15 Gbps Communication over an USB3.0 Cable and Even More

Dr. Andreas C. Wolf
Managing Director
Dr. Wolf Wireless GmbH
Teltow, Germany
aw@dw-w.com, www.dw-w.com

Prof. Dr. Christoph Scheytt,
Department Head of IHP GmbH,
Frankfurt (Oder), Germany
www.ihp-microelectronics.com

Abstract— **Parallel Sequence Spread Spectrum (PSSS) is a physical layer (PHY) base band technology. It was selected for the wireless sensor network standard IEEE802.15.4-2006 [1], because the data rate and performance were increased by PSSS.**

The main question to answer was during that USB3.0 project if PSSS could even enhance the communication over USB 3.0 cables. For the USB transmission a PSSS version with a different encoding then for IEEE802.15.4-2006 is used to enhance the data rate adapted to the spreading and cross talking of USB cables. Presented are the architecture of the whole test system, transceiver and offline processing model and the performance results.

I. Introduction

There is an increasing demand off data rate for wired transmissions. The limited bandwidth of the cable, i.e. the USB 3.0 cable causes a demand of spectral efficient physical layer (PHY) technologies. OFDM combined with other technologies is could fulfilling that demand but has the bottle neck of complexity and high power consumption for high data rates in the Gbps data rate segment. PSSS, initial published by Wolf [2] has promising features for fulfilling those demands too with lower complexity and higher throughput.

For investigating the performance that could be reached, a PSSS baseband design was developed for 5 Gcps with a bandwidth of 2.5 GHz and a spectral efficiency of 3 Bit/s/Hz. This combination of spectral efficiency and chip rate was the most performing one. S21 of the 1m USB 3.0 cable system had an attenuation about 15 dB at 8 GHz, 7 dB at 2.5 GHz. Fig. 1 shows the transfer function (absolute of S21) vs. frequency for the USB forum reference model [3] compared to the transfer function of the used hardware shown in Fig. 2. The transfer functions are for the whole system, that consist out of backplanes, connectors and the USB3.0 cable.

The design was made as an offline simulation model, the transmission was executed in real time. Fig. 3 shows the model with the USB link included. The base band (BB) data for the transmitter (Tx) were calculated offline and then stored into an transient generator. The transient generator was adapted to a USB Tx , as shown in Fig. 3. For the USB Cable a reference cable with USB3.0 to SMA converter was used. The received base band data of the Rx , see also Fig. 3, were sampled and stored at a digital storage oscilloscope (DSO). The sampled BB data were post processed for synchronization, channel estimation, PSSS reference calculation for channel deconvolution, PSSS decoding and BER calculation.

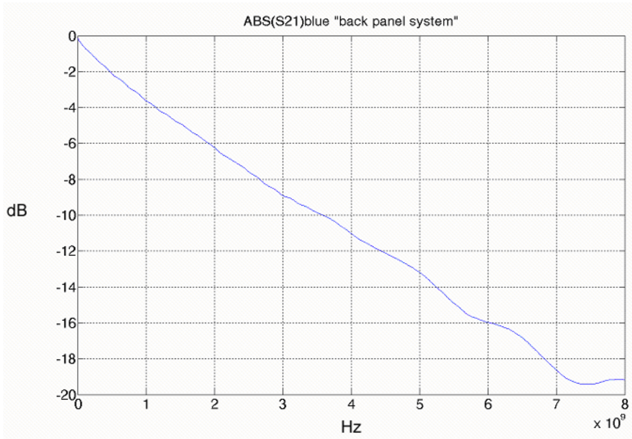

Figure 1 Transfers function of the USB3.0 cable system model form the USB forum, www.usb.org.

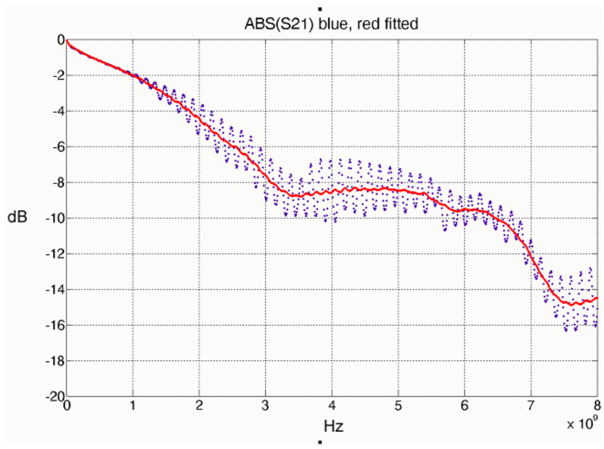

Figure 2 Transfers function of the real world USB3.0 cable system. Red the original and blue the fitted one.

