15 Gbps and more over an Single USB3.0 Cable Pair with PSSS Baseband Technology

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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 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 as well as performance results.

Introduction: There is an increasing demand for high data rates in short-range communication between computers and peripheral devices. The limited bandwidth of low-cost cables, e.g. a USB 3.0 cable, requires spectrally efficient physical layer (PHY) technologies which have to cope with highly dispersive channels. Orthogonal Frequency Division Multiplexing (OFDM) combined with other technologies could fulfil that demand but has the bottle neck of complexity and high power consumption at Gbps data rates. Parallel Spread-Spectrum Sequencing (PSSS), initial published by Wolf [2] has promising features for fulfilling those demands too with lower complexity than OFDM and comparable 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 best performing one. S_{21} 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 S_{21}) 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 baseband data of the receiver (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.

The channel estimation and the deconvolution of the channel worked nearly perfect. In Fig 4. the measured channel response in the time domain is shown and in Fig. 5 the deconvolved one is given. – The channel estimation is made by correlation in the time domain from a transmitted m-sequence that has travelled the communication channel. - The sampling rate is 10 GSps and the chiprate is 10 GCps. In Fig 4 the channel is spread over 20 samples which is similar to 20 chips. The deconvolved channel response exhibits a spread of just about two chips, which is the ideal minimal duration. The missing of side slobes 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.

On the Tx side a precoding of the PSSS symbols was used. 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 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 as cyclic extension. The cyclic extension is needed similar to OFDM in order to avoid ISI in the decoded signal.

Results: 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 operation is lower due to additional noise caused from crosstalk from the down link in Fig. 3.

Conclusion: The measurement setup with arbitrary waveform signal generator and Digital Sampling Oscilloscope (DSO) exhibited a Signal to Noise Ratio (SNR) of only 20 dB. The main reason is the jitter of 20 ps, which is in the range of 10% of the chip duration of 200ps at 5 Gcps. The USB cable itself offers a much higher SNR than 20 dB. That opens the path to even higher data rates with PSSS using optimized hardware. 30 Gbps or more seems to be reachable for a single USB3.0 cable pair. In short-range cable communication standards like USB or Thunderbolt usually analog-digital-mixed-signal transceiver implementations dominate because of their energy- and chip-area-efficiency. Other than OFDM PSSS can be implemented easily in an analog-digital-mixed-mode circuit, which allows for a very energy- and area-efficient implementation of spectrally-efficient short range communication links.

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.

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Figure captions:

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

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

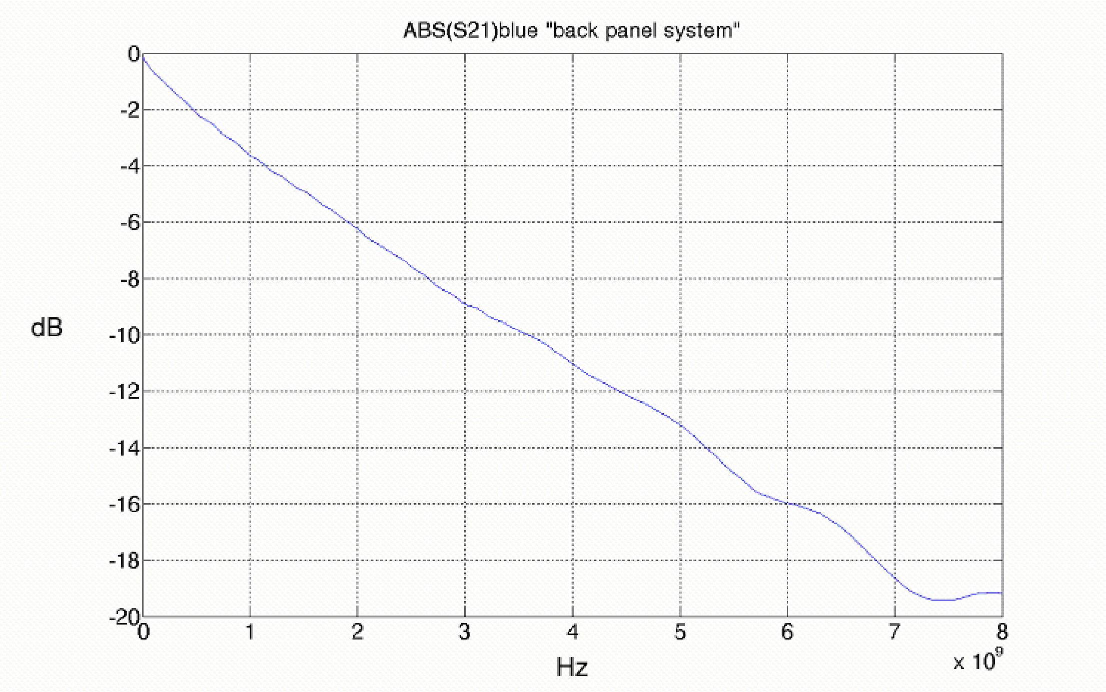
Fig. 3 Experimental PSSS transmission system.

