Fast Track

Investigation and simulation of high-speed gigabit transmission for POF-based MOST networks

For future in-car infotainment systems, high-speed communications networks are necessary. Applications like parallel transmission of HD-video content, side and front view cameras, software update of connected components and USB-connected consumer devices will be the main factor for higher bandwidth demands. MOST150 is the latest automotive bus designed for that purpose. However, with increasing information data, even higher data rates in the gigabit per second range are of interest.

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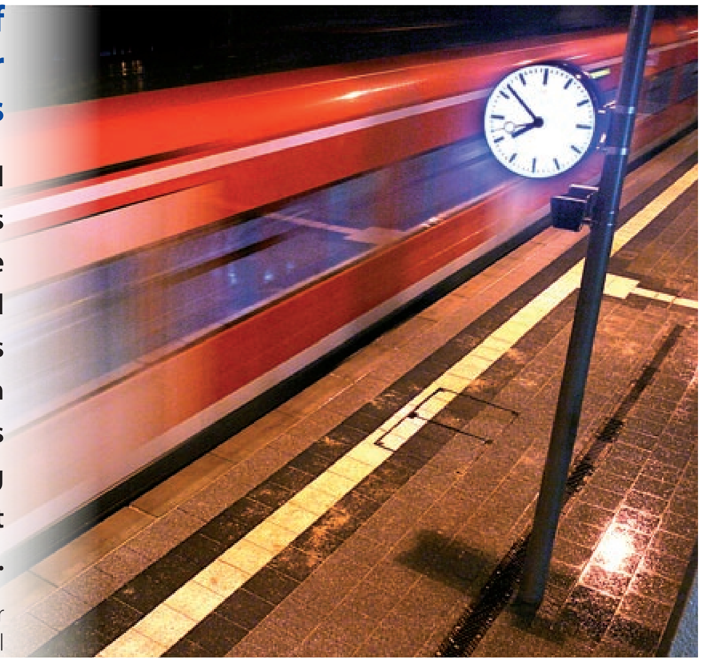

(Source: Deutsche Bahn AG)

In this paper, several solutions for meeting this challenge are described. The research is based on Matlab simulation and takes into account the MOST150 physical layer. This proposal ensures the backward compatibility with today's already used POF wire harness.

Enhancing the MOST150 electronic transceivers by introducing 8-level pulse amplitude modulation (8PAM), Reed Solomon (RS) encoding, pre-filtering and adaptive post equalization, or in another approach the zero forcing Tomlinson-Harashima precoding (ZF-THP), gigabit per second transmission over a plastic optical fiber (POF) is achieved.

The cost sensitive automotive market is the reason to investigate the possibility of 2 to 3 Gbit/s transmission based on the already used and proven POF physical layer. Unlike in conventional gigabit optical transmissions, instead of laser diodes (LD) cost-effective LEDs from MOST150 are used as transmitter. The integrated electronic modules, which perform actions like peaking and clamping, are removed from the transceivers in order to be replaced by advanced ones.

■ Modelling the optical channel

In the MOST physical layer basic specification [1], POF is characterized by a Gaussian low-pass filter. Correspondingly, a 10 to 15 m POF has a 3 dB bandwidth between 95 MHz and 135 MHz. As the LED and the LD have larger bandwidths, the overall optical transmission link can be modelled by a Gaussian low-pass filter with the following electrical transfer function:

$$H_0 = A \times e^{-2(\pi\sigma f)^2} \times e^{-j \times 2\pi f \tau \times L_{POF}} \qquad (1)$$

And the impulse response:

$$h_0(t) = \frac{A}{\sqrt{2\pi\sigma}} \times e^{\frac{-(t-\tau L_{POF})}{2\sigma^2}} \qquad (2)$$

With A the linear fiber loss, σ = 0.132/B the standard deviation, B = 1009 × L_{POF} – 0.8747 MHz the 3 dB bandwidth, $\tau = 4.97 \times 10^{-9}$ s/m and L_{POF} the fiber length in meter.

■ Prefiltering and adaptive post equalization

The big gap between the one hundred MHz POF bandwidth and the gigabit transmission speed makes the inter symbol interferences (ISI) in the received signal rather critical. To cope with it, 8PAM is used to reduce the symbol rate by a factor of 3, RS (255, 223) coding is applied to further decrease the bit error rate (BER) from 10^{-3} to 10^{-9}, and post adaptive equalizers are used to follow the minor changes in the optical channel. For a bit rate of 3 Gbit/s, a fifth order fractionally spaced high-pass filter is inserted as a pre-filter between the modulator output and the LED.

