A Design of High-Order APSK Constellations With PAPR Constraints for Single-Carrier BICM Systems

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Abstract— **The majority of modern communication systems adopt quadrature amplitude modulation (QAM) constellations. However, they suffer from a high peak-to-average power ratio (PAPR) as the modulation order grows, which severely reduces the efficiency of the power amplifier. This issue becomes even more critical when the signal points are non-uniformly spaced to improve the achievable information rate (AIR) along with bit-interleaved coded modulation (BICM). On the other hand, amplitude phase shift keying (APSK) constellations provide important benefits compared to QAM due to their circular shape, helping to increase the AIR and reduce the PAPR. In this work, we propose a systematic design approach for a class of APSK constellations composed of multiple concentric rings, each containing the same number of points. In the proposed method, all the radii of the rings are determined by a single parameter, making it easier to identify the best constellation that increases the AIR while keeping the PAPR within limits. Simulation results indicate that in a single-carrier system with pulse shaping, the proposed 1024-APSK constellation increases the AIR by 0.25 bits per symbol compared to the regular 1024-QAM with the same signal PAPR, or it can reduce the PAPR by 1.0 dB while maintaining the same spectral efficiency.**

I. Introduction

Spectrally efficient coded modulation techniques should remain essential for future communications systems to meet the growing demand for high data-rate communications. While bit-interleaved coded modulation (BICM) is widely adopted for its high spectral efficiency and robustness against fading channels [1], there is a non-negligible gap between the achieving information rate (AIR) and the Shannon capacity, especially when using standard uniform quadrature amplitude modulation (QAM). To bridge this gap, constellation shaping has been extensively studied as a means of optimizing the distribution of non-uniform constellations (NUCs).

In fact, several modern wireless communications standards adopt numerically optimized NUCs in conjunction with BICM. For instance, the third-generation standard from the Advanced Television Systems Committee [2], called ATSC 3.0, uses two-dimensional NUCs (2D-NUCs) for lower modulation orders between 16 and 256 and one-dimensional NUCs (1D-NUCs) for higher orders such as 1024-NUC and 4096-NUC [3]. However, NUCs may introduce two key practical challenges as the modulation order M^2 increases. One major concern is the computational complexity associated with demapping. Specifically, 2D-NUCs, which are freely optimized in the complex plane, offer significant shaping gains in terms of AIR, but their demapping complexity grows exponentially with the modulation order, on the order of $\mathcal{O}(M^2)$. These considerations may explain the rationale behind the adoption of 1D constellations for high-order scenarios in practical communication systems such as ATSC 3.0, where the demapping complexity remains linear, i.e., $\mathcal{O}(M)$. Another critical issue is the peak-to-average power ratio (PAPR). Since NUCs often resemble Gaussian distributions, they usually have a higher PAPR than standard uniform QAM, which can significantly lower the efficiency of the power amplifier. This issue becomes more critical in 1D-NUCs due to their rectangular structure. Therefore, exploring alternatives to such NUCs for even higher-order scenarios is of considerable interest.

Amplitude phase shift keying (APSK), the main focus of this study, features a circular constellation structure that inherently offers lower PAPR than QAM. As a result, APSK is often used in satellite communications, as suggested by the Digital Video Broadcasting standards DVB-S2 and DVB-S2X [4], where tolerance to nonlinear distortion and phase noise is crucial. Among various APSK types, this work focuses on Gray-APSK, first introduced in [5]. The Gray-APSK constellation consists of multiple concentric rings, each containing the same number of points; thus, it can be fully separated into amplitude and phase components. This separation not only simplifies constellation design but also significantly reduces demapping complexity. In addition, several simplified demappers for Gray-APSK constellations have been proposed in [6–8], and it has been demonstrated that the extra difficulty in demapping compared to QAM is still tiny.

