Unravelling 5G Complexity: Engaging Students with TIMS-Powered Hands-on Education

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

***Keywords* - 5G, OFDM, TIMS, modelling, digital modulation.**

I. Introduction

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

II. 5G - The Mobile Communication of the Future

Mobile communications has become an integral part of our everyday life. Today we live in the era of evolving fourth generation of mobile communications bringing us much more variety of services and increased performance over the previous generations of mobile networks. The logical step after this 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]. Such 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].

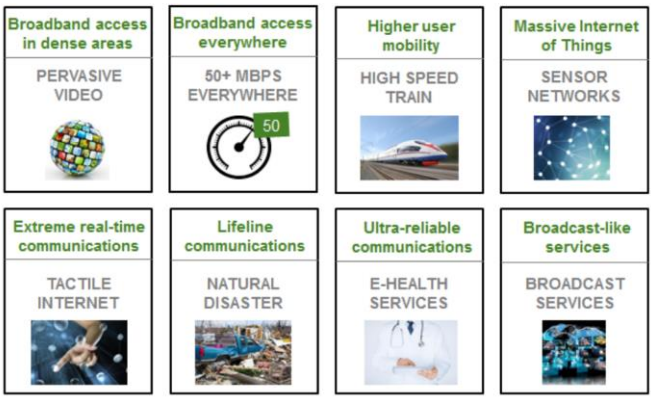

Fig. 1. 5G use case families and related examples. Source: www.ngmn.org

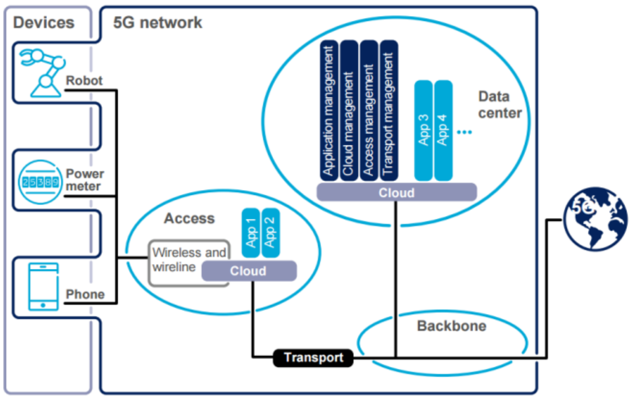

Fig. 2. The 5G system. Source: www.ericsson.com

"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 multi-connectivity concept is shown in Fig.3.

Fig. 3. The 5G multi-connectivity 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.

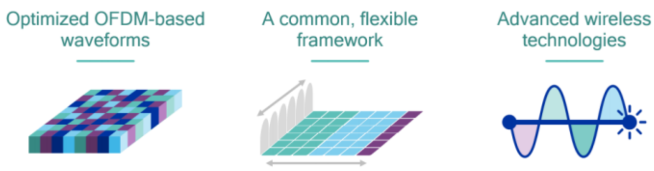

Fig. 4. The 5G NR foundational design elements.
Source: www.qualcomm.com

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.

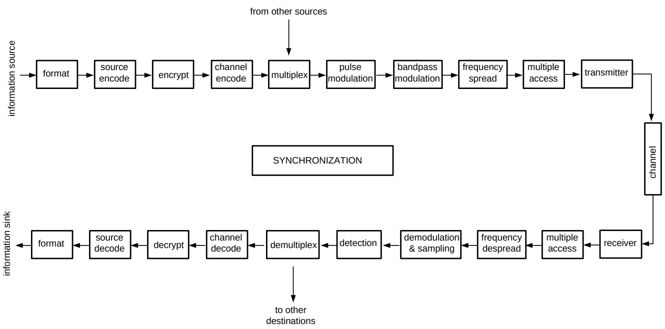

Fig. 5. Block diagram of digital communication system (DCS)

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 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 modelling the functionality of a single block 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 systems, 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 students to learn the 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. The next section will briefly describe 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 the inverse operations of the upper line of blocks.

In the following paragraphs a short demonstration of 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 in the case of a Smartphone is 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 a separate output synchronisation signal and also an embedded code within the serial data stream. A variable frequency sinusoidal message is provided which is 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. Modern channel coding is a rather complex issue. To gain knowledge with coding theory students can start with simple experiments such as: 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, binary cyclic code can also be used. These experiments are performed using TIMS BLOCK CODE ENCODER/DECODER modules. A more complex coding scheme using convolutional codes 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 the TIMS-DSP-6713 module using appropriate software. The 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.

