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A real time transmission system of long distance for nuclear logging

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Abstract Some specified chips in traditional Manchester-II encoding/decoding designs are used to guarantee strictly the stability of the input wave, otherwise the capacity of anti-interference and resilience are degraded seriously. In this paper, a new Manchester-II encoding/ decoding system is used for nuclear logging by a 7 000 m armoring cable. A thorough hardware wave tracking decoding algorithm is proposed and realized in a FPGA hardware chip. An on-site measurements show that this transmission system can decode correctly in real time, with a bit error rate of better than 10^{-10}.

Key words Long distance transmission, Hardware real time decoding algorithm, Nuclear logging, Armoring cable, Manchester II code

1 Introduction

Nuclear well logging is based on measuring natural γ-rays, or γ-rays or neutrons reflected from the formation atoms. At a depth of 5.5 km, a nuclear logging head works at 180°C under 140 MPa[1]. Therefore, armored cables (single or multi-conductor) are used for signal transmission between the logging head and ground instrument[2]. Because of non-linear transmission performance of a cable, however, the transmitted signals are seriously distorted, as higher frequency components lose more during their transmission. A longer cable needs higher data baud rate and causes more serious signal distortion[3]. It is difficult to increase the data baud rate and to recover the signals, then, the transmission system is a bottleneck for nuclear logging technique.

To maximize usability of cable bandwidth and data throughput, the data need be encoded. Manchester-II encoding, having the ability of clock recovery and anti-interference, is preferably used in well logging. Traditionally, to increase the transmission efficiency via well logging cable, Manchester-II data are converted into AMI (Alternate Mark Inversion[4]) codes at the transmitting end. The positive and negative AMI pulses are generated by the rising and falling edges; respectively, of the Manchester-II code; and the digital positive and negative pulses are fed to respective input port of an analog subtracter. Finally, a compound analog signal is generated, with positive and negative voltage, shaped by a low-pass filter, and sent to the transmission cable. To increase signal/noise ratio at the signal receiving end, the signal should be conditioned, i.e. amplified, filtered, and equalized. After AMI code is converted into Manchester- II code, the data are fed to some kind of Manchester-II decoding chip or digital signal processor for decoding[5].

A traditional design needs specific Manchester -II encoding and decoding chips[6,7], hence the difficulties of reducing the cost, power dissipation, and circuit size. And in the signal conditioning of extreme requirements, imperfect input signal and environmental interference make the encoding and decoding chip panic easily. The AMI positive and negative pulses are in pairs, but an AMI negative pulse disappears according to the standard Manchester-II encoding chip[7], making the logging head in disorder due to this disequilibrium of AMI polarity.

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In this paper, a transmission system is proposed for long armored cables, and a full hardware algorithm realized in a FPGA (Field Programmable Gate Array) chip is utilized to encode and decode the Manchester - II code. This transmission system, in data rate of 230 kbps, works well for nuclear logging with an armored cable of up to 7 km, and is advantageous in real time ability, high reliability and resilience, as shown by laboratory and *in situ* tests.

2 Cable transmission system

The communication system of nuclear logging has a data-transmitting module on the ground and a data-receiving module in the well, connected by a multi-conductor armored cable of 7 km. Command and configuration data are sent by the ground module, and the down-well module receives data from the ground, executes some data acquisition tasks, and returns the acquired data to the ground.

Fig.1 shows schematically data transmission of a ground module. The M2 mode is a semi-duplex mode with 20.83 kbps command downloading baud rate and 41.67 kbps data uploading baud rate[8]. The two M5 or M7 modes are of 93.75 kbps baud rate to upload the acquired data to ground. The total data baud rate is about 230 kbps. The downloading signals in small baud rate are not affected as seriously as the uploading signals of large baud rate, hence no need of a complex down-well module for data recovery. But this is not the case for the ground module, which receives signals distorted seriously. In this paper, we illustrate the ground instrument design only.

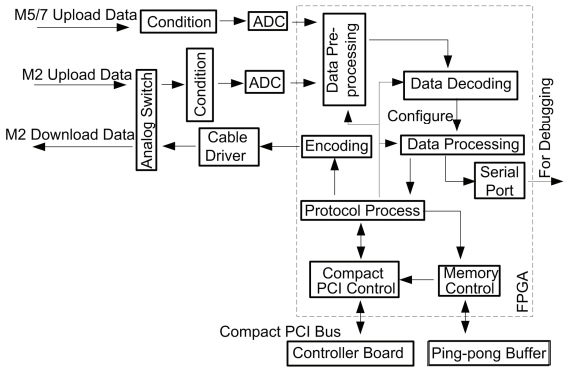

Fig.1 Structure of the transmission system on the ground.