Several extensions of Gray-APSK constellations have been studied in the literature. In [9], APSK constellations with fewer uniformly spaced rings were proposed to reduce PAPR. However, this amplitude design does not reflect the statistical structure of the complex plane, making it suboptimal from the BMI perspective. More recent studies [10, 11] have focused on maximizing AIR by numerically optimizing both the ring radii and phase offsets. Nevertheless, these methods do not consider the PAPR increase introduced by geometric shaping, which can limit their practical applicability. In addition, [12] proposes a 2D constellation design that maximizes the minimum Euclidean distance to reduce symbol error rates. While the resulting circularly uniform structure is also favorable for PAPR, its effectiveness in terms of AIR is limited to uncoded scenarios at very high SNR.

In this work, we propose a new method for designing Gray-APSK constellations that jointly considers AIR and PAPR.

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Specifically, the ring radii are determined based on a truncated Gaussian distribution controlled by a single parameter. This truncated Gaussian-based design was first suggested for one-dimensional QAM constellations in our earlier work [13], where we showed that the constellation can be adjusted between uniform and Gaussian shapes according to the operating signal-to-noise ratio (SNR). The present work extends this concept to two-dimensional APSK constellations. Unlike the original Gray-APSK design with fixed ring radii, the proposed method allows for more flexible control over the overall constellation shape, making it easier to adjust and improve AIR while keeping within a specific PAPR limit. In our computer simulations, the performance of BICM single-carrier systems employing the proposed 1024-APSK constellations is evaluated in terms of bit error rate (BER) and the actual distribution of baseband signal PAPR. These results are also compared with those of the 1D-NUC adopted in ATSC and a 2D-NUC proposed in a recent study [14]. As a result, the proposed constellations are shown to achieve excellent trade-offs between BER and PAPR, demonstrating their potential as practical alternatives to conventional QAM in spectrally and energy-efficient single-carrier systems.

The main contributions of this paper are outlined as follows:

- A systematic approach for designing Gray-APSK constellations is developed, where the radii of all rings are determined by a single design parameter, allowing for easy constellation adjustment.
- The achievable shaping gain in BICM is numerically evaluated under various PAPR constraints. The results demonstrate that the proposed scheme can effectively enhance the AIR for a given PAPR constraint through simple parameter optimization.
- The performance of BICM single-carrier systems using the proposed APSK constellations is evaluated through computer simulations. It is shown that the proposed APSK scheme consistently achieves excellent trade-offs between BER performance and baseband signal PAPR.

The rest of this paper is organized as follows: Section II first reviews the structure of Gray-APSK constellations and then introduces the proposed design approach with enhanced flexibility. Section III evaluates the proposed scheme for shaping gain in BICM, considering various PAPR constraints. Section IV presents simulation results for BICM single-carrier systems employing the proposed APSK constellations, highlighting the PAPR of the baseband signal and the BER performance in an AWGN channel. Finally, Section V concludes the paper.

II. Adaptive Constellation Design for Gray-APSK

In this work, we focus on a certain class of APSK constellations, known as Gray-APSK, and propose a more flexible design in which the set of ring radii is dynamically determined by a single parameter. Compared to the original design with fixed ring radii, which approximates a Gaussian distribution [5], the proposed scheme allows the constellation shape to transition smoothly between uniform and Gaussian-like distributions.

A. Overview on Gray-APSK Constellation Structure

For a given pair of non-negative integers m_1 and m_2, an M-ary Gray-APSK constellation consists of $M_r = 2^{m_1}$ concentric rings, each with $M_\theta = 2^{m_2}$ equally spaced points sharing the same phase offset. Accordingly, $m_1 + m_2 = m$ ($= \log_2 M$) and each constellation point is defined as

$$X_{i,k} = r_k \exp\left(j\pi(2i+1)/M_\theta\right), \tag{1}$$

for $k = 0, 1, \ldots, M_r - 1$ and $i = 0, 1, \ldots, M_\theta - 1$, where $j = \sqrt{-1}$, the phase offset is assumed to be π/M_θ, and r_k is the radius of the k-th ring.

As for the bit mapping, the m bits of each symbol are divided into m_1 bits for the amplitude component and m_2 bits for the phase component. Due to this separation, Gray labeling can be applied independently to both components without modifications, which is why this structure is often referred to as Gray-APSK [5].

