

Spectral-Efficient Gapped Index Modulation for FTN-*m*CAP in Bandlimited VLC

Yungui Nie, Chen Chen¹, Senior Member, IEEE, Zhihong Zeng², Xiaodi You³, Harald Haas⁴, Fellow, IEEE, and Gangxiang Shen⁵, Senior Member, IEEE

Abstract—A low-complexity gapped index modulation (GIM) scheme was proposed to mitigate inter-band interference (IBI) in faster-than-Nyquist multi-band carrierless amplitude and phase modulation (FTN-*m*CAP), but incurs spectral efficiency (SE) loss due to silent subbands. To address this, three spectral-efficient GIM schemes are proposed. First, the quadrature GIM aided FTN-*m*CAP (FTN-*m*CAP-QGIM) is proposed, and an enhanced LLR detector is designed accordingly. Second, a variable GIM aided FTN-*m*CAP (FTN-*m*CAP-VGIM) scheme is proposed to support variable subband activation. Third, a variable quadrature GIM aided FTN-*m*CAP (FTN-*m*CAP-VQGIM) is proposed to further enhance the SE of FTN-*m*CAP-VGIM. Extensive simulations and hardware experiments are conducted to evaluate the performance of three spectral-efficient GIM schemes. The experimental results demonstrate that FTN-8CAP-VQGIM supports a compression factor of 0.53 at a target bit error rate (BER) of 3.8×10^{-3} , and achieves a 113% enhancement in SE compared with 8CAP.

Index Terms—Visible light communication, carrierless amplitude and phase modulation, faster-than-Nyquist.

I. INTRODUCTION

WITH the continuous advancement of sixth-generation (6G) communication technologies, the data transmission demands in frontier fields, such as artificial intelligence (AI), are expected to experience exponential growth. However, the scarcity of spectrum resources limits the enhancement of radio frequency (RF) communication capacity [1]. Visible light communication (VLC), with several advantages such as abundant spectrum resources, high security and low cost, can serve as a viable alternative to RF communication [2],

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Yungui Nie, Xiaodi You, and Gangxiang Shen are with Jiangsu New Optical Fiber Technology and Communication Network Engineering Research Center, Suzhou Key Laboratory of Advanced Optical Communication Network Technology, the Institute for Broadband Research and Innovation (IBRI), and the School of Electronic and Information Engineering, Soochow University, Suzhou, Jiangsu 215006, China (e-mail: shengx@suda.edu.cn).

Chen Chen and Zhihong Zeng are with the School of Microelectronics and Communication Engineering, Chongqing University, Chongqing 400044, China (e-mail: c.chen@cqu.edu.cn).

Harald Haas is with the Department of Engineering, University of Cambridge, CB2 1PZ Cambridge, U.K.

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[3]. However, the data rate of light emitting diode (LED)-based VLC systems is constrained by the limited modulation bandwidth of the LED, typically in the few-MHz range [4].

To extend the available modulation bandwidth of the VLC system, pre-equalization [5] and post-equalization [6] have been widely used. On the other hand, when the modulation bandwidth of the LED is fixed, spectrally efficient schemes such as carrierless amplitude and phase modulation (CAP) [7] and orthogonal frequency division multiplexing (OFDM) [8] have been proven effective in improving the data rate of VLC systems. Compared to OFDM, CAP offers the advantages of lower peak-to-average power ratio (PAPR) and reduced implementation complexity. As the demand for higher data rate and better adaptability to complex environments grows, research into multi-band CAP (*m*CAP) has emerged as a key focus [9]. In order to achieve higher spectral efficiency (SE), faster-than-Nyquist *m*CAP (FTN-*m*CAP) [10], [11], [12], regarded as an enhanced version of *m*CAP, has been proposed. However, as spectrum compression increases, FTN sampling causes more severe inter-band interference (IBI). Several IBI mitigation schemes have been studied for FTN-*m*CAP. Most of them suffer from high complexity, relying on techniques such as LMS-Volterra filtering [10], machine learning [13], neural networks [11] and Tomlinson-Harashima precoding (THP) [12]. Recently, a new gapped index modulation (GIM) [14] has been implemented on the transmitter side to mitigate the IBI, which transmits signals by activating k gapped subbands out of m , leaving the silent subbands to eliminate IBI. However, the silent subbands in GIM scheme leads to a non-negligible SE loss.