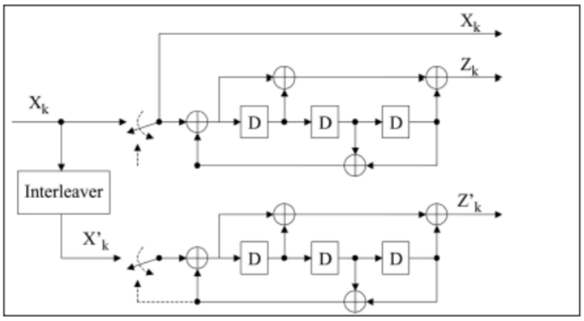

Fig. 6. UMTS turbo encoder (taken from Valenti and Sun).

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 in complex numbers. To visualize terms like: complex numbers, complex exponential, etc. TIMS has developed a standalone software enabling visualisation of complex numbers called: EQ vector Visualiser, see Fig.7.

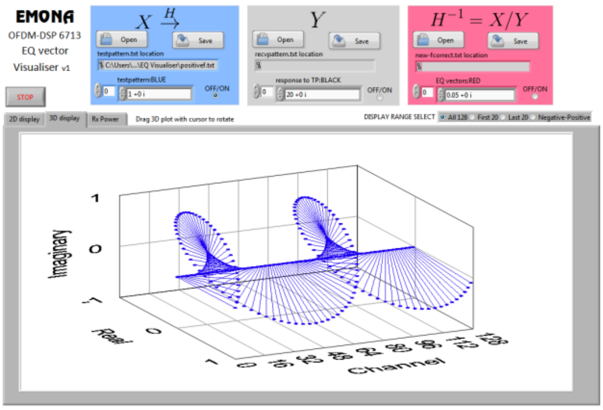

Fig. 7. Complex exponential: $z = e^{j8\pi f t}$.

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

To model a complete OFDM bandpass system using 4QAM modulation TIMS has developed an 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 to help students' understanding the real physical meaning of IDFT. Many of them when they see a known formula for IDFT:

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

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. Using the 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]".

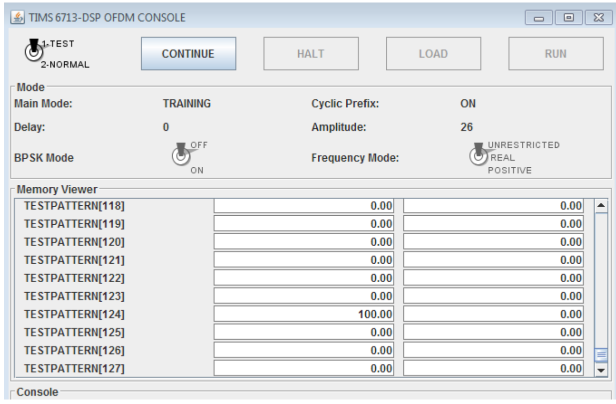

Fig. 8. TIMS OFDM GUI, setup for generating: f = - 4 [kHz].

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.

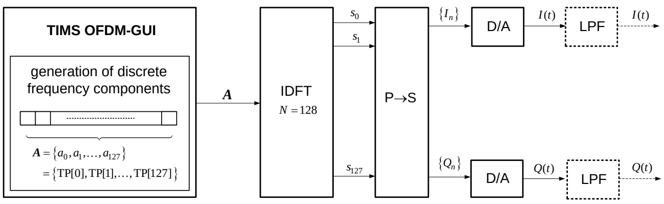

Fig. 9. Block diagram for IDFT experiment.

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.

