# A Novel Non-Stationary Multipath Fading Channel Model Based on Propagation Measurements Using SDR and FPGA

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***Abstract*** —Non-stationary multipath fading channel models are necessary for the design and optimization of communications systems (the 5th generation mobile networks - 5G, the (Industrial) Internet of Things, etc.). These models are considered as essential components of channel simulators which are similar to physical radio channels. This article describes a progressive novel method of adaptive non-stationary multipath fading channel models based on a real measurement of Channel Impulse Response (CIR). The designed system measures, classifies and subsequently adaptively changes the parameters of a transmission channel model. The proposed concept is based on the Software Defined Radio (SDR) and Field Programmable Gate Array (FPGA) which are implemented on the modular platform of PCI Extensions for Instrumentation (PXI). This approach enables to approximate and subsequently adaptively model any transmission environment. Thanks to the application of the adaptive parameter setting approach we can create unique dynamic models of real transmission channels which can be used for designing, testing and optimizing new trends in the field of wireless communications systems (new modulation formats, algorithm testing, channel equalization, optimization of source and channel coding, guard interval adaptation, etc.).

***Index Terms***—Multipath Fading, Channel Model, CIR - Channel Impulse Response, SDR - Software Defined Radio, PCI Extensions for Instrumentation, FPGA - Field Programmable Gate Array, ISI Inter-Symbol Interference.

## I. Introduction

Current models, or more precisely software simulators, used for modelling transmission channel characteristics are only static; see [1]-[4]. Since the static approach to the modelling of transmission channels is from the point of view of real measurements very idealized, it can cause problems when testing new wireless communications system technology, see [5] and [6]. Methods which show quite good results during the simulation cannot be applied and implemented in a real environment (e.g. elimination methods of Inter-Symbol Interference, ISI), see [4]. Another finding is the fact that static simulators cannot be used sequentially. Similarity between such simulated radio channels and real radio channels is minimal. Furthermore, currently used simulators cannot be used to apply the feedback and sequence principles of new generation radio networks (5th generation mobile networks or 5th generation wireless systems - 5G), see [2], [3], [7], and [8]. New generation radio network - 5G are the proposed next telecommunications standards beyond the current 4G/IMT-Advanced standards. 5G planning aims at higher capacity than current 4G, allowing a higher density of mobile broadband users, and supporting device-to-device, ultra-reliable, and massive machine communications, see [9]-[12]. New generation 5G research and development also aims at lower latency than 4G equipment and lower battery consumption, for better implementation of the Internet of Things (IoT).

This article is focused on the design and realization of a novel non-stationary multipath fading channel model based on propagation measurements using SDR (Software Defined Radio) and FPGA (Field Programmable Gate Array), [13]-[17]. National Instruments software defined radios (SDRs) provide the design solution to rapidly prototype wireless communications systems, which leads to faster results. You can present applications with real-world signals such as Multiple Input, Multiple Output (MIMO) and LTE/WiFi testbed. To design a non-stationary multipath fading channel model, it is necessary, in the first stage, to carry out a measurement of real radio channel impulse response. This article presents a well-known oscilloscopic method of the radio channel impulse response with the Dirac's pulses extended with the possibilities of current professional measurement devices and FPGA. Instead of periodic Dirac's pulses, the short sine signals are being sent. As a receiver there is a SDR with the sample rate of 130 MS/s and FPGA with the mathematical mean algorithm, see [18]-[20]. The advantage of this method is much higher speed in comparison with the measurements

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with VNA. Current technical practice uses CIR methods for measurements such as oscilloscopic, FFT, correlation [5], which are too slow and compute-intensive for the required measurement speed and resolution.

## II. The Real Radio Channel Impulse Respone Measurement

Fig. 1 shows the principal scheme of CIR measurement method. The measurement system consists of PC with connected PXIe which includes FlexRIO FPGA PXIe-7966 and RF SDR NI-5791 to 130 MS/s. The transmitter (TX) periodically transmits 8–16 ns long sine pulses in the frequency band of 900 MHz every 800–5000 ns. The receiver (RX) catches the pulses which passed the multipath radio channel, creating CIR. FPGA mathematically calculates an average of 1000–20000 CIR arriving at one CIR which is then sent into a superior system. Due to a low TX power, a low sensitivity of SDR and long coaxial cables two amplifiers ERA-1 and BGY925 must be added. The RX antenna has two SAW filters B3725 and two LNA MAR-8 and ERA-5. An omnidirectional sector and beam antennas were used for carrying out the measurements.

