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Bitloaded Modified Enhanced Subcarrier Index Modulation OFDM for Visible Light Communications

Víctor Monzón Baeza, Juan José García Fernández and Ana García Armada
Deparment of Signal Theory and Communications. Universidad Carlos III de Madrid.
vmonzon@tsc.uc3m.es, jjgarcia@tsc.uc3m.es, agarcia@tsc.uc3m.es

***Abstract*— This paper investigates the use of bit loading algorithms in order to use ESIM OFDM in frequency selective channels. This work focuses on maximizing the bit rate minimizing the loss of spectral efficiency because of the insertion of idle subcarriers. Besides, the modified ESIM OFDM is generalized to support groups of subcarriers of arbitrary size based on the number of idle subcarriers. The effect of this generalization, as well as the new bit distribution after using bit loading, on the peak to average power ratio (PAPR) and the bit error rate (BER) are analyzed. Additionally a novel way to evaluate the BER in such a system is proposed. The proposed scheme is shown to outperform the original ESIM OFDM performance in terms of PAPR, at the cost of a small degradation of the BER. This improvement in the PAPR makes the proposed scheme a good candidate for Optical Wireless Communication (OWC) systems, and in particular for Visible Light Communication (VLC) systems.**

I. Introduction

In the future wireless systems demanding higher data rates will drive the search for alternatives offering higher spectral efficiency than those used in current systems, such as OFDM (Orthogonal Frequency Division Multiplexing) which is used in LTE and LTE-Advanced [1]. Not only higher spectral efficiency is sought, but also novel technologies that can cope with the expected high capacity demand of future wireless systems. VLC (Visible Light Communications) [2], [3], [4] is one of the candidates for transmission technologies in 5G [2], [5] that are getting an important attention both from the research community and the industry because of its numerous potential advantages [3]. One of the main drawbacks of OFDM is its high PAPR (Peak to Average Power Ratio) [1], which is a serious problem for VLC systems [3].

The spectral efficiency of OFDM can be improved by considering more advanced modulation techniques, such as SIM (Subcarrier Index Modulation) OFDM [7]. This approach uses the subcarrier indexes to convey information according to an OOK (On-Off Keying) modulation. On the subcarriers an M-QAM or M-PSK will be used. Despite having a higher spectral efficiency than traditional OFDM, SIM OFDM has the problem that is prone to burst errors, due to error propagation, which can degrade the performance in terms of Bit Error Rate (BER).

In order to deal with the burst errors, and also with the still present high PAPR, [6] proposes a refinement called ESIM (Enhanced SIM) OFDM. In this, the subcarriers are grouped in pairs and the OOK modulation bits are used to select the position within the two subcarriers of the pair. The result is that many subcarriers remain inactive, significantly improving the PAPR, at the cost of a slightly reduced spectral efficiency. Additionally, the impact of error propagation is constrained to the span of the subcarrier pair.

SIM and ESIM OFDM improve the spectral efficiency and the PAPR figure of traditional OFDM. However, previous works [7], [6], did not offer a thorough characterization of the BER and the PAPR for these advanced techniques.

Moreover, a feature of receiver photodiode, which is used in practical VLC system, is a significant modulation bandwidth which imposes that VLC channel is well modeled as frequency selective.

The current work focuses on two contributions:

- A research of ESIM in frequency selective channel is developed by using bit loading. This technique allows to boost the spectral efficiency which is lost through the insertion of idle subcarriers.
- An improvement over ESIM is offered by considering groups of size that can take values other than two. The dependence of the PAPR and the BER on this parameter is analyzed, as well as the variation of the PAPR with the order of the constellation used in each active subcarrier.
- A new general BER expression is derived for ESIM OFDM. This new expression, compared to the method proposed in [6], offers a much more accurate solution, in particular for low SNR (Signal to Noise Ratio). Additionally, the derived expression can be easily extended to other modulation schemes such as M-QAM (Quadrature Amplitude Modulation) and M-PSK (Phase Shift Keying).

The rest of the paper is organized as follows. In Section II the ESIM OFDM scheme proposed in [6] is briefly reviewed. In Section III a new approach for analyzing the BER is presented. In Section IV bit loading algorithms for ESIM OFDM are investigated. PAPR is analyzed in Section V for several modulation parameters. Finally, Section VI presents the conclusions and further lines for future work.