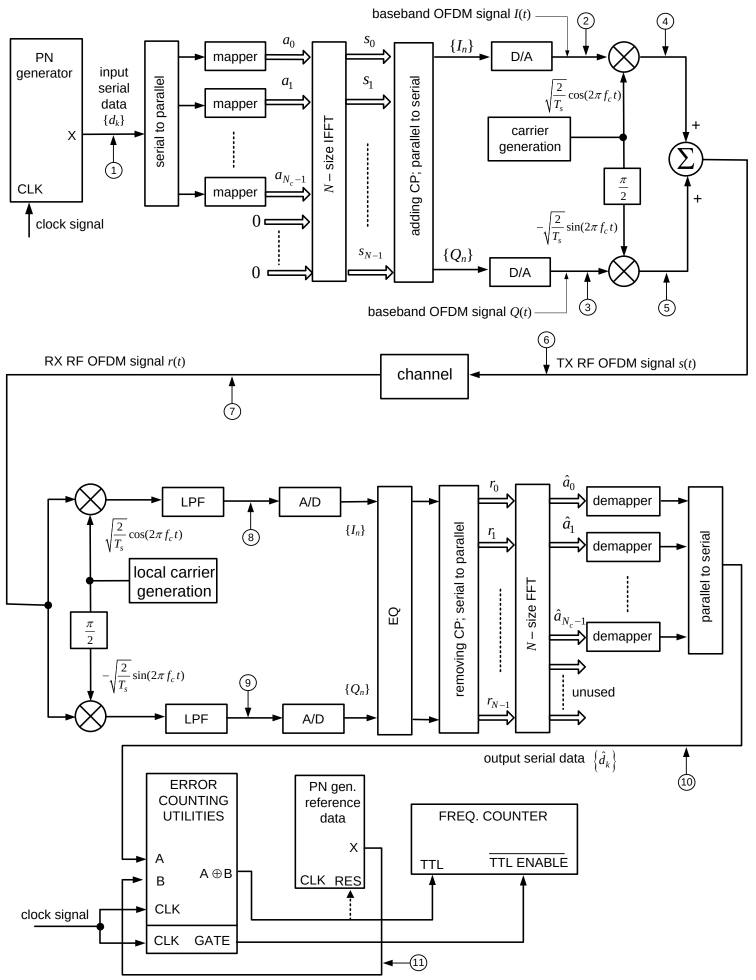

Fig. 10. Block diagram of OFDM modem.

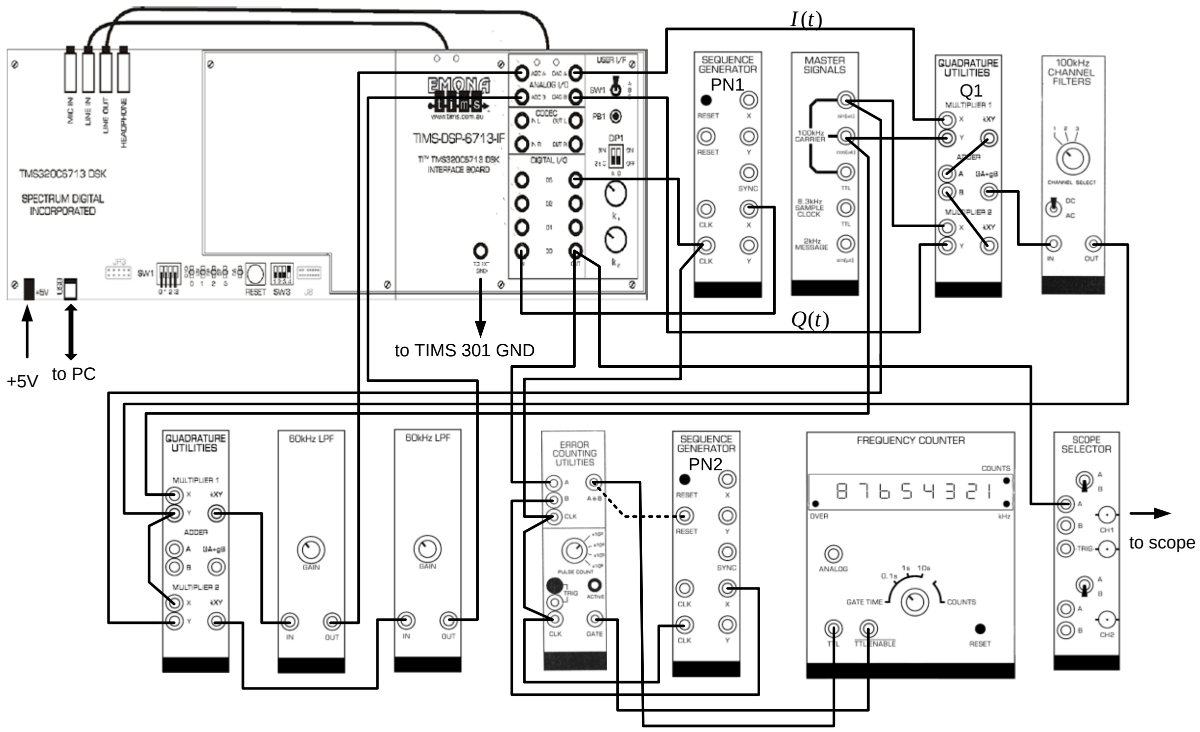

Fig. 11. Wiring diagram of OFDM modem.

