Amplitude shaping method, receiving method, processing unit and generator unit for an amplitude shaper, and an amplitude shaper

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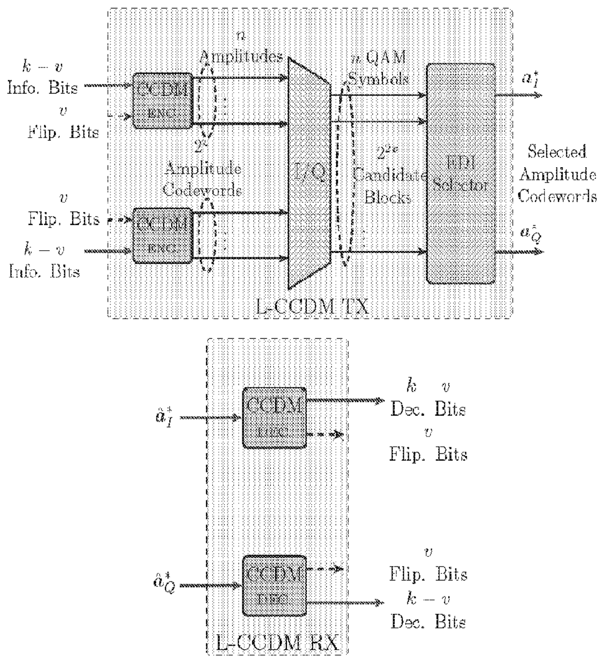
Fig. 2



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(57) **Abstract:** An amplitude shaping method for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the method comprising: - obtaining a bit input sequence; - inserting flipping bits into the bit input sequence, resulting in extended bit sequences, wherein flipping bits are configured to be zero or one during combinatoric generation; - generating symbol sequence candidates based on the extended bit sequences, using combinatoric generation; - determining respective energy dispersion indexes for the generated symbol sequence candidates; - selecting a symbol sequence from among the generated symbol sequence candidates based on their respective energy dispersion indexes; and - extracting amplitude codewords based on the selected symbol sequence.

[Continued on next page]

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TECHNICAL FIELD

The present disclosure generally relates to amplitude shaping. Particular aspects of the present disclosure relate to an amplitude shaping method, a receiving method, a processing unit and a generator unit for an amplitude shaper, an amplitude shaper, a computer program and a computer program product.

BACKGROUND

Driven by high-bandwidth-demanding applications, such as cloud computing, 5G wireless, high-definition video streaming, and virtual reality, probabilistic shaping (PS) has become an indispensable technology in fiber optical communications [1]. Probabilistic shaping functionality mostly relies on an amplitude shaper, and there are some popular shapers such as constant-composition distribution matcher (CCDM) [2], multiset-partition distribution matcher (MPDM) [3], product distribution matcher (PDM) [4], enumerative sphere shaping (ESS) [5], [6]. However, these amplitude shapers were initially tailored to additive white Gaussian noise (AWGN) channel and neglect the temporal structure of transmitted symbols. As a consequence, when these shapers are adopted in nonlinear fiber channels, the shaping gains are undermined significantly, since the shaped signal suffers severely from nonlinear interference noise (NLI), which is known as one major obstacle hindering the transmission rate increase in fiber optical communications.

To combat the NLI penalty enhanced by constellation shaping, several approaches are known, which will be described below in the detailed description.

SUMMARY

It is a shortcoming of the known approaches that they lack optimisation of the temporal structure of symbol sequences. Moreover, it is an insight of the inventors that a signal-to-noise ratio and an achievable information rate gain, or equivalently a reach extension, may be improved.

Therefore, in a first aspect of the present disclosure, there is provided an amplitude shaping method for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the method comprising:

- obtaining a bit input sequence;
- inserting flipping bits into the bit input sequence, resulting in extended bit sequences, wherein flipping bits are configured to be zero or one during combinatoric generation;
- generating symbol sequence candidates based on the extended bit sequences, using combinatoric generation;
- determining respective energy dispersion indexes for the generated symbol sequence candidates;
- selecting a symbol sequence from among the generated symbol sequence candidates based on their respective energy dispersion indexes; and
- extracting amplitude codewords based on the selected symbol sequence.

By generating symbol sequence candidates by inserting flipping bits into the bit input sequence, and by determining respective energy dispersion indexes (EDIs) for those symbol sequence candidates, a suitable or even optimal symbol sequence may be selected, for extracting amplitude codewords in order to modulate the bit input sequence into symbols for transmission on the channel. Since the EDIs have been taken into account, nonlinear interference noise may be reduced, thus allowing to improve the signal-to-noise ratio and the achievable information rate gain, or equivalently the reach.

Preferably, the selecting comprises selecting the symbol sequence having the smallest respective energy dispersion index.

Preferably, the bit sequence comprises an initial first half and a subsequent second half, and a greater number of flipping bits are inserted in the first half, preferably at the beginning of the bit input sequence, than in the second half.

In this way, if lexicographic ordering is used to index the sequences, the temporal structure of candidate amplitude codewords may be improved, because changes in the first half, preferably at or near the beginning of the bit input sequence have a greater impact than changes in the second half.

Preferably, the method comprises appending the flipping bits as a prefix to the bit input sequence.

Preferably, the energy dispersion index represents a ratio of a variance of a windowed energy of the symbol sequence to a mean of the windowed energy of the symbol sequence, wherein the variance and the mean are averaged over the blocklength.

Preferably, the channel is an optical fiber channel.

Preferably, the symbols are modulated using constant composition distribution matching, CCDM.

In a second aspect of the present disclosure, there is provided a receiving method, implemented in a receiver unit, the method comprising:
- receiving, on a channel, symbols modulated using the method of any previous claim;
- decoding the modulated symbols; and
- discarding the flipping bits from the modulated symbols.

Preferably, the modulated symbols are decoded using constant composition distribution matching, CCDM, decoding.

In a third aspect of the present disclosure, there is provided a processing unit for an amplitude shaper for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the processing unit comprising:
- an input interface configured for obtaining symbol sequence candidates, wherein the symbol sequence candidates are generated using combinatoric generation based on

extended bit sequences resulting from inserting flipping bits into a bit input sequence, wherein flipping bits are configured to be zero or one during combinatoric generation;
- a calculating unit configured for determining respective energy dispersion indexes for the generated symbol sequence candidates;
- a selecting unit configured for selecting a symbol sequence from among the generated symbol sequence candidates based on their respective energy dispersion indexes;
wherein the processing unit is configured for outputting the selected symbol sequence.

The skilled person will understand that analogous considerations and advantages may apply to embodiments of the processing unit as for the amplitude shaping method described above, *mutatis mutandis*.

In a fourth aspect of the present disclosure, there is provided a generator unit for an amplitude shaper for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the generator unit being configured to:
- obtain a bit input sequence;
- insert flipping bits into the bit input sequence, resulting in extended bit sequences, wherein flipping bits are configured to be zero or one during combinatoric generation; and
- generate symbol sequence candidates based on the extended bit sequences, using combinatoric generation;
wherein the generator unit is configured for outputting the generated symbol sequence candidates.

The skilled person will understand that analogous considerations and advantages may apply to embodiments of the generator unit as for the amplitude shaping method described above, *mutatis mutandis*.

In a fifth aspect of the present disclosure, there is provided an amplitude shaper for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the amplitude shaper comprising:

- a generator unit as described above;
- a processing unit as described above, wherein the input interface of the processing unit is coupled to an output of the generator unit; and
- an extractor unit coupled to an output of the processing unit and configured for extracting amplitude codewords based on the selected symbol sequence.