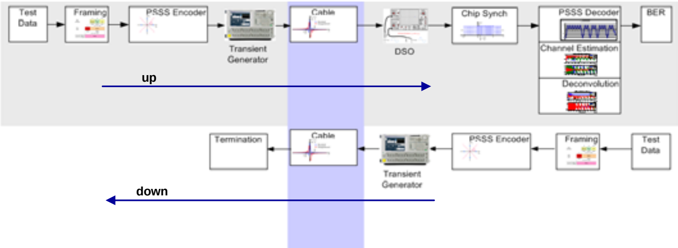

Figure 3 Experimental PSSS transmission system.

II. PSSS TECHNOLOGY

A. Basics

PSSS uses for the encoding m-sequences in parallel. Equation (1) describes the base m-sequence ms_1.

$$ms_1 = \left(m_{11}, m_{21}, ..., m_{M1}\right) \tag{1}$$

The coding table is given by EN and contains cyclic shifted m-sequences of ms_1.

$$EN = \begin{bmatrix} m_{11} & ... & m_{1N} \\ m_{21} & ... & m_{2N} \\ m_{M1} & ... & m_{MN} \end{bmatrix} \tag{2}$$

For the encoding the data D (3) is multiplied with EN (2).

$$D^T = \left(d_1, d_2, ..., d_N\right) \tag{3}$$

$$S = EN \cdot D \tag{4}$$

Each data bit of D is spread with a cyclic shifted m-sequence. The spreaded bit are added column wise. The decoding can be reached by cyclic cross correlating the PSSS-Symbol S with the base m-sequence ms_1. This operation is similar to using a matrix DE for decoding.

$$DE = EN^T \tag{5}$$

$$CCF = S \cdot DE \tag{6}$$

CCF presents the cyclic cross correlation between the PSSS symbol S and the decoder matrix DE. The reconstruction is done by threshold decision as described in (7).

$$d'_n(ccf_n) = \begin{Bmatrix} d'_n = 0;\ ccf_n \le \left(Max\left\{CCF\right\} + Min\left\{CCF\right\} \div 2\right) \\ d'_n = 1; ccf_n > \left(Max\left\{CCF\right\} + Min\left\{CCF\right\} \div 2\right) \end{Bmatrix} \tag{7}$$

$d'_n(ccf_n)$ is the reconstructed data word. Depending on implementation targets of PSSS different threshold algorithms are available.

B. Deconvolution Extension of PSSS

For deconvolving the influence of the channel transmission H shall represent the channel response in the time domain. G' should be the PSSS symbol S filtered by the channel response H. In the time domain CCF is now

$$CCF = G' \tilde{\otimes} ms_1^{-1} = S \tilde{\otimes} H \tilde{\otimes} ms_1^{-1} \tag{8}$$

with $\tilde{\otimes}$ as cyclic convolution in the time domain. Calculating H^{-1} as inverse channel response in the time domain results in

$$CCF' = S \tilde{\otimes} H \tilde{\otimes} H^{-1} \tilde{\otimes} ms_1^{-1} = S \tilde{\otimes} ms_1^{-1} \tag{9}$$

where CFF' presents the deconvolved decoded PSSS symbol.

Combining the inverse channel response H^{-1} with the decoding reference ms_1^{-1} to

$$\widehat{ms}_1^{-1} = H^{-1} \tilde{\otimes} ms_1^{-1} \tag{10}$$

as new correlation and decoding reference for the PSSS symbols. That simplifies the PSSS decoder, because the calculation of the decoding reference with the inverse channel has only to be made when the channel changes. The PSSS decoding is therefore even with deconvolution just a cyclic convolution operation similar to the decoding without deconvolution.

III. PERFORMANCE RESULTS

The channel estimation and the deconvolution of the channel worked nearly perfect. In Fig 4. is shown the measured channel response in the time domain and in Fig. 5 the deconvolved one. – The channel estimation is made by correlation in the time domain out of an transmitted m-sequence that has passed the transmission channel. - The sampling rate is 10 Gsps and the chiprate is 10 Gsps. In Fig 4 the channel is spread over 20 samples which is similar to 20 chips. The deconvolved channel response has just a spread about two chips, which is the ideal minimal duration. The missing of side slopes in the deconvolved one shows also the quality of the deconvolution. The deconvolution even compensated the transfer filter function of the DSO and the transient generator. The remaining fluctuation of the signal is caused by the limited signal to noise ratio (SNR). The deconvolution is the key to high spectral efficiency with PSSS version with minimal code distance.