To further improve the SE of bandlimited VLC systems, we propose three spectral-efficient GIM schemes: quadrature GIM aided FTN-*m*CAP (FTN-*m*CAP-QGIM), variable GIM aided FTN-*m*CAP (FTN-*m*CAP-VGIM) and variable quadrature GIM aided FTN-*m*CAP (FTN-*m*CAP-VQGIM). The main contributions of this work are as follows: three spectral-efficient GIM schemes are first proposed to further improve the SE and an enhanced LLR detector is designed for FTN-*m*CAP-QGIM. The superiority of the proposed scheme is validated by extensive simulations and experimental results.

II. PRINCIPLE

A. Principle of FTN-*m*CAP-QGIM

Figs. 1(a) and (b) illustrate the principles of FTN-*m*CAP-QGIM transmitter and receiver, respectively. In the

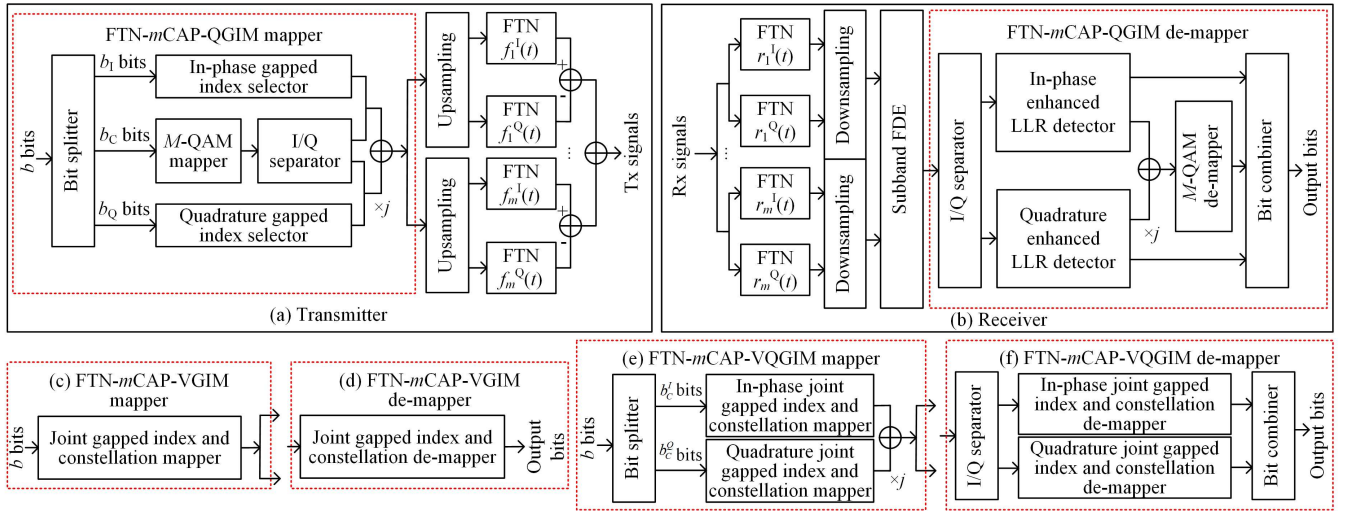


Fig. 1. Principles of (a) the transmitter and (b) the receiver of FTN-*m*CAP-QGIM; (c) the mapper and (d) the de-mapper of FTN-*m*CAP-VGIM; and (e) the mapper and (f) the de-mapper of FTN-*m*CAP-VQGIM.

TABLE I
THE EXAMPLE OF FTN-*m*CAP-QGIM WITH $m = 8$ AND
 $k = 4$ MAPPING TABLE

Index bits	$\{\bar{I}^I, \bar{I}^Q\}$	Index bits	$\{\bar{I}^I, \bar{I}^Q\}$
0 0 0 0	{1, 3, 5, 7, 1, 3, 5, 7}	1 0 0 0	{1, 4, 6, 8, 1, 3, 5, 7}
0 0 0 1	{1, 3, 5, 7, 1, 3, 5, 8}	1 0 0 1	{1, 4, 6, 8, 1, 3, 5, 8}
0 0 1 0	{1, 3, 5, 7, 1, 4, 6, 8}	1 0 1 0	{1, 4, 6, 8, 1, 4, 6, 8}
0 0 1 1	{1, 3, 5, 7, 2, 4, 6, 8}	1 0 1 1	{1, 4, 6, 8, 2, 4, 6, 8}
0 1 0 0	{1, 3, 5, 8, 1, 3, 5, 7}	1 1 0 0	{2, 4, 6, 8, 1, 3, 5, 7}
0 1 0 1	{1, 3, 5, 8, 1, 3, 5, 8}	1 1 0 1	{2, 4, 6, 8, 1, 3, 5, 8}
0 1 1 0	{1, 3, 5, 8, 1, 4, 5, 8}	1 1 1 0	{2, 4, 6, 8, 1, 4, 6, 8}
0 1 1 1	{1, 3, 5, 8, 2, 4, 6, 8}	1 1 1 1	{2, 4, 6, 8, 2, 4, 6, 8}

