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Constellation Design for Future Communication Systems: A Comprehensive Survey

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ABSTRACT The choice of modulation schemes is a fundamental building block of wireless communication systems. As a key component of physical layer design, they critically impact the expected communication capacity and wireless signal robustness. Their design is also critical for the successful roll-out of wireless standards that require a compromise between performance, efficiency, latency, and hardware requirements. This paper presents a survey of constellation design strategies and associated outcomes for wireless communication systems. The survey discusses their performance and complexity to address the need for some desirable properties, including consistency, channel capacity, system performance, required demapping architecture, flexibility, and independence. Existing approaches for constellation designs are investigated using appropriate metrics and categorized based on their theoretical algorithm design. Next, their application to different communication standards is analyzed in context, aiming at distilling general guidelines applicable to the wireless building block design. Finally, the survey provides a discussion on design directions for future communication system standardization processes.

INDEX TERMS Bandwidth, communication waveforms, mobile communications, spectral efficiency, wireless communications.

I. INTRODUCTION

A. WHY IS CONSTELLATION DESIGN IMPORTANT AND CHALLENGING?

WIRELESS communication systems are experimenting a considerable evolution due to the increase of the different data traffics that they must convey. The advent of new technologies such as Internet of Things (IoT) [1], 5G [2], and the most recent satellite communications [3], combined with the users' demand for high-quality multimedia content for Digital Terrestrial Television (DTT) and direct to home (DTH) satellite TV systems [4], [5] impose a new paradigm on the spectral efficiency of the communication systems.

The limit at which data can be transmitted was set by Shannon's seminal work [6], [7]. During the last decades, many researchers have put their efforts on approximating to that limit creating advanced coding techniques, such as Low-Density Parity-Check (LDPC) codes [8], [9], turbo codes [10], polar codes [11], etc.Some of these codes are considered as capacity-approaching codes, performing in the boundary of the error-free region. Other techniques, which are already being considered for the upcoming wireless communications systems, are Non-Orthogonal Multiple Access (NOMA) [12], Light Fidelity (LiFi) [13] or Faster-Than-Nyquist (FTN) algorithms [14].

All these techniques are not transparent to the constellation shape that modulates the information bits. What is more, part of their effectiveness relies on the constellation behind them. Therefore, the constellation design is also a critical stage to enable these new technologies' potentiality. The constellation itself and its symbols must gather as much information as possible. This necessity brings out the so-called massive order constellations (i.e., higher than 256 symbols). Several examples can be found in the latest versions of the IEEE 802.11 ax/be [15]–[17], where 1024 and 4096 constellation sizes for high throughput are considered, respectively. Another example of massive order constellations is ATSC 3.0, where 1k and 4k constellation sizes are included [18].

Next-generation mobile communication systems such as 5G and its successor 6G must also provide a massive amount of data with very low latency [19], [20]. These requirements imply the design of capacity approaching constellation schemes and, at the same time, simple designs to lighten the demapping complexity. There are already several works dealing with this issue [21], [22], but there has not been yet proposed a general design for a simple and efficient set of constellations.

B. WHAT IS EXPECTED FOR NEXT GENERATION WIRELESS COMMUNICATIONS?

Up to now, mobile communications standards have gathered the interest of the majority of users and service providers. The standardization of 5G New Radio (NR) in 2018 was considered an opportunity to migrate several traditional services to 5G systems under the umbrella of convergence. The convergence of fixed and mobile services, for instance, is a popular example that 5G could anchor [23]. Nevertheless, with the deployment of 5G taking off and potential new applications arising, it can be foreseen that next-generation mobile communication standards (i.e., 6G) should solve the already detected limitations of 5G: system coverage, the interconnection of everything (IoE) and the mobile communication demands of the year 2030 and beyond [24].

Although there is no clear description of what 6G is, it is expected to have enhanced capabilities compared to 5G and broaden the applicable use cases. In fact, several recent works envision the use of 6G for novel applications such as, in [25], where holographic communications are proposed; in [26], where the combination of Machine Learning and Quantum Computing seems to be near or in [27], where authors suggest that 6G will reinforce mobile ultra-broadband communications, super IoT and artificial intelligence.

In order to cover the new requirements and the proposed use cases, a group of disruptive technologies will be considered for their integration in 6G. Some representative examples are energy transfer and harvesting to potentiate massive machine type communications (mMTC) and to develop a combination of use cases like massive ultra-reliable low latency communications (mURLLC) [28]. In addition, to fulfill the strict capacity requests, it is expected that 6G will use higher frequency bands than 5G [29].

Doubtlessly, this ever-increasing demand for tighter requirements and novel use cases and applications opens the door to the innovation of several aspects of the communication chain, including the physical layer. In particular, the design of convenient constellation designs aims to provide a massive and robust solution to increase communication capacity and reliability.

C. THE CONTRIBUTIONS OF THIS PAPER

Although several survey papers have been published in relation to different aspects of the communication chain, such as different coding alternatives [8]- [11], or multiplexing techniques [12], only a few works have studied the constellations, even if they are a critical aspect of any communications system. In [30], a comparative study is presented about multidimensional constellations, but only for Sparse Code Multiple Access (SCMA) systems. The survey in [31] introduces the family of spatial modulation, which is based on communications that include MIMO. Then, [32] presents a double survey work on coding and modulation techniques, whereas the target is optical communications. Therefore, to the best knowledge of the authors, a survey on constellation design for any wireless communication system is missing, and the goal of this paper is to present an extensive analysis covering this gap. In summary, the contributions of this paper include:

1) Provide a set of steps and guidelines to design the constellation scheme of any communication system.
2) Analyze the constellation design alternatives and the most relevant approaches in the literature.
3) Analyze the constellation design techniques in some of the most representative use cases of the future communication systems (i.e., 5G/6G, terrestrial broadcasting, and satellite communications).
4) Definition of the most important constellation properties that any successful communication system must fulfill.

The organization of this paper is shown in Fig. 1. For a comprehensive study of the existing solutions, this work gathers in Section II the basic concepts of the main system models, constellations used in wireless systems, comprehensive guidelines for the design of constellations of any communication system. It introduces the main characteristics of the demappers. A survey of the existing constellation and design methods for wireless communication systems classified in different techniques is presented in Section III. Then, in Section IV, the paper identifies and compares the most appropriate constellation schemes for the main wireless communication systems intending to make the design of these blocks easier for the upcoming wireless technologies. Section V contributes to the constellation design providing the design directions that must follow any of these blocks for the upcoming generation communications systems. State-of-the-art works are evaluated under these properties to check out their efficiency from different points of view. Finally, the authors present several future research lines and conclusions in Section VI.

II. A TUTORIAL ON CONSTELLATIONS

This section aims to unify the most relevant aspects to take into account in the constellation design. First, as a background, the most relevant system models are introduced today to design and validate constellations. This subsection is necessary to understand where constellations are located

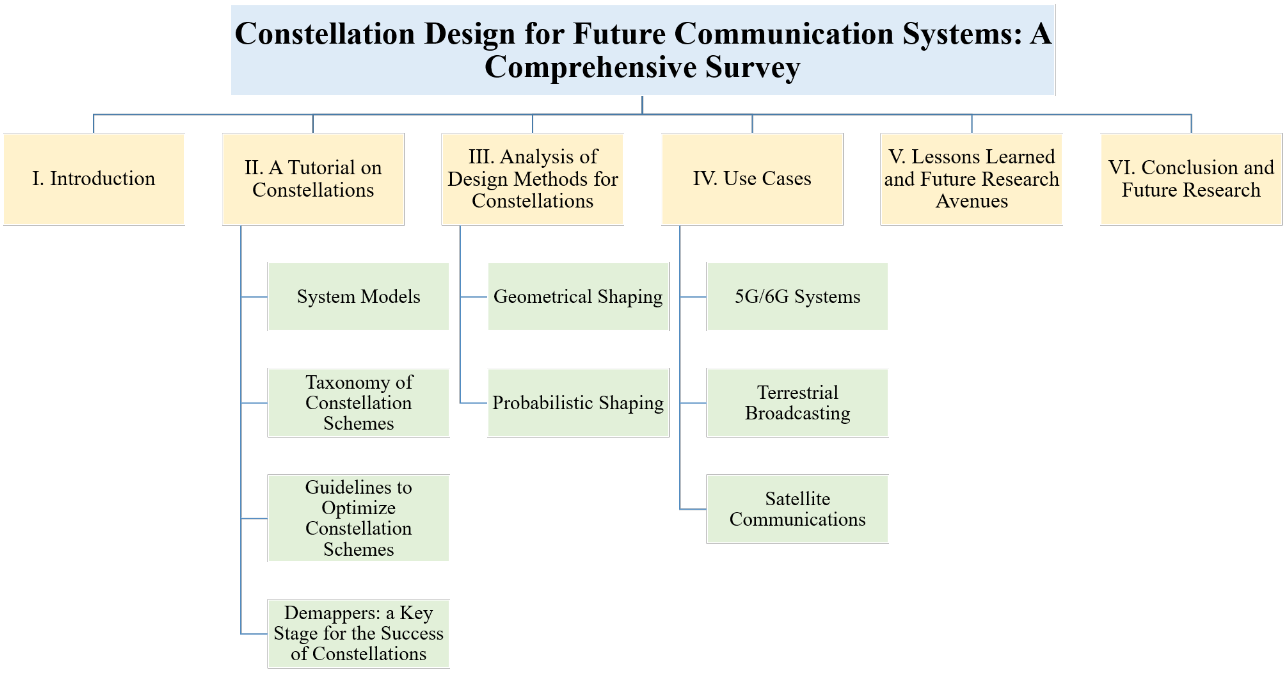

FIGURE 1. Organization of the paper.

in a communications system and their impact. Second, a classification of the constellation types is presented, and the main characteristics of each one are defined. Subsequently, taking as reference recent articles related to constellation design, a proposal is defined on how to efficiently design constellation schemes. Finally, the last subsection aims to classify and describe the main functions of the demappers since these elements are located in the reception chain and are in charge of carrying out the complementary operation to the constellations.