Fig. 4 Real world transmission channel response.

Fig. 5 Real world transmission channel response deconvolved.

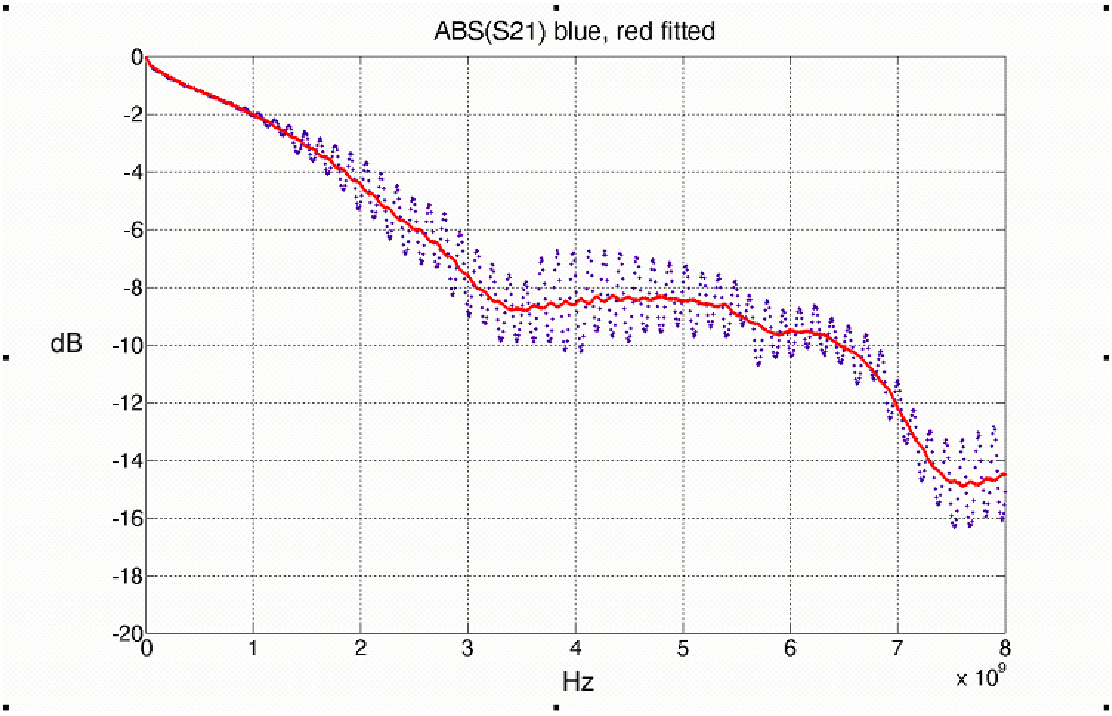
Fig. 6 Packet Data unit of the PSSS system.

Figure 1



ABS(S21)blue "back panel system"
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
dB
0
1
2
3
4
5
6
7
8
Hz
x 10^9

Figure 2



ABS(S21) blue, red fitted
dB
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
1
2
3
4
5
6
7
8
Hz
x 10^9

