From simulations to field tests: PXI-based software defined wireless platform for performance evaluation of FM-DCSK

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***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 (FM-DCSK) 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 chip 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."

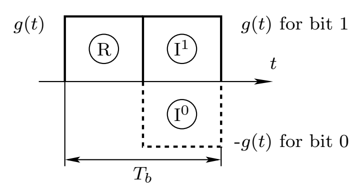

Fig. 1. Structure of FM-DCSK TR signal.

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.

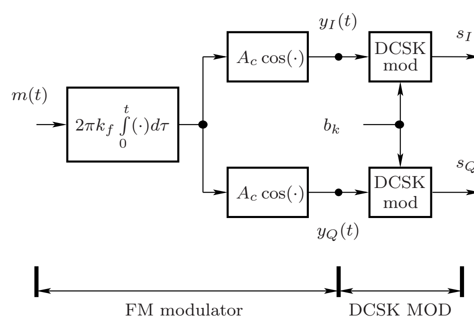

Fig. 2. BB equivalent of FM-DCSK modulator.

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].

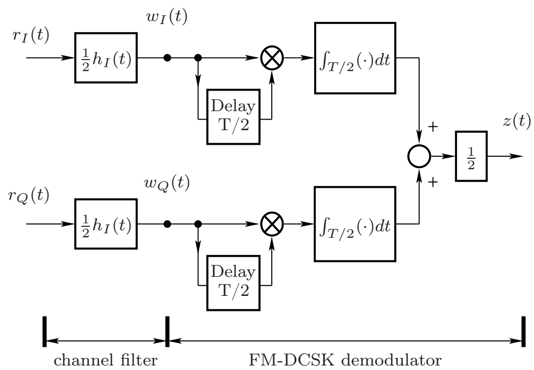

Fig. 3. BB equivalent of FM-DCSK demodulator.

The application of BB equivalents is essential since digital signal processing in the PXI system relies on the complex envelopes.

B. Channel model

The BB equivalent of radio channels can be defined by either (i) their *complex impulse response* provided by a standard committee [3] or (ii) a *tapped delay model*. For simplicity, the tapped delay model elaborated by the PCS Joint Technical Committee and published in [4] is considered here for office, residential and commercial environments. These channel models are integrated into the BB signal processing algorithm at the transmitter side. The BB model of a multipath propagation channel can be formulated as

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

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 τ_i and its attenuation α_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. Photo of the PXI-based SD wireless platform is shown in Fig. 4 where the PXI-based HW platfrom can be seen in the upper left corner.

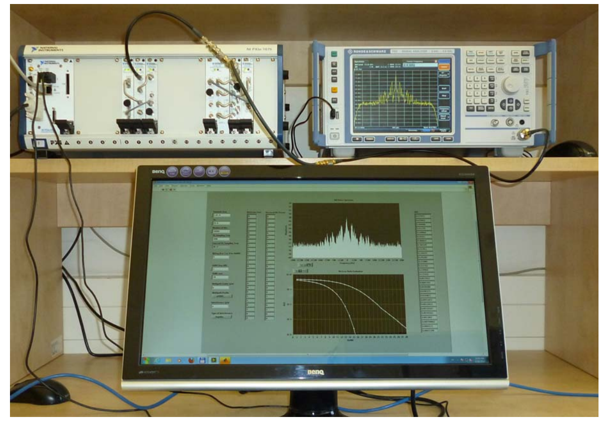

Fig. 4. Picture of the PXI-based universal SD wireless platform.

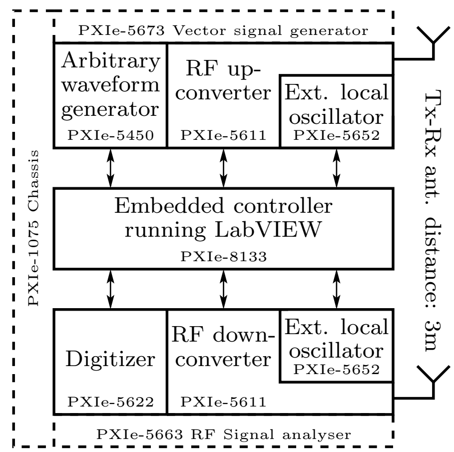

Fig. 5. Block diagram of the PXI-based HW platform

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 platfrom 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, R, 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 λ is the wavelength of the RF carrier.