The integrated data communication system is realized on a Compact PCI platform consisting three components: analog signal conditioning, and FPGA digital processing, with embedded software. Because of attenuated uploading signals in considerable background noise, the signal shall be conditioned, the noise be filtered, and the gain be controlled to process them. Then the analog signal is digitized in the ADC before it comes into the FPGA for digital processing. The input signal of FPGA is in AMI code, and the AMI and Manchester-II decoding are all realized in the FPGA. The FPGA digital processing module is therefore the main component in the cable transmission system.

Decoding can be considered as a reverse procedure of encoding (Fig.2). In the FPGA, the AMI positive and negative pulse code shall be recovered from the ADC output digital signal, and the Manchester-II code shall be recovered, too. The data transmitted from down-well are finally recovered from the Manchester-II code.

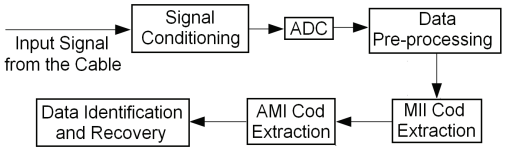

Fig.2 Data decoding procedure.

The digitized signals are processed in FPGA to eliminate low frequency noises, e.g. 50-Hz utility noise on the 7-km cable (The data pre-processing will be discussed in Section 3). After pre-processing, the data are fed to the data decoding module for AMI and Manchester-II code extraction. The data are decoded from the Manchester-II data.

The decoded data are stored in a ping-pong structure memory to improve the real time performance and decrease the system dead time. Eventually, the data are sent to the system software for processing or stored in the Compact PCI bus. This compact transmission logic structure (Fig.1) was designed with a FPGA based on the Compact PCI platform, which facilitated the design, realization and debugging. For digitizing the analog signals, an 8-bit ADC chip with 1 MSps sampling rate is good enough.

3 Design of data pre-processing

The data pre-processing is to eliminate low frequency interference super-imposed on normal signals, with a

band-pass filter suitable for armored cables. The 7-km cable of Rochester 7-H-464D well logging was measured by HP3598A S-parameter analyzer [10], and a linear phase-frequency response was indicated (Fig.3). To avoid the phase distortion, we used a finite impulse response filter for data filtering of linear phase.

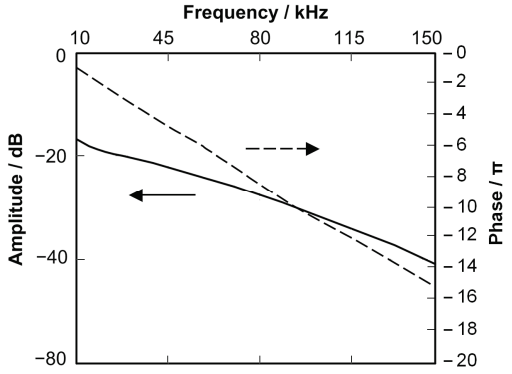

Fig.3 Response of amplitude and phase as function of frequency for Rochester 7-H-464D cable (M5 Mode).

Band-pass filters in linear phase[11] have the form of $j(\pi/2-\alpha\omega)$, and its transmission function filter is

$$H_d(e^{j\omega}) = H_d(\omega)e^{j(\pi/2-\alpha\omega)} = e^{j(\pi/2-\alpha\omega)} \quad \omega_1 \le |\omega| \le \omega_2$$
$$= 0 \qquad 0 \le |\omega| < \omega_1,\ \omega_2 < |\omega| \le \pi \tag{1}$$

Where, $H_d(\omega)$ is the amplitude characterization in frequency domain, and α is the phase shift constant. Then the unit impulse- response function is

$$h_d(n) = \frac{1}{2\pi}\int_{-\pi}^{\pi} H_d\, e^{j\omega} \times e^{j\omega n} d\omega$$
$$= \frac{1}{2\pi}\left[\int_{-\omega_2}^{-\omega_1} e^{j(\frac{\pi}{2}-\omega\alpha)} \times e^{j\omega n} d\omega + \int_{\omega_1}^{\omega_2} e^{j(\frac{\pi}{2}-\omega\alpha)} \times e^{j\omega n} d\omega\right]$$
$$= \frac{\cos[\omega_2(n-\alpha)] - \cos[\omega_1(n-\alpha)]}{\pi(n-\alpha)} \tag{2}$$