This work attempts to modify the design of such Gray-APSK constellations. Based on the above definition, the design problem essentially reduces to determining the number of rings M_r, the number of symbols per ring M_θ, and the set of ring radii $\mathcal{R} = \{r_0, r_1, \ldots, r_{M_r-1}\}$.

B. Allocation of Rings and Symbols per Ring

The performance of Gray-APSK strongly depends on the number of rings, 2^{m_1}, and the number of symbols per ring, 2^{m_2}. Since $m_1 + m_2 = m$, there are $m + 1$ possible combinations of $\{m_1, m_2\}$ for a given modulation order $M = 2^m$. Most previous studies on Gray-APSK adopt the combination $\{m_1, m_2\} = \{m/2 - 1, m/2 + 1\}$, since it maximizes the AIR in BICM under AWGN channels. However, alternative configurations may become beneficial when considering design criteria beyond AIR in AWGN. For instance, reducing m_2 (i.e., increasing m_1) lowers the signal density in the phase domain, which may improve robustness against phase noise. In fact, several studies on constellation optimization for strong phase noise channels have shown that constellations with fewer phase-domain symbols yield better performance [15–17].

In contrast, the focus of this work is on configurations with $\{m_1 \leq m/2-1, m_2 \geq m/2+1\}$. While reducing the number of rings 2^{m_1} may not be optimal from the AIR perspective, it is expected to help reduce the PAPR, since the constellation structure gradually approaches that of 2^m-PSK. Therefore, to explore favorable trade-offs between AIR and PAPR, we consider constellations with $M_r \in \{1, 2, \ldots, 2^{m/2-1}\}$ rings, each containing $M_\theta = M/M_r$ symbols. We refer to these constellations as $(M_r \times M_\theta)$-APSK.

C. Systematic Design Approach for Ring Radii

We introduce a new systematic approach for determining the set of ring radii $\mathcal{R} = \{r_0, r_1, \ldots, r_{M_r-1}\}$. In this approach, the ring radii are designed such that the resulting constellation approximates a Gaussian distribution, similar to the original Gray-APSK. However, the effective range of the reference Gaussian distribution is truncated using a single design parameter to adjust the resulting constellation shape.

Assuming that equiprobable Gray-APSK symbols follow a circular symmetric Gaussian distribution $z \sim \mathcal{CN}(0, 2\sigma^2)$, the constellation rings should be placed such that the values of the cumulative distribution function (CDF) are evenly spaced. As the magnitude of the complex Gaussian variable $r = |z|$ follows a Rayleigh distribution, the CDF as a function of r is given by

$$F(r) = \int_0^r \frac{r'}{\sigma^2} \exp\left(-\frac{r'^2}{2\sigma^2}\right) dr' = 1 - \exp\left(-\frac{r^2}{2\sigma^2}\right). \quad (2)$$

To partition this distribution into M_r equiprobable regions, the k-th tentative radius $\hat{r}_k$ is determined such that

$$F(\hat{r}_k) = 1 - \exp\left(-\frac{\hat{r}_k^2}{2\sigma^2}\right) = \frac{2k+1}{2M_r}. \quad (3)$$

Assuming $2\sigma^2 = 1$ since normalization will be applied afterwards, the k-th tentative radius $\hat{r}_k$ is given by

$$\hat{r}_k = \sqrt{-\ln\left(1 - \frac{2k+1}{2M_r}\right)}, \quad k = 0, 1, \ldots, M_r - 1. \quad (4)$$

The above equation agrees with the original Gray-APSK design proposed in [5]. To provide more flexibility in the resulting constellation distribution, we introduce a parameter $\rho \in (0, 1]$ that limits the effective range of the reference CDF. Then, the modified ring radius $\hat{r}_k$ is obtained by

$$\hat{r}_k = \sqrt{-\ln\left(1 - \rho\frac{2k+1}{2M_r}\right)}, \quad k = 0, 1, \ldots, M_r - 1. \quad (5)$$

Finally, scaling the magnitude to meet the energy constraint such that $\sum \hat{r}_k^2 = M_r$ leads to the desired set of ring radii $\mathcal{R} = \{r_1, r_2, \ldots, r_{M_r}\}$. Note that the APSK constellation set obtained by (1) with a given set of parameters $\{M_r, M_\theta, \rho\}$ is denoted as $\mathcal{A}(M_r, M_\theta, \rho)$ in the subsequent studies.