A. SYSTEM MODELS

One of the significant challenges in communication system engineering is to ensure the reliable transmission of digital information through a noisy channel. The first works related to this field are found in [33] and [34] by H. Nyquist and R. V. L. Hartley. However, it was not until 1948 and 1949 when C. E. Shannon introduced a unified mathematical theory of communication [6], [7]. Shannon established in 1949 the upper bound of a communications system for error-free reception under the AWGN channel. Since then, many experts have focused on getting close to that limit to design the most efficient communication systems. Indeed, in the so-called power-limited regime (low Signal to Noise Ratio, SNR), there are already two coding techniques that are very close to the upper bound: turbo codes defined in [35] by Berrou et al. in 1993 and the LDPC codes proposed by Gallager in 1962 [36] and reinforced by MacKay and Neal in 1997 [37]. Both alternatives have been included in commercial communication systems such as LTE (Turbo codes) and 5G (LDPC), and several studies have demonstrated their capacity to approach closely Shannon's limit in the low Signal-to-Noise Ratio (SNR) region [38]. The maximum channel capacity for the power-limited regime is bounded by one bit per symbol.

When the channel conditions are good enough, more than one bit per symbol can be transmitted in the so-called bandwidth-limited regime (i.e., high SNR). The transmitted signal is comprised of more than two constellation symbols, and the goal is to find the most efficient way to transmit the information bits. The most widely known solution is the Coded-Modulation (CM) scheme, in which the channel encoder is directly connected to the modulator, associating several bits to one constellation symbol. The main challenge is constructing the CM system that operates close to Shannon's limit with reasonable complexity. Several proposals have been made for the bandwidth-limited regime during the last years to construct efficient CM systems. Then, Trellis Coded Modulation (TCM) was the first popular CM scheme described by Ungerboeck in [39] and [40], which is based on successive partitioning of the expanded M-ary signal set into subsets with increasing minimum Euclidean Distance (ED). TCM is a combination of coding and modulation, and the word Trellis stands for the use of Trellis/Convolutional codes. Afterward, Multi-Level Coding (MLC) was proposed in [41] by Imai and Hirakawa. MLC protects each bit of the signal point with a unique binary code using m parallel encoders connected to one of the m bit positions of the mapper. In contrast to TCM, MLC provides flexible transmission rates and block codes. Finally, Bit-Interleaved Coded Modulation (BICM) was introduced in 1992 by Zehavi [42]. BICM makes the encoder and the modulator independent introducing a bit interleaver between them. Although the ED measure of BICM decreases with respect to TCM and MLC, the code diversity increases, providing better system performance under fading conditions.

In conclusion, as shown in [43] for AWGN channels and a given complexity, TCM outperforms BICM. In the case of uncorrelated narrowband Rayleigh fading channels, BICM provides better performance. If iterative decoding is taken into account, BICM shows superior performance than the other CM schemes studied for AWGN and uncorrelated narrowband Rayleigh channels. However, in real-time systems where latency is a key aspect, iterative decoding schemes are not appropriate.

B. TAXONOMY OF CONSTELLATION SCHEMES

In the context of constellation and modulation schemes, there are five main classes of modulation that abound in digital data transmission: cubic, orthogonal, circular, rectangular, and hexagonal [44]. These classes provide different geometric approaches in order to construct different constellation schemes depending on the basis functions. The basis functions must fulfill two main requirements: they must be orthogonal to all the others, and they must be normalized. Cubic constellations, for instance, are commonly used for simple data communications and in OFDM systems for channel estimation. They provide robustness against noise and channel impairments at the cost of low channel capacity. Orthogonal signal sets are not widely used as they provide low spectral efficiency, and their application is limited to amateur radio, caller ID, and emergency broadcasts. Cubic and circular constellations are commonly used in satellite communications as they provide low Peak-to-Average Power Ratio (PAPR) [45]. Rectangular signal constellations are widely used in broadcast, broadband systems, and terrestrial wireless links. They offer a good trade-off between system capacity and robustness. Hexagonal constellations are used in Spatial Modulation (SM) [46]. They reduce the PAPR in OFDM systems and have comparable bandwidth efficiency and minimum Euclidean distance compared with efficient schemes such as Quadrature Amplitude Modulation (QAM). N defines the number of basis functions used to transmit the constellation symbols. Therefore, depending on the value of N, N-dimensional signal constellation can be constructed. Fig. 2 shows a classification of the different constellation topologies and different types of constellation schemes for each topology.

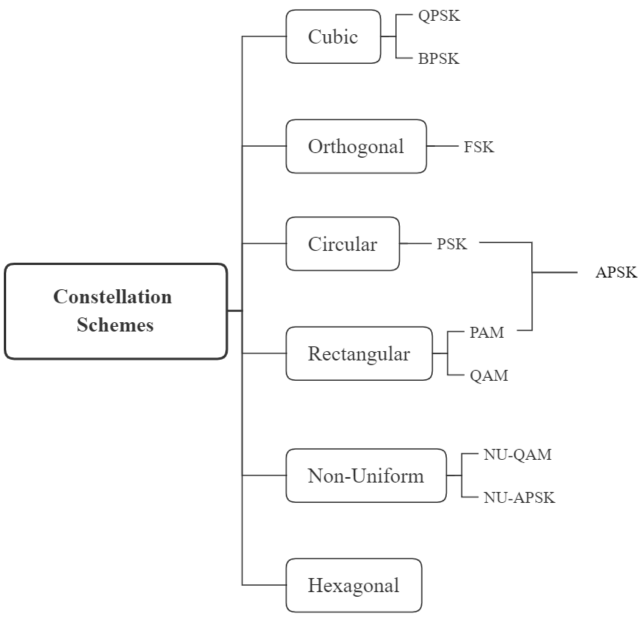

FIGURE 2. Diagram of basic constellations schemes.

1) Cubic constellation

Cubic constellation refers to a direct mapping of a sequence of $N = b$ bits into the components of the basis vectors in a corresponding N-dimensional signal constellation, where b is the number of bits per constellation symbol. Classical BPSK (Binary Phase Shift Keying) and QPSK (Quadrature Phase Shift Keying) are family members (see Fig. 3(a) and Fig. 3(b)). BPSK is created by one basis function (sinusoid) that modulates the sequence of data symbols. BPSK is composed of two constellation points, each carrying one bit, with a separation of 180 degrees in the constellation diagram. It is the most robust modulation technique. Classical applications include long-distance wireless communications, e.g., CDMA, WiMAX, WLAN, DVB-S2, or DVB-T2. In contrast to BPSK, QPSK constellations use two orthogonal basis functions to carry two-bit per symbol with the same amplitude and with phase shifts of multiples of 90 degrees. QPSK is used in several space communication systems [47], satellite, broadband, and broadcast wireless standards such as DVB-S2, LTE, DVB-T2, and ATSC 3.0.

2) Orthogonal constellation

The main characteristic of orthogonal constellations is the linear increase of the number of basis functions with constellation symbols. Therefore, the number of bits per dimension is lower than for cubic constellations. One of the most well-known orthogonal constellations is the frequency shift keying (FSK) [48]. In frequency modulation, the information bits are encoded into the frequency component of the transmitted signal. Therefore, the transmitted signal has a constant envelope, enabling the use of non-linear amplifiers and minimizing the modulated signal sensitivity to channel or hardware amplitude distortion. However, the spectral bandwidth occupied is higher than in the amplitude and phase modulation. Only one basis function per symbol period is transmitted. FSK can be extended if the number of basis functions N is increased at the cost of higher bandwidth growing linearly with N.