To reduce the spectral leakage, some windows [12] are added into the function. The output signal of the filter is

$$f_{\text{out}}(n) = f_{\text{in}}(n)h(n) = \sum_{n=0}^{N-1} f_{\text{in}}(n)\ h(N-n) \tag{3}$$

where, $h(n) = h_d(n)W_N(n)$, N is the number of sampling points, $W_N(n)$ is the window function, $f_{\text{in}}(n)$ is the input data sequence and $f_{\text{out}}(n)$ is the output sequence. Since $h(n)$ is odd symmetry about $(N-1)/2$, Eq.(3) can be simplified as

$$f_{\text{out}}(n) = \sum_{n=0}^{\frac{N}{2}-1} [f_{\text{in}}(N-1-n) - f_{\text{in}}(n)]\ h(n) \tag{4}$$

Fig.4 demonstrates the logic algorithm of this pre-processing filter realized in FPGA. The following points shall be noted. (1) The FPGA cannot do float computation, so the filter parameter $h(n)$ was computed by the host software, and multiplied by a certain factor such that the coefficient is an integer. And as running parameters, the integer coefficients are downloaded to the FPGA logic via the Compact PCI. (2) Because of the multiplier to $h(n)$, the sampling points (N) shall be of a suitable size, so as not to dissipate too much of the FPGA resource. (3) Overflow may occur in high probability during the computation because all the data are integer. Then, the amplifier factor and the effective number bit of the multipliers should be integrated. (4) The output data should be reduced properly, before sending them to the decoding module, so as to save memory usage of the FPGA. High precision computation is not necessary because the decoding algorithm is based on the signal wave tracking (see Section 4). We could use shift register to simplify a multiplication or division. For example, amplifying a number by 2.3 can be done with a factor of 2 or 4. This makes it easier to realize the algorithm in FPGA. Fig.5 shows the MATLAB simulation results of the data pre-processing, indicating that the low frequency partial components in the original wave are eliminated.

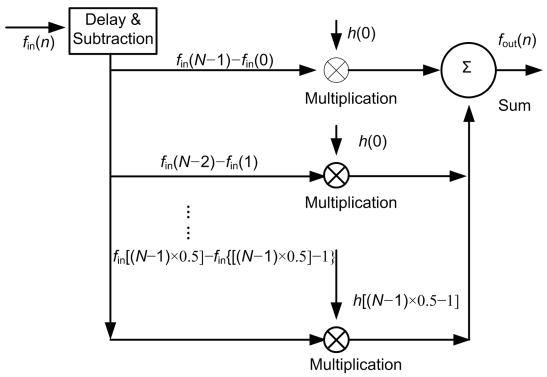

Fig.4 Algorithm structure of pre-processing filter.

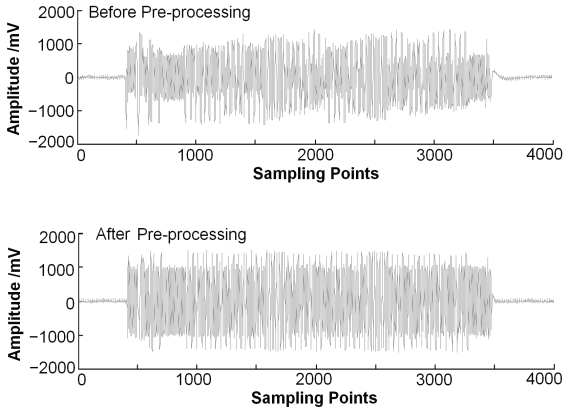

Fig.5 MATLAB-simulation of the data pre-processing effect.

4 Decoding algorithm

After pre-processing, the equalized waves are good enough to decode. Since the transmission cable is of linear phase response, the equalized peaks can represent the rising edges of Manchester-II code or valleys for the falling edges. Then, the data can be decoded by a wave-tracking algorithm, i.e. we can track the peaks and valleys of the equalized wave, extract the AMI± codes, and regenerate the Manchester-II code.

4.1 AMI code extraction

A peak/valley can be tracked by a threshold method, just like a discriminator[13]. Traditionally, there is an analog discriminator in the front end to acquire the digital wave, but it is difficult to get a digital wave with edges corresponding to the extreme points of input analog waves (peaks or valleys). This may result in instability of the Manchester-II code edges and complicate the decoding, making the decoding chip panic easily.