II. ESIM OFDM with arbitray group size

This paper proposes a variation of the ESIM OFDM scheme of [6]. The OFDM system considered consists of N subcarriers available for transmission that are clustered in groups of L subcarriers each, instead of these groups being formed by just two subcarriers as it is the case in [6]. From all the subcarriers in each group, at any given time only one will be active, leaving $L_{\text{off}} = L - 1$ idle. Only the first or the last of the subcarriers in the group may be chosen to transmit information, and this will be used to transmit one bit per group with an OOK modulation, as in the original paper, while each active subcarrier will be modulated using an M-QAM or M-PSK.

It is assumed that the information is transmitted in blocks of B bits $\{b_1, \ldots, b_B\}$ with $B = \frac{N}{L}(1 + \log_2(M))$, where M is the order of the constellation used in each active subcarrier. For the exposition, in this paper it will be considered that this constellation is an M-QAM.

The information bits are then separated into two substreams, $b_{\text{OOK}} = \{b_1, \ldots, b_{N/L}\}$ and $b_{\text{QAM}} = \{b_{N/L+1}, \ldots, b_B\}$. The first substream selects which subcarrier within the group is active. The second substream selects the symbol to transmit through the active subcarrier.

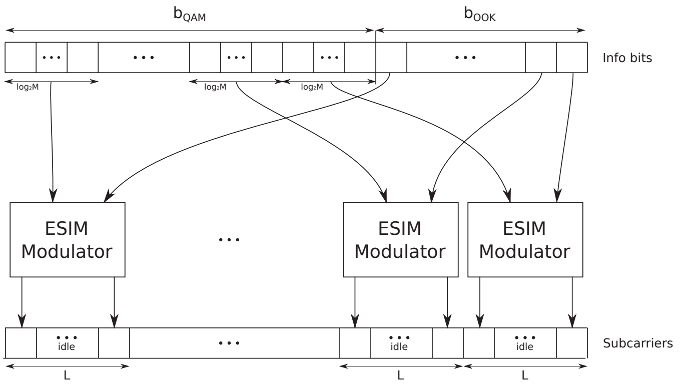

Fig. 1. ESIM OFDM modulation approach for groups of arbitrary size L.

Fig. 1 shows a schematic representation of the proposed procedure, where it can be seen how the information bits are organized in two substreams and then used to select the active subcarrier and the constellation symbol to be transmitted.

In the case that $L > 2$, there exist several options to choose the pair of subcarriers between which the active subcarrier must be placed. In the Tab. I the considered options for $L = 3$ are shown.

TABLE I

PLACEMENT SUBICARRIERS

Options	Pairs of subcarriers
Option 1	subcarriers 1 and 2
Option 2	subcarriers 1 and 3
Option 3	subcarriers 2 and 3
Option 4	the best among the above Op.

Recall, the active subcarrier within the pair is chosen by OOK modulation. In Fig. 2 is shown that the PAPR is improved only in option 4 and this improvement is 0.5 dB which is not worth compared to the cost of reporting to the receiver which option is transmitted in each transmission. Thus, in this work, the active subcarrier is selected between the first or the last within the group, to facilitate the decision and to improve the BER.

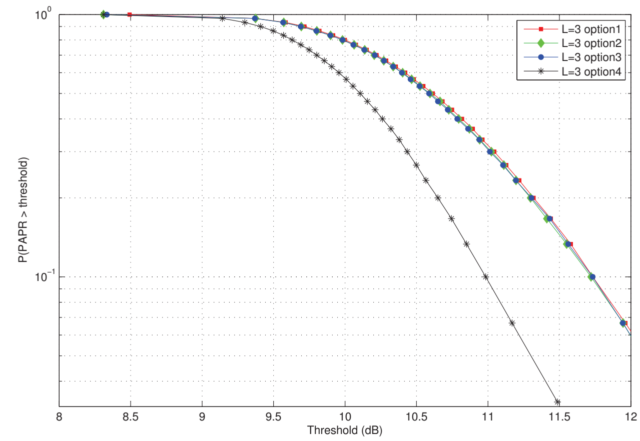

Fig. 2. Influence of the options to place active subcarrier inside of the group.