FTN-*m*CAP-QGIM mapper, the input *b* bits are fed into the bit splitter, dividing the total *b* bits into three parts: b_C , b_I and b_Q . In the meantime, the total of *m* subbands are categorized into activated and silent states. More specifically, the first part b_C bits are mapped to *M*-ary quadrature amplitude modulation (*M*-QAM) symbols on the *k* activated subbands, whose in-phase and quadrature components are then separated by an I/Q separator. The remaining b_I and b_Q bits are respectively used to determine the in-phase and quadrature gapped indexes of *k* activated subbands out of *m*. The gapped indexes of FTN-6CAP-QGIM with $k = 3$ corresponding to in-phase component contain {1, 3, 5}, {1, 3, 6}, {1, 4, 6}, {2, 4, 6}. The example of FTN-8CAP-QGIM with $k = 4$ mapping table is illustrated in Table I, where $\bar{I} = \{\bar{I}^I, \bar{I}^Q\}$ is the gapped index set. Additionally, the gapped indexes of FTN-6CAP-QGIM with $k = 2$ corresponding to in-phase component contain {1, 3}, {1, 4}, {1, 5}, {1, 6}, {2, 4}, {2, 5}, {2, 6} and {3, 6}, and the gapped indexes of FTN-8CAP-QGIM with $k = 2$ corresponding to in-phase component contain {1, 3}, {1, 4}, {1, 5}, {1, 6}, {1, 7}, {1, 8}, {2, 5}, {2, 6}, {2, 7}, {2, 8}, {3, 6}, {3, 7}, {3, 8}, {4, 7}, {4, 8} and {5, 8}. The in-phase and quadrature components share the same gapped index set. Hence, the SE for FTN-*m*CAP-QGIM with *M*-QAM constellation in bandlimited VLC systems can be expressed as follows

$$SE_{\text{FTN-}m\text{CAP-QGIM}} = \frac{b_I + b_Q + k \log_2(M)}{(1 + \alpha)(1 - \beta)m}, \quad (1)$$

where α and β ($0 \leq \beta \leq 1$) denote the roll-off factor of the square-root raised cosine (SRRC) filter and the spectrum compression factor, respectively, with α set to 0.5. *B* is the total bandwidth before spectrum compression. The remaining steps are detailed in [14].

In the FTN-*m*CAP-QGIM de-mapper, to reduce the detection errors of log-likelihood ratio (LLR) detector, the enhanced LLR detection is performed separately on the in-phase and quadrature components. The index combinations used in FTN-*m*CAP-QGIM scheme are regarded as legal gap indexes, and those not used are illegal. Here, we focus on the detection of the in-phase component as an example. For the enhanced LLR detection, LLR detection is first performed, followed by a comparison of the detected gapped indexes with the gapped indexes used at the transmitter side. If an unused gapped index is found, it is considered a detection error and recorded as an illegal gapped index. The signal is extracted and the ML detection is performed separately. Considering the 7% forward error correction (FEC) coding limit, LLR detection achieves a relatively low detection error probability, while the proposed enhanced LLR further improves the detection accuracy of LLR detection. Compared with LLR, the additional complexity of enhanced LLR lies in performing ML detection when a detection error occurs, which is specifically determined by the probability of the occurrence of illegal gapped index.