The skilled person will understand that analogous considerations and advantages may apply to embodiments of the amplitude shaper as for the amplitude shaping method described above, *mutatis mutandis*.

In a sixth aspect of the present disclosure, there is provided a transmitter unit comprising the amplitude shaper as described above.

The skilled person will understand that analogous considerations and advantages may apply to embodiments of the transmitter unit as for the amplitude shaping method described above, *mutatis mutandis*.

In a seventh aspect of the present disclosure, there is provided a receiver unit comprising:

- an input interface configured for receiving, on a channel, symbols modulated using the amplitude shaping method of any one of the embodiments as described above; and
- a decoder configured for decoding the modulated symbols and for discarding the flipping bits from the modulated symbols.

Preferably, the decoder is configured for decoding the modulated symbols using constant composition distribution matching, CCDM, decoding.

In an eighth aspect of the present disclosure, there is provided a computer program, comprising instructions configured for, when executed on at least one processing unit, performing the amplitude shaping method of any one of the embodiments as described above, or comprising instructions configured for, when executed on at least one processing unit, performing the receiving method of any one of the embodiments as described above.

In a ninth aspect of the present disclosure, there is provided a computer program product comprising a computer-readable medium storing the computer program of claim 16.

The skilled person will understand that analogous considerations and advantages may apply to embodiments of the computer program and of the computer program product as for the amplitude shaping method described above, *mutatis mutandis*.

DETAILED DESCRIPTION

Currently, for the design of NLI-tolerant amplitude shapers, one direction is to optimize the probability distribution of input symbols, meanwhile assuming the symbols to be independent identically distributed (i.i.d.). Originated from the EGN model, the standardized fourth moment (a.k.a. kurtosis) of transmitted symbols has been widely accepted as a metric that indicates the NLI magnitude [7]–[9]. In [10], an optimized PMF for nonlinear fiber channel is designed with the help of kurtosis. In [11], the NLI-optimized MPDM is proposed, where blockwise compositions of the symbol sequences having low kurtosis are selected for transmission.

Alternatively, one can manipulate the temporal structure of the symbol sequence, since transmitted symbols that comply to certain temporal structures could exert great influence on the NLI [12]–[14]. A straightforward approach to improving the NLI tolerance of amplitude shaper is simply using short shaping blocklengths [15]. This nonlinear shaping gain enabled by short shaping blocklengths is intuitively attributed to the fact that the generated symbol sequences have fewer clusters of identical symbols [16], [17]. However, a guiding principle for the temporal structure of symbol sequences was missing.

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Embodiments according to the present disclosure, referred to list-encoding CCDM (L-CCDM), improves the nonlinear tolerance of transmitted symbols NLI. The nonlinear tolerance of a symbol block is indicated by a recently proposed metric called energy dispersion index (EDI), which accurately predicts the NLI of correlated symbols. L-CCDM consists of (multiple) standard CCDM and an EDI selecting module. L-CCDM selects symbol sequences with the lowest EDI from a list of candidate symbol blocks. These candidates are generated after inserting flipping bits along with information bits into the standard CCDM. In this manner, compare to standard CCDM, L-CCDM generates low-EDI symbol blocks with higher probability.

Based on a typical PS architecture at the transmitter side as shown in Fig. 1, the proposed L-CCDM replaces the two amplitude shapers with red inputs and outputs.

The system model of this disclosure is implemented at the transmitter side as shown in Fig. 2, which is an amplitude shaper encoder comprising: two CCDM circuits; an EDI computing and selecting circuit.

EDI is computed based on a realization of *n*-length symbol sequence $[x_1, x_2, \ldots, x_n]$. As shown in Fig. 3, a windowed energy sequence $[g^W_{1+W/2}, g^W_{2+W/2}, \ldots, g^W_{n-W/2}]$ is constructed. Then, the EDI is estimated numerically as

$$\hat{\psi} = \frac{\delta^2_{G^W}}{\mu_{G^W}},$$

where μ_{G^W} is the estimated windowed energy mean, i.e.,

$$\mu_{G^W} = \frac{\sum_{i=1+W/2}^{n-W/2} g_i}{n-W},$$

and $\delta^2_{G^W}$ is the estimated windowed energy variance, i.e.,

$$\delta^2_{G^W} = \frac{\sum_{i=1+W/2}^{n-W/2} (g_i - \mu_{G^W})^2}{n-W-1}.$$

The interaction between the above components are described above and in Fig. 2. The EDI computing and selecting operations improve the NLI tolerance of the transmitted symbols,. Alternatively, the circuits are computational circuits.

Fig. 2 displays the block diagram of L-CCDM. First, the amplitude codeword candidates are introduced on top and bottom branches, which is done by inserting flipping bits along with the information binary sequence into CCDM. These flipping bits are preferably appended as the prefix of the information bits to yield QAM symbol block candidates with diversified EDI. As one flipping bit changes between 0 and 1, a CCDM encodes twice (or alternatively two parallel CCDMs encode simultaneously) yielding 2 candidates of amplitude codewords. Hence, ν flipping bits allow the combinatoric generation of 2^{v} amplitude codeword candidates, which are paired into one dimension of the complex symbols. In the meantime, the same procedures are conducted over another dimension. Then, L-CCDM generates QAM symbols that are in the same quadrant. Given the amplitude codewords from two dimensions, a list of 2^{2v} pseudo QAM symbol block candidates are obtained. Next, the EDIs of all the candidate symbol blocks are measured, or calculated, and L-CCDM selects the "best" candidate that has the smallest EDI. Finally, the selected QAM symbol block determines the output amplitude codewords on two dimensions. At the receiver, the only modification required in L-CCDM is to merely discard the flipping bits after the standard CCDM decoding.

Apparatus, such as, a data processor, a receiver or transceiver, include at least the following components:
at least one processor, at least one memory and the computer program instructions being configured to cause the processor to perform a method of any one of the embodiments according to the present disclosure.

The L-CCDM circuit comprising the improved algorithmic steps of the disclosure may be a processor or data processor unit for use with any device in optical communication channels, for example of a data center interconnect applications, long haul / metro links. The channels described above may be at least memory channels.

Alternatively, the algorithm may be represented as a computer program product stored on a storage device which may be inserted into a device such as a transmitter or receiver or transceiver for use in optical communication systems as described above. Alternatively, the algorithm may be embodied in software that can be downloaded and loaded into a device.

Embodiments according the present disclosure can also be used in a variant PS architecture that use a different mapping strategy. For example, some PS architectures assign one symbol block across in-phase and quadrature dimensions jointly. Embodiments according to the present disclosure may also be applied for improving the performance by slightly changing the I/Q mux in Fig. 2 such that it adapts to the used mapping strategy.

Embodiments according to the present disclosure may be implemented using FPGAs or be part of an ASIC.

Algorithm Optimization and Simulation Results

In what follows, the performance of PS using 256QAM with standard CCDM and L-CCDM are analyzed in an ideal multi-span WDM fiber system by using the symmetrized split-step Fourier method. For L-CCDM, the window length used is $W=100$ and at most $v=4$ flipping bits are demonstrated. $v=0$ flipping bit represents standard CCDM. Maxwell-Boltzmann distribution with slightly larger entropy is used by L-CCDM to cover the addition rate loss due to flipping bits.