D. Example

In Fig. 1, the proposed (8×32)-APSK constellation is shown as blue circles with $\rho = 0.76$ while the APSK constellation used in DVB-S2X is shown as orange crosses for comparison. Even though the DVB-S2X constellation has rings with different optimized sizes, the proposed APSK constellation, designed using only a single parameter, has a very similar shape. This demonstrates that our method can easily manage the Gray-APSK distribution with a much simpler design process. The following section will discuss constellations designed for specific PAPR and AIR targets.

III. Numerical Analysis

In this section, we evaluate the performance of the proposed APSK scheme in terms of the achievable shaping gain under several PAPR constraints. We compare the results with the 1D-NUC in the ATSC standard [3] and the state-of-the-art 2D-NUC proposed in [14]. Throughout this work, all schemes are considered within the framework of BICM employing binary-reflected Gray code (BRGC).

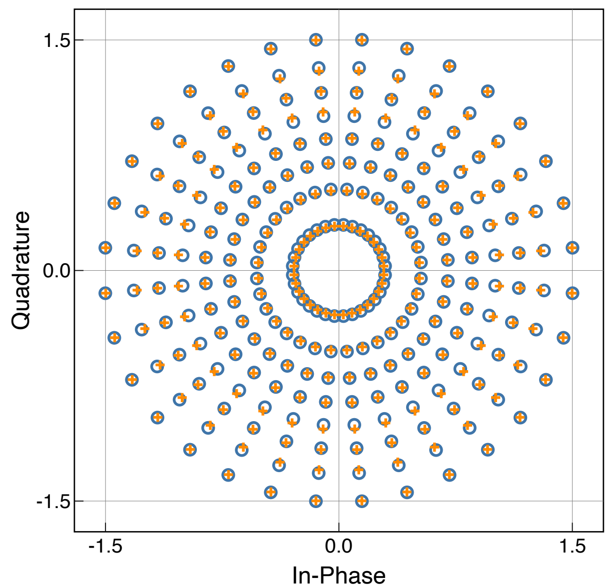


Fig. 1: Comparison between the proposed (8×32)-APSK constellation (shown as blue circles) and the corresponding constellation adopted in DVB-S2X (shown as orange crosses).

A. Parameter Optimization

To identify the constellations that are expected to perform well, it is necessary to evaluate their achievable information rates. Since this work focuses on BICM systems, the total bit-wise mutual information (BMI) [1] serves as an appropriate measure. At a specified channel SNR γ, it is expressed as

$$C(\mathcal{A}, \gamma) = m - \sum_{i=0}^{m-1} \mathbb{E}_{Y,b}\left[\log_2 \frac{\sum_{x \in \mathcal{A}} p_{Y|X}(Y \mid x)}{\sum_{x \in \mathcal{A}_b^{(i)}} p_{Y|X}(Y \mid x)}\right], \quad (6)$$

where $b \in \mathbb{F}_2$ is a random variable representing the bit of the binary channel, $\mathcal{A}$ is a set of constellation points, $\mathcal{A}_b^{(i)}$ represents the set of constellations in the i-th binary channel with the bit specified by b, and $\mathbb{E}$ denotes expectation.

In particular, this work aims to maximize the AIR under a given PAPR constraint. For a set of normalized M-ary APSK constellation points $\mathcal{A}$, the PAPR depends only on the outermost radius and is given by $\mathrm{PAPR}(\mathcal{A}) = r_{M_r-1}^2$. Accordingly, for a given target PAPR constraint ξ and reference SNR γ, the optimization problem is formulated as

$$\begin{aligned} \max_{M_r, \rho} \quad & C\Big(\mathcal{A}(M_r, M_\theta, \rho), \gamma\Big), \\ \text{subject to} \quad & \text{PAPR}(\mathcal{A}) \leq \xi, \\ & M_r \in \{1, 2, \ldots, \sqrt{M}/2\}, \\ & M_\theta = M/M_r, \\ & \rho \in (0, 1]. \end{aligned} \quad (7)$$

Note that the reference SNR should be set to approximately the value at which the system achieves the target spectral efficiency (e.g., 8.00 bits/symbol in this work).

