Implementation of FM-DCSK modulation scheme on USRP platform based on complex envelope

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Abstract— FM-DCSK transmitted reference modulation scheme with autocorrelation receiver offers a very robust and simple transceiver configuration. However the noise performance of such a system is relatively poor. Although the theoretical noise performance of transmitted reference systems has been derived, its validation by real measurements has not yet been carried out. The paper shows the implementation of an FM-DCSK system on USRP platform based on the complex envelope approach. The theoretical noise performance of FM-DCSK modulation scheme with autocorrelation receiver is validated through real measurements.

1. Introduction

Noncoherent modulation schemes offer worse noise performance compared to their coherent counterpart but in many recent low cost hand-held wireless devices featuring low power consumption the simple and robust architecture is a must. Transmitted Reference (TR) modulation scheme applying FM-DCSK signals with autocorrelation receiver may satisfy the demands of such devices.

In Section 2 the paper introduces the TR systems and FM-DCSK technique, then in Sec. 3 the issues influencing the noise performance of a TR system are detailed and the theoretical bit-error-ratio (BER) is given.

Section 4 shows an implementation method of communication systems via the implementation of FM-DCSK system using a Universal Software Radio Peripheral based on the theory of complex envelopes [1]. The signals appearing in the FM-DCSK system at the transmitter and at the receiver will be evaluated by real measurements. The theoretical BER of FM-DCSK systems with autocorrelation receiver is validated by real measurements.

2. Transmitted Reference Systems

2.1. Model for TR Modulation

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 a TR signal is shown in Fig. 1, where $g(t)$ denotes an arbitrary carrier wavelet, τ is the chip duration and $\Delta T \geq \tau$ gives the delay between the two chips. The best noise performance is achieved by the antipodal modulation scheme 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."

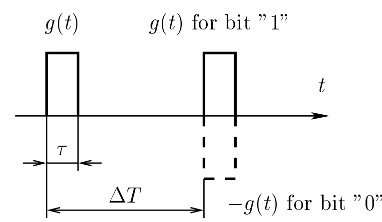

Figure 1: Structure of a TR signal.

The unique feature of a TR radio system is that the reference chip is not recovered at the receiver but it is transmitted via the same telecommunication channel as the information bearing chip. This solution makes the TR radio system very robust against the linear and nonlinear channel distortions, but it has a serious drawback: both the reference and information bearing chips are corrupted by the channel noise. One may conclude that the noisy reference chip results in a noise performance degradation but this statement is valid only if a distortion free channel is considered. Since in a TR system both the reference and information bearing chips undergo the same channel distortion, the TR system offers a better system performance when distortion is present in the channel, provided that the loss caused by the noisy reference chip is less than the gain arising due to the perfect correlation of the reference and information bearing chips. The reference chip should be considered as a test signal used to measure the actual channel characteristics. Consequently, the TR system may be used even in a time-varying channel.

Note that the model shown in Fig. 1 gives the transmitted signal for FM-DCSK [2].

2.2. TR Autocorrelation Receiver

Due to the special structure of TR signal, the information bits may be recovered from the sign of correlation measured between the reference and information bearing chips as shown in Fig. 2. The channel filter is a bandpass filter that determines the noise bandwidth of receiver. The integrator is a integrate-and-dump circuit. In consequence of the antipodal modulation scheme, the optimum decision threshold is always zero independently of the signal-to-noise ratio (SNR) measured at the demodulator input [2].

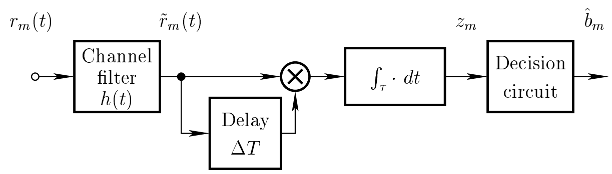

Figure 2: Block diagram of TR autocorrelation receiver.

3. Noise Performance of TR Systems

FM-DCSK systems belong to the TR systems where a chaotic carrier is used as $g(t)$. The advantages of TR systems are: (i) the optimum decision threshold is always zero, consequently, there is no need for an adaptive threshold control and training sequence, (ii) the reference chip measures the actual channel characteristics, (iii) a simple autocorrelation receiver may be used.

The TR systems also have a few disadvantages: (i) transmission of a reference chip results in a loss in the energy per bit E_b (however, this loss may be reduced if more than one information bearing chips are transmitted after one reference chip), (ii) the reference chip is also corrupted by the channel noise.