Figure 3

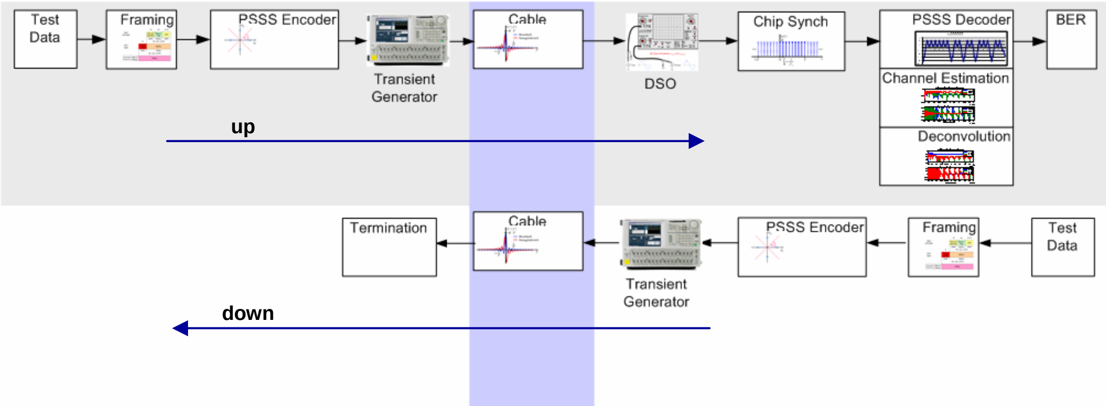

Test Data
Framing
PSSS Encoder
Transient Generator
Cable
DSO
Chip Synch
PSSS Decoder
BER
Channel Estimation
Deconvolution
up
Termination
Cable
Transient Generator
PSSS Encoder
Framing
Test Data
down

