Is Ultra-High Order QAM Necessary for Delta-Sigma Modulator in Mobile Front-Haul?

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Abstract: We propose a delta-sigma-modulator (DSM) using multi-stage-noise-shaping (MASH) structure. Record high efficiencies of 1.016 (hard-decision forward-error-correction, FEC) and 1.166 (soft-decision-FEC) are achieved in the proposed MASH-DSM without the need of ultra-high-order quadrature-amplitude-modulation (QAM). © 2024 Author(s)
OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications

1. Introduction

To satisfy the exponential growth of mobile traffic, centralized/cloud radio access network (C-RAN) has been proposed to improve the network efficiency. C-RAN is divided into the central units (CUs), the distributed units (DUs) and the radio units (RUs). The connections between the CU and the DU and between the DU and the RU are known as the mobile back-haul (MBH) and the mobile front-haul (MFH) respectively [1]. Optical fibers are used in the MBH and MFH to provide high bandwidth transmission. Digital radio-over-fiber (DRoF) in common public radio interface (CPRI) [1] is utilized in the MFH due to its robustness against the channel effect. However, the CPRI suffers from the low spectrum efficiency owing to the requirement of maintaining the high fidelity of analog signals. As a result, the delta-sigma modulator (DSM) is proposed to enhance the spectrum efficiency [2]. Moreover, in the DSM scheme, the digital-to-analog converter (DAC) can be replaced with the low-pass filter in RUs. This can further reduce the deployment cost. Recently, different 1-bit resolution DSMs has been proposed [2]. To pursue higher spectrum efficiency, 2-bit resolution DSMs using single-loop structure [2-4] or quantization noise suppression structure [5-6] have been demonstrated. In these works, the efficiencies are improved via generating the ultra-high order QAM (e.g. 4194304-QAM [2]) for the orthogonal frequency division multiplexing (OFDM) signals. Table I summarizes the recent works on highly efficient DSM schemes with the ultra-high order QAM. Since there are some works employing the in-phase/quadrature-phase (I/Q) modulation, the DSM efficiency is halved for the fair comparison. The DSM efficiency here is defined as how many information bits at the DSM output per transmitted symbol. However, the ultra-high order QAM will give rise to the computational burden of processing the demodulation at user equipments (UEs). For example, during the hard decision (HD), the log-likelihood function is computed for all possible symbols and the decoder will select the maximal one. As the symbol alphabet is enlarged, the computation for the decoder will dramatically increase. For the soft decision (SD), the log-likelihood ratio (LLR) will be calculated for each bit, further aggravating the decoding burden at UEs. Hence, a DSM with high efficiency and not too high order QAM is desirable.

In this work, a DSM scheme with the multi-stage noise shaping (MASH) structure is proposed. Up to the authors' knowledge, record high efficiencies of 1.016 (HD forward-error-correction, FEC) and 1.166 (SD-FEC) are achieved with the relaxed over-sampling rate (OSR) requirement. Average QAM orders of < 9 are utilized. We believe the proposed MASH DSM scheme can be adopted in the MFH with lower processing complexity at UEs.