The minimum subcarrier spacing in TIMS OFDM implementation is $\Delta f = f_u = 1[kHz]$. Hence the OFDM symbol duration (without CP) is $T_s = 1/\Delta f = 1[ms]$. From the TIMS OFDM software specification follows that the Cyclic Prefix (CP) takes 25% of the OFDM symbol time, thus with a CP the OFDM symbol time is increased to $T_{s\_CP} = 1.25 \cdot T_s = 1.25[ms]$. The CP can be directly observed on OFDM baseband signals (signal **2** in Fig.10) shown in Fig.12. In order to highlight the 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 to position B temporarily.

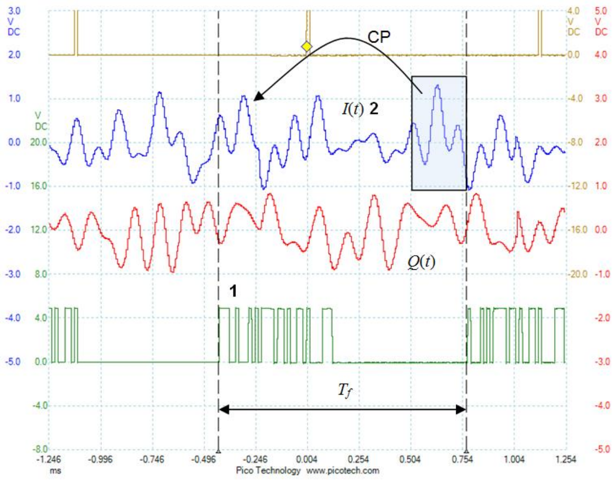

Fig. 12. OFDM baseband signal (outputs of DACs) − check points **1** and **2** on the block diagram.

As shown in Fig.10, a quadrature baseband signal modulates 100kHz carrier signal to the 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

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

, which can be easily verified by using spectral analyzer (see Fig.13.)

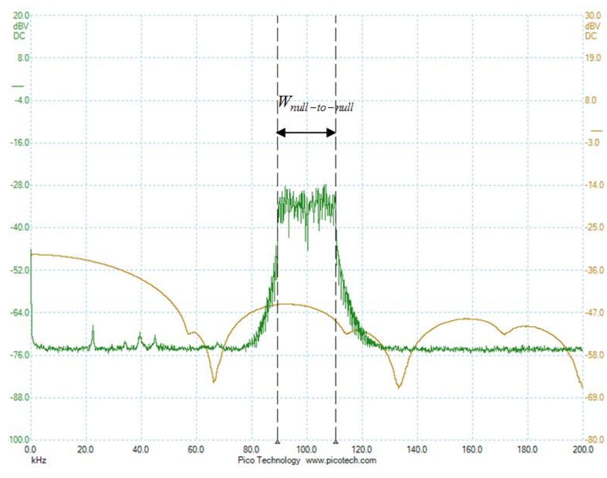

Fig. 13. OFDM spectrum - check point **7** in the block diagram Fig.10

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

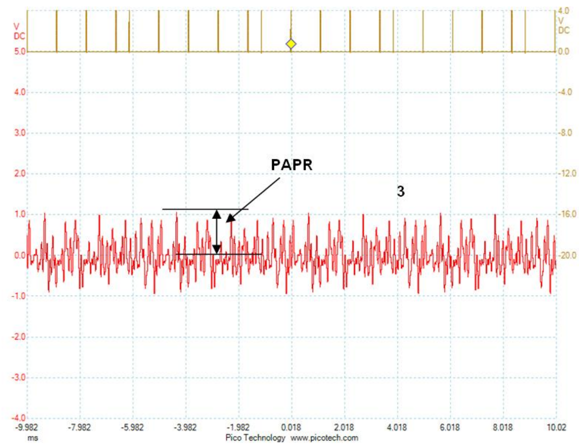

Fig. 14. Amplitude variations of the OFDN baseband signal - check point **3** on the block diagram.

Practical measurements show that the measured PAPR value of the generated OFDM signal is app. 9dB, which corresponds with max. theoretical value (assuming square QAM) of 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 correct reception, BER instrumentation was implemented in Fig.10.