A. Performance Fixed Transmission Distance

Fig. 4 displays the effective SNR vs. launch power at transmission distance of 1600 km by using standard CCDM and L-CCDM, where blocklength is $n=1800$ and the total transmission rate is fixed at 10.4 bit/4D-symbol. The inset shows that the EDI of transmitted symbols is improved with more flipping bits. In comparison with the -0.66 dB EDI of standard CCDM, L-CCDM suppresses the EDI to -4.03 dB at $v=4$, hence, the improved NLI tolerance yields an effective SNR gains that amounts to 0.35 dB compared to standard CCDM. The optimal launch power for L-CCDM with $v=4$ is -3 dBm, which is 0.5 dBm higher than that for standard CCDM.

Fig. 5 further visualizes how the effective SNR of each QAM block is improved as the EDI decreases. Compared to standard CCDM, Fig. 5 shows that because the L-CCDM of $v=4$ moves the EDI cloud to smaller EDI level, the effective SNR cloud of the L-CCDM locates at higher regime. Fig. 6 also shows that the EDI distribution of L-CCDM are constrained, and subsequently yields a higher and more concentrated effective SNR distribution.

The AIR results displayed in Fig. 7 have accounted for the rate loss caused by flipping bits. The effective SNR gains brought by L-CCDM of $v=4$ translates into AIR gains of 0.22 bit/4D-symbol. Regarding bit-error rate (BER) in Fig. 8, L-CCDM significantly outperforms standard CCDM within the range of -4.5 dBm to -2.5 dBm.

B. AIR and BER Results

Fig. 9 shows the AIR at various transmission distances. Fig. 9 also shows the post-FEC BER of uniform signalling and the post-deshaper BER of PS (markers), which indicate BERs below 1×10^{-4}. All the results are obtained at optimal launch powers. The transmission rate of uniform 256QAM is adjusted by changing FEC code rate, whilst the transmission rate of PS is adjusted by changing shaping rate. At transmission rate of 9.6 bit/4D-symbol that yields data rate of 307 Gbps, compared to the 480 km shaping reach extension brought by standard CCDM, L-CCDM of $v=4$ provides 33% (160 km) more transmission distance, which corresponds to reach extension of 8%.

C. Blocklength Analysis

For a fixed v, if n is large enough, the introduced loss v/n of L-CCDM would be negligible. For a fixed n, using more flipping bits means more chances to select a QAM symbol block with lower EDI. Meanwhile, the CCDM implementation are burdened with long blocklength n, and extra 2^v CCDM encoding iterations that grows exponentially with flipping bit number. The EDI measurement also takes up some complexity budget. Therefore, the parameters of L-CCDM are supposed to be carefully chosen to reach a trade-off between performance and complexity. Fig. 10 shows the blocklength-dependent effective SNR at 1600 km. It can be seen that longer blocklength n yields lower effective SNR in both cases. L-CCDM generally experiences higher SNR due to the decrease of EDI, meanwhile the effective SNR gains over standard CCDM becomes larger in long blocklength regime. Fig. 11 shows the AIR vs. blocklength n after taking into account the additional rate loss of flipping bits. The AIR gains of L-CCDM is not obvious for short blocklengths since 4 flipping bits takes a large portion of rate. The AIR achieves the maximum at the blocklength of $n=1350$. For longer blocklengths over $n=1350$, the AIR starts to decrease because of the effective SNR decrease.

In a further developed embodiment, the reliability of each bit may be updated after each iteration, at the expense of increased extra memory and decoding complexity.

In one aspect, embodiments according to the present disclosure may provide a simple and effective algorithm to improve the NLI tolerance of the transmitted signal, without significant change to the existing probabilistic shaping architecture. Therefore, embodiments according to the present disclosure may advantageously be integrated into optical transceivers to boost the transmission data rates/distance in the 100G/400G or beyond optical communication links.

Elements of the present disclosure may also be suitable for other amplitude shapers that the optical communication community is interested in (e.g., ESS, MPDM). The EDI selection procedures could in principle boost the nonlinear shaping gains of all these amplitude shapers.

The scope of the present disclosure should not be construed to be limited to the above-described examples, but is determined by the appended claims.

A scientific paper authored by the inventors describing various example embodiments according to the present disclosure is appended. The skilled person will understand that the disclosure of the scientific paper is intended to be within the ambit of the present disclosure, and that various embodiments and features from the scientific paper may be combined with embodiments described above, within the scope of the appended claims.

CLAIMS

1. An amplitude shaping method for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the method comprising:
- obtaining a bit input sequence;
- inserting flipping bits into the bit input sequence, resulting in extended bit sequences, wherein flipping bits are configured to be zero or one during combinatoric generation;
- generating symbol sequence candidates based on the extended bit sequences, using combinatoric generation;
- determining respective energy dispersion indexes for the generated symbol sequence candidates;
- selecting a symbol sequence from among the generated symbol sequence candidates based on their respective energy dispersion indexes; and
- extracting amplitude codewords based on the selected symbol sequence.

2. The method of claim 1, wherein the selecting comprises selecting the symbol sequence having the smallest respective energy dispersion index.

3. The method of any previous claim, wherein the bit sequence comprises an initial first half and a subsequent second half, and wherein a greater number of flipping bits are inserted in the first half, preferably at the beginning of the bit input sequence, than in the second half.

4. The method of any previous claim, comprising appending the flipping bits as a prefix to the bit input sequence.

5. The method of any previous claim, wherein the energy dispersion index represents a ratio of a variance of a windowed energy of the symbol sequence to a mean of the windowed energy of the symbol sequence, wherein the variance and the mean are averaged over the blocklength.

6. The method of any previous claim, wherein the channel is an optical fiber channel.

7. The method of any previous claim, wherein the symbols are modulated using constant composition distribution matching, CCDM.

8. A receiving method, implemented in a receiver unit, the method comprising:
- receiving, on a channel, symbols modulated using the method of any previous claim;
- decoding the modulated symbols; and
- discarding the flipping bits from the modulated symbols.

9. The method of claim 8, wherein the modulated symbols are decoded using constant composition distribution matching, CCDM, decoding.

10. A processing unit for an amplitude shaper for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the processing unit comprising:
- an input interface configured for obtaining symbol sequence candidates, wherein the symbol sequence candidates are generated using combinatoric generation based on extended bit sequences resulting from inserting flipping bits into a bit input sequence, wherein flipping bits are configured to be zero or one during combinatoric generation;
- a calculating unit configured for determining respective energy dispersion indexes for the generated symbol sequence candidates;
- a selecting unit configured for selecting a symbol sequence from among the generated symbol sequence candidates based on their respective energy dispersion indexes;
wherein the processing unit is configured for outputting the selected symbol sequence.

11. A generator unit for an amplitude shaper for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the generator unit being configured to:
- obtain a bit input sequence;
- insert flipping bits into the bit input sequence, resulting in extended bit sequences, wherein flipping bits are configured to be zero or one during combinatoric generation; and

- generate symbol sequence candidates based on the extended bit sequences, using combinatoric generation;

wherein the generator unit is configured for outputting the generated symbol sequence candidates.

12. An amplitude shaper for encoding and modulating a bit input sequence into symbols for transmission on a channel, wherein symbols transmitted on the channel are susceptible to nonlinear effects, the amplitude shaper comprising:

- a generator unit according to claim 11;
- a processing unit according to claim 10, wherein the input interface of the processing unit is coupled to an output of the generator unit; and
- an extractor unit coupled to an output of the processing unit and configured for extracting amplitude codewords based on the selected symbol sequence.

13. A transmitter unit comprising the amplitude shaper of claim 12.

14. A receiver unit comprising:

- an input interface configured for receiving, on a channel, symbols modulated using the method of any one of claims 1-7; and
- a decoder configured for decoding the modulated symbols and for discarding the flipping bits from the modulated symbols.

