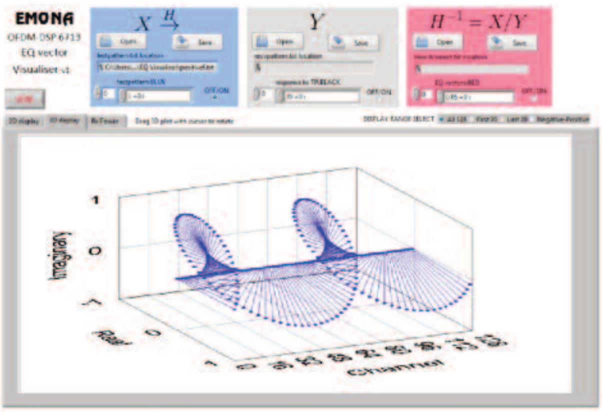


Fig. 7. Complex exponential: $z = e^{j8\pi f t}$.

This helps students to better understand the generation of quadrature signals - necessary for OFDM symbol modulation.

To modell a complete OFDM bandpass system using 4QAM modulation TIMS has developed OFDM modem module. The core of the OFDM modem is realized in TIMS-DSP 6713 module. Module control is via Java-based TIMS OFDM GUI. In the test mode students can manually set the input vector parameters for IDFT. Experience has proved that this feature is very useful for thorough students understanding the real physical meaning of IDFT. Many of them when they see a known formula for IDFT:

$$s_k = \frac{1}{N}\sum_{n=0}^{N-1} a_n \exp\left[\frac{j2\pi kn}{N}\right], \qquad k = 0,1,\ldots,N-1$$

they are not able to correct answer questions like: "what is the highest generated frequency for given N and fundamental frequency, or what is the negative frequency?". TIMS-DSP 6713 module implements $N = 128$ point FFT. By using TIMS OFDM GUI students can easily change independently real or imaginary part of any of 128 coordinates of the IDFT input vector composed of frequency domain samples, see Fig.8. Coordinates are denoted as: "TESTPATTERN[0÷127]".

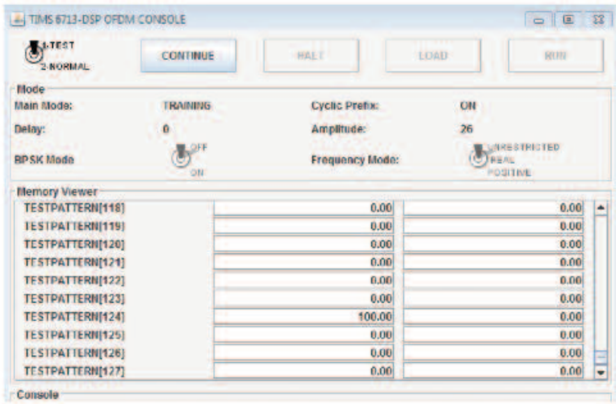


Fig. 8. TIMS OFDM GUI, setup for generating: f = - 4 [kHz].

A very simple experiment with block diagram in Fig.9 enables students to generate using IDFT: DC component, the lowest/highest and positive/negative generated frequency.

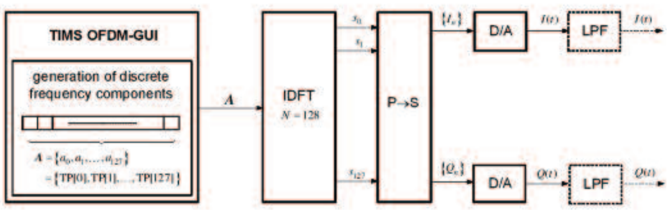


Fig. 9. Block diagram for IDFT experiment.

By using several other TIMS modules it is possible to create a complete OFDM modem, its block diagram and wiring diagram is in Fig.10 and Fig.11 respectively. The real world natural bursty traffic behaviour is mimicked by frame organization of transmitted data (obtained from PN generator) – signal **1** in Fig. 10.