The spectral efficiency of a traditional OFDM system is given by

$$\eta_{\text{OFDM}} = N \log_2(M) \tag{1}$$

while for the proposed ESIM OFDM system, it is given by

$$\eta_{\text{ESIM}} = B = \frac{N}{L}(1 + \log_2(M)) \tag{2}$$

It can be seen in (2) how the spectral efficiency of the proposed system is affected by the size of the subcarriers group L and consequently by the number of inactive subcarriers L_{off}.

The influence of these parameters on the BER and PAPR is analyzed in Section III and Section V respectively.

III. ANALYSIS OF THE BER OF ESIM OFDM

As it has been explained, ESIM OFDM uses the information bits to generate two concatenated modulations: an OOK to select the active subcarrier, and another digital modulation, *e.g.* M-QAM, that will be transported in the active subcarrier. In the following derivations, an M-QAM is assumed to be used in each subcarrier, and there is Additive White Gaussian Noise (AWGN) at the receiver, with zero-mean and variance $\sigma^2 = \frac{N_0}{2}$. The bit error probability can then be defined as

$$P_{e,\text{ESIM}} = \frac{1}{k+1} P_e^{(1)} + \frac{k}{k+1} P_e^{(2)} \tag{3}$$

where $k = \log_2(M)$, $P_e^{(1)}$ is the probability of error in the first modulation phase, the subcarrier selection, and $P_e^{(2)}$ is the probability of error in the second phase. These two probabilities of error are derived in Subsection III-A and Subsection III-B, respectively.

A. BER of OOK block

The identification of the active subcarrier is critical because it affects the whole detection process and the global $P_{e,\text{ESIM}}$. This paper proposes a different approach to that followed in [6] to analyse the BER, making it simpler. Typically OOK decision is made using a threshold, but in the case under study here, the decision can be made by comparing pairs of subcarriers and deciding which one has the maximum power, meaning it is the active one. In order to do so, first consider two random variables $X \sim \mathcal{N}\left(\mu_X, \sigma^2\right)$ and $Y \sim \mathcal{N}\left(\mu_Y, \sigma^2\right)$. Suppose that $X < Y$, then the probability of error when deciding which one is the greatest is equal to

$$\Pr\left(X > Y\right) = \Pr\left(X - Y > 0\right) \tag{4}$$

Calling $Z = X - Y$, then $Z \sim \mathcal{N}\left(\mu_X - \mu_Y, 2\sigma^2\right)$, and the probability of error can be writen as

$$\Pr\left(Z > 0\right) = \int_0^{\infty} f_Z\left(z\right) \mathrm{d}z = Q\left(\frac{\mu_Y - \mu_Z}{2\sigma^2}\right) \tag{5}$$

The probability of error for the OOK decision is given by

$$P_e^{(1)} = \frac{1}{2} P_{e,\text{sc}1} + \frac{1}{2} P_{e,\text{sc}2} \tag{6}$$

where $P_{e,\text{sc}1}$ and $P_{e,\text{sc}2}$ are the probability of detecting as active the first and the last subcarrier, when it is not, respectively. These two values are identical so that the total probability of error is

$$P_e^{(1)} = \sum_{i=1}^{M} Q\left(\sqrt{\frac{\gamma_i E_b}{N_0}}\right) \tag{7}$$

where the term within the sum is equal to (5) including a scaling factor γ_i that accounts for the different positions of the M symbols, and is given by $\gamma_i = \frac{P_i}{\sqrt{M}}$, with P_i the power of the i-th symbol.

Fig. 3 compares the $P_e^{(1)}$ computed using (7), using the formula from [6], and with the results from simulations, for the case of using 4-QAM.

The expression (7) is completely general, and it can be used for any digital modulation of the active subcarriers, because it is based on the comparison of pairs of subcarriers, so each symbol of the modulation is compared with zero, when the subcarrier is inactive, and only the factors γ_i may change depending on which modulation is used.