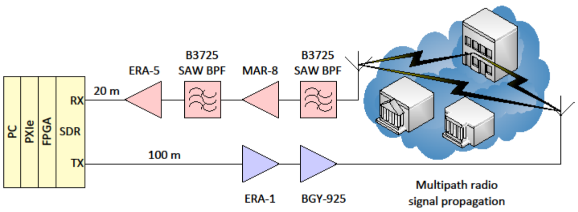


Fig. 1. Block diagram of the CIR measurement method.

The NI-5791 provides continuous frequency coverage from 200 MHz to 4.4 GHz. It features a single-stage, direct conversion architecture that provides high bandwidth in the small form factor of a FlexRIO adapter module. The onboard synthesizer, which is the local oscillator (LO), sets the center frequency for acquisition and generation, and you can export it to other modules for multiple input, multiple output (MIMO) synchronization.

The PXIe-7966 provides flexible, customizable I/O for LabVIEW FPGA. It includes 132 single-ended I/O lines configurable as 66 differential pairs. You can pair the PXIe-7966 with FlexRIO adapter modules that offer high-performance analog and digital I/O. Together, the two modules create a reconfigurable instrument that you can program with LabVIEW FPGA software.

The measurement was carried out in a densely built-up agglomeration. Fig. 2a and Fig. 2b show the recordings of CIR characteristics of sector and omnidirectional antennas. To better demonstrate the results in the form of CIR, we created the video recordings of 3D graphs, see [21]. Graphs in Fig. 2a and Fig. 2b show a significant impact of multipath propagation. Together with a sharp movement of the antenna there is a sharp fluctuation of the amplitude of individual radio-paths A. Approximating and receding obstacles cause changes in the delay of a particular radio-path B. Multipath propagation includes an infinite number of radio-paths C. CIR has theoretically an infinite length, but interferences from surrounding devices and a small dynamic range do not allow to measure low-level signals with the delay greater than 1.5 μs which is under the noise-floor level.

When using the sector antenna in Fig. 2, there is in most cases just one beam which is dominant at exactly one point of time. In modern radio networks, since the occurrence of two and more beams of multipath propagation in sector antennas causes Inter Symbol Interference (ISI), not every technology can suppress ISI well. When using the omnidirectional antenna in Fig. 2b more dominant beams with different delay times usually arrive at the receiver. Therefore, due to a low gain of the omnidirectional antenna, these antennas are not used in radio networks. To simplify the development of new modulations and radio networks, the following simulator was designed.

## III. Radio Channel Simulator of Critical Temporary

Fig. 3 shows a simplified functional diagram of the multipath radio channel simulator. Such created radio channel simulator is based on the measured CIR characteristics of real transmission environment. From the recordings of CIR characteristics of a particular environment (a city built-up area), using mathematical and statistical analyses, we obtained a maximum speed of changes in a beam amplitude, a maximum speed of changes in a beam path length, a maximum speed of changes in a beam phase, an average occurrence distribution of a particular number of dominant beams, beam delays and beam amplitude delays, maximum amplitudes for a given beam delays, etc. In this way, a table is generated for every type of environment, showing the configuration parameters for a radio channel simulator of critical temporary effects.

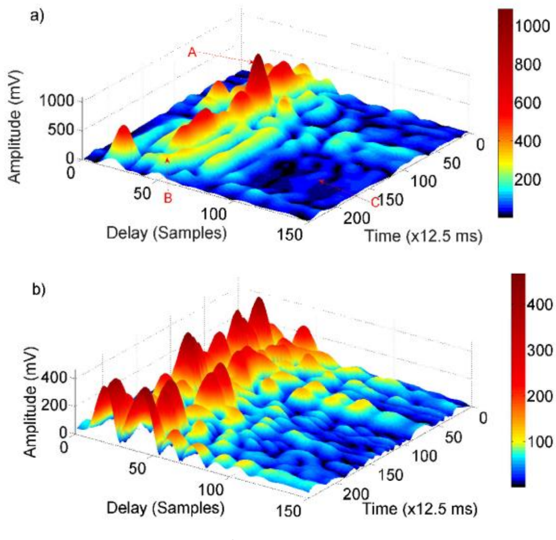


Fig. 2. Final 3D histograms of the CIR real measurement (measurement time 3 s, measurement speed 80 CIR/s), a) sector antenna b) omnidirectional antenna.

