Design and Implementation of Analyzing Instrument for Broadband Powerline Communications

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***Abstract*—This paper deals with the design and implementation of the analyzing instrument for the broadband powerline communication. This instrument has integrated functions for channel estimation, noise power spectrum measurement, and impedance measurement. It consists of a digital board with high speed DSP and FPGA chips, an analog board as a front-end adaptation to the powerline medium, and a Windows GUI application for presenting measurement results. This paper gives measurement algorithms used in this system and a description of the hardware and software prototype.**

***Keywords*— Broadband PLC, analyzing instrument, hardware prototype**

I. Introduction

THE power supply networks are available worldwide in a very large number of households or buildings, and can be used for communication purpose. Nowadays, the powerline communication technology seems to be an alternative solution for the realization of broadband access networks. However, the powerline medium was originally designed for optimal electrical power transportation, severe line attenuations and delay effects exist in the frequency range for data signal transmissions, especially up to 30 MHz. Such bad channel properties are based on the variation of impedances on the powerline. Moreover, the presence of unpredictable noise is another important impairment [1].

These problems is not only dependent on the specific powerline, but also time dependent as electrical equipment are connected and disconnected to the powerline, or activated and deactivated. Therefore, to have detailed knowledge about the powerline channel or install the PLC application at specific sites, numerous measurements are necessary at different locations and times.

Standard instruments such as network analyzer, spectrum analyzer, etc are not optimized for powerline measurements and are not compact to handle. The measurement setup is very troublesome and takes a lot of time. Moreover, additional post-processing on measurement results might be necessary. In some cases, they will not be possible for economic reason.

Backgrounds like these are reasons why we develop an analyzing instrument for broadband powerline communication. Actually, there were similar works which had been already developed at industrial companies [2-4]. The product presented in [2, 3] had been a pioneer work, but it is currently unavailable and the product in [4] has a limited functionality for a specific platform.

We made the instrument which has compact and cost-efficient system configuration, provides easy measurement setup, and processes measured data fast. The instrument can measure channel properties including attenuation, phase, and delay, noise spectrum, and impedance on the powerline. Unlike standard instruments, the powerline analyzing instrument performs measurements easily due to the compact system configuration specialized for powerline environments.

The rest of the paper is structured as follows. Hardware designs of the instrument are described in Section II. Then, software designs of the instrument are followed in Section III. Channel, noise and impedance analysis algorithms used in this work are described in Section IV. Finally, the paper will be summarized in Section V.

II. Hardware Designs

The analyzing instrument that we've developed consists of a digital board with high speed DSP and FPGA chips, an analog board as a front-end adaptation to powerline medium, and a

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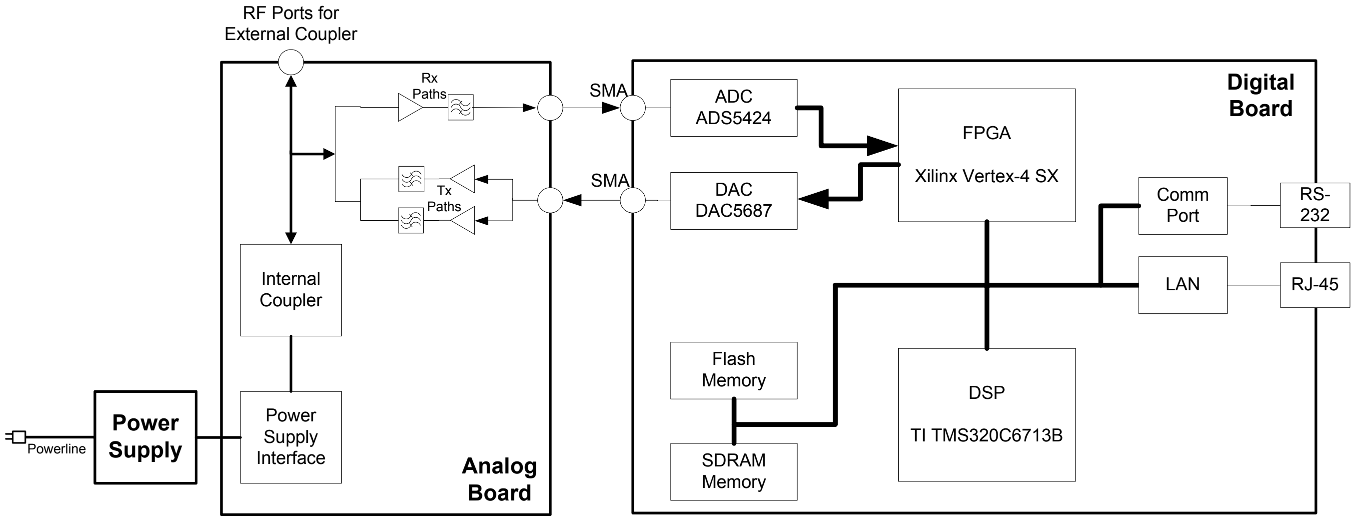

Fig. 1. Hardware concept for the powerline analyzing instrument

Windows GUI application for presenting measurement results.