15. The receiver unit of claim 14, wherein the decoder is configured for decoding the modulated symbols using constant composition distribution matching, CCDM, decoding.

16. A computer program, comprising instructions configured for, when executed on at least one processing unit, performing the method of any one of claims 1-7, or comprising instructions configured for, when executed on at least one processing unit, performing the method of any one of claims 8-9.

17. A computer program product comprising a computer-readable medium storing the computer program of claim 16.

Fig. 1

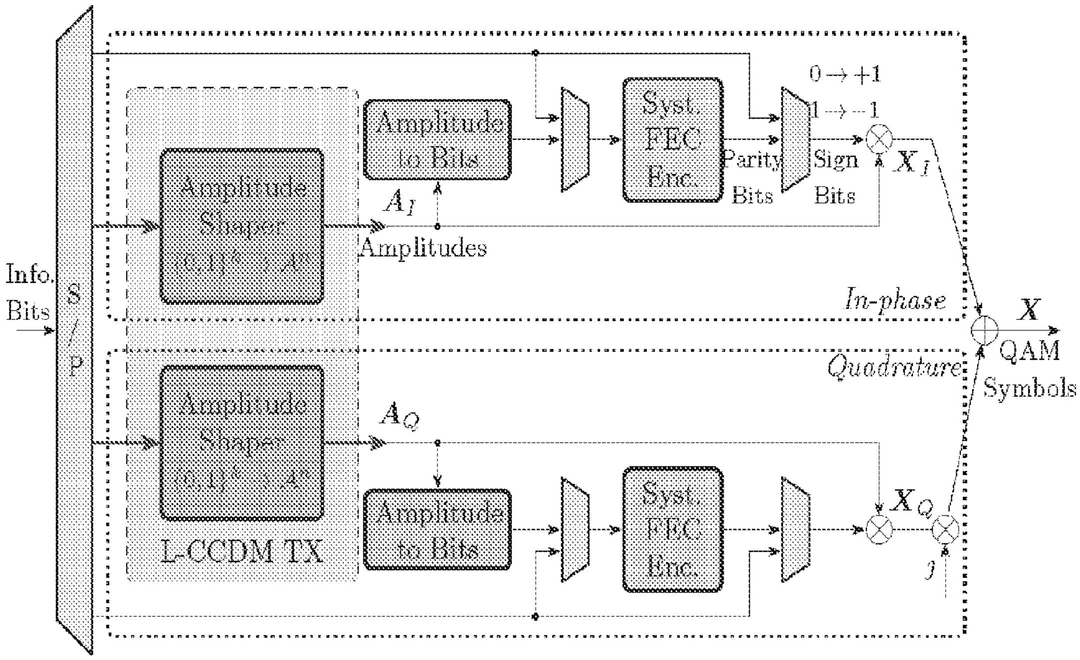

Info. Bits
S / P
Amplitude Shaper
Amplitude to Bits
Syst. FEC Enc.
0 → +1
1 → −1
Parity Bits
Sign Bits
A_I
Amplitudes
X_I
In-phase
X
QAM Symbols
Quadrature
A_Q
X_Q
L-CCDM TX
j

Fig. 2

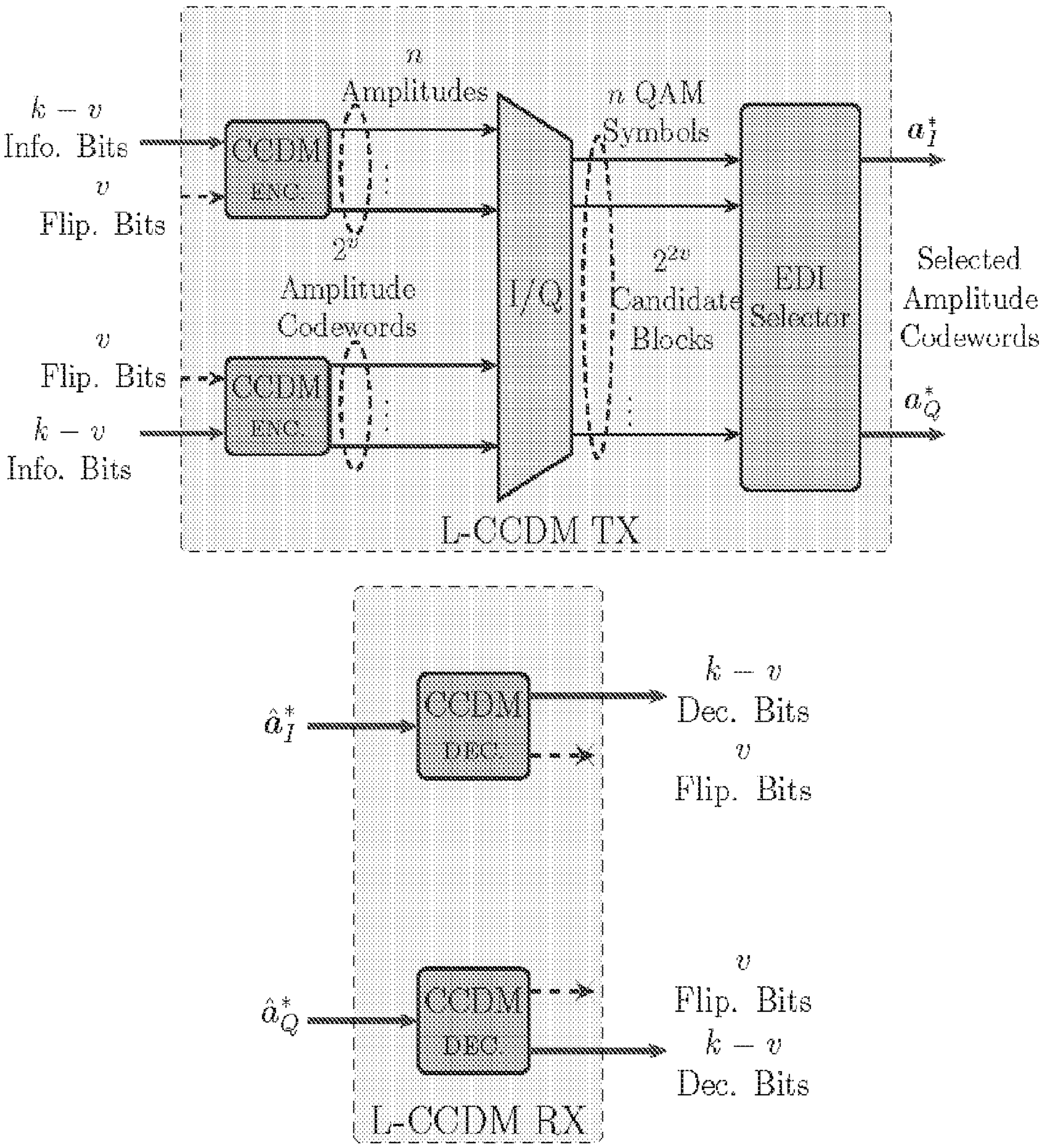

n
Amplitudes
k − v
Info. Bits
v
Flip. Bits
CCDM
ENC
2^v
Amplitude
Codewords
I/Q
n QAM
Symbols
2^{2v}
Candidate
Blocks
EDI
Selector
a_I^*
Selected
Amplitude
Codewords
a_Q^*
v
Flip. Bits
CCDM
ENC
k − v
Info. Bits
L-CCDM TX
$\hat{a}_I^*$
CCDM
DEC
k − v
Dec. Bits
v
Flip. Bits
$\hat{a}_Q^*$
CCDM
DEC
v
Flip. Bits
k − v
Dec. Bits
L-CCDM RX