Table I. Summary of recent works on DSM schemes with ultra-high order QAM

Ref.	Year	DSM Structure	OSR	2^M - QAM	I/Q	Transmitted Format	DSM Efficiency	Performance criterion**
[2]	2021	Single loop	16	22	Yes	16 QAM	$22/16 \times 1 \times 0.5 = 0.6875$	EVM
[3]	2021	Single loop	8	14	No	PAM4	$14/8 \times (470/1000) \times 1 = 0.8225$	EVM
[4]	2023	Single loop	10	16	Yes	16 QAM	$16/10 \times (900/1024) \times 0.5 = 0.703$	Hard Decision
[5]	2022	Quantization Noise suppressed	8	16	No	PAM4	$16/8 \times (900/2048) \times 1 = 0.879$	Hard Decision
[6]	2023	Quantization Noise suppressed	10	19 20	No	Pol. OOK	$19/10 \times (450/1024) \times 1 = 0.834$ $20/10 \times (450/1024) \times 1 = 0.878$	Hard Decision 20% Soft Decision
This work*	2023	MASH	5	(Avg.) 11.66 (Avg.) 13.08	No	PAM4	(Avg.) $11.66/5 \times (450/1024) \times 1 = \mathbf{1.025}$ (Avg.) $13.08/5 \times (450/1024) \times 1 = \mathbf{1.150}$	Hard Decision 20% Soft Decision
This work*	2023	MASH	3	(Avg.) 7.61 (Avg.) 8.73	No	PAM4	(Avg.) $7.61/3 \times (410/1024) \times 1 = \mathbf{1.016}$ (Avg.) $8.73/3 \times (410/1024) \times 1 = \mathbf{1.166}$	Hard Decision 20% Soft Decision

* In this work, due to the application of the bit loading, each subcarrier will have different QAM orders, and the average values are shown here.

2. Working principle of the proposed MASH DSM and Experimental Setup

Before introducing the proposed MASH DSM, the traditional DSM schemes will be revisited for defining some terminologies and pointing out their limitations. In the traditional DSM, the input signal is analog (e.g. OFDM format) and the output signal is in digital form. It consists of one 1-bit/2-bit quantizer and one single-loop feedback filter. This filter can be recognized as the signal transfer function (STF) and the noise transfer function (NTF). The STF typically stands for the delay for the input signal only while the NTF serves as a high-pass/band-stop filter and aims to suppress the noise introduced by the quantization at certain interval of frequencies. Therefore, although the signal is digitalized after the DSM, the analog input signal can be hidden at this interval of frequencies and extracted by using a simple low-pass/band-pass filter. However, due to the stability issue of the feedback filter, there exists the trade-off between the noise suppression level and the noise suppression region. Moreover, since the input signal is supposed to be arranged in this region, over-sampling of the input signal is necessary. As a result, even though higher in-band noise suppression and ultra-high order QAM can be achieved with narrower noise suppression region, the efficiency of the DSM is still limited owing to the requirement of higher OSR. According to Table I, higher than 2^{14}- QAM can be obtained when the OSR is 8 ~ 10.

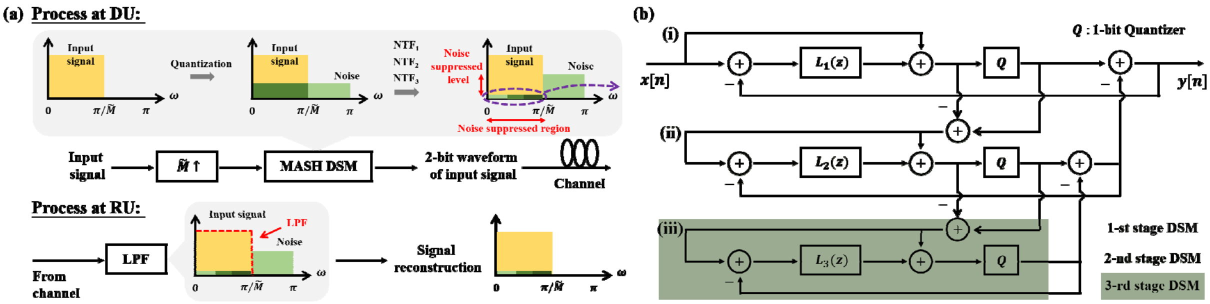

Fig. 1. (a) The working principle and (b) the structure of the MASH DSM.