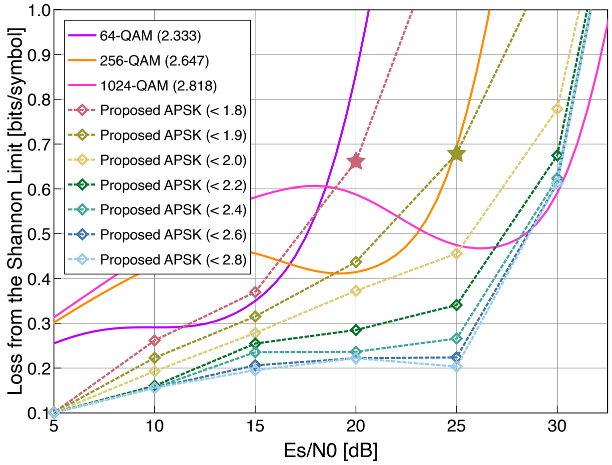


Fig. 2: Loss from the Shannon limit for BICM systems using various constellations with different PAPR constraints. Constellations with $M_r < 2^{m/2-1}$ are highlighted with stars.

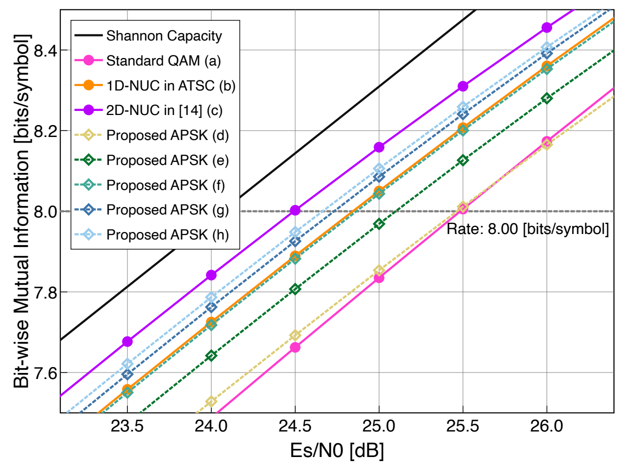


Fig. 3: Comparison of BMI performance for several representative constellations designed for a code rate of $4/5$ (i.e., spectral efficiency is 8.00 bits per complex channel use).

B. Achievable Shaping Gain in BICM

The shaping gain is typically assessed by the difference between the achievable information rate and the Shannon capacity, known as the *loss from the Shannon limit* [18]. For a given constellation set $\mathcal{A}$ at an SNR γ, it is defined as

$$L(\mathcal{A}, \gamma) \triangleq \log_2(1+\gamma) - C(\mathcal{A}, \gamma) \quad (8)$$

in bits per symbol. The results are shown in Fig. 2, where the number next to each legend indicates the actual PAPR value or the target PAPR constraint used in the optimization. We obtain all plotted points by selecting design parameters according to equation (7) for each corresponding SNR. The result reveals that the loss of standard QAM increases as the modulation order increases. On the other hand, the proposed APSK with the loosest PAPR constraint (i.e., $\xi = 2.8$) maintains a small loss from the Shannon limit across a wide range of SNRs. Moreover, even under more strict constraints (e.g., $\xi = 2.0$), the proposed APSK still achieves higher AIR than standard QAM, despite a significantly lower PAPR. These results indicate that the proposed APSK provides a consistently favorable trade-off between AIR and PAPR.