3) Circular constellation

The main characteristic of circular schemes is the equal phase distribution, and constant amplitude of constellation symbols [49]. This sort of constellation is called phase-shift

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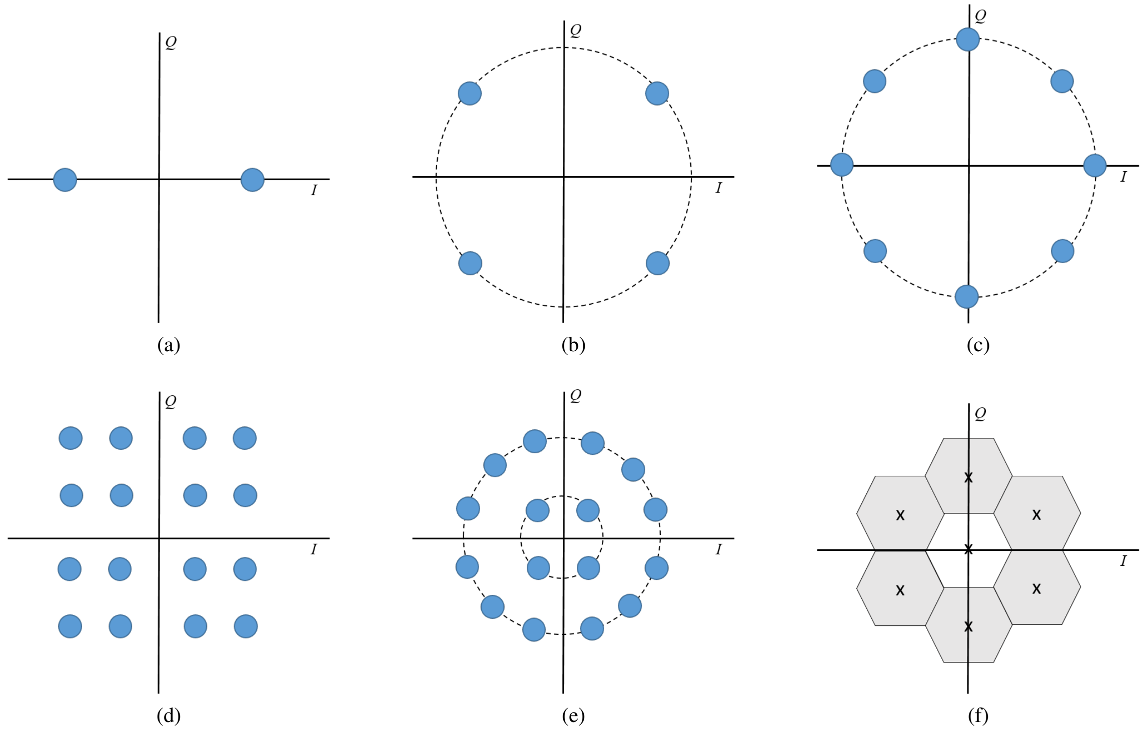

FIGURE 3. Summary of constellation diagrams: (a) BPSK, (b) QPSK, (c) 8PSK, (d) 16QAM, (e) 16APSK, (f) Hexagonal constellation.

keying (PSK), and the information bits are conveyed in the phase of the transmitted signal. A two-dimensional signal space is needed for the transmitted signal, identical to the QPSK case. The basis functions are the same as for QPSK. Although any number of phases can be used, 8PSK (8 angles) is usually the highest order (see Fig. 3(c)). The error rate for higher-order constellations is considerably increased w.r.t. other types such as QAM. Satellite communications systems, for instance, DVB-S2, use QPSK and 8PSK constellations for their low PAPR. For a given bandwidth, PSK is less susceptible to errors than PAM/ASK. Compared to FSK, PSK has higher spectral efficiency, but the detection and recovery process is more complex.

4) Rectangular constellation

Rectangular constellations are characterized by equally spaced constellation symbols, independently of the number of signal space dimensions. Depending on the number of basis functions, two main types of rectangular constellations can be considered. The simplest form of linear modulation is the PAM [50], which is a one-dimensional constellation scheme with constellation order $M = 2b$. PAM does not have a quadrature component, and the information bits are transmitted in the signal amplitude. The main advantage of PAM is the simple receiver and transmitter schemes. Although in current communications systems, PAM is not widely used, it is a common construction block in transmitting and receiving modules of two-dimensional constellations such as QAM [51] (see Fig. 3(d)). The construction of the QAM constellation comes from the two-dimensional generalization of the PAM. Using two orthonormal basis functions in the same symbol period, QAM provides two degrees of freedom to encode the information bits, i.e., amplitude and phase components of the transmitted signal. QAM is widely used in many communication systems, including broadband (LTE), broadcast (DVB-T/T2, ATSC 3.0, ISDB-T), WLAN (802.11 family), and Fixed Wireless Links. Its wide acceptance relies on its spectral efficiency and low implementation complexity.

Combining the PSK and PAM schemes allows the construction of the amplitude-phase shift keying (APSK) constellations. APSK symbols are placed on several concentric circles of the different radius with equally spaced angles (see Fig. 3(e)). The basis functions are identical to the QAM case. APSK constellations are commonly used in satellite communications systems, providing higher spectral efficiency than QAM with low PAPR. On the receiver side, the system complexity is increased w.r.t. QAM because a two-dimensional demapper is needed.

5) Non-uniform constellations (NUC)

Constellations with non-uniformly spaced and equiprobable points are known as geometrically shaped constellations [52]. The construction of these signal sets is based on several metrics depending on the target of the communication system, i.e., maximization of channel capacity, minimization of bit error probability, or robustness against a determined type of fading channel.

Different schemes can be designed based on the restrictions applied to the constellation shaping, namely degrees of freedom (DOF). The most widely known families are the non-uniform APSK (NU-APSK) and non-uniform QAM (NU-QAM) constellations. In NU-APSK, the constellation points are non-uniformly spaced across circles of different radius. This solution provides higher spectral efficiency than APSK without a PAPR increase. For NU-QAM, two main choices are depending on the number of DOF: one-dimensional NU-QAM (1D-NU-QAM) and two-dimensional NU-QAM (2D-NU-QAM). 1D-NU-QAM is equivalent to two non-uniform PAM signals. Their square shape characterizes them, and their design is limited by the possible degrees of freedom of each constellation point of the PAM signals. The advantage is their higher gain if compared with uniform QAM constellations and the negligible demapping complexity increase. On the other hand, in 2D-NU-QAM, all the constellation points have full freedom of mobility at the optimization stage, and they are circularly shaped for low and mid-SNR ranges. Furthermore, they present more gain than 1D-NU-QAM, but at the cost of increasing complexity at the demapping stage as they require a two-dimensional demapper. A clear example of the relevance of these constellations is their incorporation into the latest version of the ATSC 3.0 standard [18].

6) Hexagonal constellation

Finally, the hexagonal constellation is a type of irregular constellation where the number of constellation symbols is not a power of 2 of the number of information bits (see Fig. 3(f)). Another type of irregular constellation is the non-square QAM constellation shown in [53]. The main characteristic of hexagonal constellations is the hexagonal lattice at which each constellation symbol is placed. The hexagonal scheme is the densest packing of regularly spaced points in two-dimensional signal sets, providing low PAPR with comparable bandwidth efficiency and minimum Euclidean distance to QAM. However, the encoder and detector for hexagonal lattice constellations and the assignment of binary information are more complex than for QAM as it has a non-power-of-two number of constellation points.

C. GUIDELINES TO OPTIMIZE CONSTELLATION SCHEMES

The solution suggested in this section is not the only way to design efficient constellation schemes but, it has been demonstrated to be an efficient methodology for terrestrial broadcasting [54]–[56], satellite communications [57]–[59], and mobile 5G [52], [60], applications.

First, it is necessary to define the system model for which the constellation is designed. The coding and decoding technique biases the system model. In LDPC decoding, where the transmitted bits are fed into the coder, and the receiving bit probabilities are used to perform the decoding step, bit-oriented system models are used, e.g., BICM. If turbo coding is considered, symbol coding and decoding occur as in CM systems. The selection of the system model provides the analytical function to evaluate during the design process. In TCM and MLC schemes, the encoder and constellation blocks are dependent on each other. For BICM models, the constellation is independent of the encoder or FEC used.

Afterward, the design of the constellation is based on two different approaches: geometrical or probabilistic shaping. The design methodology selection also depends on the information source (video, audio, and voice). For unequal occurrence probability of bits, probabilistic shaping is recommended, whereas if the probabilities of bit occurrence values are equal, geometrical shaping is chosen. The previously mentioned steps allow determining the objective function to be evaluated in the design process.

Then, the design targets of constellations should be defined: capacity or robustness. Each system model can be described using an associated channel capacity function. For example, the BICM channel capacity is shown in [61]. Another possible function under evaluation may be the system Bit Error Rate (BER). It is important to note that there will always be a parameter that maximizes or minimizes the value of the function. In the case of the BICM channel capacity, this value is the position of the constellation symbols and the bit labeling. In the cases of the BER, the goal is to minimize its value using the same parameters.