B. BER of QAM block

After detecting the active subcarrier, the rest of the bits should be obtained by detecting which symbol was transmitted. An error at this stage can be due to two factors:

- The active subcarrier is correctly detected, and in a regular digital demodulation process of the M-symbol constellation an error occurs.
- The active subcarrier is wrongly detected, and the detected symbol is also wrong.

This can be formulated as

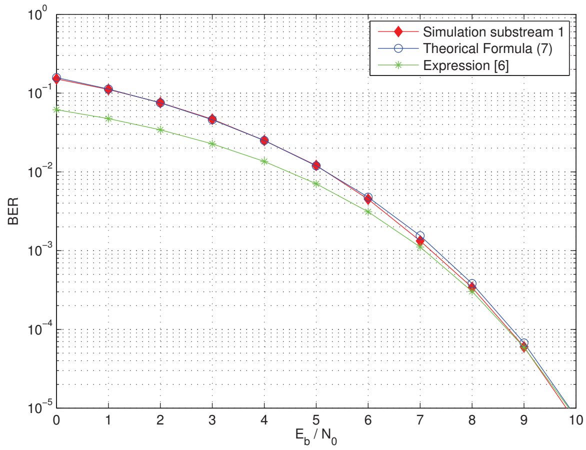

Fig. 3. $P_e^{(1)}$ using 4-QAM. Comparison with [6].

$$P_e^{(2)} = \frac{1}{2} P_e^{(1)} \hat{P}_{\text{QAM}} + \frac{1}{2}\left(1 - P_e^{(1)}\right) P_{\text{QAM}} \tag{8}$$

where $\hat{P}_{\text{QAM}}$ is the probability of having an error when detecting the symbol after the identification of the active subcarrier was wrong. This probability is very close to 1 as demodulating an incorrectly subcarrier always incurs a symbol error. P_{QAM} is the probability of error of the original constellation, including a factor $\beta = \frac{\bar{P}}{\sqrt{M}}$, with $\bar{P}$ the average power of the constellation, that accounts for the change in the average power of the signal due to the insertion of idle subcarriers. *E.g.* for an M-QAM it is

$$P_{\text{QAM}} = Q\left(\sqrt{\frac{\beta E_b}{N_0}}\right) \tag{9}$$

C. BER of ESIM OFDM

Combining the results from Subsection III-A and Subsection III-B, the total BER in (3) can be expressed as

$$\begin{aligned} P_{e,\text{ESIM}} = & \frac{1}{k+1}\left(2 + \left(1 - Q\left(\sqrt{\frac{\beta E_b}{N_0}}\right)\right) k\right) \\ & \cdot \sum_{i=1}^{M} Q\left(\sqrt{\frac{\gamma_i E_b}{N_0}}\right) \\ & + \frac{k}{2(k+1)} Q\left(\sqrt{\frac{\beta E_b}{N_0}}\right) \end{aligned} \tag{10}$$

In Fig. 4 and Fig. 5 the total BER expressed in (10) is shown for different values of the ratio of inactive subcarriers, as well as different modulation orders. The results are shown only for 64 total subcarriers because the BER performance does not depend on this number as in [6]. What these figures show is how the performance, in terms of BER depends on modulation order and the number of inactive subcarriers. In any case, although the BER may be slightly affected by the insertion of the inactive subcarriers, it will be seen in the next sections that its influence on the PAPR is much more important.

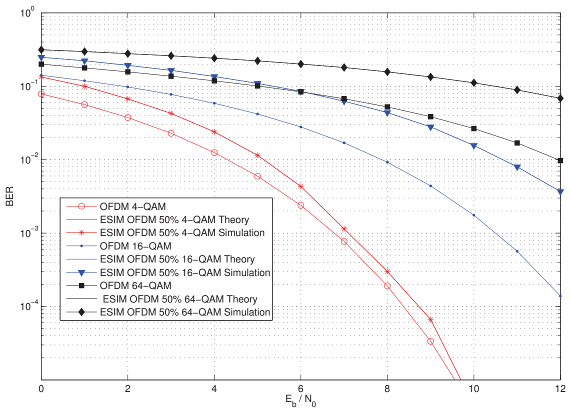

Fig. 4. Pe total in ESIM OFDM for $L = 2$.