Constellations with a smaller number of rings $M_r < 2^{m/2-1}$ are highlighted with stars in the figure. Stringent PAPR constraints select these constellations as optimal, but they significantly reduce AIR compared to standard QAM. This may suggest that a significant reduction in PAPR (e.g., $\mathrm{PAPR}(\mathcal{A}) < 1.9$) can only be achieved at the cost of a substantial degradation in AIR.

In the subsequent studies, we focus on APSK constellations designed for an SNR of $25.00\,$dB with PAPR constraints ranging from 2.0 to 2.8. All selected constellations share the same configuration with $M_r = 2^{m/2-1} = 16$ rings and $M_\theta = 2^{m/2+1} = 64$ symbols per ring, while varying the design parameter ρ to control the balance between AIR and PAPR.

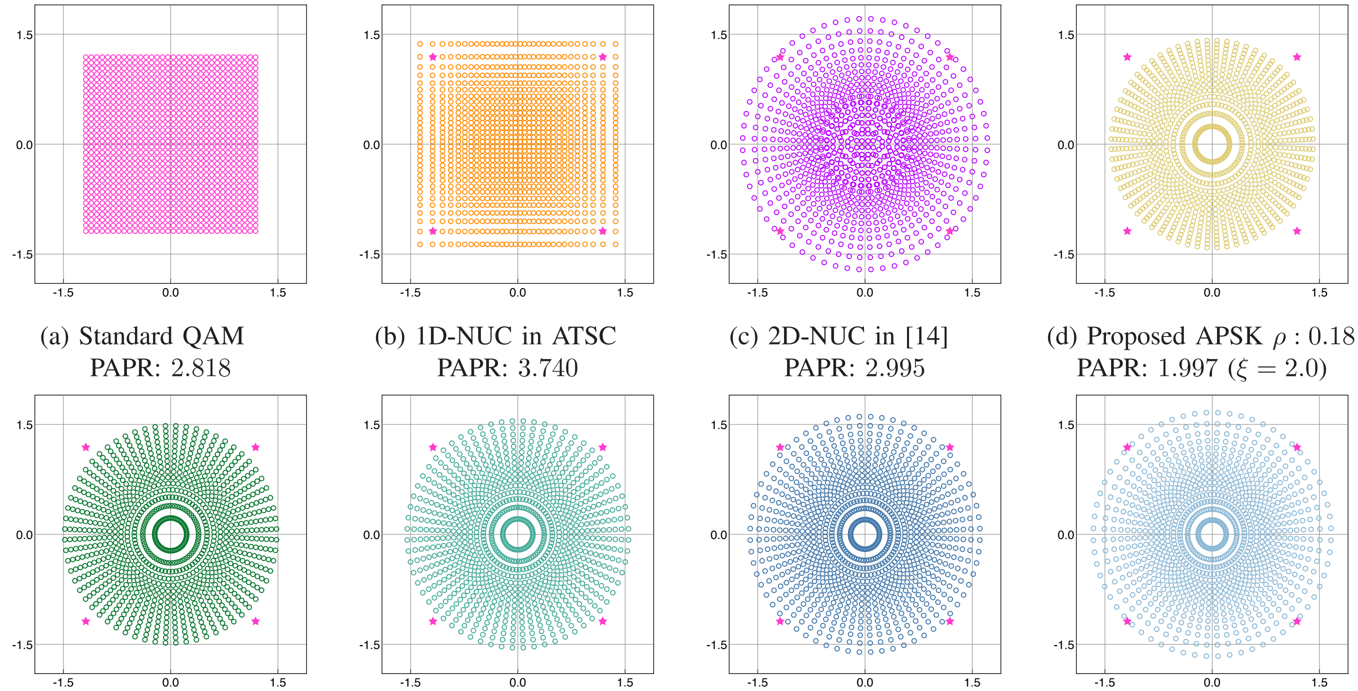
C. BMI Comparison with Other Shaping Schemes