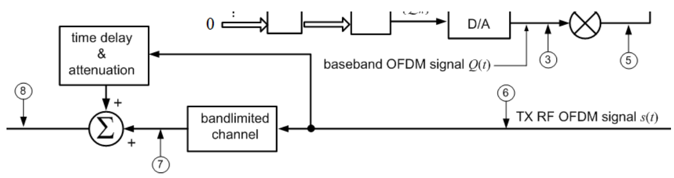

Fig. 15. Implementation of time invariant multipath channel.

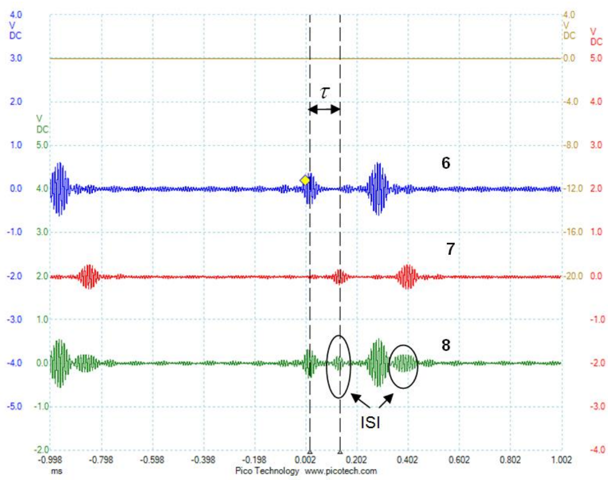

Fig. 16. Pilot signals in time domain - LOS and delayed path - check points **6** , **7** and **8** on the block diagram.

Using BER instrumentation students can easily verify that without equalisation it is not possible to achieve correct reception. One of the big advantages 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 the calculated correction (**H**$^{-1}$) can be observed using EQ Visualiser software (see Fig.17.)

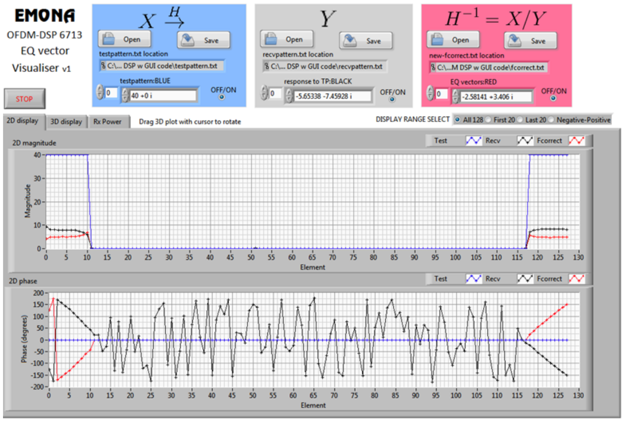

Fig. 17. EQ Visualiser - channel transfer function (black), calculated correction (red).

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

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

The 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 are 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 implements a matched filter. One of the most valuable properties (in my opinion) of TIMS system is the possibility of 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.

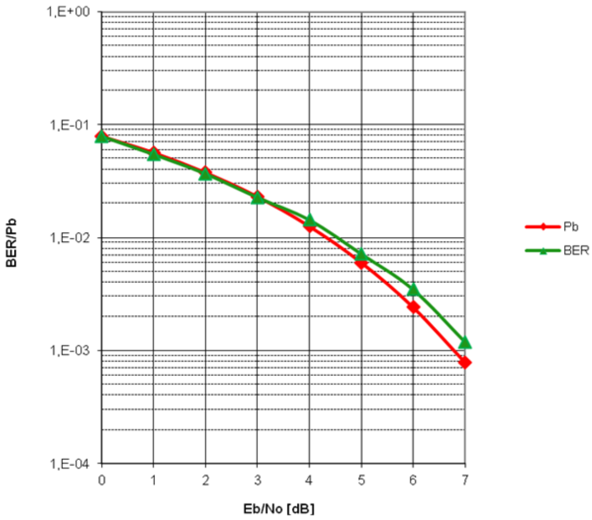

Fig. 18. Pb versus measured BER for coherent QPSK signalling (in an ideal distortion less channel).

IV. Conclusion

In this paper a modelling approach to study the new generation of a 5G mobile system was described. Even though its physical layer is far more complex than described here it is fundamentally 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 the complex "telecommunication texts" of the future.

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