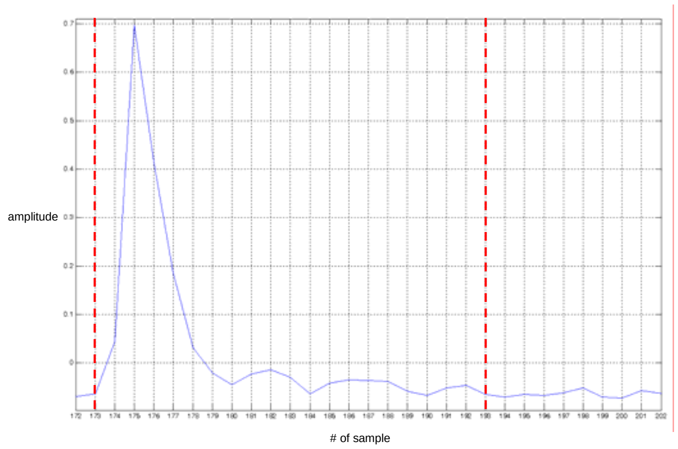

Figure 4 Real world transmission channel response.

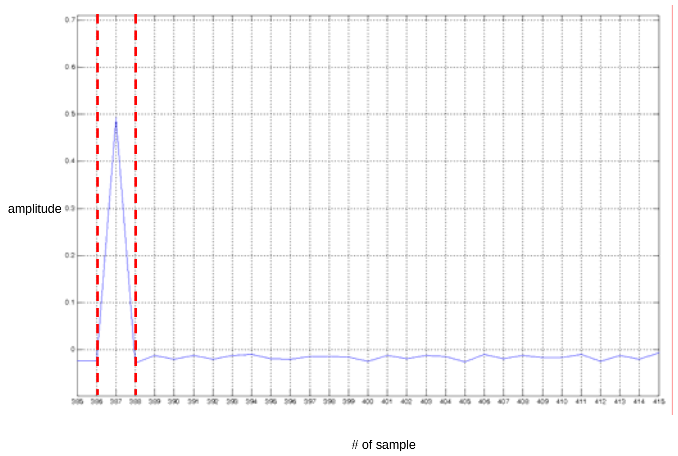

Figure 5 Real world transmission channel response deconvolved.

On the Tx side a precoding of the PSSS symbols was used similar to that in IEEE802.15.4-2006. It allows to reduce the Peak Average Power Ratio (PAPR) below 5 dB and increase the processing gain of PSSS. The reduced PAPR allows even to use a low back off to the 1dB compression point for the PA.

The used format of the packet data unit (PDU) is shown in Fig. 6. For the packet oriented data a preamble is used at the PDU beginning for synchronization and channel estimation. The rest of the PDU is filled with PSSS symbols and it cyclic extension. The cyclic extension is needed similar as for OFDM for avoiding ISI for the cyclic correlation for the PSSS decoding.

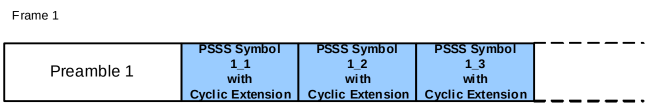

Figure 6 Packet Data Unit of the PSSS system.

For half duplex 15 Gbps @ BER 2e-6 and for full duplex 12 Gbps @ BER 2.5e-5 have been reached. Both with a spectral efficiency of 3 Bit/s/Hz and for a single cable pair. The data rate for full duplex is lower due to additional noise caused by cross talking from the down link in Fig. 3. The cross talking was reduced by using different PSSS base codes for up and down link.

IV. Conclusion

The Digital Sampling Oscilloscope (DSO) and the transient generator offer only a reachable Signal to Noise Ratio (SNR) of 20 dB in the used setup. The main reason therefore is the jitter of 20 ps, which is in the range of 10% of the chip duration of 200ps at 5 Gcps which could be much lower for an optimized integrated hardware. The USB cable offers much higher SNR then 20 dB. That opens the path to higher data rates with PSSS with an optimized hardware. 30 Gbps or even more seems to be reachable for a single USB3.0 cable pair with optimized hardware.

V. Future Steps

PSSS could be implemented in an analog digital mix mode design, which would reduce compared to OFDM drastically the power demand and chip size. Nearly the same Baseband could be used for enhancing wireless data transmissions for data rates above 1 Gbps. Even different MiMo extensions are available therefore.

References

[1] IEEE: IEEE802.15.4-2006, www.ieee.org.

[2] Wolf, A.: ‘PSSS Patents EP04701288.5-1515/1584151, DE 10 2004 033 581, US 20060256850’.

[3] USB Forum: ’USB3 Compliance S-Parameter Model Usage’, http://compliance.usb.org/index.asp?UpdateFile=USB3&Format=Standard#58.