The Windows GUI application is included in a personal computer (PC). Fig. 1 illustrates the general structure of the powerline analyzing instrument. The digital board (Fig. 2) in the instrument includes a high-performance Digital Signal Processor (DSP), multi million-gate FPGA, high-resolution Digital-to-Analog Converters (DACs) and Analog-to-Digital Converters (ADCs), sufficient memory (SDRAM 32 MB, Flash 4 MB), 10/100 Mbps Ethernet interface, and dual-port RS-232. The DSP used in this system is Texas Instruments TI-TMS320C6713B which delivers up to 1800 million floating-point operations per second (MFLOPS), 2400 million instructions per second (MIPS) operating at 300 MHz. The FPGA is Xilinx Virtex-4 SX which offers 2.5 million-gate capabilities and gives high-performance solution for digital signal processing applications.

The ADC is Texas Instruments ADS5424 which gives 14 bit resolution and 105 MHz maximum sampling rate and the DAC is Texas Instruments DAC5687 which gives 16 bit resolution and 500 MHz maximum sampling rates. The ADC and the DAC convert signal and data to/from the analog board. The digital board has a RJ-45 Ethernet port which sends the measurement data to a laptop PC and receives the control message from the PC. A RJ-235 port is used for binary data signal exchanges with a debug monitor. The user can configure the system setting or acquire measurement data with the Windows GUI application installed on the PC.

The analog board (Fig. 3) has internal coupling circuit which couples the powerline test signal from the mains AC signal, two seperated Tx paths for channel and impedance analysis, one Rx path for received signals, and the power supply interface which delivers power for driving the analog board and the digital board. The signals coming from the Tx paths are amplified and low-pass filtered. After that, they pass the internal coupling circuit for powerline transmission. The analog board also has additional RF port for an external coupler. Therefore, a medium-voltage (MV) coupler or any other user-defined couplers can be used with the instrument. On the other hand, the signals coming from the powerline via the coupling circuit or the external coupler are attenuated or amplified to be agreeable to the input range of the ADC. Then, they pass the Rx path including band-pass filtering. After filtering, the signals are analog-to-digital converted with a sampling rate of 100 MHz, into a 14 bit word. The digitized signal is fed into the FPGA and the DSP for channel or impedance analysis.

III. SOFTWARE DESIGNS

There are three kinds of analysis supported in the instrument: channel analysis, noise analysis, and impedance analysis. The user can create only one analysis simultaneously. This is performed by the user in the Windows application. In addition to the creation of the analysis process, the Windows application is responsible for monitoring and controlling of the analysis process running on the DSP. After creation of an analysis, the control message for the analysis process is transferred to the DSP. Then, the process on the DSP is executed independently of the Windows application. The real-time operating system running on the DSP has helped make it possible. After the reception of the control message, the software on the DSP reports the analysis results to the Windows application, repeatedly. Thus, real-time processing of continuous data streams is possible.

The user can set and optimize the measurement condition such as the display unit, the frequency range and so on. The most important role of the Windows application is presenting the analysis result to the user with graphical aids. The user can read the results in terms of the high-resolution graphs.