Fig. 3 compares the BMI among various 1024-point constellations optimized at an SNR of 25.00 dB targeting a code rate of $4/5$. The corresponding normalized constellation diagrams are shown in Fig. 4. For a visual comparison of PAPR, the outermost four points of the standard QAM are highlighted as pink stars in each diagram. For the proposed APSK constellations (d) through (h), the parameter ρ has been chosen to maximize the BMI under each PAPR constraint ξ. We first observe that the 1D-NUC adopted in ATSC improves the BMI from the standard QAM. However, as seen in Fig. 4 (b), this gain comes with a substantial increase in symbol PAPR. Additionally, while the 2D-NUC proposed in [14] achieves the highest BMI among the representative constellations, it also shows a slight increase in symbol PAPR compared to the standard QAM. On the other hand, all proposed APSK constellations outperform the standard QAM while maintaining a lower symbol PAPR. In particular, the constellations with $\rho = 0.84$ and $\rho = 0.90$ even surpass the 1D-NUC adopted in ATSC.

Comparing the proposed APSK constellations with different PAPR limits shown in Fig. 4 (d) through (h), we see that when the PAPR limit is loosened, the constellation gets closer to the original Gray-APSK, which has a Gaussian-like distribution (meaning ρ is near 1). Conversely, under more stringent PAPR constraints, the constellations tend to approach a uniform distribution (i.e., ρ close to 0). These uniformly distributed constellations may be suboptimal from the BMI perspective, but under some PAPR constraints, they become promising candidates due to their moderate symbol PAPR values.

IV. Simulation Results

This section evaluates the system-level performance of the BICM single-carrier (BICM-SC) system employing the proposed APSK constellations, focusing on bit error rate (BER) and baseband signal PAPR. The transmitter applies a root



(a) Standard QAM PAPR: 2.818

(b) 1D-NUC in ATSC PAPR: 3.740

(c) 2D-NUC in [14] PAPR: 2.995

(d) Proposed APSK $\rho : 0.18$ PAPR: 1.997 ($\xi = 2.0$)

(e) Proposed APSK $\rho : 0.55$ PAPR: 2.196 ($\xi = 2.2$)

(f) Proposed APSK $\rho : 0.74$ PAPR: 2.397 ($\xi = 2.4$)

(g) Proposed APSK $\rho : 0.84$ PAPR: 2.585 ($\xi = 2.6$)

(h) Proposed APSK $\rho : 0.90$ PAPR: 2.766 ($\xi = 2.8$)

Fig. 4: Comparison among the standard QAM, the 1D-NUC in ATSC, the 2D-NUC in [14], and the proposed APSK constellations, where (d)–(h) correspond to the constellations designed under PAPR constraints ranging from 2.0 to 2.8.

TABLE I: Simulation Setup

Framework	BICM-SC with RRC filtering ($\alpha : 0.35$)
Modulation	1024-constellations: Standard QAM [Fig. 4 (a)] 1D-NUC of ATSC 3.0 [Fig. 4 (b)] 2D-NUC of [14] [Fig. 4 (c)] Proposed (16×64)-APSK [Fig. 4 (d)-(h)]
Coding	Punctured Turbo code
Decoding	Log-MAP (iteration: 15)
Code rate	4/5
Codeword length	30720
Channel	AWGN

raised cosine (RRC) pulse shaping filter with a roll-off factor $\alpha = 0.35$, and the receiver performs ideal matched filtering. The simulation setup is detailed in TABLE I.

A. PAPR Comparison

We first evaluate the actual PAPR distribution of baseband signals shaped by an RRC filter. Each observation is taken over a segment of 1024 modulation symbols, and the PAPR is defined as the ratio of the segment's peak power to its average power. The complementary cumulative distribution function (CCDF) curves of the PAPR for single-carrier systems modulated with different constellations are shown in Fig. 5. We can see that both the 1D-NUC and 2D-NUC, designed to improve the BMI, greatly raise the baseband signal PAPR compared to the standard uniform QAM, which is a major drawback of using non-uniform constellations. Nevertheless, all of the proposed APSK constellations achieve considerably lower PAPR than other non-uniform constellations, even though they offer potential improvements in error rate performance. The most significant PAPR reduction is achieved by the constellation (d) with $\rho = 0.18$.