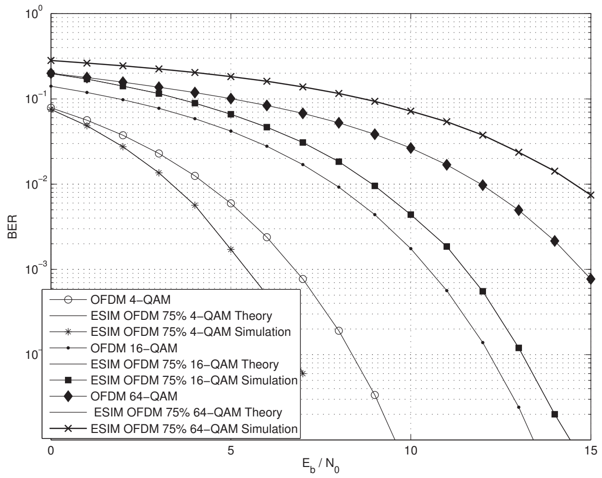

Fig. 5. Pe total in ESIM OFDM for $L = 3$.

IV. Bit Loading Algorithm in ESIM OFDM

The VLC channels are well modeled as frequency selective. Therefore an adaptive bit allocation is proposed here. The bit loading is generally performed on every subcarrier to attain a target error rate while maximizing the total rate of the system. This paper proposes a modified version of the algorithms of Chow [9] and Levin-Campello (LC) [10] for ESIM OFDM. It is assumed that the synchronization and channel estimation tasks have been successfully performed, so that the transmitter can use the channel information, $|H_i|^2$, to find the number of bits, b_i, to be transmitted in each subcarrier i.

For the simulations, the following time domain channel model is considered

$$h[n+1] = h[n] + 0.7h[n-1] + 0.3h[n-2] + 0.09h[n-3] \quad (11)$$

The modification that is proposed in this paper is only to perform bit loading in those subcarriers selected by the information bits b_{OOK}. To find the number of bits b_i for i^{th} subcarrier, the next expression may be used

$$b_i = \log_2(1 + \frac{\text{SNR}(i)}{\Gamma}) = \log_2(1 + \frac{E_i |H_i|^2}{\Gamma \sigma_n^2}) \quad (12)$$

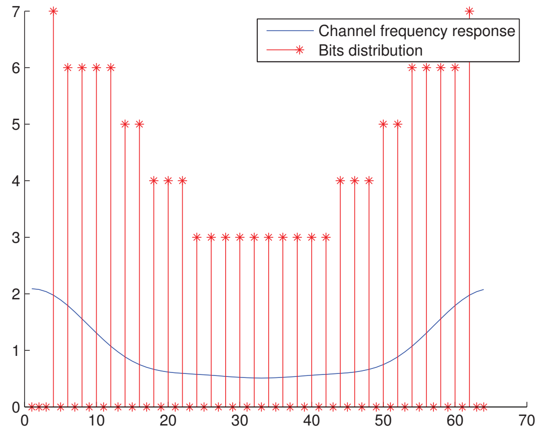

Fig. 6. Evolution of the total number of bits per symbol.

where $\text{SNR}(i)$, E_i and $|H_i|^2$ are the SNR, transmitted energy and channel gain of i^{th} subcarrier, respectively. σ_n^2 is the noise variance and Γ the SNR gap representing how far the system is from the Shannon channel capacity and it depends on the objective bit error rate and modulation scheme. For ESIM OFDM, Γ may be derived solving the well-known SNR gap approximation for M-QAM

$$\Gamma = \frac{\text{SNR}_b}{2^b - 1} \quad (13)$$

where each SNR is obtained by simulating the P_e for different b_i and L, and selecting the SNR that yields a fixed $P_e = 10^{-3}$. The results are collected in the Table II.

TABLE II
Value SNR Gap Γ

Bits in QAM constellation (b)	2	4	6	8	Γ
SNR_b (L=2)	8dB	14 dB	20 dB	25 dB	4.2 dB
SNR_b (L=3)	10dB	16 dB	21 dB	27 dB	5.2 dB

In Fig. 6 an example of a bit distribution is shown together with the channel frequency response using LC algorithm for the example channel (11) and considering 64 subcarriers. The distribution is symmetric due to the consideration of Hermitian symmetry necessary to transmit an optical signal required in VLC systems. Also, the 50% idle subcarriers can be noted.