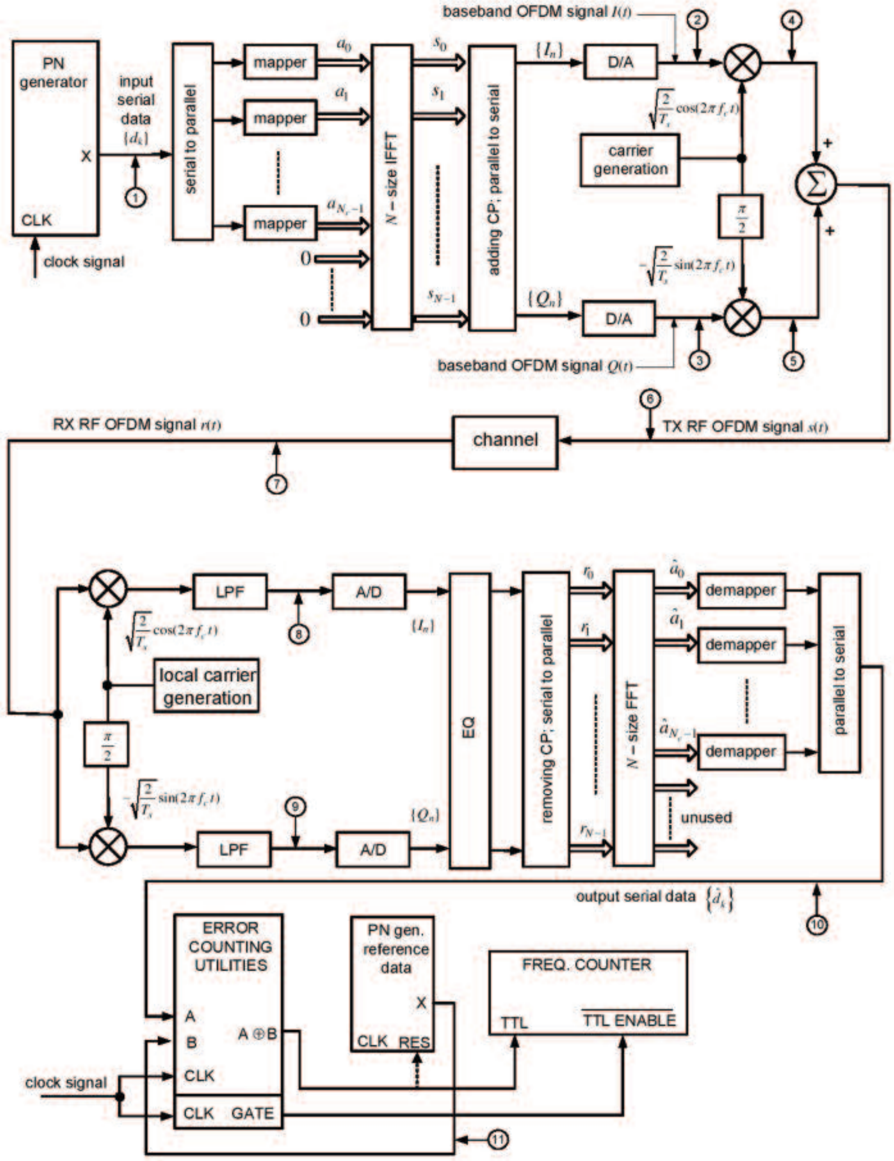
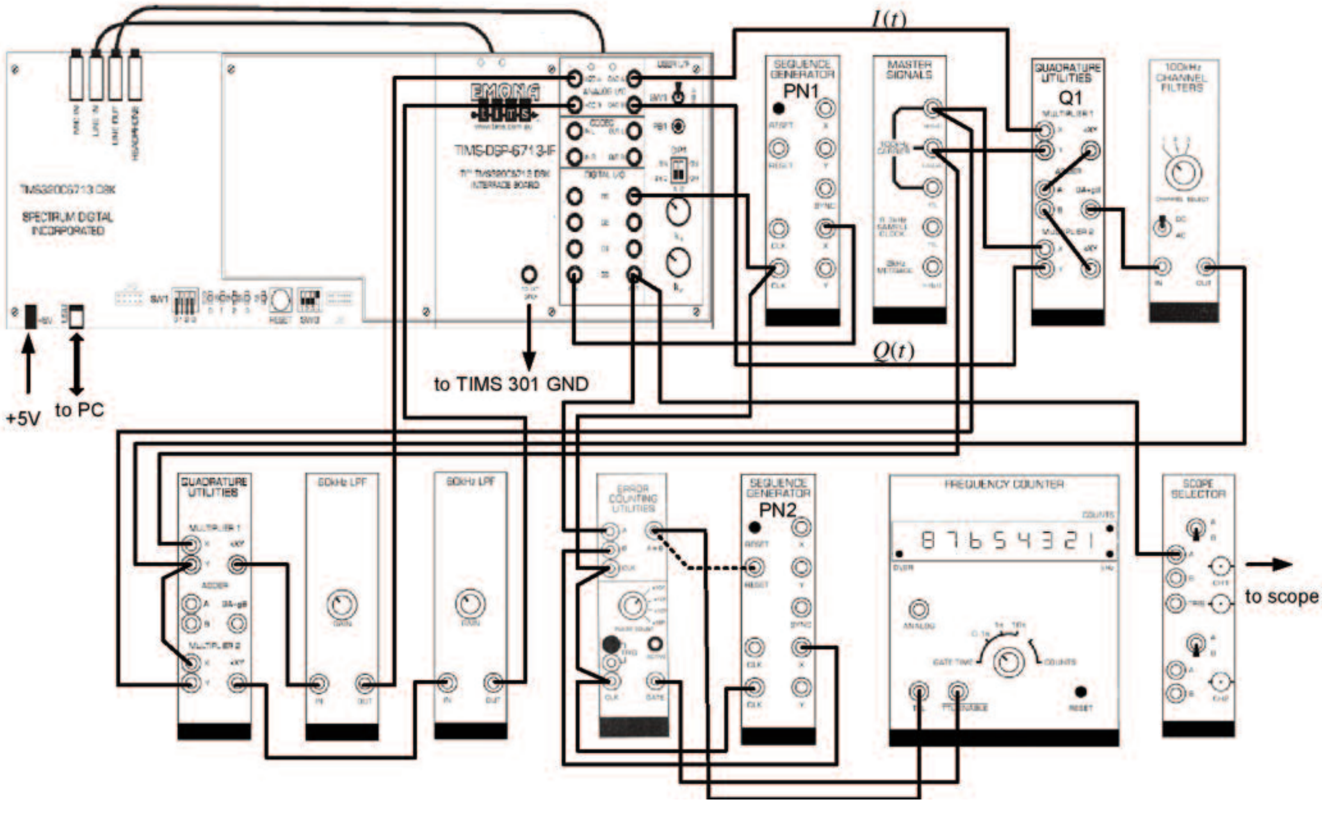