Once the function under evaluation is decided, the following steps are generally related to the optimization process: optimization (global, local), the number of global or local maximums or minimums. Eventually, the optimization methodology is chosen: simulation-based or analytical optimization.

D. DEMAPPERS: A KEY STAGE FOR THE SUCCESS OF CONSTELLATIONS

The demapper performs the complementary operation of the mapper by extracting the bitstream from the received complex stream. Therefore, the demapping/detection stage is critical for the success of constellation designs, and there are some characteristics and requirements that demappers have to fulfill. In fact, one of the most complex challenges to achieve is a considerable latency reduction, which is mandatory for the next-generation wireless communication systems. A considerable quantity of data, sent and processed via complex techniques, must be recovered in just a few milliseconds [62]. The success mainly depends on the decoding and demapper steps.

Nonetheless, the challenge of creating a low complexity demapper does not only come from the low latency rule. The inclusion of new constellation schemes in a communication system does not come for free. The Maximum Likelihood (ML) optimal decoder [63], which guarantees the best performance, is an expensive solution, and it increases the computational and memory requirements with the constellation size. Consequently, low complexity decoders must be found in order to reduce the receiver complexity for the new generation devices.

In order to select the adequate approach, the detection/demapper stage can also be divided into several advanced detection algorithms. First, the ML function of the optimal detector depends on the EDs between the received observation and all the constellation symbols. This approach is valid for CM system models [39], [40]. For BICM systems [64], the possible bit values of the transmitted symbols are taken into account, and the detector calculates the Log-Likelihood Ratio (LLR) values. The second detection technique is the Maximum A Posteriori (MAP) detector, whose main difference w.r.t the ML is that it assumes some probability distribution on the transmitted signal and selects the estimated symbol that maximizes the receiving probability [65], [66]. Finally, the Max-Log detector simplifies the LLR calculation by reducing the number of mathematical computations with respect to the ML detector while EDs are unaltered.

E. LESSONS LEARNED

On the one hand, the analysis of the existing system models presents different alternatives depending on the Key Performance Indicator (KPI) evaluated and the parameters of the use case. For example, BICM seems to be the best option for aggressive propagation channels (e.g., Rayleigh), while TCM is a better alternative for AWGN channels.

On the other hand, depending on the geometric approaches, different constellation schemes can be constructed. Among all the classes presented, cubic, circular and rectangular solutions are the most common solutions in commercial communication standards. In addition, NUCs are a novel constellation technique based on non-uniformly spaced and equiprobable points that might be used in future wireless systems. Moreover, a specific methodology for the generation and optimization of constellation schemes has been detailed.

Finally, the demapping stage should also be considered in the constellation design since it is directly related to the complexity of the receiver.

III. ANALYSIS OF DESIGN METHODS FOR CONSTELLATIONS

During the last decades, an intense effort has been carried out in order to design the most efficient constellation schemes with high spectral efficiency. This section analyzes the state-of-the-art constellation design methodologies, which are organized into two groups: geometrical shaping (GS) and probabilistic shaping (PS). Additionally, some other additional approaches are also analyzed.

A. GEOMETRICAL SHAPING

The case of non-uniformly spaced and equiprobable symbols is known as Geometrical Shaping (GS) constellation [67]. This structure allows modifying different parameters of a communication system, such as the BER or channel capacity. Table 1 shows a summary of the most relevant works present in the literature.

Constellation designs based on geometrical shaping use two criteria: minimizing the error probability and maximization of the channel capacity. In [74] and [77], an error probability metric is considered to design efficient constellation schemes. The authors of [74] study the GS approach to design constellation schemes with $M > 2$ to minimize the probability of error. These authors derive an asymptotic expression of the minimum distance for large SNR to calculate the error rate. With this expression, they design locally optimum constellations using a gradient-search procedure. The initial conditions are chosen from several random M-point arrays. The gradient-search algorithm is tested for $M = 4, 7, 8, 16$ and 19 for a single SNR value associated with an error rate of approximately 10^{-6}. The results show a minimum value of $M = 8$ in order to obtain power savings with respect to standard QAM schemes. In [77], the author considers cost functions such as optimization for minimum symbol error rate, maximum BICM capacity, maximum signal set capacity, and maximum exploitation of perfect a priori information. Constellations up to 32 points are designed based on both bit labeling and symbol constellation showing that gains in the order of several tenths of a dB are achievable.

Works in [68]–[72] focus on maximizing the channel capacity of different system models in order to approach Shannon's limit. They use the same solution to increase the channel capacity, i.e., approximate the probability density function (pdf) of the transmitted signal to a Gaussian one. As Shannon stated in his seminal work, the highest capacity for an AWGN channel is obtained when the transmitted signal presents a Gaussian distribution. The authors in [68] demonstrate theoretically that equiprobable signaling in low dimension space achieves channel capacity for the memoryless Gaussian channel. The designed signal set is also shown to be related to the input power, i.e., different signal sets should be used depending on the SNR value. However, the main drawback of this work is that the proposed signal sets have a very high PAPR value. Later on, equiprobable non-uniformly spaced ASK constellations for AWGN channels were designed in [69] for the BICM. Parallel decoding capacity was considered (each bit level is considered separately) in order to reduce the designing complexity. The use of Non-Uniform ASK (NU-ASK) provides higher capacity gains than uniform ASK for high order modulation schemes for BICM systems. However, the shaping gain with the method proposed in this work is lower than other proposed shaping methods and, for higher-order modulation schemes, the ultimate gain of 1.53 dB is not achieved. The main advantage of the work is the simplicity of the method proposed. Fragouli et al. [70] use non-uniform constellations to achieve shaping gains for parallel concatenated turbo codes. The approach considered is to approximate the output signal to a Gaussian distribution. However, as the points near the center are closely spaced, there is a high error floor. The authors design a two-step process to avoid this situation. First, a semi-random interleaver is used in order to lower the error floor. Then, they use the encoder that leads to a higher overall free distance with the selected interleaver. The simulation results show that for four bit/s/Hz, the designed non-uniform 64QAM via GS offers an improvement of 0.2 dB if turbo codes are used with respect to the 64QAM under Gaussian noise. Zesong et al.

TABLE 1. Analysis of GS Methods

Method	Metric	Advantages	Disadvantages
GS Gaussian Approximation: [68]–[71]	Channel Capacity	Easy implementation. Good results for the AWGN channel	Loss for fading channels. High PAPR values
Maximization of the system model channel capacity: [72], [73]	Channel Capacity	Provides optimum constellation schemes if the optimization problem is correctly carried out. Valid for any system model	Depending of the system model, difficult implementation. Requires a prior study of the optimization problem
Gradient-search: [74]	Error Probability	For $M \geq 8$ obtain power saving with respect to standard QAM schemes	Local optimization. Negligible gain for $M \leq 8$
Coded Bits Grouping for Turbo Decoding: [71]	Channel Capacity	Gains from 0.5 to 1 dB for high order modulations and low and middle SNR values	Valid for BTCM systems. Computational complexity increase
AMI and PAMI approximation for AWGN noise with phase jittering scenarios: [72], [73]	Channel Capacity	Good results for AWGN channels with thermal and phase noises. Low time consumption and similar results compared to the standard method	Valid only if capacity-approaching codes are used
Warping/Condensation: [75], [76]	Channel Capacity	Gain for low SNRs. Demapping complexity reduction. Negligible time consumption at the transmitter	Loss for high SNR value

[71] consider GS design for Binary Turbo Coded Modulation (BTCM). They propose to modify the criteria considered in previous works. The output signal does not follow a Gaussian distribution. In Turbo decoding, the information bits are usually more critical than the parity bits for decoding BER performance. Therefore, the authors divide the output coded bits into at least two sub-flows. Based on this consideration, the mapping rule is optimized, and gains from 0.5 to 1 dB are achieved for high order modulations and low and middle SNR values.

In the case of non-Gaussian noise scenarios, such as phase noise or iid noise process and independent of the symbol being transmitted, works in [72] and [73] present a different solution for each case. The authors in [72] focus on maximizing the channel mutual information via GS for 8, 16, 64, and 256 constellation points. The channel model is a complex AWGN channel with phase jitter, and a simulated annealing algorithm is used to optimize the signal and label the constellation points jointly. The authors also propose a computationally efficient approximation of the Average Mutual Information (AMI) and Pragmatic Average Mutual Information (PAMI) for channels with memoryless thermal and phase noises. The results conclude that if the constellation optimization is done in AWGN channels, the signal sets are susceptible to phase noise. The system performance showed that AMI and PAMI are the adequate objective functions to design constellations in systems that use capacity-approaching codes. Regarding non-Gaussian noise, Kayhan et al. [72] propose different global and local optimization algorithms for optimal signal set design. The authors study the optimization problem considering that the noise process is iid and independent of the transmitted symbol. In the field of local algorithms, Sequential Quadratic Programming (SQP) is considered because a feasible solution always exists, and the objective function may be used directly as a merit function. For the global solution, the stochastic approach based on the Multi-Level Single Linkage (MLSL) algorithm is used as it is an intelligent way of generating initial points for the local algorithm. The results show that the methodology proposed in this work can overcome the performance of the standard SQP method.