Fig. 7 shows the evolution of the bit rate for ESIM OFDM using bit loading for 64 subcarriers compared to the original ESIM OFDM. For the objective BER, the simulations report an increase in spectral efficiency especially for 50%, while for 75% the improvement is notable only for E_b/N_0 bellow 7dB.

V. Analysis of the PAPR

The PAPR of a signal $x[n]$ is defined as the quotient between the peak power and the mean power of the signal [12]. Measured in an N-length symbol it is

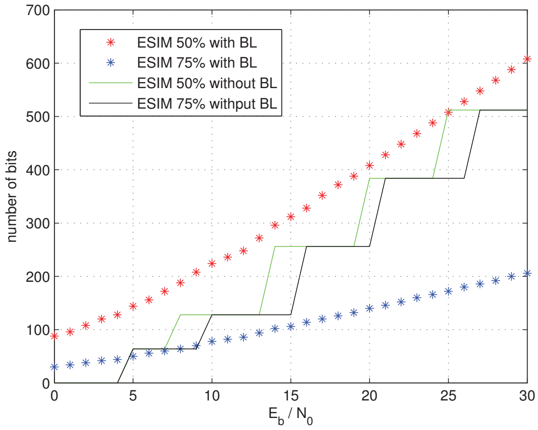

Fig. 7. Evolution of the total numbers of bits transmitted.

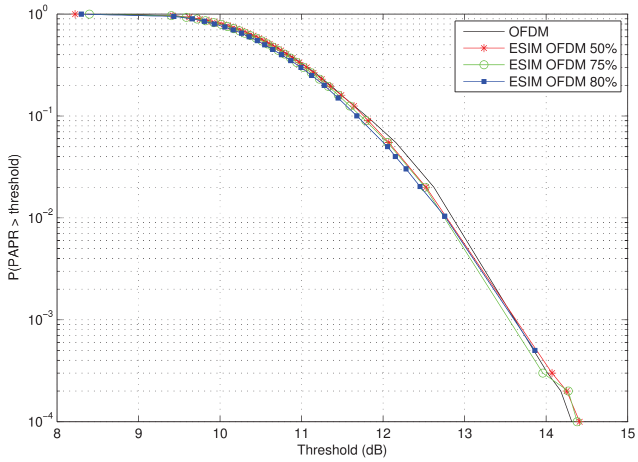

Fig. 8. PAPR ESIM OFDM 64-QAM and 1024 subcarriers.

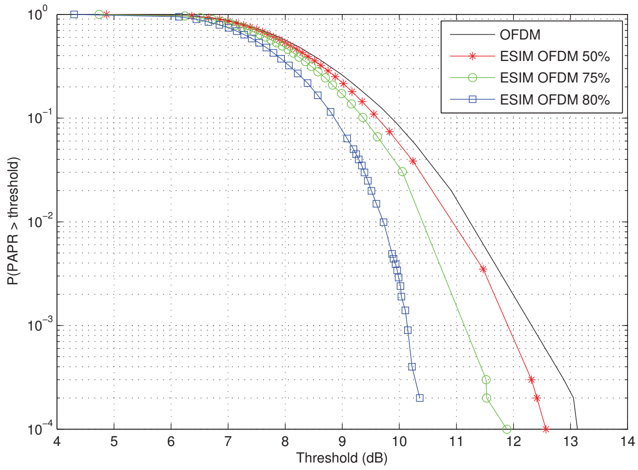

Fig. 9. PAPR ESIM OFDM 64-QAM and 64 subcarriers.

$$\mathtt{PAPR} = \frac{\max_{n} |x[n]|^2}{\frac{1}{N}\sum_{n=1}^{N} |x[n]|^2}. \tag{14}$$

A conventional OFDM system has a high PAPR [1]. A high PAPR means that the signal has a very high dynamic range, which translates into very stringent requirements for different parts of the communications equipment. VLC systems are particularly sensitive to the PAPR, because LEDs that are used as transmitters do not behave well with signals changing drastically in amplitude [3]. Additionaly, some applications of VLC are intended for indoors systems, where the light is used for lighting apart from being used for communications, and it is not acceptable to have a light that is flickering beyond some range [4], so it is interesting to constrain the PAPR of the transmitted signal as much as possible.

