Abstract—A universal software defined wireless platform and a specific method for its application is proposed here to perform field test measurements for performance evaluation of communications system. The platform implements every application, starting from the transmitter and receiver of wireless link, the virtual measurement instruments for the baseband signals and the performance evaluation algorithm, purely in software which solution offers high level of flexibility, and it provides an easy and cheap solution for performance testing. Since a PXI-based HW platform is also included in the solution proposed here, every physical RF analog signals generated or processed in software can be recovered. Both the analog RF output and input of the transceiver are available, therefore real field tests can be performed, even more, the performance of a communications system can be evaluated in a real operating network. In this paper the performance of FM-DCSK wireless communications system, operated in the 2.4-GHz ISM band, is evaluated based on real field tests using PXI platform. A systematic method for validation of system implemented on the PXI HW is provided.

I. INTRODUCTION

Transition from simulations to field test measurements is a very time consuming and expensive process if the conventional approach is used where (i) a chipset implementing the new idea is developed first and then (ii) the performance of the new system is evaluated against the real application environment. The alternative solution is to check the performance of the new idea only by computer simulation. The latter approach has a huge risk because the system performance cannot be evaluated in real field tests. Any error done in modelling or simulation results in a completely wrong conclusion.

In our approach (i) everything is or can be implemented in software but (ii) all physical RF analog signals can be recovered and processed. Property (i) offers the required level of flexibility, the cheap and fast implementation, while Property (ii) makes the system evaluation possible in a real environment where the physical RF analog signals are measured. Such a system, referred to as universal Software Defined (SD) wireless platform, can be connected even to an already existing and operating communications network.

This contribution shows the development, validation and application such a platform via the implementation of FM-DCSK communications systems. To achieve the theoretically attainable minimum sampling rate, the concept of complex envelopes are used in the SD wireless platform and every SW algorithm is run in baseband (BB).

II. RADIO SYSTEM TO BE IMPLEMENTED AND TESTED

In a Frequency-Modulated Differential Chaos Shift Keying (FMDCSK) system [1], as alternative to spread spectrum systems, a chaotic waveform is used to carry the information. Chaotic waveforms are noise-like wideband signals having no frequency, phase or amplitude. Consequently, radio chipsets developed to built conventional wireless communications systems cannot be applied, the use of SD approach and PXI-based universal HW platform is the only way to (i) implement an FM-DCSK transceiver, (ii) carry out the necessary field tests, (iii) measure its BER performance and (iv) prove the feasibility of the FM-DCSK system.

A. Operation principle and baseband model of FM-DCSK system

In a binary TR system two signals, called chips, are used to transmit one bit information. The first chip serves as a reference, while the second one carries the information.

The structure of an FM-DCSK TR signal is shown in Fig. 1, where \( g(t) \) denotes the chaotic wavelet, \( T_b \) is the bit duration. The bit duration equals \( T_b/2 \). Antipodal modulation scheme is used where the information bearing chip is equal to the delayed reference chip for bit “1,” and to the inverted and delayed reference chip for bit “0.”

![Fig. 1. Structure of FM-DCSK TR signal.](image1)

BB model of FM-DCSK modulator and demodulator has been developed in [2]. Figure 2 shows the BB equivalent of FM-DCSK modulator where \( m(t) \) denotes the chaotic wavelet, \( b_i \) is the digital bit stream to be transmitted, \( s_I(t) \) and \( s_Q(t) \) are the I/Q components, respectively, of the complex envelope of transmitted RF signal \( s(t) \). Note, the constituting blocks of modulator, such as FM modulator and DCSK modulator, are identified in the figure.

![Fig. 2. BB equivalent of FM-DCSK modulator.](image2)
BB equivalent of FM-DCSK demodulator is given in Fig. 3 where $r_I(t)$ and $r_Q(t)$ are the I/Q components, respectively, of the complex envelope of received noisy RF signal $r(t)$, $h_I(t)$ and $h_Q(t)$ are the I/Q components of the complex impulse response of channel filter and $z(t)$ denotes the observation signal. For more details and the step of derivation of BB equivalents refer to [2].

$$
\tilde{r}(t) = \sum_{i=1}^{N} \alpha_{i} \tilde{s}(t - \tau_{i}) \exp(-j2\pi f_C \tau_{i}) + \tilde{n}(t)
$$

where $\tilde{s}(t) = s_I(t) + js_Q(t)$ and $\tilde{r}(t) = r_I(t) + jr_Q(t)$ is the complex envelope of the transmitted and received signals, whose I/Q components can be identified in Figs. 2 and 3, respectively. $N$ is the number of the propagation paths, the $i$-th path is characterized by its delay $\tau_i$ and its attenuation $\alpha_i$, $f_C$ is the RF center frequency. The RF AWGN channel noise, characterized by its BB equivalent $n_I(t)$ and $n_Q(t)$, is also generated in BB. Note, $\tilde{n}(t) = n_I(t) + jn_Q(t)$.