B. Principle of FTN-*m*CAP-VGIM/VQGIM

Figs. 1(c) and (d) illustrate the principles of FTN-*m*CAP-VGIM mapper and de-mapper, respectively. For the FTN-*m*CAP-VGIM mapper, the *m* subbands are treated as a subblock, within which *k* subbands are activated, with *k* being variable. The subblock signals are determined by the gapped indexes of the *k* activated subbands and *M*-QAM constellation symbols. Let $\mathcal{K} = \{0, 1, \dots, \lceil \frac{m}{2} \rceil\}$ denote the set of activated subbands, where $\lceil \cdot \rceil$ denotes the ceil operator and $\lceil \frac{m}{2} \rceil$ represents the maximum number of subbands that can be activated. Taking $m = 6$ and 8 for example, the gapped indexes of FTN-6CAP-VGIM with $\mathcal{K} = \{0, 1, 2, 3\}$ contain {0}, {1}, {3},

TABLE II
REQUIRED M -QAM CONSTELLATIONS FOR DIFFERENT SCHEMES
BASED ON FTN-6CAP AND FTN-8CAP

Schemes	$R = 27.78$ Mbps	Schemes	$R = 25$ Mbps
FTN-6CAP	4/4/4/4/2/2-QAM	FTN-8CAP	4/4/4/4/2/2/2-QAM
FTN-6CAP-GIM, $k = 2$	16/8-QAM	FTN-8CAP-GIM, $k = 2$	16-QAM
FTN-6CAP-GIM, $k = 3$	8/8/4-QAM	FTN-8CAP-GIM, $k = 4$	8/8/4/4-QAM
FTN-6CAP-VGIM	8-QAM	FTN-8CAP-VGIM	8-QAM
FTN-6CAP-QGIM, $k = 2$	4-QAM	FTN-8CAP-QGIM, $k = 2$	4-QAM
FTN-6CAP-QGIM, $k = 3$	4-QAM	FTN-8CAP-QGIM, $k = 4$	4-QAM
FTN-6CAP-VQGIM	4-QAM	FTN-8CAP-VQGIM	4-QAM

{4}, {6}, {1, 4}, {1, 6}, {1, 3, 6} and {1, 4, 6}, and the gapped indexes of FTN-8CAP-VGIM with $\mathcal{K} = \{0, 1, 2, 3, 4\}$ contain {0}, {1}, {3}, {5}, {8}, {1, 3}, {1, 5}, {1, 8}, {3, 8}, {1, 3, 8}, {1, 5, 8}, {2, 5, 8}, {3, 5, 8} and {1, 3, 5, 8}. Hence, the SE for FTN- m CAP-VGIM with M -QAM constellation in bandlimited VLC systems can be expressed by

$$SE_{\text{FTN-}m\text{CAP-VGIM}} = \frac{\lfloor \log_2 \left(\sum_{i=0}^{\lfloor \frac{m}{2} \rfloor} n_i M^{k_i} \right) \rfloor}{(1 + \alpha)(1 - \beta)m}, \quad (2)$$

where n_i is the number of gapped indexes used when activating k_i subbands and $\lfloor \cdot \rfloor$ is the floor operator.

Subsequently, Figs. 1(e) and (f) illustrate the principles of FTN- m CAP-VQGIM mapper and de-mapper, respectively. For the FTN- m CAP-VQGIM mapper, the input b bits are divided into b_C^I and b_C^Q , each independently mapped using the FTN- m CAP-VGIM mapping process. Hence, the SE for FTN- m CAP-VQGIM in bandlimited VLC systems can be expressed by

$$SE_{\text{FTN-}m\text{CAP-VQGIM}} = \frac{\lfloor \log_2 \left(\sum_{i=0}^{\lfloor \frac{m}{2} \rfloor} n_i^I (M^I)^{k_i} \right) \rfloor + \lfloor \log_2 \left(\sum_{i=0}^{\lfloor \frac{m}{2} \rfloor} n_i^Q (M^Q)^{k_i} \right) \rfloor}{(1 + \alpha)(1 - \beta)m}, \quad (3)$$

where n_i^I and n_i^Q denote the number of gapped indexes used for activating k_i subbands in the in-phase and quadrature components, respectively. For the FTN- m CAP-VGIM/VQGIM de-mapper, ML detector is employed for signal detection. The complexity in terms of complex multiplications for FTN- m CAP-VGIM is $O(2^S E_{\text{FTN-}m\text{CAP-VGIM}} m)$. Similarly, the complexity in terms of complex multiplications for FTN- m CAP-VQGIM is $O(2^S E_{\text{FTN-}m\text{CAP-VQGIM}} m)$.

