SLM Peak-Power Reduction Without Explicit Side Information

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Abstract—Selected mapping (SLM) peak-power reduction [1] is distortionless as it selects the actual transmit signal from a set of alternative signals, which all represent the same information. The specific signal generation information needs to be transmitted and carefully protected against bit errors. Here, we propose an extension of SLM, which employs scrambling and refrains from the use of explicit side information in the receiver. Some additional complexity and nearly vanishing redundancy is introduced to achieve markedly improved transmit signal statistics. Even though SLM is applicable with any modulation, we concentrate on orthogonal frequency-division multiplexing (OFDM) in this letter.

Index Terms—OFDM, out-of-band power, PAR, peak-power reduction.

I. INTRODUCTION

ONE MAJOR drawback of OFDM is the high peak-to-average power ratio (PAR). If nonlinearities are overloaded by large signal peaks, intermodulation among subcarriers and undesired out-of-band radiation is caused. Hence, amplifiers must operate with large power back-offs to keep out-of-band power below specified limits. Previous work on probabilistic PAR reduction includes tone injection [2] which employs an expanded signal constellation and a modulo reduction in the receiver to allow for PAR optimization in OFDM systems with large signal constellations. Tone reservation [2] dedicates some tones which generate an additive correction signal to cancel signal peaks. In [3], an optimized set of subcarrier phase rotations for systems with binary phase-shift keying is presented to lower the ultimate PAR. We propose to extend the distortionless and flexible SLM scheme [1], which improves the PAR statistics by introducing little redundancy. In SLM, the transmitter generates a set of sufficiently different candidate signals which all represent the same information and selects the most favorable for transmission. The approach is applicable with all types of modulation, but here, we focus on OFDM.

The letter is organized as follows: Section II describes OFDM signaling. In Section III, the SLM approach is reviewed and our extension is presented. Section IV shows simulations for transmit signal statistics and spectra.

II. OFDM TRANSMISSION

In an OFDM transmitter, binary data is mapped onto D_u (<u>u</u>sed) of the subcarrier amplitudes A_ν, $0 \leq \nu < D$ with $D \geq D_\mathrm{u}$. Inactive (so-called virtual) subcarriers are set to zero to shape the transmit signal's <u>p</u>ower <u>s</u>pectral <u>d</u>ensity (PSD). The **subcarrier vector** $\mathbf{A} = [A_0, \ldots, A_{D-1}]$ is transformed by a D-point IDFT to obtain the T-spaced signal samples a_κ of the current OFDM symbol, which are transmitted by ordinary T-spaced pulse-amplitude modulation. A guard interval (cyclic prefix) is not considered as it does not affect the PAR. The receiver performs the DFT to obtain received sub-carrier amplitudes Y_ν for demapping and decoding from the received samples y_κ.

III. SLM WITH SCRAMBLING

A. Review of Selected Mapping (SLM)

In selected mapping (SLM) [1], [4] (and related [5], [6]), it is assumed that U statistically independent alternative transmit sequences $\boldsymbol{a}^{(u)}$, $0 \leq u < U$, which represent the same information are generated by some suitable algorithm. Finally, the sequence $\boldsymbol{a}^{(\breve{u})}$ with lowest peak power is selected for transmission.

To perform the appropriate inverse operation, the SLM receiver requires knowledge about the selection in the current symbol period. Thus the number $\tilde{u}$ needs to be transmitted to the receiver unambiguously. Obviously, $\lceil \log_2 U \rceil$ bits are required to explicitly represent this side information, which is of highest importance to recover the data. SLM requires U IDFT's in the transmitter, while the receiver still needs only one DFT.