■ Zero Forcing Tomlinson Harashima Precoding (ZF-THP)

Using post equalizers can reduce ISI, however it is at the expense of noise enhancement or error propagation. A way out is to move the equalizers to the transmitter side as a pre-filter. However, in this case the dynamic range of the time domain signal is increased, which puts additional burden on the DAC. This drawback can be overcome by proper pre-coding.

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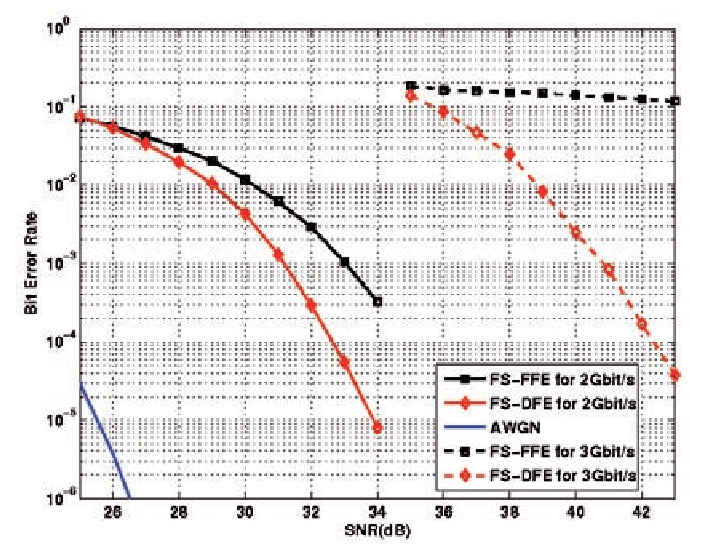


Figure 1. 2 Gbit/s and 3 Gbit/s transmission with post equalizers.

The Tomlinson-Harashima precoding (THP) was investigated, which is a linear pre-coding method to cope with ISI and is capable of stabilizing the inverse channel filter without increasing the dynamic range of transmitted signals [2]. In several aspects it fits well for the applied scheme: first, the POF channel is a slowly time-variant channel, since the in-car environment like temperature or humidity, changes slowly within several consecutive data blocks. Second, THP is particularly suitable for MPAM transmission. Third, the transmitted signals are bound by THP with respect to the dynamic range of LED. The transmission scheme with THP and ZF-FFE is sometimes called ZF-THP.

Signal-to-noise ratios

In this section, the signal-to-noise ratio (SNR) margins right after the photo diode are estimated. This is essential for analytical studies as well as for simulations. In theory, every optical receiver can be modelled as a combination of a photodiode, an input resistor and an amplifier. They contribute noise to the system in the form of quantum noise, diode dark current noise and thermal noise. So the SNR can be estimated as [3]:

$$\mathrm{SNR} = \frac{\langle I_p^2 \rangle}{\langle I_{shot}^2 \rangle + \langle I_{thermal}^2 \rangle} = \frac{(R_0 \times P)^2}{2 \times e \times (R_0 \times P + I_{dark}) \times B + \frac{4 \times k \times T \times B}{R}} \quad (3)$$

With I_p the photodiode current, I_{dark} the dark noise current (300 nA in this case), $I_{thermal}$ the thermal noise current, R_0 the spectral sensitivity (0.35 A/W), P the received optical power, e the elementary charge, B the receiver bandwidth, b the Boltzmann constant, T the absolute temperature and R the resistance.

As the minimum and maximum received optical power at SP3 according to [1] is –2 dBm and –22 dBm respectively, the SNR range can be estimated. As a result, the SNR ranges from 20.4 ~ 59.5 dB without a pre-filter (B = 135 MHz), and from 18.4 ~ 57.6 dB with a pre-filter (B = 210 MHz), with R = 50 Ω and T = 300 K. For the simulation, AWGN is generated with the power defined by the receiver SNR, which is bound by 20.4 and 59.5 dB without a pre-filter (B = 135 MHz), and by 18.4 and 57.6 dB with a pre-filter (B = 210 MHz). After equalization, the data sequence is decoded by the RS decoder. The result is compared with the transmitted bit sequence to get the BER. The target BER is 4×10^{-3}, so RS(255,223) coding is able to decrease the BER to 10^{-9}.