With the MASH structure, this trade-off can be considerably relaxed and the efficiency can be improved. The MASH DSM can be regarded as the cascade of traditional DSMs, wherein the difference between the input and the output of the quantizer is the input signal of the next stage of the DSM. The overall quantization noise, in principle, is only originated from the quantizer of the final stage. Th advantage of the MASH structure is that the effective NTF is the multiplication of the NTFs in all stages. This implies extending the noise suppression region and consequently lowering the OSR requirement without sacrificing the noise suppression level is achievable since the overall system can be stable if the stability in each stage is satisfied. Figs. 1(a) and (b) respectively show the working principle and the structure of the MASH DSM. In Fig. 1(b), *x[n]* and *y[n]* are the input and the output of the MASH DSM. *L(z)* denotes the auxiliary filter for the NTF at each stage, and Q is the 1-bit quantization operator. At the Tx-side, the input OFDM signal is up-sampled. There are three stages in the proposed MASH DSM, as can be seen in Fig. 1(b); and hence three NTFs contribute to the effective NTF. In this work, two effective NTFs implementing on the MASH DSM with different noise suppression levels and the suppression regions are presented. In Case I, as shown in Fig. 2(a), the average noise suppression level is around 37 dB and the suppression region is up to 0.167 in normalized frequencies, which indicates the OSR of 5 ~ 6 is enough. In Case II, the noise suppression level is further relaxed to be approximately 27 dB as shown in Fig. 2(b) and the suppression region up to 0.256 can be attained, indicating the low OSR requirement of only 3 ~ 4. After the MASH DSM block, the digital waveform with 4-level (i.e. PAM4) is generated and transmitted into the channel. At the Rx-side, a single low-pass filter (LPF) is applied to extract and reconstruct the hidden OFDM signal, as illustrated in Fig. 1(a).

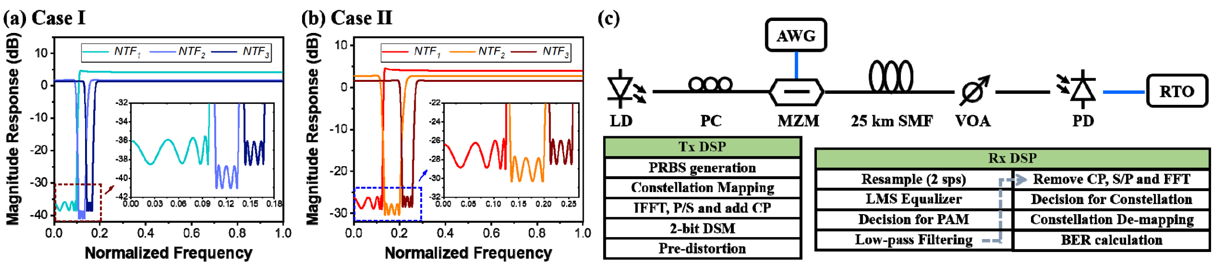

Fig. 2. The proposed effective NTFs with (a) Case I: higher noise suppression level and the narrower suppression region. (b) Case II: lower noise suppression level and the wider suppression region. (c) Experiment setup and flow diagrams of Tx and Rx DSPs.

Fig. 2(c) shows the experimental setup for validating the proposed MASH DSM. The laser diode (LD) is modulated using the 10 GHz Mach-Zehnder modulator (MZM), driven by the arbitrary waveform generator (AWG) with DSM signals. The Tx-side DSP involves the constellation mapping of PRBS sequences, the traditional OFDM encoding, the MASH DSM block and the pre-distortion for the PAM4 signal. After 25 km transmission, the optical signal is received by the 10 GHz photodetector (PD) and captured by the real-time scope (RTO). The Rx-side DSP includes the resampling, the equalization, the decision for PAM4, the low-pass filtering, the traditional OFDM decoding, the constellations de-mapping and the bit-error-rate (BER) measurement. The FFT size is 1024 while the numbers of active subcarrier in Case I and Case II are 450 and 410. Besides, the OSRs in Case I and Case II are set to be 5 and 3.