In many applications only a limited amount of *a priori* information is exploited in order to get a more robust or simpler detector configuration. Due to the special structure of TR signals the elements of signal set are always separated in the frequency domain regardless of the type of carrier $g(t)$. This separation is shown by measurements in Sec. 4. The spectrum of bits "1" and "0" contain only the even and odd harmonics, respectively, of the bit duration T [3]. In an autocorrelation receiver only this limited amount of *a priori* information is exploited.

If only this separation in the frequency domain is exploited during the detector construction then only one condition has to be satisfied to achieve the best noise performance, namely, the transmitted energy per bit has to be kept constant [4]. This condition is always met in case of fixed waveform communications, but is not automatically satisfied in chaotic communications where the carrier $g(t)$ varies from bit to bit even if the same bit is transmitted repeatedly. In chaotic communications an extra signal manipulation, for example the frequency modulation in FM-DCSK, is required to generate a carrier with constant E_b.

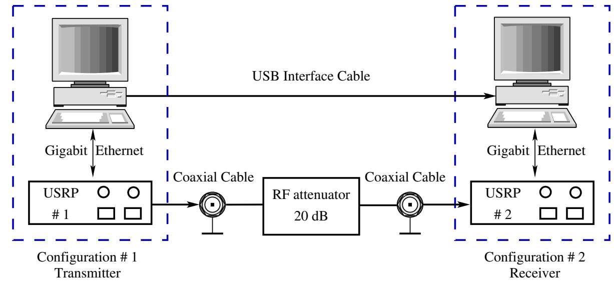

Figure 3: Block diagram of test bed developed for FM-DCSK radio link.

The equation developed in [4] for noise performance may be generalized to any kind of TR systems implemented with an autocorrelation receiver. The BER is obtained as

$$P_e = \frac{1}{2^{2B\tau}} \exp\left(-\frac{E_b}{2N_0}\right) \sum_{i=0}^{2B\tau-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \times \sum_{j=i}^{2B\tau-1} \frac{1}{2^j} \binom{j+2B\tau-1}{j-i} \quad (1)$$

where $N_0/2$ denotes the two-sided psd of channel noise. This equation is valid for both fixed and chaotic carriers provided that E_b is kept constant.

In Equation (1), τ denotes the energy capture time of autocorrelation receiver. In a well designed system the chip duration is equal to the capture time, this is why these parameters are not distinguished in Fig. 1 and in (1). Note that the noise performance of a TR system depends on the product of $2B\tau$, but the delay $\Delta T - \tau \geq 0$ between the reference and information bearing chips has no influence on the noise performance. The dependence on $2B\tau$ reflects the fact that both the reference and information bearing chips are corrupted by the channel noise.

4. Implementation and Measurement of FM-DCSK TR System on USRP Platform

Universal Software Radio Peripheral (USRP) is a computer-hosted hardware platform for the implementation of software defined radio. Each USRP device includes a receive (Rx) block and a transmit (Tx) block. The USRP approach relies on equivalent baseband (BB) signal processing of RF bandpass signals [1]. It performs all the waveform specific signal processing steps, such as modulation and demodulation, in BB on a host-computer while all the general purpose operations requiring high-speed data processing, such as interpolation and decimation, are carried out on an FPGA available on the main board of USRP device. The Rx block extracts the complex envelope from the RF bandpass signal while the Tx block reconstructs the RF bandpass signal from the complex envelope [1].

The block diagram of the implemented test bed including both the transmitter and the receiver is shown in Fig. 3.

The implementation and evaluation of FM-DCSK radio system has carried out in the following steps:

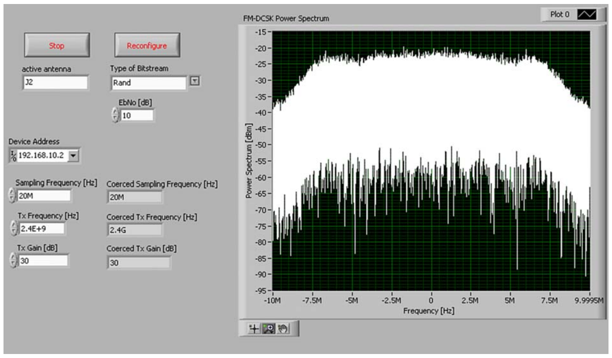

Figure 4: GUI of the transmitter implemented for the generation of the complex envelope and controlling USRP#1. It visualize the BB spectrum of FM-DCSK signal for random bit sequence.