Reducing inter symbol interferences

The first approach uses an adaptive Fractionally Spaced Feed-Forward Equalizer (FS-FFE) or alternatively a Fractionally Spaced Decision Feed back Equalizer (FS-DFE). The purpose of a DFE is to reduce ISI while minimizing the noise enhancement. The received signal is sampled with twice the symbol rate before being fed into the equalizers. Throughout this article, a DFE also contains a feed-forward part.

Both equalizers use the Recursive Least Squares (RLS) and Least-Mean-Square (LMS) adaptive algorithms to update the taps once per symbol. The RLS algorithm does the joint optimization for forward and feedback weights and is used for the training data block to ensure rapid tap convergence. The LMS algorithm is used thereafter to ensure rapid execution speed.

Figure 1 shows the simulated results for 2 Gbit/s and 3 Gbit/s trans-

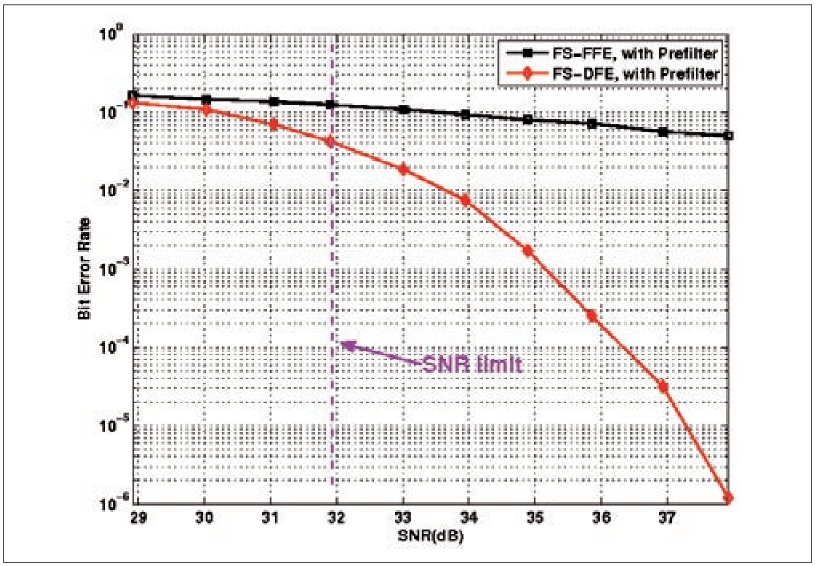


Figure 2. 3 Gbit/s transmission with pre-filter and post equalizers.

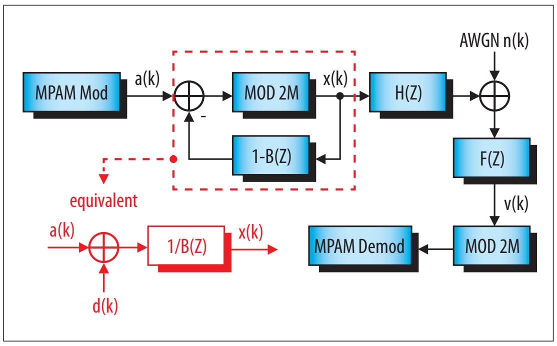


Figure 3. Block diagram for ZF-THP transmission.

mission with merely post equalization and no RS coding. An error free transmission is reached with SNR between 31.5 dB for DFE and 33.5dB for FFE at 2 Gbit/s. From this point on, BER curves hit the RS correction threshold and stay below it, so RS coding is able to further decrease the BER to 10^{-9}.

For 3 Gbit/s transmission, the FFE BER no longer touches the RS threshold even if SNR is high enough. While for DFE, the BER curve hits the RS correction threshold when SNR equals 41.5 dB at 3 Gbit/s, which is nearly 10 dB more than at 2 Gbit/s. Compared with the SNR range which is from 20.4 to 59.5 dB without a pre-filter, 41.5 dB lies somehow in the middle SNR region.

In next scenario, a fifth order fractionally spaced pre-filter is inserted between the MPAM output and the input of the LED. It does the electrical compensation and broadens the total bandwidth B from 135 to 210 MHz. Since the pre-filter contains negative taps, which change some positive samples into negative ones, a DC must be added to make all data positive again so they can be launched into the LED. This has a significant drawback of reducing the actual transmit signal power due to the power spent on DC. Therefore, with pre-filtering, the actual SNR upper limit is reduced to 32 dB.