3. Results and Discussion

Figs. 3(a) and (b) show the signal-to-noise ratio (SNR) distributions of the proposed MASH DSM, in which the effective NTFs in Case I and in Case II are applied, respectively. Afterwards, the bit-loading is performed for these two SNR distributions according to the HD-FEC threshold (BER = 3.8×10^{-3}) and the SD-FEC threshold (BER = 2.4×10^{-2}). The results of the carrying information bits based on the HD and the SD criteria are shown as the bright blue line and the dark blue line in Fig. 3 (a) and the bright purple line and the dark purple line in Fig. 3(b). The average bits in Case I are 11.66 and 13.08 for the HD and SD criteria, respectively, and they reduced to 7.61 and 8.73 in Case II. The respective efficiencies are calculated to be 1.025 and 1.016 for Case I and Case II under the HD criterion, and they increase to 1.150 and 1.166 for Case I and Case II if the SD criterion is employed. It is worth to mention that in spite of the decrease in the average bits in Case II, the efficiency does not reduce since the OSR requirement is accordingly relaxed. This result demonstrates the feasibility of the highly efficient MASH DSM scheme with the regular order QAM, which can lighten the burden of processing the demodulation at UEs. The realizations of the constellations are revealed in Fig. 3(c), where the 4096-QAM with the HD criterion and the 8192-QAM with the SD criterion in Case I are in the left-hand side, and the 256-QAM with the HD criterion and the 512-QAM with the SD criterion in Case II are in the right-hand side. Lastly, the BER curves of the OFDM signal in these four cases are measured and presented in Fig. 3(d). It is noted that the SNR distribution does not depend on the channel but the effective NTF, provided that the digital signal (i.e. PAM4) is able to be successfully recovered. Therefore, the lower bounds of the BER curves will be clamped based on the bit-loading optimization when the received power is high enough to transmit the PAM4 signal. According to our measurement, it is observed that there is no symbol error detection of the PAM4 signal as the optical power is higher than -14 dBm and the BER curves are clamped at the level below the threshold of the chosen criterion, validating the proposed MASH DSM can achieve the previously claimed efficiencies.

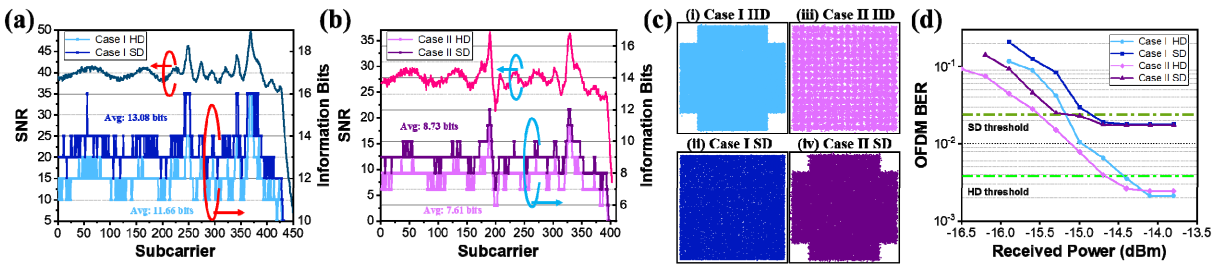

Fig. 3. Measured SNRs and bit-loadings in (a) Case I and (b) Case II. (c) Constellations of (i) 4096-QAM (HD criterion) (ii) 8192-QAM (SD criterion) in Case I (iii) 256-QAM (HD criterion) (ii) 512-QAM (SD criterion) in Case II (c) Measured BER curves of four cases.

4. Conclusion

We proposed and experimentally demonstrated a MASH DSM structure. Two effective NTFs were presented. Record high efficiencies of 1.025 and 1.016 under the HD criterion and 1.150 and 1.166 under the SD criterion were validated with the relaxed OSR requirement. Average QAM orders of < 9 were successfully realized, which could reduce the computational burden of demodulation at the UEs.

Acknowledgment This work was supported by National Science and Technology Council, Taiwan (NSTC-112-2221-EA49-102-MY3, NSTC-110-2221-E-A49-057-MY3).

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