During field test measurements not channel models but antennas and real channel environment have been used. The application of channel model in the PXI system is explained in Sec. IV.

### III. Description of the PXI-based SD Wireless Platform

The PXI-based SD wireless platform performs all the waveform-specific signal processing steps, such as modulation and demodulation, in BB on the host PC in SW while all the general purpose operations requiring high-speed data processing, such as interpolation and decimation, digital-to-analog and analog-to-digital conversion and RF up and downconversion are carried out by the PXI modules. The chassis offers advanced timing and synchronization capabilities. The block diagram of the PXI-based platform is shown in Fig. 5, the components are identified. The PXI peripheral modules constitute a vector signal generator (VSG) as transmitter (Tx) and a RF signal analyser (RFSA) as receiver (Rx). For field test measurements the separation distance, $D$, of Tx and Rx antennas was always far field, i.e., $R > 2D^2/\lambda$, where $D$ is the aperture of the antenna used, and $\lambda$ is the wavelength of the RF carrier.

### A. PXI-based HW platform

Peripheral component interconnect eXtensions for Instrumentation (PXI) environment offers a standardized PC-hosted professional modular platform for high performance measurement and automation systems [6]. Every PXI platform has three constituting components, the (i) host PC or (embedded) system controller, (ii) PXI peripheral modules and (iii) chassis that houses the controller and rack-mounted modules. The chassis offers advanced timing and synchronization capabilities. The block diagram of the PXI-based platform is shown in Fig. 5, the components are identified. The PXI peripheral modules consist of arbitrary waveform generator (AWG) that can be identified on the top left in Fig. 5.

### B. Software platform for accessing PXI devices

Efficient software platform to get access to PXI system is LabVIEW. LabVIEW integrates all the components needed for (i) controlling the PXI system, (ii) the implementation of SD applications and (iii) the evaluation of system performance. The functional block diagram of the SW for the PXI-based wireless platform is shown in Fig. 6. The FM-DCSK modulated signal samples, generated in the BB, are uploaded to the memory of arbitrary waveform generator (AWG), that can be identified on the top left in Fig. 5.
for the generation and reception of RF signal are passed to the RF
upconverter and downconverter modules, respectively, by the SW. The
digitized samples of the received signal are fetched and demodulation
is done in the baseband by SW.

The PXI architecture shares timing and synchronization signals,
therefore, tight and precise synchronization can be achieved among
PXI modules. The skew can be even less than 20 ps. To achieve this
tight synchronization careful configuration of PXI modules is required
that includes three basic steps: (i) configuration of the PXI system
to use homogeneous triggers, (ii) synchronization of the analyser
and generator sections and (iii) initiation the signal generation and
acquisition at the same time. These steps can be identified in the
right middle of Fig. 6 implemented in LabVIEW.

LabVIEW offers a user interface, referred to as “Front Panel,”
where all the signals can be visualized and all the parameters can
be entered. The Front Panel of PXI-based SD wireless platform
developed to measure the performance of the FM-DCSK radio link
is shown in Fig. 7. System parameters, BB spectrum of received
signal, BER curves, recovered bit sequences are visualized on the
Front Panel.

C. Integration of Matlab-based FM-DCSK into PXI platform

Modulation and demodulation of FM-DCSK, generation of channel
noise, multipath propagation are all implemented in BB and in
MATLAB by integrating them into LabVIEW during the PXI-based
implementation of FM-DCSK system. Matlab code can be integrated
into LabVIEW via “MATLAB script” window that runs the MATLAB
SW engine in the background and provides a SW interface to pass
or share BB signals between the two platforms.

D. Operation principle of the bit recovery procedure

When the BB samples of the received waveform are available, the
beginning of the bits has to be recovered: in our burst mode communi-
cation, an antipodal training bit sequence, located at the beginning of
every packet has been processed by a correlation algorithm. Then, the
recovery of bits, i.e., the demodulation can be performed. In the last
step the information carrying bits have been identified using a start
frame delimiter bit sequence defined by IEEE802.11. BER evaluation
is based on the comparison of the a priori known transmitted bit
sequence and the recovered bit sequence.

IV. APPLICATION OF PXI-BASED WIRELESS PLATFORM FOR
PERFORMANCE EVALUATION

The PXI-based Tx unit generates the required modulated wave-
form by transforming the I/Q components, i.e. the complex envelope
of BB signal into the RF domain. By exploiting the SD approach
even channel conditions can be implemented in BB and they can
be added in SW to the complex envelope of modulated signal to be
transmitted. The PXI Tx unit is driven by this composite complex
envelope, consequently, its output includes both the modulated signal
and the channel effects. This capability is one of the main features
of SD PXI approach, that makes the use of an expensive channel
sounder or RF noise generator unnecessary. During the development
of the system this capability has been exploited for the validation of
the channel model and the system.