In [6] the maximum value of the PAPR is discussed but not its actual statistics. Here we show the Complementary Cumulative Distribution Function (CCDF) to analyze the impact of the design parameter on the PAPR. In particular it is studied how the total number of subcarriers, the number of inactive subcarriers, and the order of the constellation M affect the PAPR.

Introducing idle subcarriers has an overall effect of lowering the mean power of the signal, which may lead to an increase in the PAPR. Nevertheless, it will be shown that this is not the case for all the scenarios.

First, the constellation used is a 64-QAM and the ratio of inactive subcarriers is varied. Fig. 8 shows the result of the PAPR obtained when the total number of subcarriers is 1024, while Fig. 9 shows the result for a system with only 64 subcarriers. The comparison, in both cases is done with a conventional OFDM system, and it can be seen how the higher the number of subcarriers in the system, the lower difference between ESIM OFDM and the standard OFDM. Nonetheless for system with a low number of subcarriers, it can be seen how the PAPR is effectively reduced with respect to the unmodified OFDM.

Then, in Fig. 10, the constellation is set to a 16-QAM, and the rest of the parameters are varied. It can be seen how for the case of having a 50 % of inactive subcarriers, which is the original proposition of [6], the PAPR does not improve with respect to a conventional OFDM system. If the number of subcarriers per group is increased, and hence the ratio of inactive subcarriers in the group, the PAPR starts improving, up to a point where a 4 dB improvement can be observed.

It is clear from the results that the PAPR is not just influenced by the number of subcarriers in the underlying OFDM system, but also by the size of the groups used for ESIM that can be tuned to get a superior PAPR with respect to the original proposal of groups of two subcarriers, and with respect to a conventional OFDM system.

The technique of introducing idle subcarriers may be similar to other methods such a *Tone Reservation* [14], but with the advantage that ESIM OFDM solves the problem of loss of spectral efficiency using a second digital modulation. There-

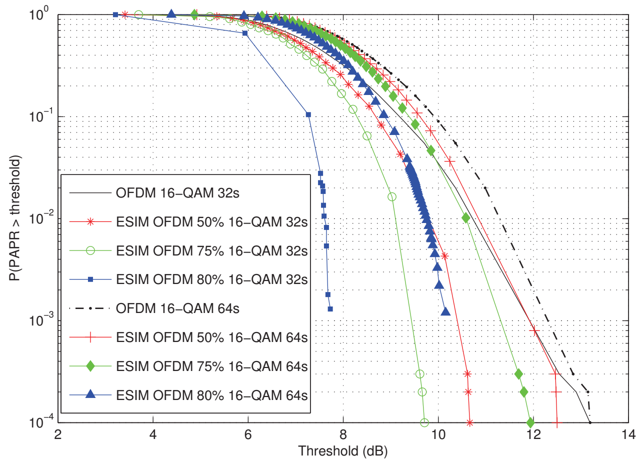

Fig. 10. PAPR ESIM OFDM 16-QAM.

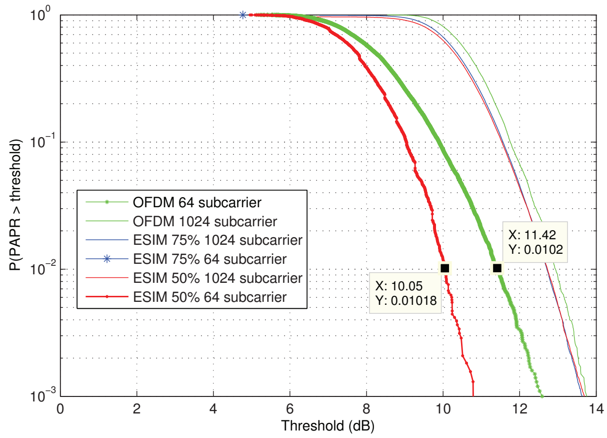

Fig. 11. PAPR ESIM OFDM with Bit Loading.

fore, there is a trade-off between the spectral efficiency that is possible to get, and the improvement in the PAPR and the BER performance, that can be controlled via the size of the ESIM subcarrier groups.