III. RESULTS AND DISCUSSIONS

In this section, we conduct simulations and experiments to evaluate the performance of three spectral-efficient GIM schemes. The numbers of subbands are set to $m = 6$ and 8, respectively. B is fixed at 25 MHz. To ensure a fair comparison at the same data rate R , the required M -QAM constellations for different schemes are summarized in Table II.

First, as shown in Fig. 2(a), we analyze the performance of different detectors for FTN-6CAP-QGIM over the AWGN

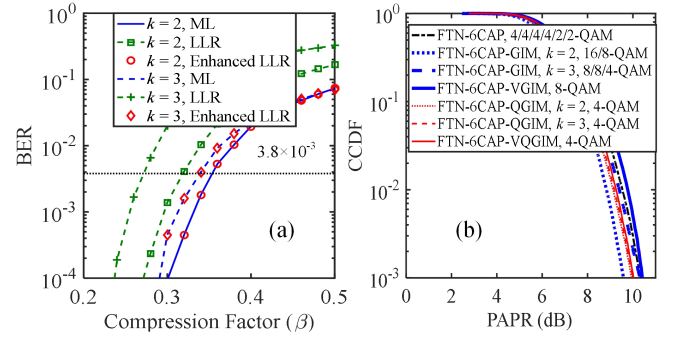


Fig. 2. (a) Comparison of different detectors for FTN-6CAP-QGIM, and (b) PAPR comparison for different schemes based on FTN-6CAP.

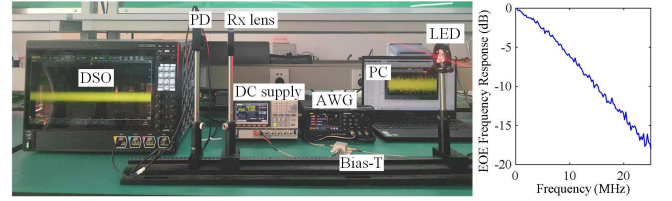


Fig. 3. Experimental setup of the VLC system based on red LED. Inset: frequency response of the complete experimental system.

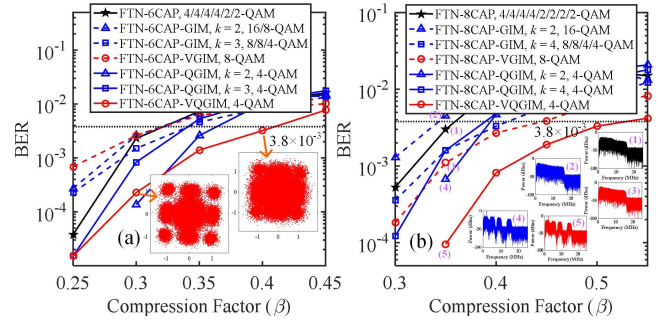


Fig. 4. Experimental BER vs. compression factor for different schemes based on (a) FTN-6CAP and (b) FTN-8CAP.

channel. We can observe that the enhanced LLR detector achieves better BER performance than LLR detector, and nearly the same BER performance as the ML detector. Fig. 2(b) compares the PAPR performance of different schemes based on FTN-6CAP with $\beta = 0.3$. It can be observed that the different schemes based on FTN-6CAP all achieve PAPR values of approximately 10 dB at the probability of 1×10^{-3} .

Subsequently, the experimental setup of a point-to-point VLC system is illustrated in Fig. 3. The sampling rates of arbitrary waveform generator (AWG, Rigol DG2102) and digital storage oscilloscope (DSO, Rigol DS70504) are 60 and 500 MSa/s, respectively. The inset in Fig. 3 depicts the measured frequency response of the system. We can see that the system exhibits a distinct low-pass characteristic, with the measured -3 dB bandwidth of about 6 MHz.

Fig. 4 presents the experimental BER versus compression factor for different schemes based on FTN- m CAP, where the peak-to-peak voltage (Vpp) is set to 6.8 V. We can observe that as the spectrum compression increases, the BER performance gradually deteriorates, primarily due to the increased IBI. For