Before field test measurements validation of the PXI platform has
to be done: a low loss RF cable with a variable attenuator connected
the Tx output to the Rx input. The importance of this step is twofold:
(i) an inevitable implementation loss, to be measured, always present
in an implemented system that has to be taken into account during the
evaluation of measurement result, and (ii) having a reliable channel
model, system performance in a physically non-available channel can
be measured or channel conditions can be tested in advance.

For the evaluation of FM-DCSK system performance the PXI-
based SD wireless platform, shown in Fig. 4, has been set up in
our laboratory. On the top left the PXI-chassis, while on the top
left a stand-alone spectrum analyser (SA) can be seen. During the
performance evaluation the spectra are always checked by stand-alone
SA beside the BB spectra of the transmitted FM-DCSK signal. A
qualitative comparison can be made between BB and RF spectra by
comparing the BB Power Spectrum of Fig. 7 and RF spectrum of the
same signal shown in Fig. 8. The two spectra are identical in terms
of their shape and dynamic-range. The effect of 40 MHz sampling
frequency can be observed at the edges of the spectrum.
A. BER performance in AWGN and multipath channels

The noise performance of FM-DCSK in different channel conditions, based on simulations are shown in Fig. 9. The bit duration equals to 2μs and the RF bandwidth is 17 MHz. Solid curve shows the theoretical performance of FM-DCSK system in an AWGN channel, derived in [7], for comparison. The dotted, dashed and dash-dotted curves show the performance of FM-DCSK system in residential, commercial and office environments, respectively. The performance degradation at $E_b/N_0=3 \cdot 10^{-4}$ is 9.6 dB, 10.9 dB and 12.3 dB in residential, commercial and office environments, respectively. These result can be used as references for the evaluation of the measured performance of FM-DCSK. First, the implementation loss has to be determined in an AWGN channel. In Fig. 10 solid curve again shows the performance in AWGN channel based on theoretical results [7]. Dashed curve is fitted to the results of cable connected measurements indicated by '+' marks for AWGN channel on the PXI-based wireless platform. Inspecting the solid and dashed curves in Fig. 10 it can be concluded that an inevitable implementation loss always prevents to achieve the theoretical noise performance. Although in a computer simulator the theoretical performance can be achieved, but real measurements cannot be done. The implementation loss is about 0.7 dB, on average, which is introduced by (i) the noise of the PXI external local oscillators used for both the transmitter and receiver, (ii) the noise contribution of the PXI up- and downconverter units and (iii) the quantization error of PXI waveform generator and digitizer, each appear in Fig. 5.

Field test measurements can be done in aware of the implementation loss. The RF cable has been removed and antennas for 2.4GHz have been installed with 3m separation to perform field tests. Dotted curve in Fig. 10 shows the simulated BER of FM-DCSK in indoor multipath environment, while the results of the field test measurements are shown by '*' marks on which the dash-dotted curve has been fitted. The BER measured in indoor residential environment using the PXI platform lags behind the results of simulations by ~1.7 dB at $E_b/N_0=10^{-4}$. Considering the implementation loss, the agreement between the simulated and measured results is very close. It means that (i) the applied channel model is validated for our system based on real field tests and (ii) the implementation of FM-DCSK is feasible on the PXI SD wireless platform.

Fig. 9. Performance of FM-DCSK system with bit duration 2μs in different multipath propagation environment. Channel conditions are implemented in SW, in the BB. The dashed, dotted and dash-dotted curves show the performance in indoor residential, office and commercial environments, respectively. For comparison the theoretical noise performance without multipath propagation is also plotted by solid curve.

Fig. 10. Measured performance of FM-DCSK system with bit duration 2μs in real channels. Solid and dashed curves show the theoretical BER in AWGN channel and simulated BER in indoor residential multipath channel. Dashed and dash-dotted fitted curves are based on real measurement results marked by '+' for AWGN, and '*' for indoor residential multipath channels, respectively.

V. Conclusions

The theory and practice of software defined wireless platform suitable for performance evaluation over various channel conditions have been discussed. Moreover, a systematic method for the validation of the implemented system has been introduced.

The PXI wireless platform implements every applications in BB. The software defined approach assures the flexibility and cheap implementation, while the PXI-based hardware establishes the transformation between the data sequences processed in baseband and the physical RF analog signals.

To show the effectiveness of the PXI-based SD wireless platform proposed here, the system performance of a 2.4-GHz FM-DCSK radio transceiver has been evaluated in AWGN and noisy multipath channels based on field test measurements. The measurement results have been compared against the theoretical and simulation results.

REFERENCES