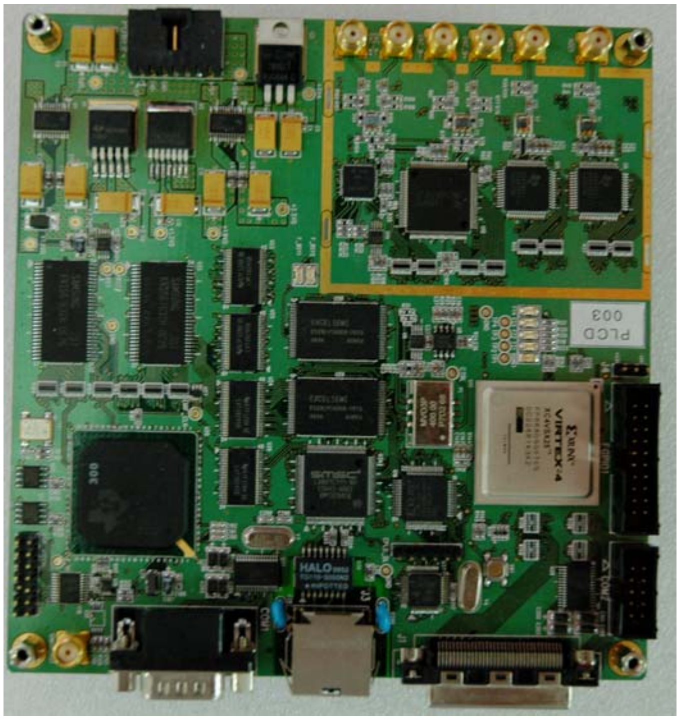

Fig. 2. Photo of the developed digital board

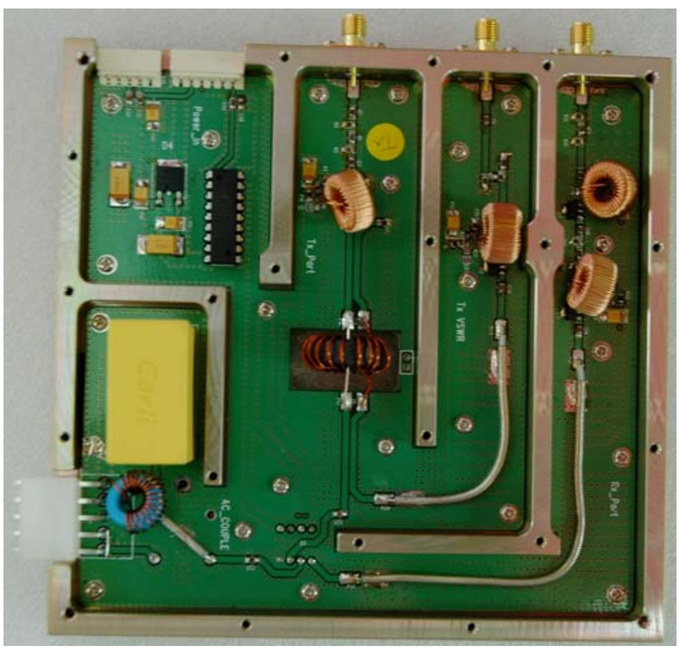

Fig. 3. Photo of the developed analog board

Moreover, the user can save measurement data to a file on the hard disk drive of the PC by using the Windows application. The files made by the Windows application are easily handled by another application such as Matlab and Excel which offers further possibilities for the automation of analysis and the evaluation of results.

IV. DESCRIPTIONS OF THE ALGORITHMS

A. Channel Analysis

Generally, the channel analysis is performed by calculating the relation between a specific signal transmitted over the channel and a signal received with channel noise. There are several methods to find the channel characteristics by using standard instruments. But, each method has some drawbacks as described follow. If a signal generator is used as a transmitter and a spectrum analyzer is used as a receiver, only attenuations over the specific spectrum can be obtained. Without an external link for the synchronization, which is impossible for measurements over larger distances, a phase distortion remains unknown. If a network analyzer is used for the channel measurement, the attenuation and the phase can be obtain simultaneously. But, it is also impossible for measurements over larger distances.

The algorithm applied in the proposed system uses periodic broadband signals. Any connection for the synchronization is not needed because the system employs the periodic signal. Moreover, channel transfer functions can be obtained directly and updated continuously because of the use of broadband signals. The time-domain channel characteristics such as impulse response and delay spread can be obtained from the inverse Fast Fouier Transform (FFT) of the channel transfer function.

The proposed channel analysis is based on the OFDM transceiver system model described in Fig. 4. The channel transfer function $H[k]$ is estimated by using the transmitted signal $B[k]$ and the received signal $R[k]$, where k is a discrete-time index for the frequency-domain. The transmitted signal $B[k]$ is BPSK-modulated periodic pilot signal which is pre-determined by the system and known at both the transmitter and the receiver. The signal $B[k]$ is modulated according to a typical OFDM transmitter structure shown in Fig. 4. After the DAC of the digital board, the transmitted digital signal is converted to the time-domain analog signal $b(t)$. Then, the signal passes the analog board of the transmitter, the powerline channel, and the analog board of the receiver in sequence. If it is assumed that the channel is time-invariant within a single measurement time unit, the input signal $r(t)$ of the ADC of the receiver is given by

$$r(t) = b(t) * h_t(t) * h(t) * h_r(t) + w(t) * h_r(t)\,, \qquad (1)$$

where $h_t(t)$ and $h_r(t)$ are the impulse response functions of transmitter and receiver analog path, respectively, and $w(t)$ is the noise of the powerline channel.