Fig. 10. Block diagram of OFDM modem.



The minimum subcarrier spacing in TIMS OFDM implementation is $\Delta f = f_u = 1[kHz]$, then the OFDM symbol duration (without CP) is $T_s = 1/\Delta f = 1[ms]$. From TIMS OFDM sw specification follows that CP takes 25% of the OFDM symbol time, thus with CP OFDM symbol time is increased to $T_{s\_CP} = 1.25 \cdot T_s = 1.25[ms]$. CP that can be directly observed on OFDM baseband signals, see signal **2** in Fig.10, is shown in Fig.12. In order to find position of the CP more easily, it is possible to set the value of CP to zero with front panel toggle switch on TIMS 6713 DSP module set in position **B**.

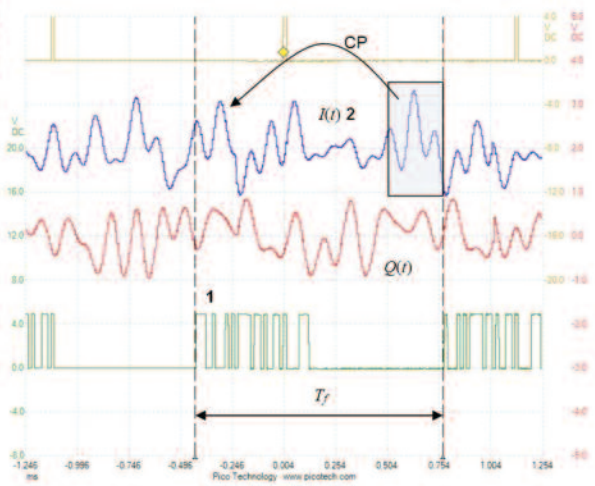


Fig. 12. OFDM baseband signal (outputs of DACs) – check points **1** and **2** on the block diagram.

As follows from Fig.10 qudrature baseband signal modulates 100kHz carrier signal to create 4QAM modulated band pass signal. The OFDM modem is transmitting in total N_c = 20 subcarriers, spaced 1 kHz apart, thus band pass bandwidth of the OFDM signal is

$$W_{null-to-null} = \left(N_c + 1/T_s\right) = 21/10^{-3} = 21[kHz]$$

, what can be easily verified by using spectral analyzer, see Fig.13.