The simulator generates several hundred simulated radio beams to which physical impacts of a radio channel are applied according to a probability distribution from the configuration parameter table. Step changes were removed from the simulated field of changes in beam characteristics using the filters. The array of changes in beam delays is transferred to the array of moving peaks. The array of changes in amplitudes and beam phases are merged into the array of continuous changes in individual beam vectors. By combining the arrays of moving peaks and continuous changes in beam vectors we can create a continuously changing CIR characteristic of the simulated radio channel with critical temporary effects.

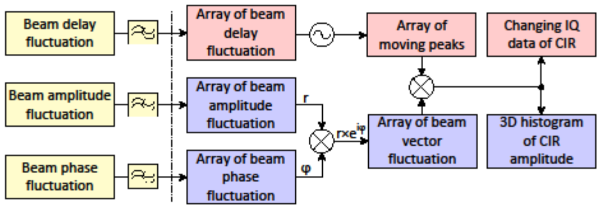


Fig. 3. Simplified functional diagram of the multipath propagation radio channel simulator.

The following mathematical equations describe individual fluctuations of physical effects on the radio channel. The complete mathematical entry of individual fluctuations is often much more complex, so only the basic idea for each of the influences is described here.

**Ray delay fluctuation:**

$$x = \mathrm{Random}(0\,..\,1) \quad (1)$$

$$f_d(x) = \frac{2x-1}{|2x-1|}\,(|2x-1|)^{\lambda_d}; \qquad \lambda_d > 1; \quad (2)$$

$$H\big(f(x)\big) = (-1\ ,1); \quad (3)$$

$f_d(x)$ – PC optimized random number generator with sided exponential distribution (2)

$\lambda_d$ – Environment configuration parameter indicates the probability of occurrence of abrupt change in beam path length

$$\Delta d(x) = \Delta d_{max} * f_d(x) \quad [S]; \quad \Delta d_{max} < 900\ S; \quad (4)$$

$$H\big(\Delta d(x)\big) = (-\Delta d_{max}\ ,+\Delta d_{max}); \quad (5)$$

$\Delta d(x)$ – Coefficient of variation of the length of the beam paths (4)

$\Delta d_{max}$ – Maximum rate of change of beam path length

$$d(t) = d(t-1) + \Delta d(x) \quad [S]; \quad (6)$$

$$H\big(d(t)\big) = (50\ S\ ,\ 950\ S) \quad (7)$$

d(t) – Ray delay fluctuation in Samples (6)

d(t-1) – Last value of ray delay fluctuation

**Ray amplitude fluctuation:**

(Volts as measured in Fig. 1)

$$x = Random(0\,..\,1) \quad (8)$$

$$\Delta f_a(x) = 2x - 1; \quad (9)$$

$$H(\Delta f_a(x)) = (-1\ ,\ 1); \quad (10)$$

$\Delta f_a(x)$ – PC optimised random number generator with bidirectional linear distribution (9)

$$f_a(t) = f_a(t-1) + \Delta f_a(x) * \lambda_a; \quad 0 < \lambda_a \ll 1; \quad (11)$$

$$H(f_a(t)) = (0{,}1); \quad (12)$$

$f_a(t)$ – Beam coefficient of variation of voltage (11)

$f_a(t\text{-}1)$ – Last value of beam coefficient of variation of voltage

$\lambda_a$ – maximum beam voltage increase

$$U_a(t) = \big(f_a(t)\big)^{\lambda_v} \quad [V]; \quad \lambda_v > 1\ ; \quad (13)$$

$$H\big(U(t)\big) = (0{,}1); \quad (14)$$

$U_a(t)$ – Voltage of the simulated beam in Volts as in Fig. 2 (13)