In [77], authors design constellations via GS using several cost functions: minimum symbol error rate, BICM capacity, signal set capacity, and exploitation of perfect a priori information. The studies presented in [78] and [79] evaluate the feasibility of such designs theoretically in terms of system capacity gain and compare GS with PS. Barsoum et al. [78] and [79] discuss the constellation design via capacity maximization and compare the GS and PS design. The authors design non-uniformly spaced constellations taking into account the joint and parallel decoding capacities for Gaussian noise. Non-uniform PAM and PSK constellation schemes are obtained, and their system performance is analyzed using LDPC codes. The results show that the non-uniform 32-PAM provides a 1.2 dB performance gain compared with conventional uniform 32-PAM. Furthermore, the results show that performance does not considerably improve if iterative decoding is considered. The most important outcome of the work is that they prove theoretically that any gain in capacity that PS can achieve can also be achieved or exceeded by equiprobable and non-uniformly spaced signaling, i.e., GS.

Finally, the authors in [80] prove that for low SNRs, the warping technique provides efficient constellation schemes in terms of channel capacity. For high SNR values, the authors conclude that uniformly spaced constellations are recommended. More in detail, this work shows that if the constellation points near the perimeter are spaced further apart than points close to the center (warping technique), then the Gaussian noise immunity of the perimeter points increases. However, the warping technique reduces the immunity to Gaussian noise for low values of Gaussian noise as points near the center are closer together than in a uniformly spaced constellation with the same average power, e.g., QAM constellation. The main conclusion of this work is that for low SNR values, the warping technique is appropriate for approaching channel capacity, while for high SNR values, uniformly spaced constellation points should be considered.

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B. PROBABILISTIC SHAPING

PS imposes a non-equiprobable distribution of the constellation points while maintaining the set of constellation points equidistant. Table 2 shows a summary of the most relevant works related to these techniques. There are two different approaches: perform the shaping operation after encoding and concatenate encoding and shaping in the same operation. For PS constellation design, there are five main criteria:

1) Approximate the distribution of the constellation points to have a Gaussian pdf via non-uniform distribution [81]. However, this solution presents problems of buffering delays.
2) Sub-constellation selection and shaping codes to reduce the PAPR of the system [82].
3) Prefix codes applied to non-equiprobable constellation schemes [83].
4) Mapping of equiprobable input words into non-equiprobable bits of the constellation scheme via Look-Up-Table (LUT) [84], [85].
5) Probabilistic Amplitude Shaping (PAS) to increase the spectral efficiency [86].

In detail, Forney et al. [81] introduce the non-uniform distribution to constellation points in order to have a Gaussian probability distribution. Although the gains achieved for uncoded schemes in higher dimensions are more than 1 dB, the authors foresee some practical problems. One way to achieve potential gain is to divide the input data bits into words of non-uniform length and map the words into signal points. However, this solution requires that the number of data bits transmitted per unit of time is a random variable, which leads to implementation problems, such as buffering delays.

Calderbank et al. [82] propose a technique based on probabilistic shaping in order to approach the entire asymptotic gain of N-sphere over N-cube in the limit $N \rightarrow \infty$. The signal constellation is divided into different subconstellations of equal size. The points inside each subconstellation are of equal probability. The selection of the subconstellation is carried out at a determined frequency using a shaping code. The designed scheme is compared with equiprobable signaling schemes of multidimensional lattices based on Voronoi regions [88]. The results show that superior PAPR is achieved with the non-equiprobable scheme.

Kschischang et al. [83] study prefix codes in order to approach the optimal performance of non-equiprobable constellation schemes. The shaping schemes designed by the authors approximate the ultimate shaping gain performance given by the Maxwell-Boltzman probabilities applied to the constellation points. Huffman procedure is proposed to design prefix codes approaching optimal performance. Two different channels are provided by these schemes: fixed-rate primary channel and variable-rate secondary channel. As pointed out in previous works, the main drawback is the variable bit rate that limits the broad applicability of non-uniform signaling.

Raphaeli et al. [84], [85] show how to create non-uniform constellation sets in the pragmatic binary turbo coded modulation system. Their proposal makes use of a table that maps equiprobable input words into non-equiprobable bits of an M-ary PAM. The results show that the proposed scheme shapes gains of 0.6 and 0.93 dB at 2 and 3 bit/dimension rates. This means that for a 6 bit/QAM symbol, a gain of 0.93 dB is achieved.

Khoo et al. [89] investigate the insertion of non-equiprobable signaling in BICM-ID systems. While a shaping code block is inserted after the convolutional encoder and before the mapper, the demapper calculates the extrinsic LLR value based on a priori LLRs generated by both shaping and convolutional decoders. The results show that the error performance of a 2 bit/s/Hz 16QAM convolutional coding scheme is improved by 0.7 dB at BER = 10^{-3} and 0.35 dB at BER = 10^{-5} selecting the adequate shaping codes.

Le Goff et al. [90] introduce a new probabilistic shaping technique for improving the performance of Bit-Interleaved Turbo-Coded Modulation (BITCM) over AWGN channels. The authors propose to split the basic constellation into several equal-sized sub-constellations with increasing average energy. The sequence of sub-constellations is specified using a shaping code, and thus, low-energy signals are transmitted more often than high-energy signals. The constellation set is labeled using Gray code, and PAM constellations are taken into account. The technique consists of inserting a single short-length binary shaping code between turbo code and modulation blocks. The simulation results show that gains of up to 0.8 dB are achieved using 16PAM signal sets. The results also demonstrate that the results remain unaltered if the demapper is removed from the iterative decoding process while the receiver complexity is reduced.

Mheich et al. [87] analyze the problem of PS in degraded broadcast channels. The authors investigate if higher achievable bit rates than those defined for Hierarchical Modulation (HM) are possible. The design of the constellation is carried out, maximizing the multidimensional AMI of the system. The results show that when the optimization of the probability density and constellation symbols positions are jointly included, higher achievable rates than HM are generated in 4PAM. This gain is translated into SNR gains of up to 2 dB.

Valenti et al. [91] consider the use of PS for BICM-ID LDPC coded systems using APSK constellations. The authors propose using a non-linear shaping encoder in which the output is more likely to be zero than one, dividing the basic constellation into several subsets. The shaped bits are used to select one subconstellation, and the unshaped bits are used to select the constellation point inside the subconstellation. The system is designed so that the system's CM capacity is used to optimize the ring of the APSK modulation and the probability distribution of the shaping code. Then, the LDPC code is optimized using Extrinsic Information Transfer Charts (EXIT) to select the adequate variable-node degree distributions. With the shaping and LPDC codes correctly optimized, the iterative system outperforms a standard DVB-S2 system by over 1 dB in the AWGN channel with 32APSK at a rate of 3 bit/symbol. The main drawback of the proposed

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TABLE 2. Analysis of PS Methods

Method	Metric	Advantages	Disadvantages
PS Gaussian Approximation: [81]	System performance for a determined error probability	Gains of more than 1 dB for uncoded schemes in higher dimensions or source coding with non-uniform probabilities of the signal points	Problems of buffering delays
PS maximization of the system model channel capacity: [87]	Channel Capacity	Provides optimum constellation schemes if the optimization problem is correctly carried out. Valid for any system model.	Depending on the system model, complex implementation. Requires a prior study of the optimization problem
Sub-constellation Selection: [82]	PAPR	Superior PAPR is achieved compared with equiprobable signaling schemes of multidimensional lattices	Delay in the constellation design because of the shaping code.
Prefix Coding: [83]	System performance for a determined error probability	Approximate to the ultimate shaping gain performance given by the Maxwell-Boltzman probabilities	Variable bit rate
Non-equiprobable Bit Mapping: [84], [85]	System performance for a determined error probability	Shaping gains of 0.6 and 0.93 dB at rates of 2 and 3 bit/dimension	The LUT increase the memory at the transmitter
Probabilistic Amplitude Shaping: [86]	Channel Capacity	Spectral efficiency between 2-10 bit/s/Hz within 1.1 dB of capacity for the AWGN channel. No iterative demapping	Only for ASK schemes. A distribution matcher is needed in the transmitter. Higher complexity

solution is the iterative receiver complexity.

Yankov et al. [92] study a rate-adaptive constellation shaping technique to approach channel capacity in Turbo Coded BICM. A family of mapping functions is designed using many-to-one constellation shaping based on Huffman code with binary-reflected Gray code. The optimal code rate, constellation, and mapping are dynamically selected based on the operating SNR. The results show that this approach reduces the gap to channel capacity, outperforming TCM schemes.