Finally, in Fig. 11, the effect on the PAPR of using bit loading is shown. Note that the number of inactive subcarriers is not significant when bit loading is used, but the total number of subcarriers is still important to improve the PAPR.

VI. Conclusions

This work extends the original proposal for ESIM OFDM to support an arbitrary size of subcarrier groups. This can be used to adapt the trade-off existent between spectral efficiency and PAPR. When the PAPR is a key parameter to take into account, like in VLC, the subcarrier group size can be modified to obtain a more favorable level of PAPR, at the expense of a small loss in spectral efficiency.

Furthermore, the use of a bit loading algorithm for ESIM OFDM is investigated in frequency selective channels, as is the case VLC. It is shown that the proposed allocation has slightly higher throughput under a BER constraint with respect to original ESIM, holding an improvement on PAPR. Therefore adaptive bit allocation may be a possible solution to avoid the loss of spectral efficiency.

The effect that other system parameters, such as the total number of subcarriers and the constellation order, have on the PAPR has also been studied. It has been observed that the improvement over traditional OFDM is higher when the total number of subcarriers is not too high, and also for low order constellations.

Additionally, an alternative expression for the BER in an ESIM OFDM system has been derived, which works better for high SNR. Compared to the original formulation, the new expression is simpler to understand and to work with, and easier to extend to the use of different transmission constellations.

The fact that ESIM OFDM with an arbitrary group size can be used to improve the PAPR of the system opens up the interesting research line of recovering the spectral efficiency loss that is incurred, for example using variations of OFDM based on the Unipolar OFDM [13].

Acknowledgement

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References

[1] R. Van Nee and R. Prasad, "OFDM for wireless multimedia communications," Boston, MA: Artech House, 2000.
[2] H. Burchardt, N. Serafimovski, D. Tsonev, S. Videv and H. Haas, "VLC: Beyond point-to-point communication," Communications Magazine, IEEE. Vol. 52, Issue 7, pp. 98-105, 2014.
[3] M.Z. Afgani, H. Hass, H. Elgala and D. Knipp, "Visible Light Communication Using OFDM," in Proc. of the 2nd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM). Barcelona, Spain: IEEE, pp. 129-134, Mar. 1-3, 2006.
[4] T. Komine and M. Nakagawa, "Fundamental analysis for visible light communication system using LED lights," IEEE Trans. Consumer Electronics. Vol. 50, no. 1, pp. 100-107, 2004.
[5] C. Felita and M. Suryanegara, "5G key technologies: Identifying innovation opportunity," in International Conference on QiR (Quality in Research),Yogyakarta, Jun 25-28, 2013.
[6] D. Tsonev, S. Sinanovic and H. Haas, "Enhanced Subcarrier-Index Modulation (SIM) OFDM," in Proc. of the International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Tokyo, Japan, Sep. 13-16, 2009.
[7] R. Abualhiga and H. Haas, "Subcarrier-Index Modulation OFDM," in Proc. of the International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Tokyo, Japan, Sep. 13-16, 2009.
[8] J. Armstrong, "OFDM for Optical Communications," Journal of Lightwave Technology. Vol. 27, no. 3, pp. 189-204, Feb. 2009.
[9] P.S. Chow, J.M. Cioffi and J.A.C. Bingham, "A practical discrete multitone transceiver loading algorithm for data transmission over spectrally shaped channels," IEEE Trans. Commun., 1995, 43(2-4), pp. 773-775.
[10] J. Campello, "Discrete bit loading for multicarrier modulation systems," PhD thesis, Stanford University, 1999.
[11] J.G. Proakis, "Digital Communications." McGraw-Hill, 1995.
[12] F. Xiong, "Digital Modulation Techniques," 2nd ed. Artech House Publishers, 2006.
[13] D. Tsonev and H. Haas, "Avoiding Spectral Efficiency Loss in Unipolar OFDM for Optical Wireless Communication," in IEEE International Conference on Communications (ICC). Sydney, NSW, 10-14 June 2014.
[14] J. Tellado, "Peak to Average Power Ratio Reduction for Multicarrier Modulation," PhD thesis, University of Stanford, Stanford, 1999.