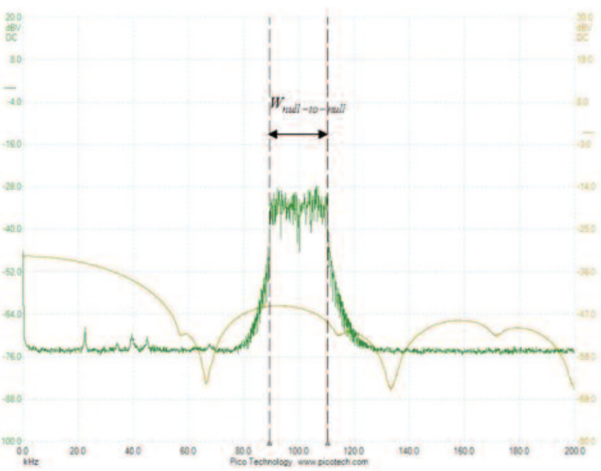


Fig. 13. OFDM spectrum - check point **7** the block diagram.

By using oscilloscope measurement feature it is easy to measure an important parameter of the OFDM signal - PAPR, see Fig.14.

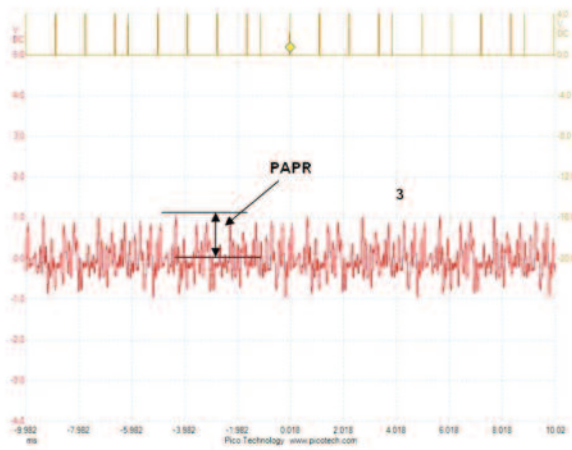


Fig. 14. Amplitude variations of the OFDN baseband signal - check point **3** on the block diagram.

Practical measurements shows that the measured PAPR value of the generated OFDM signal is app. 9dB, what corresponds with max. theoretical value (assuming square QAM) 13dB. The ability of the OFDM system to cope with multipath components (with the excess delay shorter than CP) can be simply demonstrated using TIMS 4 PATH TIME INVARIANT CHANNEL module, enabling the set delay and attenuation of 4 independent signal paths, see Fig.15. Created ISI can be clearly observed in time domain using OFDM pilot signals, see Fig.16. To evaluate a correct reception a BER instrumentation was implemented in Fig.10.

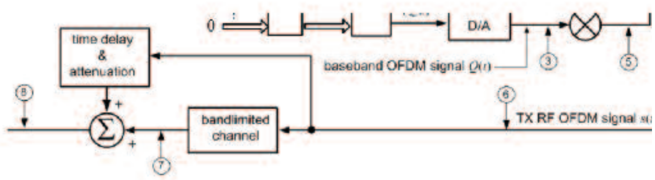


Fig. 15. Implementation of time invariant multipath channel.

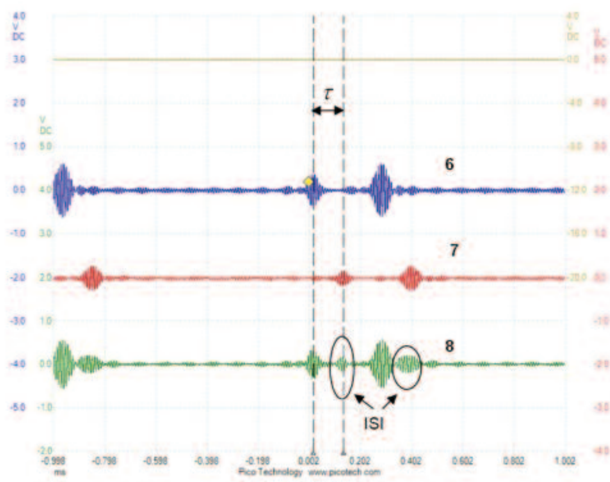


Fig. 16. Pilot signals in time domain - LOS and delayed path - check points **6** , **7** and **8** on the block diagram.