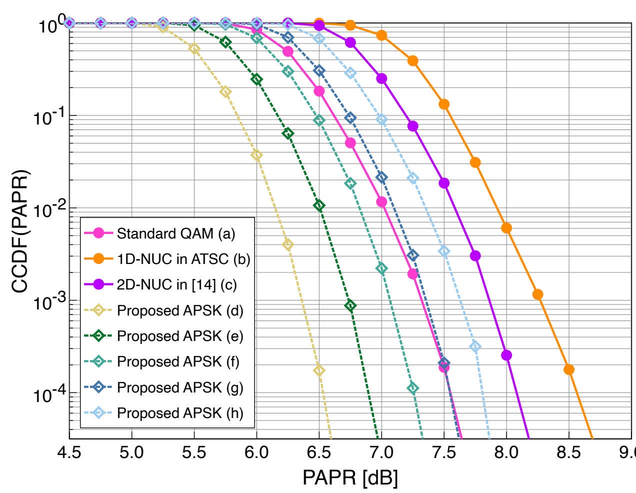


Fig. 5: CCDF of the baseband signal PAPR for BICM systems with the various 1024-point constellations shown in Fig. 4.

B. BER Comparison

Finally, we compare BER performance over an AWGN channel among the aforementioned constellations. Fig. 6 dis-

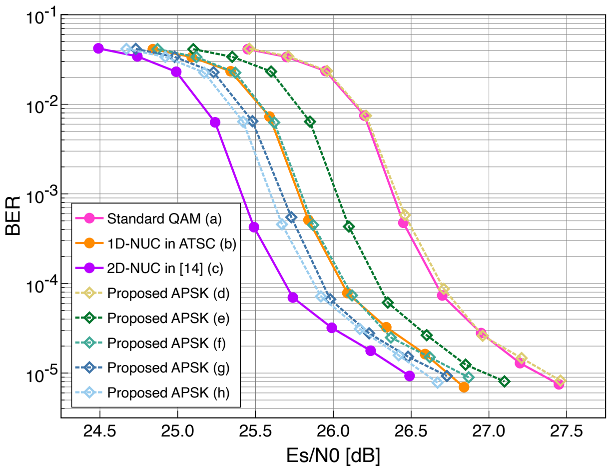


Fig. 6: BER comparison over an AWGN channel for BICM systems with the various 1024-point constellations shown in Fig. 4.

plays the results, revealing a general agreement between their BER performance and those estimated through BMI analysis in Fig. 3. We summarize the notable advantages of the proposed APSK constellations as follows:

1) The constellation (h) with $\rho = 0.90$ achieves the most significant BER improvement of about 0.8 dB from the standard QAM, with a moderate increase in PAPR. This performance also approaches within approximately 0.2 dB of that achieved by the state-of-the-art 2D-NUC based on numerical optimization.
2) The constellation (f) with $\rho = 0.74$ achieves performance comparable to the 1D-NUC in ATSC, with an even lower PAPR than the standard QAM.
3) The constellation (d) with $\rho = 0.18$ reduces PAPR by 1.0 dB compared to the standard QAM, without degrading the error rate performance.

From these results, it is apparent that, through the optimization of only a single design parameter, the proposed APSK constellation can be adaptively controlled to achieve favorable trade-offs between error rate performance and PAPR.

V. Conclusion

In this paper, we proposed a systematic method for designing Gray-APSK constellations, where the ring radii are determined based on a truncated Gaussian distribution adjusted by a single design parameter. Compared to the conventional Gray-APSK design with fixed constellation points, the proposed approach offers greater flexibility in shaping the resulting constellation. In general, a major practical drawback of non-uniform constellations is their typically higher PAPR compared to standard QAM. To address this issue, the proposed approach allows the APSK constellation to be adaptively shaped so as to maximize the AIR under a given PAPR constraint. Simulation results demonstrated that single-carrier systems employing the proposed APSK constellations can achieve excellent trade-offs between error rate performance and baseband signal PAPR. These results point to the possibility of systematically designed APSK constellations as promising alternatives to conventional QAM in future spectrally and energy-efficient single-carrier communication systems.

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