Fig. 3

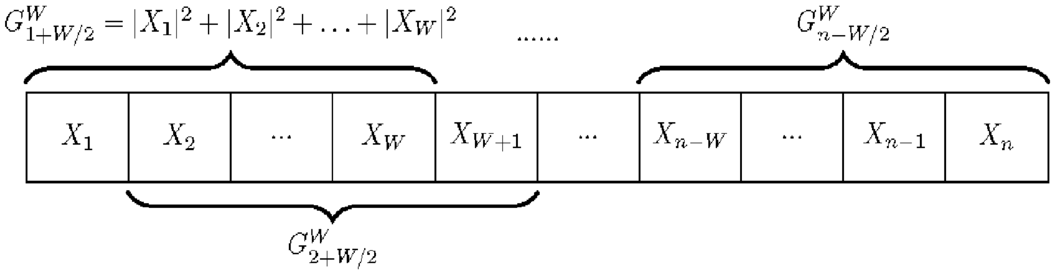
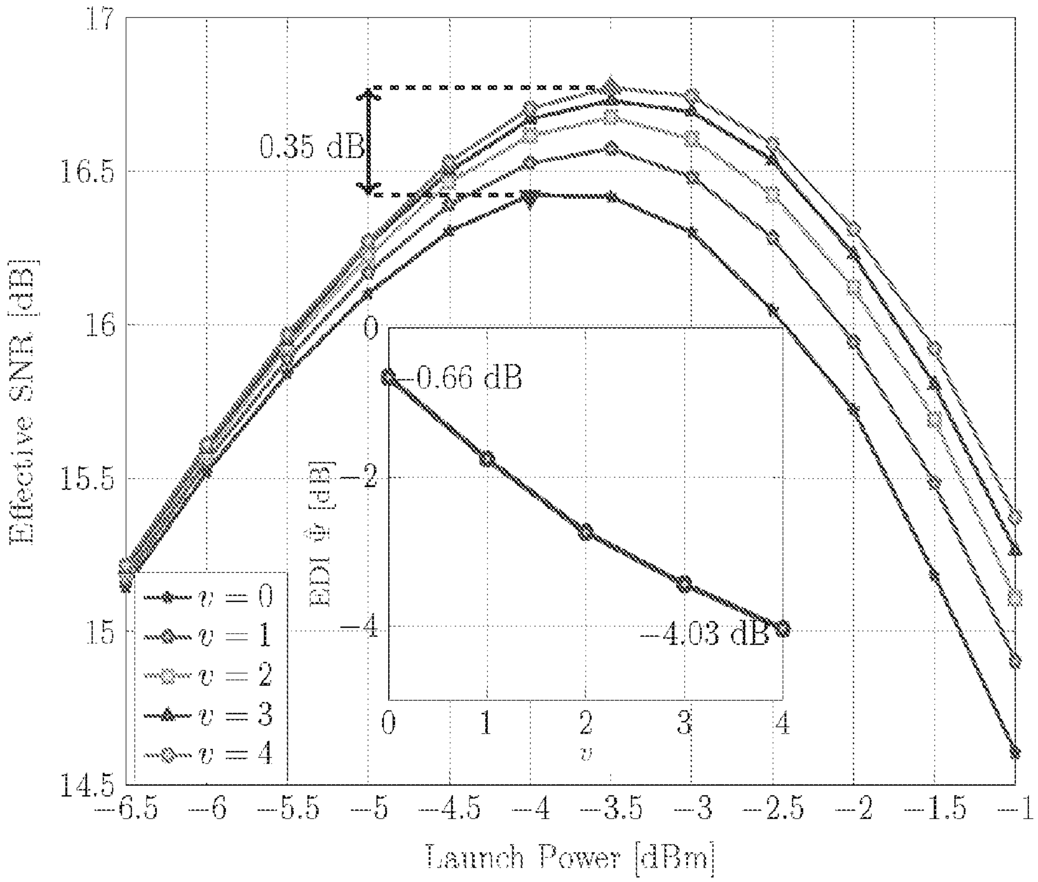


Fig. 4



17
16.5
16
15.5
15
14.5
Effective SNR [dB]
0.35 dB
−6.5
−6
−5.5
−5
−4.5
−4
−3.5
−3
−2.5
−2
−1.5
−1
Launch Power [dBm]
v = 0
v = 1
v = 2
v = 3
v = 4
0
−2
−4
EDI Φ [dB]
−0.66 dB
−4.03 dB
0
1
2
3
4
v

5/11

Fig. 5

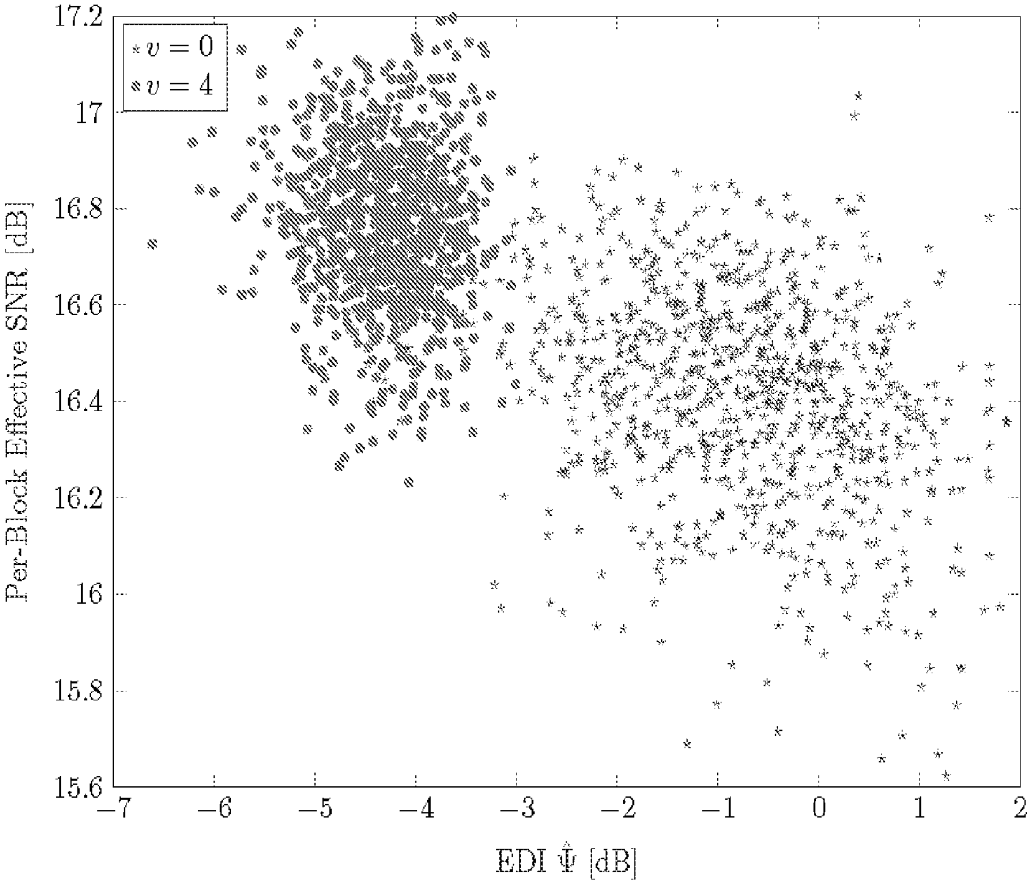

17.2
17
16.8
16.6
16.4
16.2
16
15.8
15.6
−7
−6
−5
−4
−3
−2
−1
0
1
2
v = 0
v = 4
Per-Block Effective SNR [dB]
EDI Ψ̂ [dB]