The time-domain analog signal $r(t)$ is converted into the digital signal by the DAC, and then demodulated according to a typical OFDM receiver structure shown in Fig. 4. Finally, we can obtain the frequency-domain received signal $R[k]$ at the end of the receiver structure.

To eliminate the influence of the impulse response of transmitter and receiver analog path, the calibration mode is

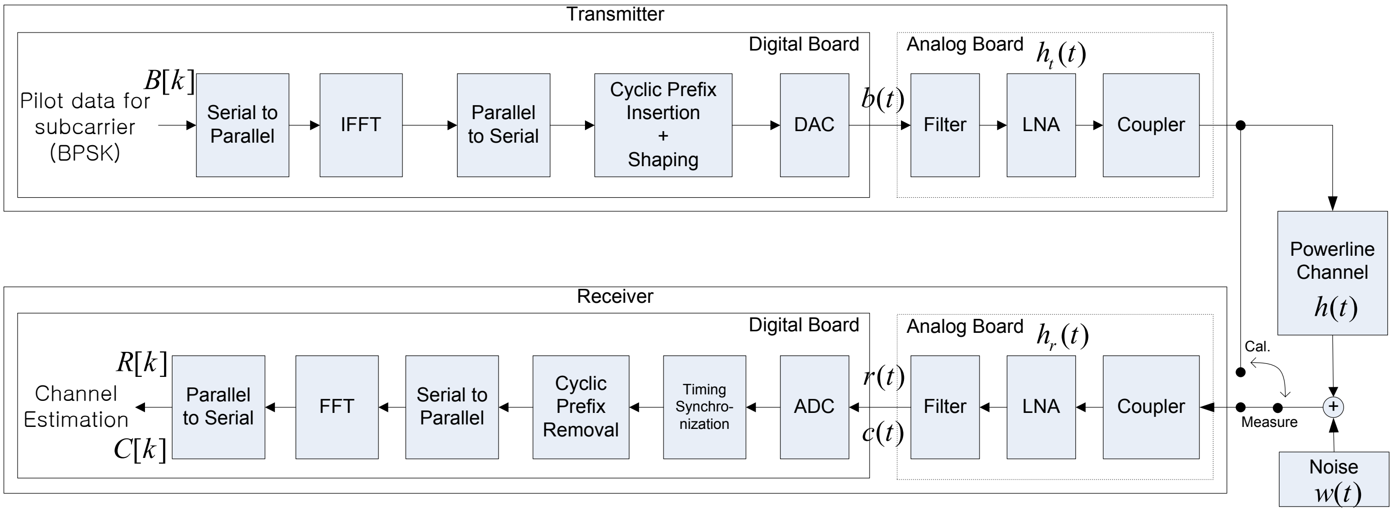

Fig. 4. System model for the channel analysis

introduced. In the calibration mode, the transmitter is directly connected to the receiver. Thus, we can obtain signal distortions which are only caused by the measurement system. The received signal $c(t)$ in the calibration mode is given by

$$c(t) = b(t) * h_t(t) * h_r(t) . \tag{2}$$

The substitution of (2) into (1) yields the following expression:

$$r(t) = c(t) * h(t) + w(t) * h_r(t) \tag{3}$$

In accordance in (3), the channel estimate on the frequency-domain, that is, the estimate of the channel transfer function is given by

$$\hat{H}[k] = \frac{R[k]}{C[k]} , \tag{4}$$

where $C[k]$ is the frequency-domain received signal at the end of the receiver structure in the calibration mode. The estimation error can be reduced by averaging several sequential estimation results because the estimation is unbiased.

In consideration of the implementation, the pre-determined periodic pilot sequence can be easily generated by the FPGA and the FFT and inverse FFT can be calculated by the DSP with low computational load and fast processing time.

B. Noise Analysis

Unlike the other telecommunication channels, the powerline channel does not represent an Addictive White Gaussian Noise (AWGN). The well-known description on the powerline noise is given in [5], which classifies the noise as a superposition of five noise types as follows.