Böcherer et al. [86] propose a new CM scheme making use of PS without iterative demapping applied to ASK constellations. The authors introduce the PAS technique, concatenating a distribution matcher and a systematic binary encoder for FEC to eliminate the iterative decoder. Various orders of ASK (4, 8, 16, 32, and 64) are considered, and only one LDPC code rate per constellation size. This CM scheme achieves spectral efficiencies ranging from 2 to 10 bit/s/Hz within 1.1 dB from the AWGN channel.

C. OTHER METHODS

1) MIMO

In the case of MIMO systems, several design procedures have been published targeting this architecture. The major part of those works addresses optimization as a function of the channel state information and the channel matrix.

Regarding the non-coherent MIMO Rayleigh fading channel, in [59] the cut-off rate expression as the design criterion and the mutual information as the performance metric are considered. The design is based on convex programming, where the optimization variables are the input probabilities and per-antenna amplitudes for the constellation points. The results show capacity increases in the low-medium SNR regime.

Maleki et al. [93] introduced a novel constellation design for spatial modulation, taking into account the effect of Channel State Information at the Transmitter (CSIT). Considering complete and imperfect CSIT, the authors propose two different constellation schemes to increase the distance among the received constellation vectors. The first solution, called Multi-antenna Spatial Modulation (MSMod), uses all the transmit antennas per transmit interval. The second solution, called Modified Space Shift Keying (MSSK) employs only one transmit antenna scheme in order to avoid a scenario where all the transmit antennas should be active simultaneously. The results show that MSMod provides better system performance than MSSK, whereas the transmit complexity is higher as Inter-Antenna Synchronization (IAS) is needed.

For indoor 2x2 MIMO Visible Light Communications (VLC), the authors in [94] create an optimal constellation scheme assuming that the Perfect Channel State Information (CSI) at the transmitter and receiver site is known. The goal is to maximize the ED between different received signal vectors under a total optical transmission power constraint. The results show that when compared to conventional MIMO-VLC solutions, the proposed scheme offers the largest minimum ED.

2) PAPR

Another research field is orientated to the PAPR reduction techniques for OFDM systems making use of constellation shaping. Selective mapping alongside cubic constellation is proposed in [95] to reduce the PAPR in OFDM systems. The cubic constellation is based on the Hadamard matrix, which provides reduced PAPR. This solution reduces the average energy and achieves a small shaping gain. Furthermore, PAPR reduction techniques can be applied to the constellation scheme proposed. The results show that the proposed scheme outperforms existing PAPR reduction techniques with no losses in energy or spectral efficiency.

Shell mapping and QAM is selected in [96] to reduce the PAPR of OFDM systems. Simulation results for different values of subcarriers (16, 32, and 128) are obtained for the proposed constellation shaping scheme, showing significant

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PAPR reduction for the OFDM system. Furthermore, the proposed scheme does not require additional side information to be transmitted to the receiver and does not increase the average power of OFDM.

3) Rotated Constellations (RC)

In order to cope with fading channels, the RC technique (a particular case of SSD) is adopted in DVB-T2 and DVB-NGH. RC can provide better system performance for specific propagation scenarios than standard constellation schemes, such as QAM. Uniform QAM schemes are rotated given an angle (optimized for each operating waterfall SNR), and afterward, an interleaving process is applied.

Polak et al. [97] compare the system performance of non-rotated and rotated constellations in DVB-T2. Using a DVB-T2 OFDM compliant system, the authors conclude that the maximum gain is achieved using QPSK modulation with RC for a 0 dB Echo channel. The authors do not include other types of fading scenarios, such as Rayleigh. A wider range of code rates and higher-order modulations should be considered in order to compare fairly rotated and non-rotated constellations.

Gozalvez et al. [98] study the use of RC in DVB-NGH to get the improved time and frequency diversity. The authors consider the joint use of the long-time interleaver and Time-Frequency Slicing (TFS) defined in DVB-NGH with RC. The study, which was carried out from the information-theoretic point of view, reveals that the RC technique can improve the performance for high code rates. Moreover, the gain obtained with RC is higher when interleaving durations up to several seconds and with TFS are implemented. The main reason is that the large signal variations are compensated.

4) LDM

ATSC 3.0 incorporates a Non-Orthogonal Multiple Access (NOMA) technique known as Layered Division Multiplexing (LDM). LDM delivers two independent services on the same frequency channel. As this technique is of recent creation, there is only one work related to constellation design for LDM. Mouhouche et al. [56] extend the use of non-uniform constellation design via GS to LDM systems. The authors consider several SNRs to optimize the sum of BICM capacity (sum of the BICM capacity at the waterfall SNR with and without LDM). While for 64 constellation points, non-uniform constellations provide an SNR gain of about 0.55 dB, for 256, system performance gains are close to 0.85 dB.

IV. USE CASES

This section provides a comprehensive discussion on the possible applications of the constellation design procedures for the most important communication systems.

A. 5G/6G SYSTEMS

In broadband systems such as 4G/LTE, the constellation schemes used are QPSK and QAM. The choice is based on their simplicity and trade-off between throughput and robustness. However, there are several proposals of GS NUCs for the 5G family of standards and the upcoming standards. Table 3 presents an analysis of the most relevant works mentioned in this section.

First, [52] proposes GS NUCs for future releases of 5G and even 6G networks. Current choices in 3GPP have discarded non-uniform QAM schemes, but NUCs have proved better performance and acceptable complexity. The design method is based on maximizing the BICM channel capacity of the 5G New Radio system. The optimized constellations provide gains up to 0.8 dB for AWGN channels.

Xu et al. [99] test the use of LDPC codes from 5G NR standard and newly designed NUCs to enable LTE-based 5G terrestrial broadcast, which is a solution expected for Release 17/18 aiming at providing convergence between broadcast and broadband networks. They present link-level simulations carried out over AWGN and TDL-B channels, and they obtain performance gains of NUCs up to 0.62 dB over the AWGN channel and up to 1.15 dB over the TDL-B channel with QAM based on Turbo codes.

In [100], a probabilistic shaping method based on reduced-exponentiation subset indexing and honeycomb-structured constellation optimization is shown to reduce the number of constellation points of the signal so that the final amount of points does not follow the traditional pattern of multiples of power exponents of 2. Results indicate that the proposed probabilistic shaping 64-to-31 carrier-less amplitude and phase modulation (CAP) can achieve gains of 1.5 dB and 3 dB over receiver sensitivity when compared with uniform 32-CAP and uniform 64-CAP at BER of 10^{-3}, respectively.

Then, authors in [101] present a different approach of novel constellation designs for 6G and beyond: reconfigurable intelligent surface (RIS)-assisted communications for index modulation (IM) techniques by proposing RIS-space shift keying (RIS-SSK) and RIS-spatial modulation (RIS-SM) schemes. Results indicate that both solutions, RIS-SSK and RIS-SM, perform correctly in extremely low SNR regions of operation (i.e., below -20 dB) and, therefore, they are good candidates to achieve ultra-reliable communications.

Finally, there are other works related to NUCs, where although new constellations are not designed, their performance is evaluated. For example, in [60], NUCs for exploiting the 60 GHz band are considered. The work bases the study on the already existing 64NUCs from the 802.11ay task group and provides simulated performance for 60 GHz indoor channels. The results prove a BER improvement of the NUCs against standard QAM. However, BER values not smaller than 10^{-4} are considered, and simulated values show an error floor in system performance figures. In addition, in [102], a step forward is presented since the use of NUCs for broadband (i.e., 5G and beyond) and broadcast (i.e., ATSC 3.0) convergence is tested under the influence of 3GPP Tapped Delay Line (TDL) propagation channels. Authors carry out simulations for up to 40 use cases, where the code rate, the code length, the mobile speed, and the channel profile (i.e., TDL-A and TDL-B) are varied. Results show

TABLE 3. Analysis of Constellation Design Methods for 5G/6G Systems

Work	Year	Method	Metric	Description
[52]	2016	Maximization of the channel capacity	Channel Capacity	NUCs are presented as a potential technique to be implemented in future 5G releases. A novel algorithm is introduced for the design of NUCs for specific MCS.
[99]	2020	Maximization of the channel capacity	Channel Capacity	To enable LTE-based 5G terrestrial broadcast, NUCs are tested in combination with LDPC codes under AWGN and TDL-B propagation channels.
[100]	2019	Maximization of the channel capacity	System performance for a determined error probability	A probabilistic shaping method based on reduced-exponentiation subset indexing and honeycomb-structured constellation optimization is proposed. In this case, the total number of constellation points does not fit the traditional pattern of multiples of power exponents of 2.
[101]	2020	Maximization of the channel capacity	System performance for a determined error probability	RIS-SSK and RIS-SM are designed to be used in IM-based systems.

that only in 6 cases gains are not obtained, whereas in the other 34 cases, NUCs show superiorities in comparison with QAM constellations, providing gains between 0.1 dB and 11 dB.