Fig. 6

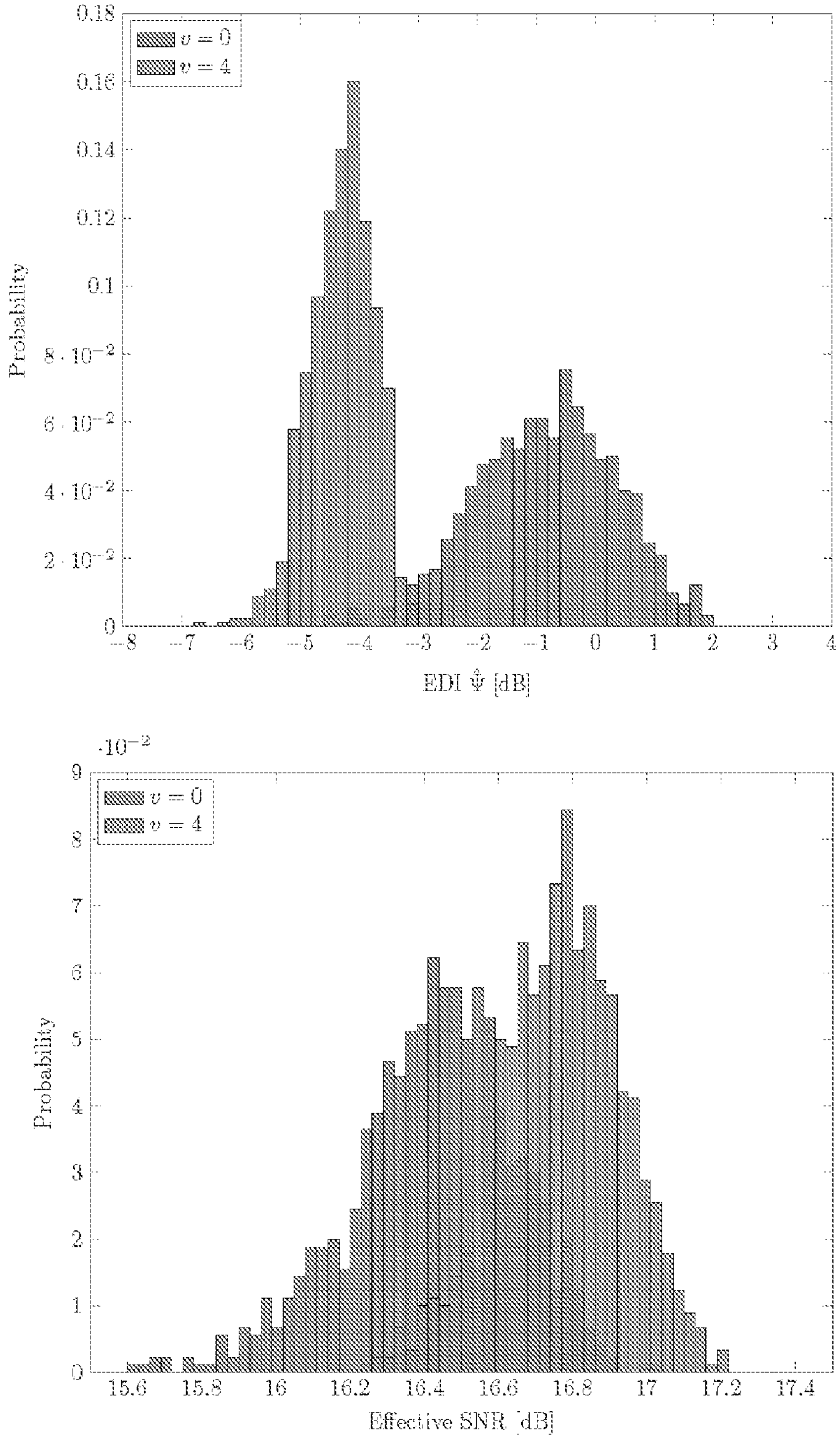

Probability
$v = 0$
$v = 4$
EDI $\hat{\Psi}$ [dB]
Probability
$\cdot 10^{-2}$
$v = 0$
$v = 4$
Effective SNR [dB]

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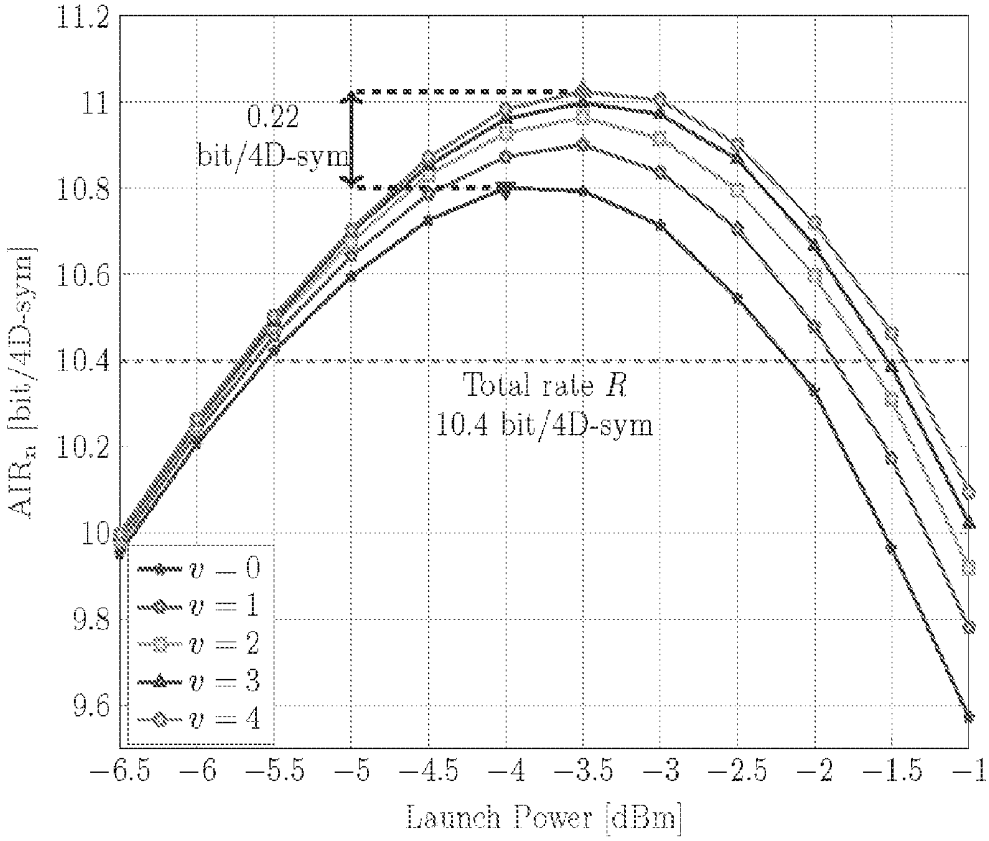
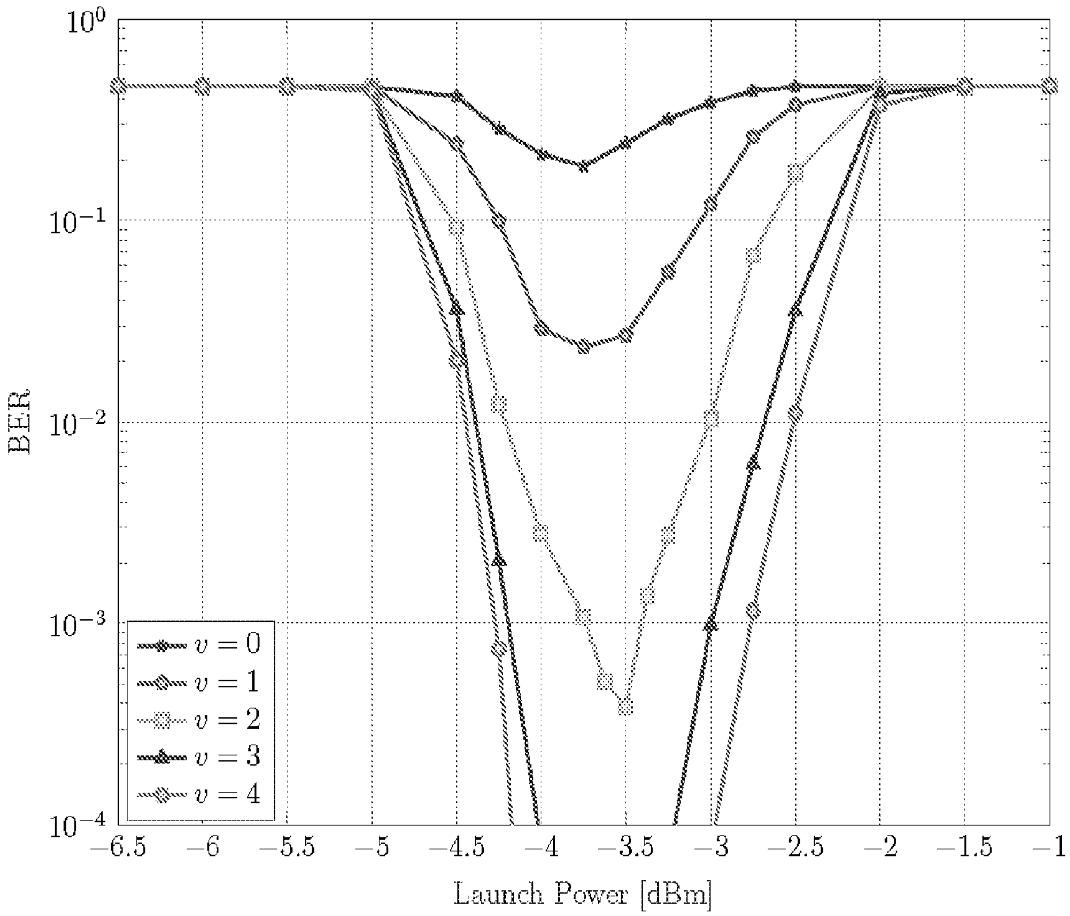
Fig. 7