B. SLM with Scrambling (and Coding)

We propose a scrambling scheme, which abstains from explicit use and careful protection of side information. Fig. 1(a) displays a block diagram of the transmitter. To generate U different transmit sequences $\boldsymbol{a}^{(u)}$, $0 \leq u < U$ representing the same information word $\boldsymbol{q}$, labels $\boldsymbol{b}^{(u)}$ are inserted as a prefix to $\boldsymbol{q}$. The labels are U different binary vectors of length $\lceil \log_2 U \rceil$, and we assume in this paper without loss of generality that $\boldsymbol{b}^{(0)} = \mathbf{0}$. The concatenated vector of the label and the information word is then fed into a scrambler consisting of a shift-register with a feedback branch only, which is reset to the zero-state before the scrambling takes place. The labels are hence used to drive the scrambler into one of U different states before scrambling the information word $\boldsymbol{q}$ itself. The scrambled output vector $\breve{\boldsymbol{q}}^{(u)}$ is then processed as usual, i.e., in our example, it is channel encoded, interleaved, and mapped to a signal constellation. After
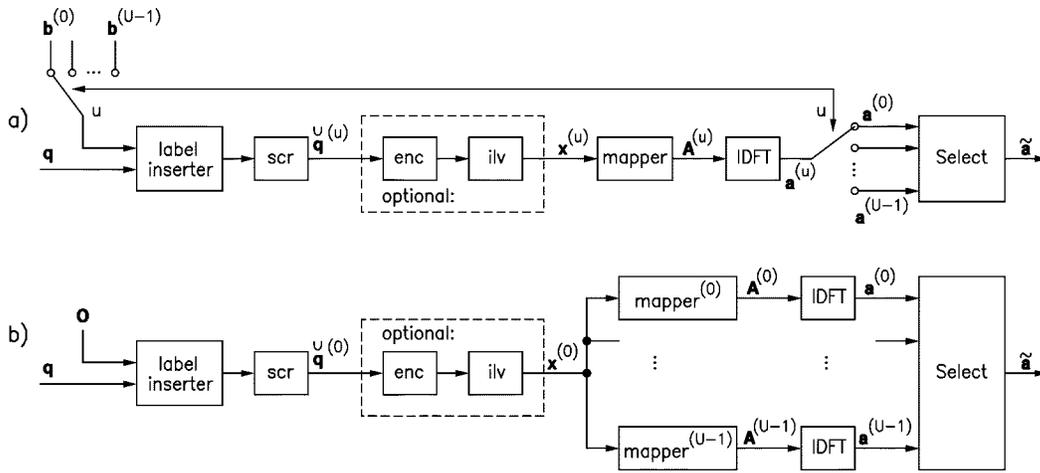
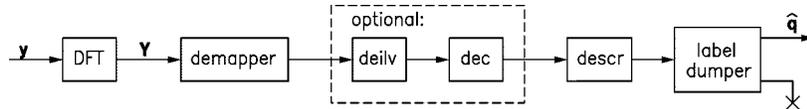Fig. 1.   SLM-OFDM transmitter with scrambling approach.

Fig. 2.   SLM-OFDM receiver for scrambling approach.

the IDFT, we obtain the transmit sequence $\boldsymbol{a}^{(u)}$ associated with the inserted label $\boldsymbol{b}^{(u)}$. This proceeding is executed for $u = 0, \ldots, U-1$, and finally the specific transmit sequence number $\tilde{u}$, which possesses the lowest peak power, is selected and transmitted $\tilde{\boldsymbol{a}} = \boldsymbol{a}^{(\tilde{u})}$.

The transmitter scheme shown in Fig. 1(b) is equivalent to the above scheme. The linearity [in GF(2)] of the label inserter, the scrambler, the channel encoder, and the interleaver can be exploited by processing the label vectors $\boldsymbol{b}^{(u)}$ and the information word $\boldsymbol{q}$ separately in these stages. Only a single interleaved codeword $\boldsymbol{x}^{(0)}$ needs to be generated, which is obtained from concatenating only the zero-label $\boldsymbol{b}^{(0)} = \boldsymbol{0}$ with $\boldsymbol{q}$ in the label inserter. Owing to the aforementioned linearity, the U different subcarrier vectors $\boldsymbol{A}^{(u)}$, $u = 0, \ldots, U-1$ can then be generated by applying U different vector mappings to $\boldsymbol{x}^{(0)}$. Observe that the vector mapping number u needs to be calculated only once from the associated label $\boldsymbol{b}^{(u)}$ and can be stored in a read-only memory, and that the mapping may be different for each element of the input vector $\boldsymbol{x}^{(0)}$. These U parallel mappings are followed by IDFT's and the selection of the most favorable transmit sequence $\tilde{\boldsymbol{a}}$ as exhibited above. From this second scheme of Fig. 1(b), we see the relationship to the SLM algorithm in [1].