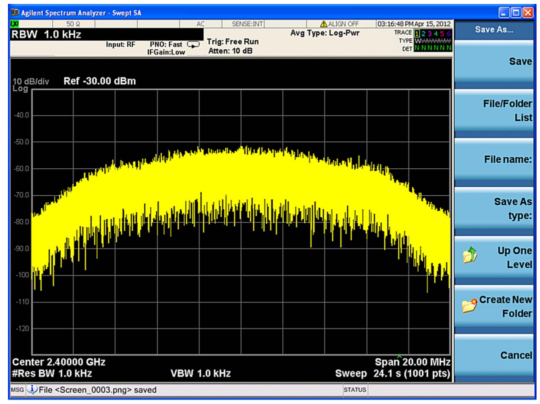

Figure 5: The RF spectrum of the transmitted RF FM-DCSK signal carrying random bit sequence at the output of USRP#1 measured by a Signal Analyser.

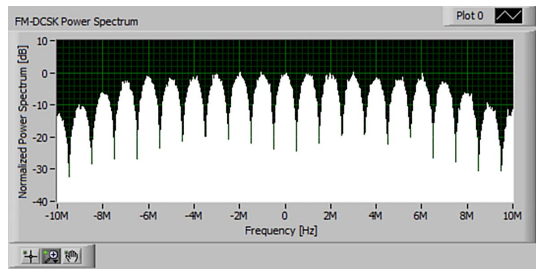

Figure 7: The spectrum of the BB FM-DCSK signal for pure bit "1" generated on the host PC when pure bit ones are transmitted.

1. The complex envelope of FM-DCSK TR signal is generated on the host PC. The BB spectrum of FM-DCSK signal is calculated from its complex envelope. The graphical user interface (GUI) of the FM-DCSK modulator and control software (SW) for USRP#1, the transmitter is shown in Fig. 4. On the right the BB spectrum of FM-DCSK signal can be seen for a random bit sequence. On the left the configuration parameters for USRP#1, the transmitter can be found.
2. The samples of the complex envelope are sent via Gigabit Ethernet to USRP#1 where the BB FM-DCSK signal is transformed into the radio frequency (RF) region, in our case up to the 2.4 GHz ISM band. The RF spectrum at the Tx output of the USRP#1 is measured by an Agilent EXA Signal Analyser (N9010A) and is shown in Fig. 5.
3. The RF FM-DCSK signal is fed into the Rx input of USRP#2 that is the receiver. USRP#2 transforms the RF signal into BB and extracts the complex envelope. The samples of the complex envelope are sent to the host PC via Gigabit Ethernet for further signal processing, such as demodulation, BER calculation, etc. The GUI of the SW that processes the received complex envelope and controls the USRP#2 is shown in Fig. 6.

The main blocks of the SW performing the reception and the control of USRP#2 can be identified in Fig. 6. The *Pattern Received* vector on the left contains the recovered random bit stream carried by the FM-DCSK signal, and can be identified as $\hat{b}_m$ in Fig. 2. The random bit stream transmitted by USRP#1 is *a priori* known at the receiver for BER evaluation as it is sent to the receiver via USB. Next to the recovered bit vector the configuration parameters of the USRP#2 receiver can be set. In the upper middle the *Received Complex Envelope* is visualized. On the right the *Baseband Power Spectrum* of the received signal can be seen. In the lower middle the *Output of demodulator* is plotted which can be identified as z_m in Fig. 2. A *Timing Recovery* has been implemented in SW whose output is plotted on the lower left side. It returns the decision time instant when the absolute maximum correlation value between the reference and information bearing chips is measured during the signalling time of one bit.

In Section 3 it has been emphasized that the elements of the signal set are separated in the frequency domain in TR systems. The BB spectrum of FM-DCSK signal can be seen for pure bit ones in Fig. 7 calculated on the host PC while the same spectrum in the RF domain measured at the Tx output of USRP#1 by a Signal Analyser is shown in Fig. 8. Note, that the spectra of the FM-DCSK signal in the BB and RF regions are identical.