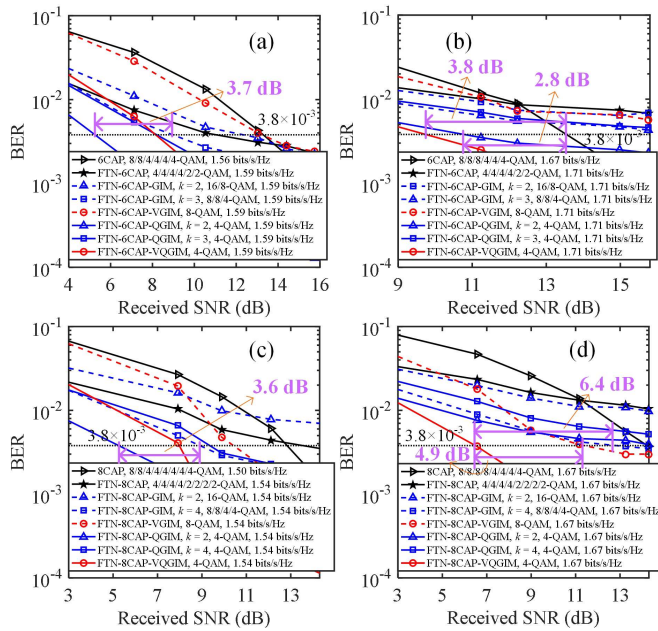


Fig. 5. Experimental BER vs. SNR for different schemes based on FTN-*m*CAP with (a) $m = 6$, $\beta = 0.3$ and (b) $m = 6$, $\beta = 0.35$, (c) $m = 8$, $\beta = 0.35$ and (d) $m = 8$, $\beta = 0.4$.

the case of $m = 6$, as shown in Fig. 4(a), FTN-6CAP-GIM with $k = 3$ achieves the largest compression factor of 0.34 to reach the 7% FEC coding limit of $BER = 3.8 \times 10^{-3}$, compared with FTN-6CAP, FTN-6CAP-GIM with $k = 2$ and FTN-6CAP-VGIM. After introducing quadrature GIM, FTN-6CAP-VQGIM achieves the largest compression factor of 0.41 among all the schemes. For a relatively high value of $m = 8$, it can be observed that, under the 7% FEC coding limit of $BER = 3.8 \times 10^{-3}$, except for the FTN-8CAP-GIM with $k = 2$ scheme, the remaining schemes based on FTN-8CAP-GIM achieve greater spectrum compression than FTN-8CAP. Importantly, FTN-8CAP-VQGIM supports the largest spectrum compression of 0.53 compared with the other schemes considered. An SE increases from 1 bit/s/Hz for 8CAP to 2.13 bits/s/Hz for FTN-8CAP-VQGIM, resulting in a substantial SE enhancement of 113%. The insets in Figs. 4(a) and (b) depict the received constellation diagrams and the received spectra of different schemes, respectively.

Fig. 5 illustrates the experimental BER versus received SNR for different schemes. At small compression factors, FTN-*m*CAP-QGIM with $k = 2$ requires the lowest SNR compared with other schemes at a BER of 3.8×10^{-3} , while at larger compression factors, FTN-*m*CAP-VQGIM requires the lowest SNR and outperforms the other schemes. Take $m = 6$ as an example to illustrate. For $\beta = 0.3$, as shown in Fig. 5(a), to reach the 7% FEC coding limit, compared with 6CAP, FTN-6CAP and FTN-6CAP-GIM with $k = 2$, FTN-6CAP-GIM with $k = 3$ requires the smallest SNR of 9.0 dB. Compared with all schemes, FTN-6CAP-QGIM with $k = 2$ requires the smallest SNR of 5.3 dB, indicating an SNR gain of 3.7 dB compared with FTN-6CAP-GIM with $k = 3$. When the compression factor is increased to 0.35, Compared

with all schemes, FTN-6CAP-VQGIM requires the smallest SNR of 9.8 dB. FTN-6CAP-QGIM with $k = 2$ and FTN-6CAP-VQGIM achieve the SNR gains of 2.8 and 3.8 dB in comparison to 6CAP, respectively.

IV. CONCLUSION

In this letter, we have proposed three spectral-efficient GIM schemes to address the non-negligible SE loss of GIM scheme for FTN-*m*CAP based bandlimited VLC systems. First, FTN-*m*CAP-QGIM is proposed to obtain a higher SE than FTN-*m*CAP-GIM, and an enhanced LLR detector is designed to reduce LLR detection errors. Second, FTN-*m*CAP-VGIM is proposed, allowing variable subband activation. Third, FTN-*m*CAP-VQGIM is proposed to further enhance the SE of FTN-*m*CAP-VGIM. The performance of three spectral-efficient GIM schemes has verified through simulations and experiments. Therefore, the proposed spectral-efficient GIM schemes hold significant potential for application in bandlimited VLC systems.

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