If the period length of the scrambler is $\geq U-1$, then the U subcarrier vectors $\boldsymbol{A}^{(u)}$ are usually satisfyingly different from each other, such that they appear to be generated statistically independent from each other. Starting a scrambler in one of $U-1$ different nonzero states before scrambling $\boldsymbol{q}$ results in a $\breve{\boldsymbol{q}}^{(u)}$, which is the sum of $\breve{\boldsymbol{q}}^{(0)}$ and one out of $U-1$ pseudo-noise sequences. Additionally, the interleaver and the nonlinear [in GF(2)] mapper boost this pseudo-randomness effect of the mappings from $\boldsymbol{q}$ to $\boldsymbol{A}^{(u)}$, which is the essential ingredient of SLM.

The corresponding receiver is depicted in Fig. 2. The received sample vector $\boldsymbol{y}$ is processed as in ordinary OFDM, i.e., DFT,

demapped (or detected), deinterleaved, and decoded. The only additional devices are a descrambler and a label dumper. The descrambler performs the inverse operation to the scrambler in the transmitter and is hence a shift-register with a feedforward branch, only. It is reset to the zero-state before descrambling starts for an OFDM symbol. If no transmission errors have occurred, the output of the descrambler is the concatenated vector of label prefix $\boldsymbol{b}^{(\tilde{u})}$ and transmitted information word $\boldsymbol{q}$. The label dumper strips off the label prefix and outputs the estimated information word $\hat{\boldsymbol{q}}$. The incorporated and transmitted implicit side information (number of selected sequence) $\tilde{u}$ is not explicitly used in the receiver and an erroneous reception of the associated label bits does not affect the error performance.

In the case that the channel code is a convolutional code, the scrambler and the channel encoder—both are shift-registers—as well as the channel decoder and the descrambler can be integrated into a single device, respectively. Thus, the additional requirements in both, transmitter and receiver, are kept very low.

IV. SIMULATION RESULTS

A. System Description

We consider an exemplary OFDM scheme for wireless Asynchronous Transfer Mode (ATM). We employ $D = 256$ and $D_{\mathrm{u}} = 219$ used carriers to allow for transmit filtering. SLM processing with an oversampling factor of two, i.e., IDFT's of size $2D$ with zero-padding are used to generate the candidate sample sequences. Oversampled signals yield sufficiently accurate peak-power information on the final continuous-time signal $s(t)$ after impulse shaping. The root-raised cosine transmit filter has a rolloff factor of $\alpha = 0.12$. Continuous-time signal simulation is performed with an oversampling by eight, i.e., $s(kT/8)$ is used to quantify the characteristic of $s(t)$.

We use a scrambler with a feedback polynomial $1+x+x^4$ and a rate-$1/2$ industry-standard convolutional code with 64 states.
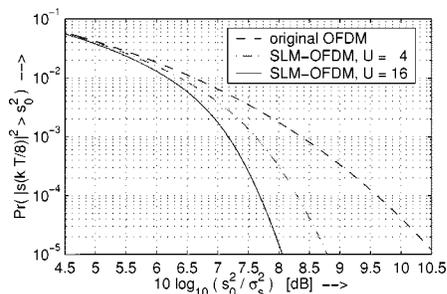
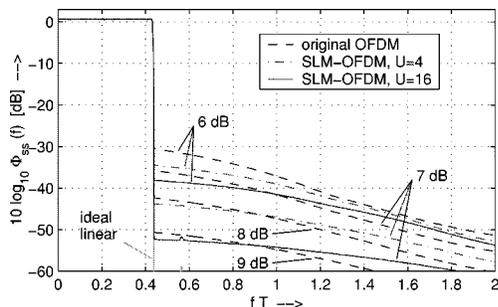Fig. 3. Power-excess probability for transmit signal $s(t)$.

Fig. 4. Power spectral density before/after soft-limiting nonlinearity for original OFDM and SLM-OFDM for various backoffs.

The bits are interleaved and mapped onto the 16 QAM symbols of one OFDM symbol. Gray labeling is used, such that a bit-interleaved coded modulation is realized. The examplary parameters allow to transport one ATM cell with 424 bit plus protocol overhead in one OFDM symbol. An OFDM-symbolwise blocked convolutional-coded system results in this example but our proposal does not require this blocking.