$\lambda_v$ – Probability coefficient of the presence of dominant rays

**Ray phase fluctuation:**

$$\varphi(t) = 2\pi\frac{\left(d(t)\cdot\frac{1}{f_S}\right)\,mod\left(\frac{1}{f_{Hz}}\right)}{\frac{1}{f_{Hz}}} - \pi \quad [rad] \quad (15)$$

d(t) – Ray delay fluctuation in Samples

$f_S$ – Sampling frequency

$f_{Hz}$ – Frequency of radio signal

According to Fig. 3 the advantage of the above described concept is the possibility of adapting the configuration parameters of a modelled communications channel on the basis of any real CIR measurements. In this way, we can extend the database of configuration parameters by any real environments which will be measured using the method in Fig. 1. The proposed concept in Fig. 3 uses a configuration parameter table (e.g. the occurrence probability of dominant paths in multipath propagation, the probability distribution of dominant paths on the delay axis, the maximum speed of changes in path length, the probability distribution of changes in path length, etc.). Mathematical relations describing partial segments of the proposed concept are generally well-known and well described in the statistical analysis.

The aim of authors was not to give a detailed mathematical description, but to propose an entirely novel approach to the dynamic radio channel generation. An original contribution of the proposed method is the possibility of generating time-space continuous radio channel, which is not allowed by current simulators. Due to the above mentioned characteristics, the realized simulator can effectively develop and test currently existing technologies as well as new appearing radio technologies, including feedback and adaptive methods (e.g. adaptive modulations, methods of channel equalization, adaptive lengths of guard interval, etc.), which cannot be provided using current radio channel simulators.

## IV. Results

Fig. 4 shows a model of the synthetic CIR characteristic of the simulated radio channel with critical temporary effects, which reflects a really measured environment of the city built-up area. Graph in Fig. 4a shows a typical overlapping of two dominant beams in the sign A, when one beam is receding, its path becomes longer and the delay increases. The beam amplitude sharply falls, allowing the second beam to arise with growing amplitude on a shorter path.

Graph in Fig. 4b shows several different states of the radio channel and transitions among them, the sign A stands for a fast-fading channel, the sign B stands for a slow-fading channel, the sign C points at hundreds of inferior paths, a transition from the sign A to the sign B describes the transition of a moving participant from the fast-fading channel into the slow-fare generaading channel. All these physical effects ted on the basis of analyzed data from the measurements in Fig. 1.

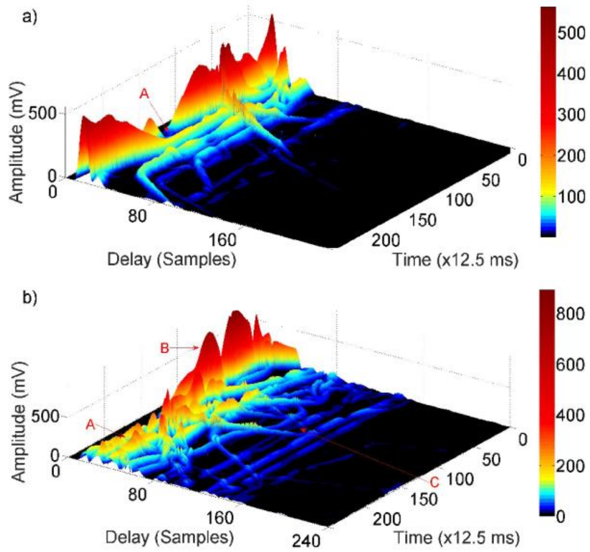


Fig. 4. Modelled 3D histograms a) dominant beam overlapping, b) transitions among different radio channels.

## V. Conclusion

A long-term extensive measurement of CIR characteristics of a particular environment is essential for the correct configuration of a created simulator. With the correct configuration parameters, the simulator can generate an infinite number of sequentially changing radio-CIRs in which we can simulate the movement of both end points and all obstacles in any direction using random speed. Slow and fast fading, drive-by with a mobile phone and so on. In this regard, none of the current radio channel simulators can be compared to a newly created radio channel simulator of temporary critical effects.

The main contribution of the work is in the creation of a virtual instrument designed for the modelling of wireless fading channels and RF impairments, applicable in wireless transmission systems.

The presented simulator can be used for developing new radio networks (5G, DVB-T3), see [22], [23] and [24]. The radio channel emulator based on the same principle can substitute measurement polygons and many different measurement environments which are necessary for the production and testing of quality of new end-devices (mobile phones, radio transmitters, DVB-T receivers). The proposed simulator can be used for the development and improvement of new and current modulation formats and radio networks even without the utilization of costly measurement equipment which is not available at all workplaces/universities/companies.

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