5. Validating the Noise Performance of FM-DCSK System by Measurements

Numerous measurements have been carried out for determining the noise performance of the implemented FM-DCSK system. Our measurements shown that the theoretical noise performance expressed by Eq. (1) and the measured noise performance of the implemented FM-DCSK system are in close agreement. Figure 9 plots the theoretical BER curves for the FM-DCSK TR system with autocorrelation receiver. From the left to the right the solid curves

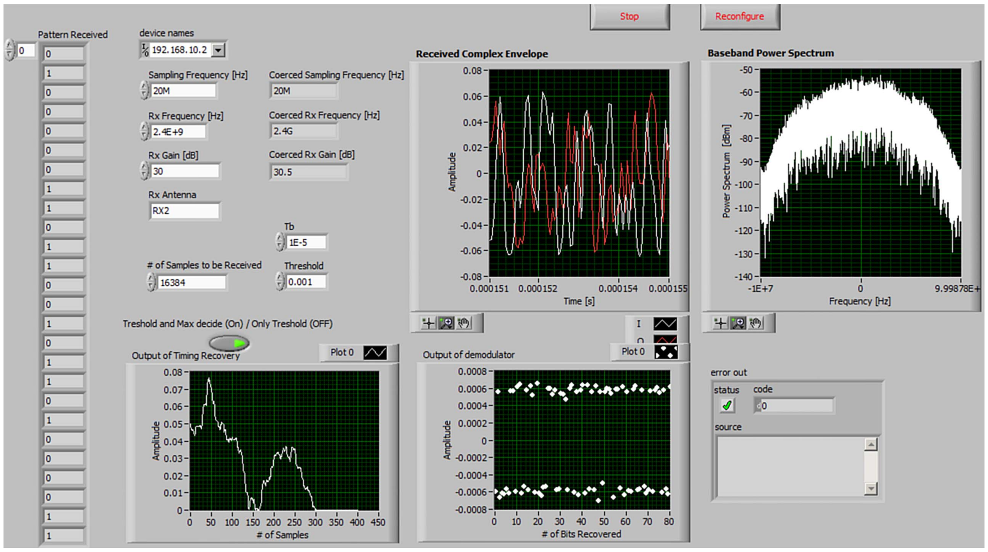

Figure 6: GUI of receiver implemented for processing of the received complex envelope and controlling USRP#2.

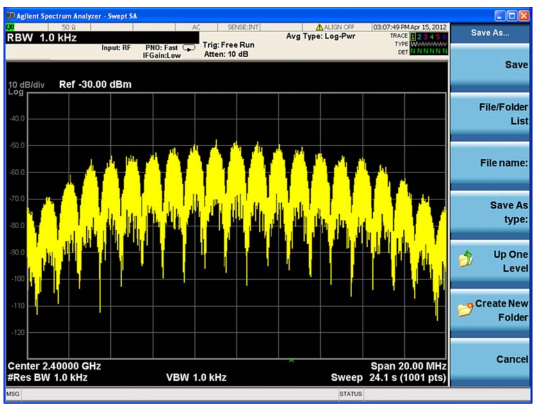

Figure 8: The spectrum of the transmitted RF FM-DCSK signal carrying pure bit "1" at the output of USRP#1 measured by a Signal Analyzer.

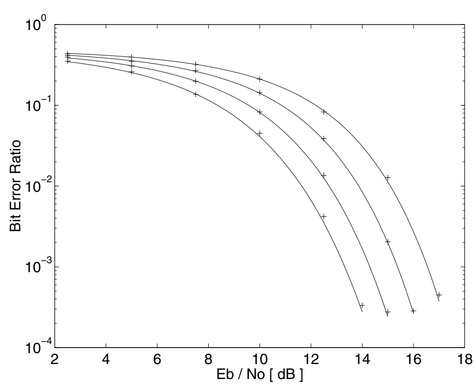

Figure 9: Noise performance of FM-DCSK system validated by measurements. Solid curves shows the theoretical BER curves from left to right for $2B\tau$=17;34;68;136. Marks '+' indicate the measurement results.

show the BER for $2B\tau$=17;34;68;136 where $2B$=17 MHz kept constant and only the chip time τ was increased. The '+' marks indicate the measured values for BER. It can be concluded that the real measurements validated the theoretical noise performance.

6. Conclusions

The paper showed a design method for the implementation of communication systems via the implementation of FM-DCSK transceiver on USRP platform based on complex envelope. All the important signals appearing in the system have been shown via real measurements. The issues determining the theoretical noise performance of an FM-DCSK system with autocorrelation receiver has been summarized and the theoretical BER has been validated by real measurements.

Acknowledgment

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