Using BER instrumentation students can easily verify that without equalisation it is not possible to achieve a correct reception. One of the big advantage of OFDM is the possibility of simple equalisation in frequency domain. The channel assessment is done by measuring the level of the received pilot signals. Channel transfer function and calculated correction can be observed using EQ Visualiser sw, see Fig.17.

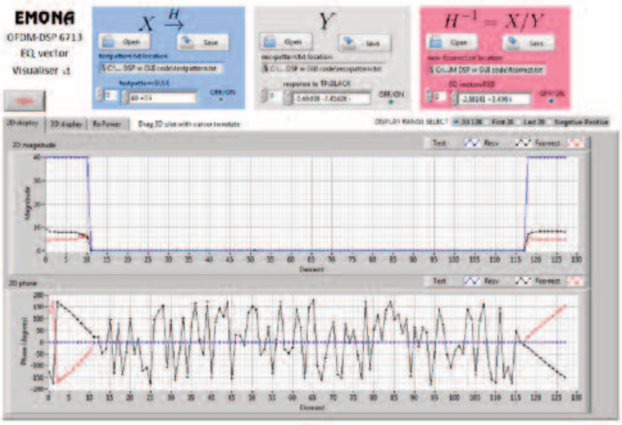


Fig. 17. EQ Visualiser - channel transfer function (black), calculated correction (red).

The calculated correction is then loaded into TIMS DSP-6713 module. By using BER instrumentation it is possible to verify that received data stream after equalisation is without errors.

In the above described setup a time invariant multipath channel module was used. TIMS also enables to investigate the properties of the other commonly used channels, such as: Rayleigh, Rice and AWGN, described in e.g. S1-14 [8].

TIMS OFDM modem has implemented 4QAM modulation. Higher order modulations can be visualized using TIMS M-LEVEL ENCODER module which supports 4, 8, and 16QAM, which currently used in LTE or 4, 8, and 16PSK constellations. The other widely used digital modulations e.g. MSK, OQPSK, π/4-DQPSK can be generated with TIMS MSK, OQPSK, π/4-DQPSK module.

In this experiment symbol detection is performed in DSP. In general, the in-depth analysis of the detection issues can be performed using TIMS INTEGRATE & DUMP module, which supplements matched filter. One of the valuable properties (in my opinion) of TIMS system is its ability of a direct quantitative comparison of gained theoretical knowledge and real measurement. The best example is the comparison of waterfall curves for *BER* and bit error probability P_b. As an example we can take BER measurement of coherent QPSK in an ideal distortion less channel, see Fig.18. This experiment is described in D7-04 [9]. In [9] BER measurement of BFSK (coherently and non-coherently detected) and DBPSK can be found.

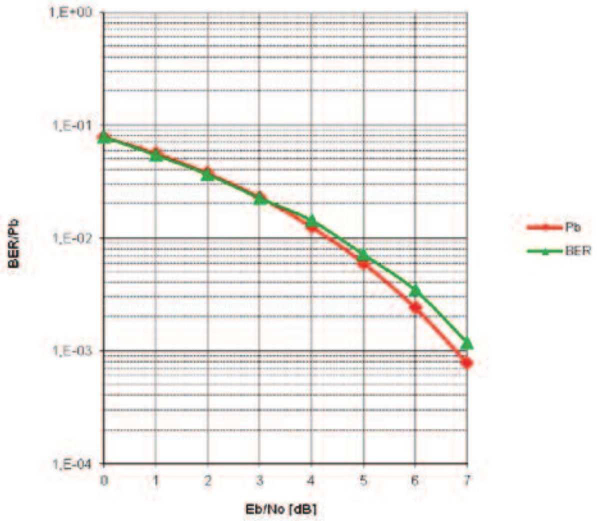


Fig. 18. Pb versus measured BER for coherent QPSK signalling (in an ideal distortion less channel).

IV. Conclusion

In this paper a modelling approach to study a new generation of mobile system was described. Even though 5G is not deployed yet and its physical layer is far more complex than described here it will be composed of a large set of simple building blocks just as the letters of the alphabet. By learning this universal alphabet TIMS helps students to learn how to read a complex "telecommunication texts" of the future.

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