B. Improved Statistics of Signal Magnitude

Fig. 3 illustrates the probability that the instantaneous power $|s(kT/8)|^2$ exceeds the power threshold s_0^2. The abscissa is normalized to the average transmit signal power σ_s^2 of $s(t)$.

We want to coin the term *probabilistic PAR* for the normalized power threshold s_0^2/σ_s^2 which is connected with some fixed power-excess probability on a sample-by-sample basis. Hence, we can say that the probabilistic PAR of conventional OFDM at excess probability 10^{-5} is 10.6 dB. This expresses that one in $100\,000$ samples exceeds a power threshold s_0^2, which is by 10.6 dB larger than σ_s^2. Obviously, we have a reduction of probabilistic PAR by 1.8 and 2.5 dB (at 10^{-5}), if we consider SLM with $U = 4$ and $U = 16$, respectively.

C. Spectral Benefit

The out-of-band power after a simple soft-limiting nonlinearity[1] is evaluated by measuring the PSD of the distorted transmit signal. Fig. 4 shows the PSDs $\Phi_{ss}(f)$ for the ideal

[1]The soft-limiter amplitude characteristic is ideally linear up to the perfectly horizontal saturation. The signal phase is not modified.

transmit signal, which does not exhibit any spectral spread, while original OFDM produces considerable out-of-band power for 6, 7, 8, and 9 dB backoff from saturation point. For comparison, we plotted the PSDs for SLM-OFDM with $U = 4$ and 16 candidates for 6 and 7 dB backoff. It can be concluded that—depending on the tolerated level of out-of-band density (often between -40 to -50 dB in wireless communications standards)—between 1 and 2 dB can be saved in backoff with 4 bits redundancy per OFDM symbol.

16QAM modulation (PAR of the signal constellation $\mathcal{A}$: 2.55 dB) is used, but the PSDs do not differ greatly, when 4PSK or 8PSK modulation is used (PAR of $\mathcal{A}$: 0 dB).

D. Bit Error Performance Loss

The rate loss for label insertion is negligible. Error propagation in the receiver's descrambler causes an increased error rate by a factor lower than the scrambler polynomial's weight. We observed a less than doubled end-to-end error rate at all signal-to-noise power ratios, which translates into 0.2 dB loss.

V. SUMMARY AND CONCLUSIONS

We proposed a powerful extension for SLM PAR reduction and demonstrated its operability for the special case of convolutionally-coded OFDM transmission. The scheme refrains from explicit transmission of side information by a label insertion and scrambling approach where only little redundancy needs to be introduced into the signal. On the other hand, the transmit signal statistics and the spectral properties in presence of transmitter nonlinearities are decisively improved such that a saving of 1 to 2 dB in backoff can easily be achieved. We emphasize again that SLM is also suitable for other modulation schemes, e.g., single carrier modulation.

REFERENCES

[1] R. Bäuml, R. Fischer, and J. Huber, "Reducing the peak-to-average power ratio of multicarrier modulation by selected mapping," *Electron. Lett.*, vol. 32, no. 22, pp. 2056–2057, Oct. 1996.

[2] J. Tellado-Mourelo, "Peak to average power reduction for multicarrier modulation," Ph.D. dissertation, Stanford Univ., Stanford, CA, Sept. 1999.

[3] V. Tarokh and H. Jafarkhani, "On the computation and reduction of the peak-to-average power ratio in multicarrier communications," *IEEE Trans. Commun.*, vol. 48, pp. 37–44, Jan. 2000.

[4] S. Müller-Weinfurtner, "OFDM for wireless communications: Nyquist windowing, peak-power reduction, and synchronization," Ph.D. dissertation, Univ. Erlangen-Nürnberg, Shaker Verlag, Germany, 2000.

[5] P. Van Eetvelt, G. Wade, and M. Tomlinson, "Peak to average power reduction for OFDM schemes by selective scrambling," *Electron. Lett.*, vol. 32, no. 21, pp. 1963–1964, Oct. 1996.

[6] D. J. G. Mestdagh and P. M. P. Spruyt, "A method to reduce the probability of clipping in DMT-based transceivers," *IEEE Trans. Commun.*, vol. 44, pp. 1234–1238, Oct. 1996.