- Colored background noise (type 1)
- Narrowband noise (type 2)
- Periodic impulsive noise, asynchronous to the main frequency (type 3)
- Periodic impulsive noise, synchronous to the main frequency (type 4)
- Asynchronous impulsive noise (type 5)

The achieved measurements have generally shown that noise types 1, 2 and 3 remain usually stationary over relatively longer periods, of seconds, minutes and sometimes even of some hours. Therefore, these three types of noise are generally analyzed on the frequency domain in terms of Power Spectral Density (PSD). The PSD of the powerline noise, that is, the noise from the viewpoint of the frequency domain, can be measured by a spectrum analyzer.

On the other hand, the noise types 4 and 5 are severely varying in time span of milliseconds and microseconds, which means PSD varies over time. Therefore, these two types of noise are generally analyzed on the time domain to find out the statistical characteristics of the noise parameters, such as the impulse width, impulse amplitude, and interarrival time distribution. The noise from the viewpoint of the time domain can be measured by the signal samples captured by a digital oscilloscope.

The instrument proposed on the paper supports both the time and the frequency domain noise analysis. It means the instrument expedites basic measurement functionality like the digital oscilloscope and the spectrum analyzer. First, the analog signals (voltages) coming from the analog board are converted into digital values by an ADC. As described before, the instrument uses a 12-bit ADC, which means that a full-scale signal at the input is converted into 4096 digital values. The instrument can sample input voltage values at specific instants of time, determined by the sampling rate up to 100 MHz. The data samples acquired over the specific time interval are then averaged and converted to display points for the time-domain plotting. This is similar to a digital oscilloscope.

Second, the input signal which is sampled at a specific sampling frequency passes through an analog filter which attenuates all frequency components above a half of the sampling frequency by 90 dB. This is the anti-aliasing filter

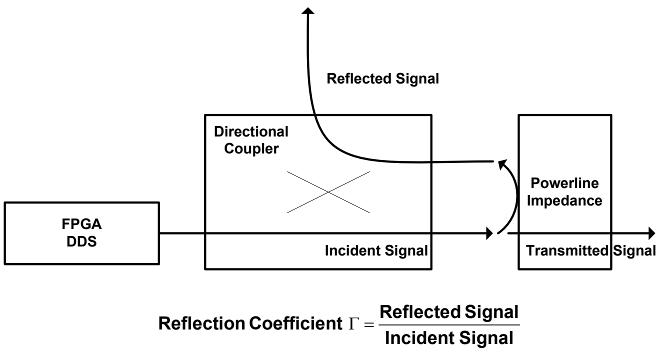

Fig. 5. Impedance measurement method (Network analysis method)

based on Nyquist's sampling theorem [6]. The resulting digital time record is then mathematically transformed into a frequency spectrum using an algorithm known as the Fast Fourier Transform (FFT). The resulting spectrum shows the frequency components of the input signal. For example, the input data sampled at 100 MHz can be converted into the frequency spectrum up to 50 MHz. This is similar to a FFT spectrum analyzer.

C. *Impedance Analysis*

Impedance is an important parameter used to characterize the powerline medium. Because of the impedance discontinuities characterizing the PLC medium, the signals are reflected several times, which results in a multipath transmission. The impedance of powerline channels is highly varying with frequency strongly depending on the location type and varying in a range between some few ohms up to a few kilo-ohms [7].

There are many techniques to find the impedance. For the impedance analysis of the powerline, we chose the network analysis method [8]. The complex impedance value Z is calculated from the reflection coefficient Γ which is obtained by measuring the ratio of an incident signal to the reflected signal which is detected by a directional coupler as described in Fig. 5 and the following equation [7]:

$$Z = Z_o \frac{1+\Gamma}{1-\Gamma}, \quad (5)$$

where Z_o is the input impedance of the instrument.

To generate an incident signal, the single-tone sinusoidal signals are generated by using the Direct Digital Synthesis (DDS) function of the FPGA. The incident signal, which can be generated by using the DDS, up to 100 MHz has a resolution of 95 Hz. For example, the FPGA has high performance that is capable of generating about 315,800 single-tones up to 30 MHz, a typical broadband powerline bandwidth.

V. Conclusion

In this paper, we have presented the design and the implementation of the analyzing instrument for broadband communication. The hardware of the instrument includes high-performance DSP and FPGA which helps the development easier and enables the analyzing process faster. The analyzed data can be presented and saved via the Windows application software. The user also monitors and controls the instrument with the application software. The instrument has three major functions: channel, noise, and impedance analysis. The corresponding analyzing algorithms applied in the proposed instrument well described in this paper. Moreover, they are implemented to be suitable to the hardware architecture.

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