Figure 2 shows the simulation result for 3 Gbit/s transmissions with pre-filter and no RS coding. For SNR higher than 35.5 dB, the DFE BER curve stays below the RS correction threshold. However, as the SNR upper limit is at 32 dB, which is marked by the dashed line in figure 2, an extra of 3 to 4 dB is needed to make the transmission possible. In this case, ways to increase SNR, such as decreasing the receiver noise or increasing the upper limit for the received optical power, must be adopted.

For FFE, on the other hand, the BER never goes below the threshold and 3 Gbit/s transmission is not possible. The overall situation becomes more critical compared with using only post equalizers.

Tomlinson Harashima Precoding limits transmit signal power

Figure 3 explains shortly how THP works. The unique sequence

$$d(k) \in 2M \times N \qquad (4)$$

(where N is an integer and M is the order of PAM) is added to the data sequence a(k) in order to create the

$$x(k) \in (-M/2, M/2) \qquad (5)$$

after the modulo-2M operation. x(k) is thereafter filtered by the overall transfer function H(Z), where

$$H(Z) = \sum_k h(k) \times Z^k \qquad (6)$$

is the Z-transform of the impulse response, and h(k) is the discrete channel impulse response corresponding to $h_0(t)$ in equation (2). B(Z) and F(Z) are the feedback and feed-forward filters designed according to ZF criteria.

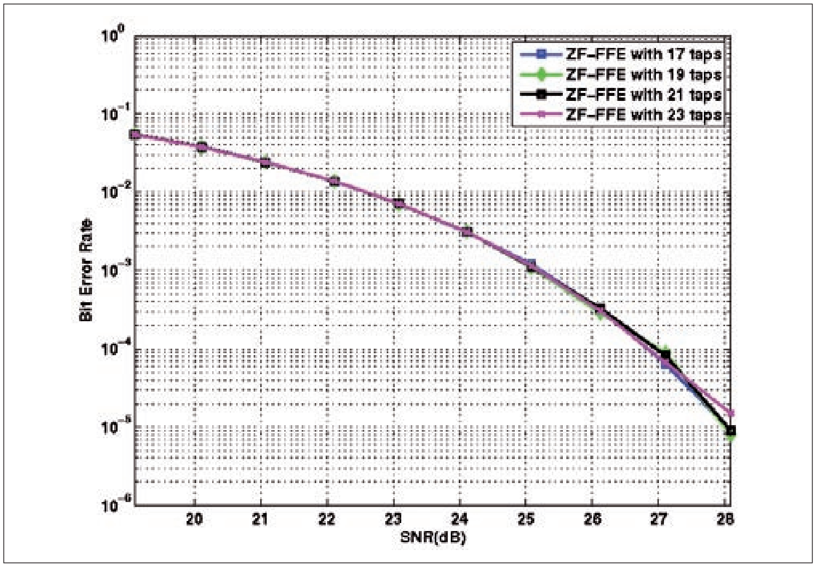


Figure 4. 2 Gbit/s ZF-THP transmission.