11.2
11
10.8
10.6
10.4
10.2
10
9.8
9.6
0.22
bit/4D-sym
Total rate R
10.4 bit/4D-sym
$v = 0$
$v = 1$
$v = 2$
$v = 3$
$v = 4$
−6.5 −6 −5.5 −5 −4.5 −4 −3.5 −3 −2.5 −2 −1.5 −1
Launch Power [dBm]
AIR_n [bit/4D-sym]

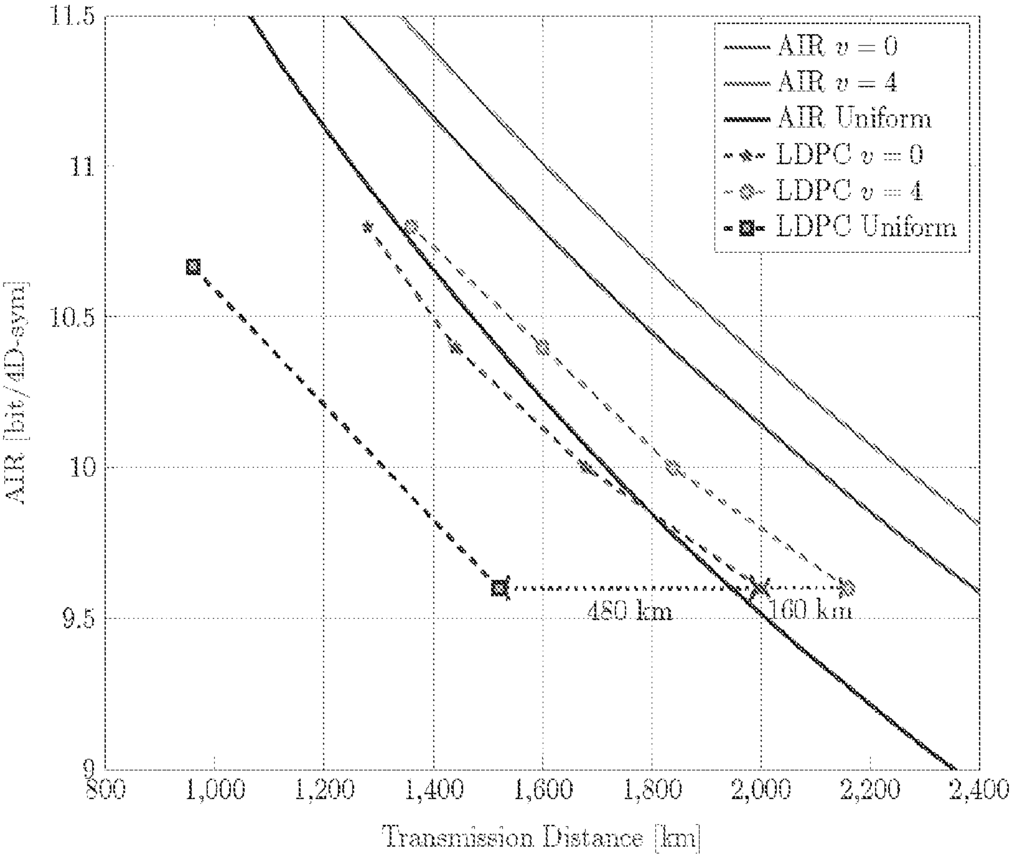
8/11

Fig. 8


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
BER
$v = 0$
$v = 1$
$v = 2$
$v = 3$
$v = 4$
−6.5 −6 −5.5 −5 −4.5 −4 −3.5 −3 −2.5 −2 −1.5 −1
Launch Power [dBm]