Figure 4

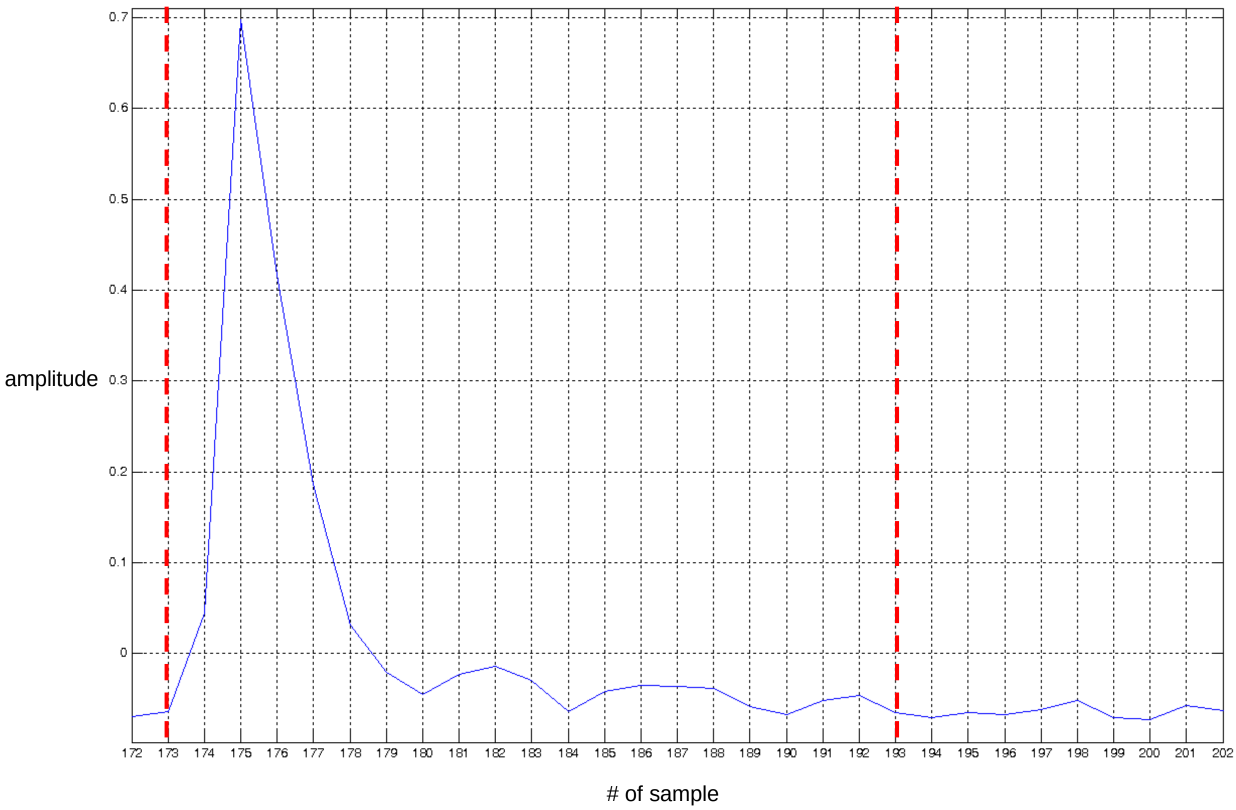
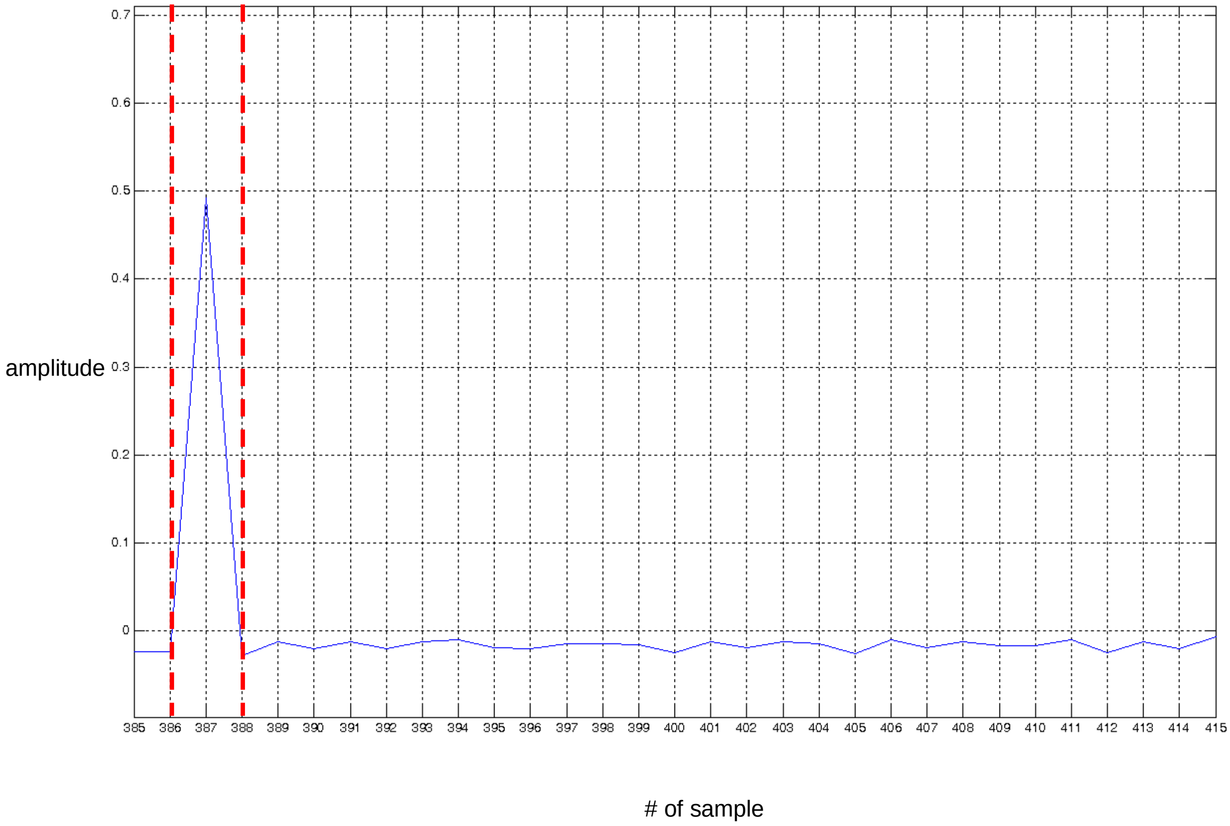
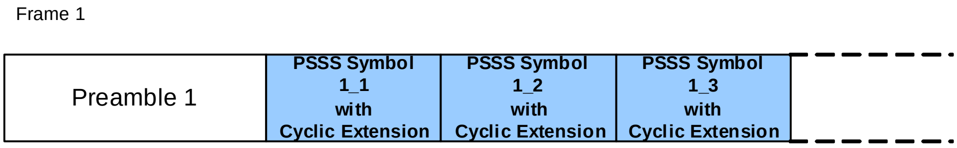

amplitude
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202
# of sample

Figure 5



amplitude
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415
# of sample

Figure 6


Frame 1
Preamble 1
PSSS Symbol 1_1 with Cyclic Extension
PSSS Symbol 1_2 with Cyclic Extension
PSSS Symbol 1_3 with Cyclic Extension