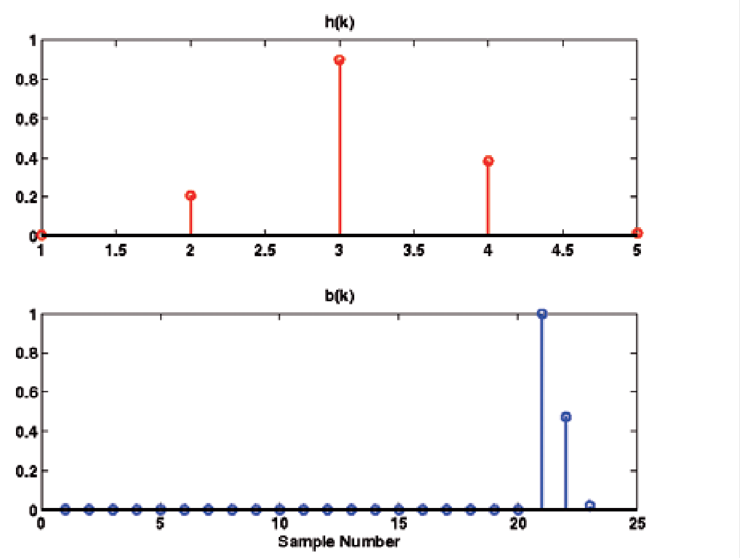
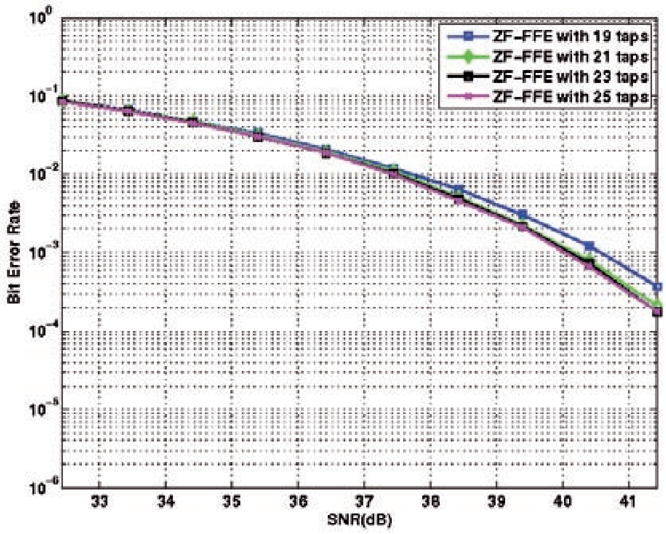


Figure 5. Discrete channel impulse response before and after ZF-FFE at 2 Gbit/s (sampled by symbol duration).



I Figure 6. 3 Gbit/s ZF-THP transmission.

First, F(Z) is chosen such that H(Z) × F(Z) is approximating causal, monic and minimum phase B(Z) is then chosen to be equal to H(Z) × F(Z) [4]. As a consequence, a(k) + d(k) can be expected after F(Z) if no noise appears.

It is worth noting that although THP limits the transmit signal power of x(k), due to the possibly large values of d(k), it increases the dynamic range of the received signal and brings extra losses to the signal to noise ratio. The more severe the ISI, the larger the d(k), and the bigger the losses are.

Figure 4 shows the BER versus SNR at 2 Gbit/s with ZF-THP and no RS coding. Compared with figure 1, the THP decreases less sharper as post equalization. This is the cost for moving the feedback equalizer to the transmitter side while retaining the dynamic range of the transmitted signals.

Figure 5 shows the discrete channel impulse response h(k) (sampled by symbol duration) and the impulse response b(k) which corresponds to B(Z) in figure 3. After ZF-FFE, b(k) is causal and monic. Except for the main tap at k = 21, all other taps of b(k) should be reduced by THP.

Similar to the last section, a DC is added due to the negative samples produced by THP. However, it is smaller than the one for pre-filtering. The actual SNR without DC power is from 11.5 ~ 50.6 dB. An error free transmission happens at 25.5 dB, which is closer to the SNR lower limit and is quite optimistic.

With 3 Gbit/s transmission, the ISI gets much more severe. Bigger tails of b(k) are left compared with figure 5, which brings a larger DC value and decreases the SNR by 10.5 dB, so the new SNR range is from 10 to 49 dB.

As illustrated in **figure 6**, the BER of ZF-THP without RS coding reaches 10^{-3} at 40.5dB, which has a 10 dB margin to the SNR upper limit. Compared with the FS-DFE scheme in figure 1, which has an 18 dB margin, one can conclude that ZF-THP works fine with 3 Gbit/s but performs worse than the FS-DFE scheme. In this article, the 2 to 3 Gbit/s data transmission in the MOST150 physical layer was examined. In order to achieve data rates even higher than 3 Gbit/s while guaranteeing system stability, further optimization for both the electronic and optical components are required. *sj*

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Literature

[1] MOST150 oPHY Automotive Physical Layer Sub-Spec. Rev. 1.0. October 2008.
[2] *Sheikholeslami, N.; Kabal, P.:* Linear Time Varying Precoder Applied to an ISI Channel. Proc. IEEE Pacific Rim conference on Communications, Computers and Signal Processing. Victoria, BC. August 1997.
[3] *Agrawal, G.:* Fiber-Optic Communication Systems. Wiley. 1992.
[4] *Wesel, R.; Cioffi, J.:* Achievable rates for Tomlinson-Harashima precoding. IEEE Transactions on information theory., Vol. 44. No. 2. March 1998.

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