To avoid this shortage of traditional extracting scheme and to improve robustness of the data decoding, we use a full digital extracting algorithm. The input wave shall be digitized and displayed in the control software, so we configure two threshold values to the extracting logic for peak and valley tracking respectively. This can be done during the system training by controlling the GUI software in the Compact PCI. Fig.6 shows the procedure of AMI extraction. The upper part is for AMI+ extraction. When the amplitude of equalized wave exceeds the positive threshold, the AMI+ wave is set to 1, and the AMI+ wave is set to zero as it reaches the wave peak. The AMI+ wave can be obtained using this tracking procedure, and the AMI− wave can be obtained similarly, by using the valley and negative threshold instead. Based on AMI± wave, it is easy to regenerate Manchester-II code. In Fig.6, the falling edge of AMI- triggers Manchester-II code to logic 1 and the falling edge of AMI+ triggers back to logic zero.

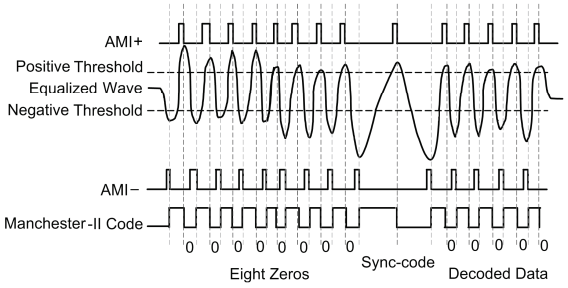

Fig.6 Extraction of AMI code.

The pre-processing filters low frequency components in the input signal, hence a relative increase of the high frequency components, which benefits in selecting the tracking thresholds. Also, the superimposed noise on the wave is eliminated by the band-pass filter, which improves accuracy of the wave tracking and falling edges of AMI± wave locating. We note that AMI+ and AMI– pulses occur alternately, and they do not occur continuously, therefore, the Manchester-II code can be obtained correctly even if the input wave is seriously out of shape.

4.2 Manchester-II code decoding

The AMI pulses reflecting the rising or falling edges of Manchester-II codes are sent to the long cable end in the well. If the cable propagates phase characterization of the AMI pulses linearly, the exact phase information of the original Manchester-II codes shall be well kept on the ground. Unfortunately, the phase propagation is just in an approximate linearity. The accumulated errors to edge positions of the recovered Manchester-II code shall be well make the decode chip panic. In addition, because of unavoidable noises, Manchester-II wave generated from AMI wave is not perfect, hence the edge deviation of considerable size that makes the decode chip panic, too. These problems prevent the communication system from

running at a higher baud rate. And the instruments may not work properly in the logging positions where noise interference is more severe. To increase the decoding robustness, system baud rate, and working efficiency, we used a decoding logic based on FPGA, as shown in Fig.7.

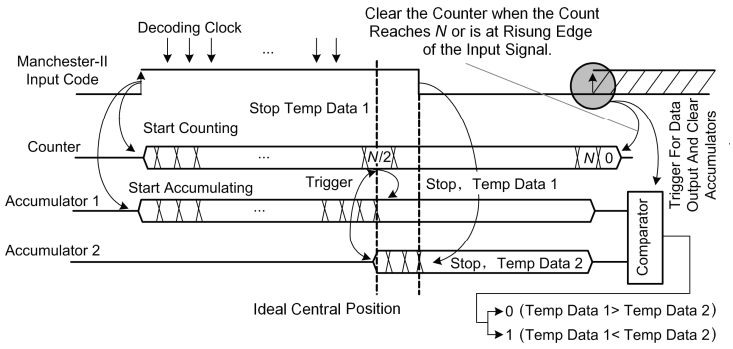

Fig.7 Timing diagram for Manchester-II decoding logic.

The decode logic enters into the procedure of decoding with a rising edge of the input, The rising edge triggers a counter of high working frequency in an invariable time width defined by the communication baud rate, which is settled in advance. If the counter is cleared by the rising edges in the input code, the width can be represented by the maximum counting value. Here, we let N denotes the width. At each side of the ideal central position of the Manchester-II code, an accumulator is triggered at the higher level side, or locked by the lower level side. Ideally, the central position is the turning point of the high and low levels. The two accumulator values should be $N/2$ and 0 or 0 and $N/2$. However, the accumulators deviate from these correct values because of the noise influence. Fortunately, with the help of AMI extraction in Section 4.1, the deviation is not larger than a quarter of a Manchester-II code width. We can find that the code can be decoded as 0 if temp data 1 > temp data 2, and as 1 if temp data 1 < temp data 2, the code can be decoded as data 1, where temp data 1 is the locked data for accumulator 1; and temp data 2 for accumulator 2. Then, we need to add just a comparator in the decode logic to obtain the transmitted data.