B. TERRESTRIAL BROADCASTING

The latest standardization efforts in terrestrial broadcasting have been DVB-NGH and ATSC 3.0. Both have made use of the GS design of constellation signals to approach channel capacity. Several references have addressed the validation of non-uniformly spaced constellations in terrestrial broadcasting in the last few years. The following paragraphs detail the contents of each work chronologically, and Table 4 presents an analysis of the most relevant works mentioned in this section. It should be highlighted that the system performance metric describes how the error rate obtained when decoding a constellation with different SNR values evolves. It is typically represented using BER/BLER/PER vs. SNR curves

In [103] and [105] Stott makes a comprehensive study of the constellation design for BICM systems focused on terrestrial applications. The author proposes a GS approach in order to design capacity-approach constellation sets. A low-complexity design method for 1D-NUC is shown, and the condensation technique is presented for low SNR values. The results show that NUCs provide significant system gains compared with conventional QAM schemes, whereas they present minimal impact on the implementation of transmitters and receivers.

Zollner et al. [104] study the optimization of high order 1D-NUCs and 2D-NUCs. These constellations present a shortcoming of only 0.036 b/s/Hz from the Shannon limit at 29 dB SNR. The authors use the interior point optimization algorithm ([106]) to design these high order constellations. This technique is both too complex and computationally expensive, and, what is more, the importance of initial conditions is not highlighted. Some parts of the post-processing steps are not included.

Barrueco et al. [107] evaluate the system performance of NUCs and RC techniques. SNR versus BER results are obtained for BER threshold 10^{-6} at the waterfall region of LDPC codes. The results show that NUCs outperform standard QAM schemes for all code rates and constellation orders. Gains up to 0.9 dB are found for the highest constellation order evaluated (64 constellation points). Regarding the RC technique, constellation orders from 4 to 64 constellation points and code rates from 5/15 to 13/15 are evaluated. The results show that if RC is used together with NUCs, system performance gains of up to 2 dB are achieved for Rayleigh iid channel.

Loghin et al. [18] revise the NUCs included in ATSC 3.0. The authors review the performance of the NUCs taking into account different channel realizations with the combination of LDPC code and bit interleaver. The results show shaping gains of more than 1.5 dB with respect to standard QAM schemes with constellation orders from 16 to 4096.

Barrueco et al. [54] provide a comprehensive study of the optimization problem, the best optimization algorithms and propose a methodology based on PSO for designing NUC constellation schemes for a wide range of SNR values. This work includes a solution for the Rayleigh iid channel with negligible capacity losses while drastically reducing computation resources and time. In terms of design time consumption, 2D constellations (16, 64, and 256) require 5, 20, and 120 minutes, respectively. For 1D constellations (1024 and 4096), 10 and 20 min are needed, respectively. BICM channel capacity and system performance results show that all the designed constellations outperform the standard QAM schemes with gains of up to 0.6351 bit/s/Hz and 1.8 dB for 4096NUC and 9/15 code rate.

The same authors propose in [75] and [76] two different condensation methodologies for massive order 2D-NUC design. The work in [76] presents two condensation methodologies. The first proposal, called condensation with optimization (CWO), is performed during the design process of the constellation. Constellation points close to each other with a Euclidean distance lower than a predefined value are merged into a single symbol. The maximum Euclidean distance between constellation points that provides negligible system performance losses is 0.1. The second solution, condensation after optimization (CAO), consists of condensing the designed constellation after the constellation is designed. This solution always provides the optimal condensation solution. However, CAO is more complex than CWO as two processing steps are followed (optimization and condensation).

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TABLE 4. Analysis of Constellation Design Methods for Terrestrial DTT Systems

Work	Year	Method	Metric	Description
[103]	2013	GS Gaussian Approximation, Maximization of the channel capacity and Condensation	Channel Capacity and System Performance	Design of NUCs via GS.
[104]	2013	Maximization of the channel capacity	Channel Capacity and System Performance	Design of high-order NUCs via GS using interior point optimization.
[18]	2016	Maximization of the channel capacity	Channel Capacity and System Performance	Analysis of the NUCs included in ATSC 3.0 for AWGN and Rayleigh *iid* channels.
[54]	2017	Maximization of the channel capacity	Channel Capacity and System Performance	GS design for BICM system models providing a comprehensive study of the optimization problem jointly with the best optimization and design algorithms for AWGN and Rayleigh channels.
[76]	2017	Condensation	Channel Capacity and System Performance	This paper presents two efficient condensation methodologies for massive order 2D-NUCs.
[55]	2016	Maximization of the channel capacity	Channel Capacity and System Performance	Optimization of NUCs via GS with RC and multi-RF techniques.

If the demapping complexity of the proposed condensed NUCs is compared to the exhaustive method ML, complexity reductions up to 93.75% are found for 2D-256NUC and 2/15 code rate.

Fuentes et al. [55] study the optimization of NUCs taking into account the RC and multi-RF transmission techniques included in ATSC 3.0. The authors propose using RC and multi-RF jointly with NUCs for high SNR values to increase the system's spectral efficiency. The multi-RF techniques considered are Channel Bonding (CB) and Time-Frequency Slicing (TFS). The rotation angle is included as an additional variable in the design of geometrical-shaped NUCs. The highest rotation gain is obtained for low-order constellations and high code rates, with a maximum gain of 1.7 dB for the QPSK 13/15 code rate. Considering the Power Imbalance (PI) of multi-RF techniques, the SNR gain obtained for a PI of 9 dB is up to 6.7 dB for the largest possible code rate and QPSK constellation.

Steiner et al. [108] compare the GS, and PS approaches applied to ATSC 3.0. The authors provide a comprehensive comparison of geometric and probabilistic shapes considering the information-theoretic achievable rates for Symbol-Metric Decoding (SMD) and Bit-Metric Decoding (BMD). The optimization problem for the geometric approach is carried out using differential evolution. In the case of probabilistic shaping, the authors use the Maxwell-Boltzmann distribution family alongside Blahut-Arimoto [109] and Cutting-Edge approaches. System performance analysis is obtained for M-ary ASK (M = 4, 8, 16, 32) and AWGN channel. The results show that PAS with BMD can close the gap of BMD to approach AWGN capacity. For GS, a gap of 0.4 dB exists for low-order modulations. However, as it is already demonstrated in [78] and [79] GS outperforms PS for high order modulations. Furthermore, the results do not consider Rayleigh fading channels.

C. SATELLITE COMMUNICATIONS

QPSK is by far the most used scheme in satellite communication systems. With the development of DVB-S2 and DVB-S2X standards, M-ary APSK constellations with uniform and non-uniform geometrical shapes have been included. Several authors have proposed M-ary APSK constellations based on GS [57], [58], [110], [112], [113] and PS [110], [111], [113], [114]. Table 5 presents an analysis of the most relevant works mentioned in this section.

Liolis et al. [110], [113] study the design of M-ary APSK constellations (M = 16, 32 and 64) for satellite applications considering two different approaches: GS and PS. For PS, the constellation points on each ring are assumed equiprobable, but the a priori symbol probability per ring is considered different. The optimization problem consists of maximizing the average mutual information of the system. The channel considered is AWGN, and phase and amplitude distortions are included. In the case of equiprobable constellation points (GS), the Gauss-Hermite quadrature rule is followed. The results show that the non-equiprobable constellations approach offers higher capacity than the equiprobable ones for relatively high SNR values.

Xiang et al. [111] improve the DVB-S2 system performance using constellation shaping and iterative demapping. The authors considered a 32-APSK constellation scheme to design the new signal set via PS. As PS requires a priori knowledge of the symbols transmitted in the design and receiver sides, the authors propose incorporating the BICM-ID system for correct signal detection. This solution provides an additional 1 dB of coding gain at a rate of three symbols over an AWGN channel at the cost of increasing the receiver complexity.

Kayhan et al. [112] use a geometrical approach to design APSK constellation schemes. The authors used the simulated annealing algorithm with a symmetry condition over the constellation points to speed up the computation for high order modulations. This algorithm optimizes the constellation points and the bit labeling jointly. 32-APSK is considered over a nonlinear satellite channel under AWGN. The system performance is analyzed with and without pre-distorters, and the results of the designed constellations are compared with the APSK modulations used in DVB-S2.