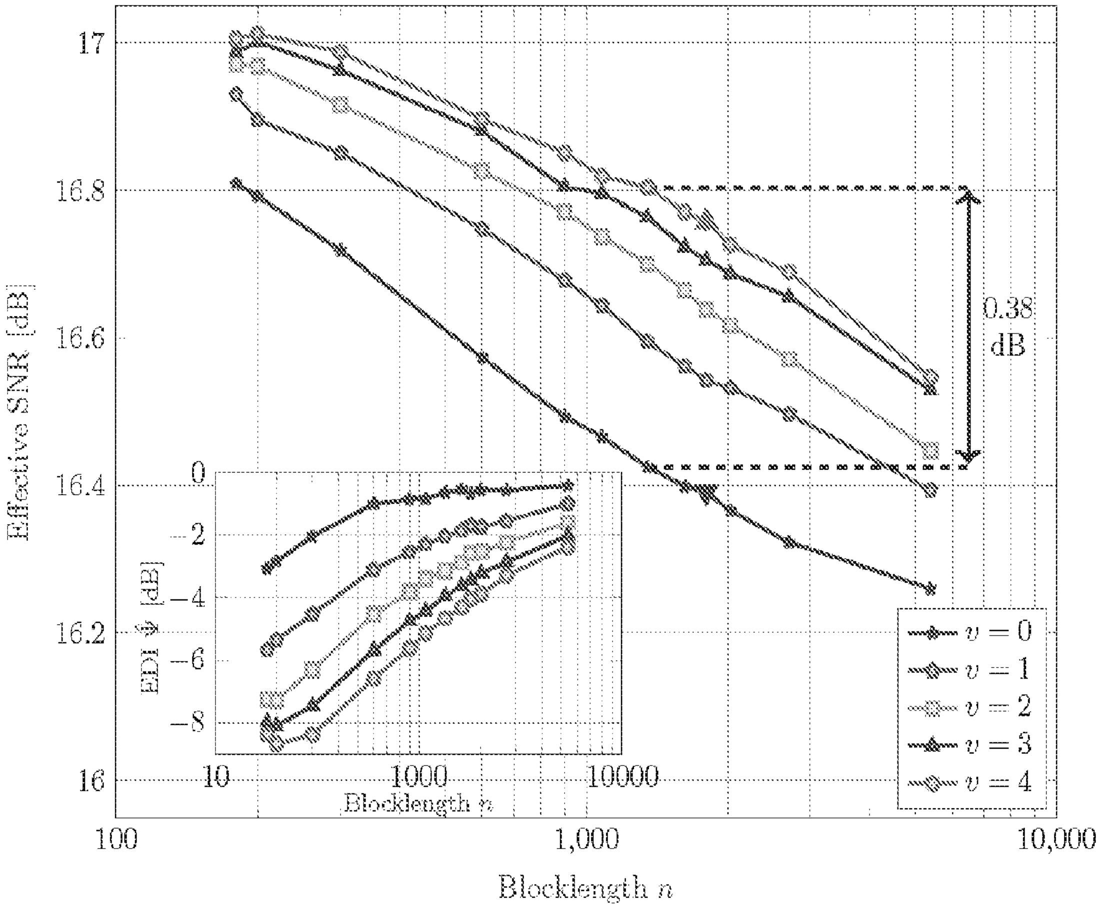
9/11

Fig. 9



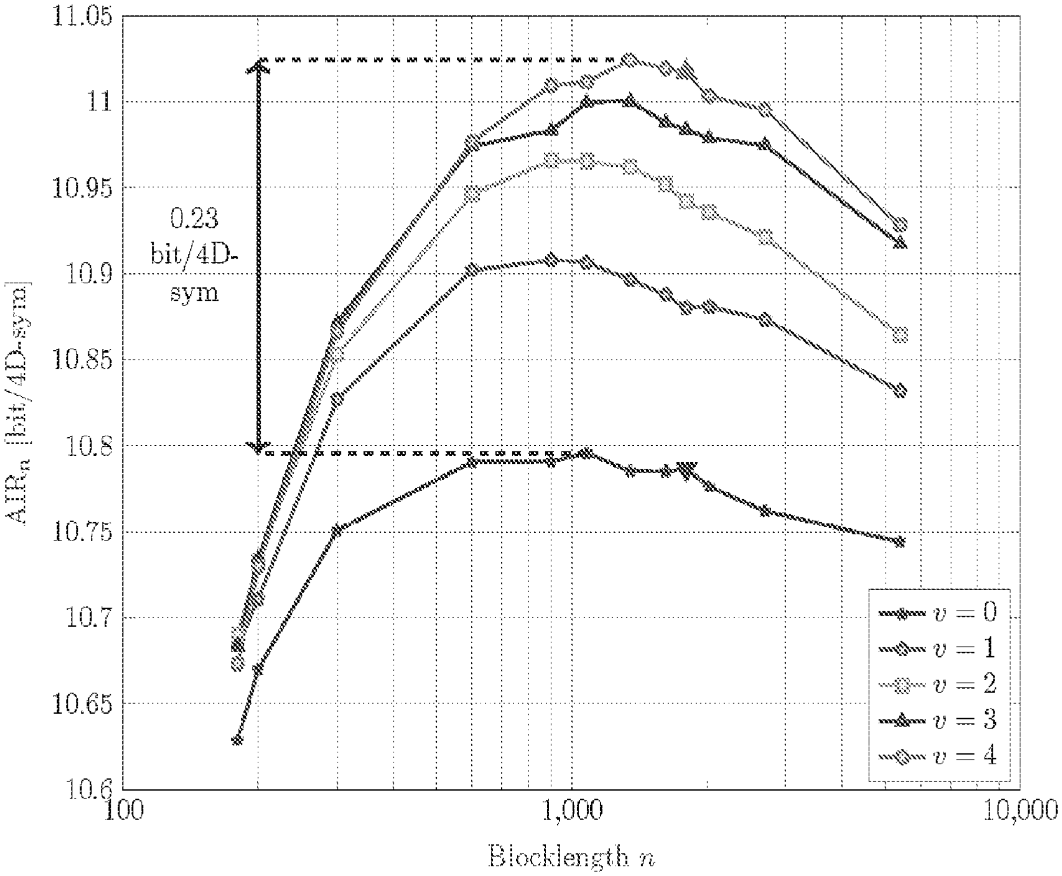
AIR $v = 0$
AIR $v = 4$
AIR Uniform
LDPC $v = 0$
LDPC $v = 4$
LDPC Uniform
AIR [bit/4D-sym]
11.5
11
10.5
10
9.5
9
800
1,000
1,200
1,400
1,600
1,800
2,000
2,200
2,400
480 km
160 km
Transmission Distance [km]

Fig. 10


Effective SNR [dB]
17
16.8
16.6
16.4
16.2
16
100
1,000
10,000
Blocklength n
0.38
dB
EDI Φ [dB]
0
−2
−4
−6
−8
10
1000
10000
Blocklength n
$v = 0$
$v = 1$
$v = 2$
$v = 3$
$v = 4$

11/11

Fig. 11


11.05
11
10.95
10.9
10.85
10.8
10.75
10.7
10.65
10.6
100
1,000
10,000
0.23
bit/4D-
sym
AIR$_n$ [bit/4D-sym]
Blocklength n
$v = 0$
$v = 1$
$v = 2$
$v = 3$
$v = 4$

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2022/050437

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L25/49 H04L25/03 H04L1/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	TOBIAS FEHENBERGER ET AL: "Analysis and Optimisation of Distribution Matching for the Nonlinear Fibre Channel", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 5 July 2019 (2019-07-05), XP081438530, sections 1-3 and 4.3 ----- -/--	1-4,6-17 5

[X] Further documents are listed in the continuation of Box C.

[ ] See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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Date of the actual completion of the international search	Date of mailing of the international search report
30 September 2022	12/10/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	El Hajj Shehadeh, Y

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INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2022/050437

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KAIQUAN WU ET AL: "Temporal Energy Analysis of Symbol Sequences for Fiber Nonlinear Interference Modelling via Energy Dispersion Index", ARXIV.ORG, CORNELL UNIVERSITY LIBRARY, 201 OLIN LIBRARY CORNELL UNIVERSITY ITHACA, NY 14853, 24 February 2021 (2021-02-24), XP081891705, sections II-IV -----	1-17
X	AMARI ABDELKERIM ET AL: "Introducing Enumerative Sphere Shaping for Optical Communication Systems With Short Blocklengths", JOURNAL OF LIGHTWAVE TECHNOLOGY, IEEE, USA, vol. 37, no. 23, 1 December 2019 (2019-12-01), pages 5926-5936, XP011758388, ISSN: 0733-8724, DOI: 10.1109/JLT.2019.2943938 [retrieved on 2019-11-26]	8,9, 14-17
A	section III; figure 5 -----	1-7, 10-13

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