The followings should be pointed out. First, in the M5/7 Manchester-II code, a synchronization bit being 1.5 times wider than the normal code is identified by width of the high level. Second, the counting value should be cleared by the rising or falling edge of the input code. This clearing condition has higher priority than the maximum baud rate set for the counter, so as to eliminate accumulate error caused by non-linear phase characterization of the cable. Third, the decoding clock frequency for the counter can be selected in a wide range. There is not a strict condition in this algorithm, and there are total 12 sampling points for each code width. If the data baud rate is 93.75 kbps, the ADC sampling frequency is 1.125 MHz.

5 Experimental verification

A training procedure is needed before running the system, for correct parameter selection and configuration of the FGPA logic. The commands are sent to down-well instruments from GUI software. Some fixed mode codes are sent to the ground receivers for checking the communication quality, such as bit error rate evaluation. By sending equalized wave to the GUI software and displaying it in a chart, the band pass filter parameters (e.g. low- and high-cut frequency) can be adjusted according to the raw wave and the base lines in the GUI. The GUI software allows operator interactions to run the parameters for data pre-processing and decoding. The training is not time-consuming, which makes it flexible to update parameters at any time. The operation parameters vary with the depth where the down-well instruments are working, so the parameters of different working environment are stored as default in the software.

A 4-order filter, i.e. N=8 in Eq.(3), with the low- and high-cut frequencies of 50 and 150 Hz as the band pass filter, respectively, was designed for onsite

test of the communication system via a 7 000 m Rochester 7-H-464D logging-well cable[10] at an oil well in Hebei province, China. In Fig. 8, the as-acquired data are compared with the filtered data, from which the data transmitted from the down-well instruments could be decoded easily. For specifying the bit error rate, data of fixed pattern were sent from the down-well site side about half an hour, the incorrect decoding on the ground were recorded, and it was found that the total bit error rate was better than 10^{-10}. Such a low bit error rate indicates the feasibility and superiority of the proposed algorithm.

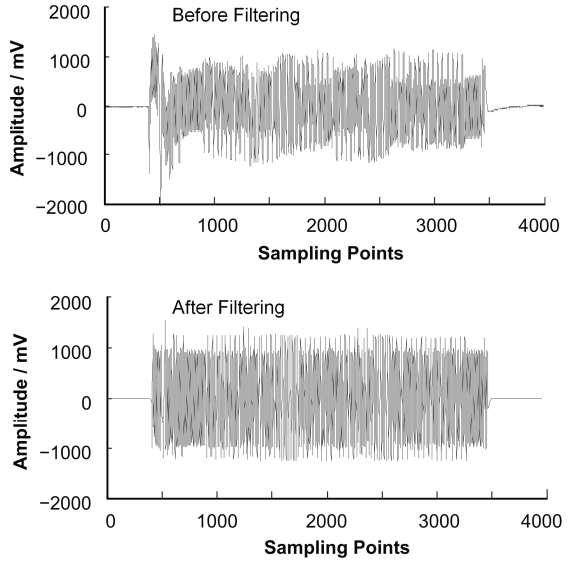

Fig.8 Data acquired on an oil well, before and after filtering.

6 Conclusions

The real time data transmission system is a key for nuclear logging. We propose a communication system embedded in a Compact PCI platform, and design an innovative hardware decoding algorithm for long distance communication via logging well cable. Compared with the traditional design with some specified decoding chips or carrier communication techniques[14], all the decoding algorithms are realized in a FPGA hardware chip. Because of low cost, strong real time performance, high reliability, the on-site measurements show that the transmission system can decode correctly in real time and achieve a bit error rate of better than 10^{-10}. The new long distance transmission system for nuclear logging is a prototype. In order to improve its practicability, many tests of working environment need be conducted by some related standards for communication systems[15,16], and modified by some SEG oilfield technical standards [17]. Also, the data baud rate need be increased by using signal pre-emphasis and equalization.

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