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. The parameters

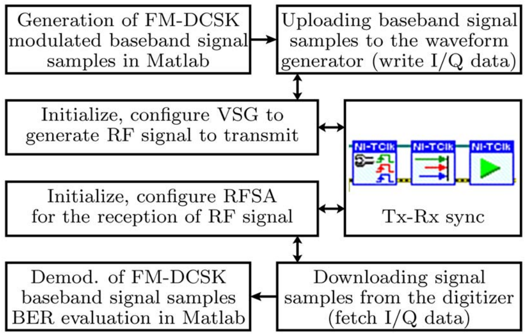

Fig. 6. Block diagram of the SW components for the wireless platform

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 communication, 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 waveform by transforming the I/Q components, i.e. the complex envelope

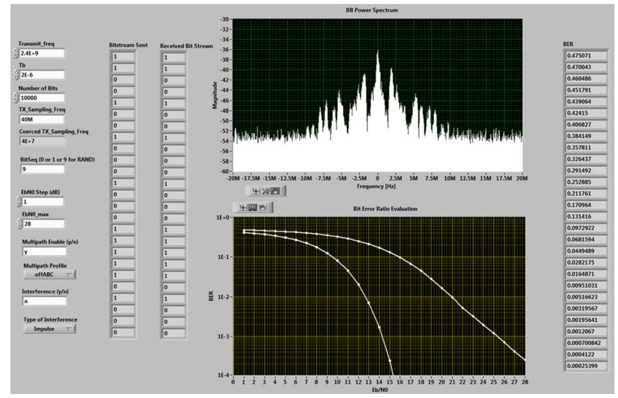

Fig. 7. User interface of the implemented FM-DCSK radio link implemented in office environment.

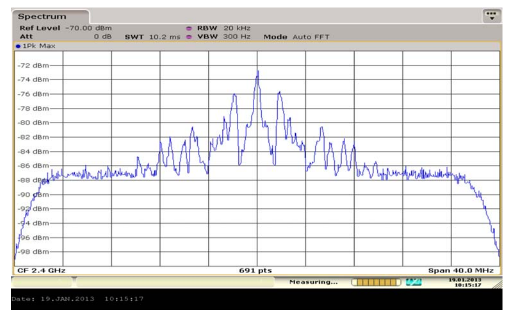

Fig. 8. Measured spectrum of FM-DCSK in office environment.

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 $2\mu s$ 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 extrernal 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 $\sim$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.

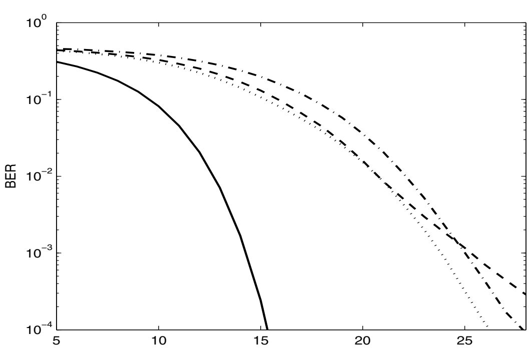

Fig. 9. Performance of FM-DCSK system with bit duration $2\mu s$ in different multipath propagation environment. Channel conditions are implemented in SW, in the BB. The dashed, dotted and dash-dotted curves show the performance in indoor residential, office and commercial environments, respectively.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

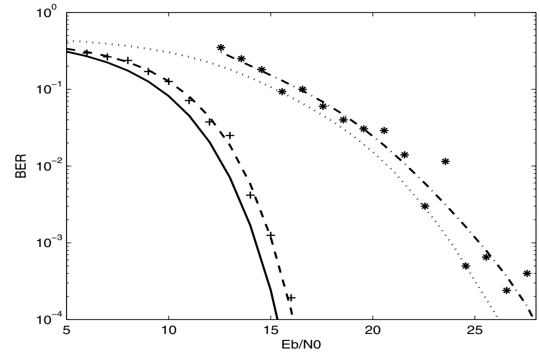

Fig. 10. Measured performance of FM-DCSK system with bit duration $2\mu s$ in real channels. Solid and dashed curves show the theoretical BER in AWGN channel and simulated BER in indoor residential multipath channel. Dashed and dash-dotted fitted curves are based on real measurement results marked by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

[1] G. Kolumbán, M. P. Kennedy, and G. Kis, "Performance improvement of chaotic communications systems," in *Proc. ECCTD'97*, Budapest, Hungary, August 30–September 3 1997, pp. 284–289.

[2] G. Kolumbán, "Performance evaluation of chaotic communications systems: Determination of low-pass equivalent model," invited tutorial at Nonlinear Dynamics of Electronic Systems, in *Proc. NDES'98*, Budapest, Hungary, July 16–18 1998, pp. 41–51.

[3] A. F. Molisch *et. al.*, *IEEE 802.15.4a Channel Model – Final Report*, IEEE802.15.4a Channel Modeling Subgroup, Online: <http://www.ieee802.org/15/pub/04/>, 2004.

[4] K. Pahlavan and A. H. Levesque, *Wireless Information Networks*. New York: Wiley, 1995.

[5] G. Kolumbán, T. Krébesz, and F. C. M. Lau, "Theory and application of software defined electronics: Design concepts for the next generation of telecommunications and measurement systems," *IEEE Circuits and Systems Magazine*, vol. 12, no. 2, pp. 8–34, Second Quarter 2012.

[6] *PXI Hardware Specification, Revision 2.2*, PCI eXtensions for Instrumentation, PXI Systems Alliance, 2004.

[7] G. Kolumbán, "Theoretical noise performance of correlator-based chaotic communications schemes," *IEEE Trans. Circuits and Syst. I*, vol. 47, no. 12, pp. 1692–1701, December 2000.