Meloni et al., [57], [58] propose the use of genetic algorithms in order to optimize APSK constellations and mapping

TABLE 5. Analysis of Constellation Design Methods for Satellite Communication Systems

Work	Year	Method	Metric	Description
[110]	2010	PS and GS maximization of the channel capacity	Channel Capacity and System Performance	Comparative study of APSK via GS and PS.
[111]	2011	PS maximization of the channel capacity	Channel Capacity and System Performance	PS with iterative demapping for DVB-S2.
[112]	2012	GS maximization of the channel capacity	Channel Capacity and System Performance	APSK design via GS for DVB-S2.
[58]	2015	GS maximization of the channel capacity	Minimum Square Error	APSK design via PS using genetic algorithm.

using geometrical shaping. The objective function is the Minimum Square Error (MSE) between the symbol generated by the memoryless source and the one estimated at the receiver. The optimization problem aims to minimize the MSE by designing new mapping techniques starting from the conventional Consultative Committee for Space Data Systems (CCSDS) mapping and constellation points for different APSK configurations. The optimization results demonstrate that the use of modified mappings and unequally spaced symbols on the same circles improves conventional APSK in terms of MSE.

D. APPLICATION OF PS TO FIBER OPTICAL SYSTEMS

Constellation design techniques in fiber optical systems differ from the ones considered in terrestrial and satellite communications. In fiber optical systems, PS is considered as the input probabilities of the bits transmitted are not the same [115]–[117]. Meanwhile, all the works refer to PS; each reference design the constellation scheme for a determined objective function. Authors in [118] aim at maximizing the channel capacity. In [119] the objective is to minimize the energy of the transmitted signal via PS and the Viterbi algorithm. The authors in [120] propose to optimize the probability mass functions, and in reference [121] error-free decoding is imposed as the design objective.

E. USE CASE SUMMARY

Examining some of the most relevant use cases in wireless communication systems is helpful to determine which type of constellation design is more relevant in each use case. In particular, broadband systems present a chronological evolution since, in previous solutions (i.e., 4G/LTE), only QPSK and QAM schemes were considered. However, several proposals were presented in order to use GS NUCs in 5G, and, although they were not approved, it is expected to be proposed again in 6G. Concerning terrestrial broadcast, the evolution that was not successful in 5G was achieved in DVB-NGH and ATSC 3.0. In fact, both standards are based on GS NUCs design of constellation. On the other hand, satellite communications do not use QAM schemes, and they are traditionally based on QPSK constellations. With the development of DVB-S2 and DVB-S2X standards, uniform and non-uniform designs are combined using M-ary APSK constellations. Finally, fiber optical systems follow a completely different trend since they are mostly based on PS constellations.

V. LESSONS LEARNED AND FUTURE RESEARCH AVENUES

Based on the survey previously presented, this section studies the most relevant features that next-generation constellation approaches should accomplish. Firstly, the most relevant properties are detailed, and afterward, the envisaged requirements for 6G systems are mapped to the constellation designs.

A. DESIRABLE PROPERTIES

The success of a new constellation design depends on a broad set of requirements. If these are accomplished, the communication system under evaluation will improve its system performance. The improvement will also depend on the other system blocks. At the transmitter side, for instance, the process in which the bits are grouped into different constellation symbols plays an essential role in the efficiency of the system [44]. In this subsection, the constellation properties that any successful communication system must fulfill are listed. Eventually, Table 6 presents a summary of the most relevant works in the literature, and the correlation with the desirable properties is checked.

1) Consistency

Complete consistency among the shaping method and the distribution of the bits of the system must be guaranteed. Taking into account that the information sources can be divided into equal (DTT systems [122]) and unequal bit probability distribution (fiber optics [123], [120]), we recommend that the constellation shape fits the bit probability distribution. Moreover, the channel capacity of the system depends on the probability of the bit transmitted and the position of the constellation symbols (the constellation itself) [85]. Therefore, a direct connection between the information bits of the source and the shaping design must be addressed by the design procedure. A clear example is the case of satellite communications, where the power amplifiers cannot deal with big values of PAPR values [124]–[126], the constellations should follow the PSK or APSK scheme.

2) Channel Capacity

In order to provide highly efficient communication systems, especially in terms of data rate, we strongly recommend designing the massive order constellations close to Shannon's limit [127]. Although existing standard constellations (e.g.,

TABLE 6. Analysis of Desirable Properties of a Constellation Scheme

Work	Description	Consistency	Capacity	Performance	Demapping	Flexibility	Independence
5G Systems							
[60]	NUCs exploiting the 60 GHz band	X		X		X	X
[52]	NUCs for future releases of 5G	X		X		X	X
DTT Wireless Systems							
[107]	Design of NUCs via GS	X	X		X	X	X
[54]	GS design for BICM system	X	X	X	X	X	X
[55]	NUCs via GS with RC and multi-RF	X		X		X	X
Satellite Communication Systems							
[111]	Study of APSK via GS and PS	X					X
[118]	APSK design via GS for DVB-S2	X		X			X
[58]	APSK design via PS using genetic algorithm	X					X

QPSK, BPSK) are close to Shannon's limit on the low SNR region [128], [129], there is still a big gap to reach the capacity limit for medium and high SNR. The design method should be flexible enough to create capacity-approaching massive order constellations in a short period (directly associated with the computational complexity), i.e., above 1024 constellation points in minutes or hours [75], [76]. We propose the use of new technologies such as Machine Learning [130]–[134] in order to balance complexity and simulation time requirements of the constellation generation and the detection stage.

3) System Performance

We consider a critical part of the constellation design to provide good system performance under different types of noise, and fading channels [73]. In fact, in many applications, the communication system must remain stable and operational under different reception conditions (noise and propagation channels) and so must remain the constellation performance [135]–[141]. AWGN noise is always present alongside several fading conditions due to the localization of the transmitter and receiver antennas. Rayleigh distribution is often considered for the evaluation of DTT communication systems [142], [143]. In the case of satellite communications, apart from AWGN, phase noise should also be considered and the constellation should be strong against both noise types [144], [145].

4) Simple Demapping Architecture

From the receiver side, there are also implications for the constellation design. We suggest designing the constellation as simple as possible to enable a simple demapping process in order to ensure reliability and to keep latency within acceptable limits [146], [147], [148]. We have based this recommendation on some common and simple receiver architectures, such as QPSK (formed of 2 PAM schemes) [149], or the M-ary APSK [150], which are commonly used in satellite applications.

5) Flexibility

The flexibility of a particular constellation is especially important in the case of existing several communication systems with similar characteristics, e.g. DTT [18] and satellite applications [57], [151]. Therefore, we recommend the flexible design of constellations to adapt them to other communication systems with similar characteristics. A good example of flexibility are the GS NUCs are used in DVB-NGH [152], which have been used as a reference to construct the ones from ATSC 3.0 [18]. The same occurs with DVB-S2 [57] and DVB-S2X [153]. The first one includes the so-called APSK schemes in order to cope with the PAPR issue. In DVB-S2X, these schemes are reused to increase the constellation orders and modify some scheme values, such as the radius and the distance between adjacent symbols.

6) Independence between Building Blocks

In order to enhance the granularity and the flexibility of the communication systems, different modulation and coding options are enabled. Generally, TCM or CM system models directly associate the constellation to a defined error-correcting technique. Nevertheless, if the constellation is independent of the error-correcting block (and other blocks), the possibilities increase, and in consequence, there will be a wider range of configurations for different scenarios [52]. Therefore, we propose to follow the BICM system model philosophy, where independence between coding and modulation blocks is guaranteed [154].

B. EVOLUTION OF CONSTELLATION SCHEMES FOR 6G

According to recently published works [155]–[157], 6G technology will be able to extend notably 5G network capabilities. In turn, among other things, the design of the constellations, as a critical block in any communication system, will be directly related to these requirements. Table 7 summarizes how the 6G requirements are more challenging than in 5G and highlights the critical ones for the constellation design process.

First, it is expected that the parameters related to the capacity of the systems, such as peak data rate, experienced data rate, and spectrum efficiency, will considerably increase. Undoubtedly, one of the critical aspects to achieve this is the design of high order constellations that allow obtaining very large spectral efficiencies (i.e., $\geq$ 4k points). However, the major disadvantage of these modulations places at the demapping stage. Consequently, the design of the appropriate

TABLE 7. Requirements of future 6G communications and impact of constellation schemes

Parameter	5G	6G	Are constellations critical?
Peak Data Rate	10-20 Gb/s	$\geq$ 1 Tb/s	Yes
Experienced Data Rate	100 Mb/s	1 Gb/s	Yes
Spectrum Efficiency	Up to 30 bps/Hz	Up to 100 bps/Hz	Yes
Mobility	500 km/h	1000 km/h	No
Latency	1 ms	10-100 μs	Yes
Device Density	10^6 Device/km^2	10^7 Device/km^2	Yes
Frequency Band	Up to 90 GHz	Up to 10 THz	No

constellations is essential and the optimal demapping process.

One of the parameters that has raised a lot of criticism in 5G, the latency, is also expected to improve considerably. In 5G URLLC systems, for instance, latency is limited to about one ms, while in 6G, it is expected to be able to achieve values close to 10 μs. However, the very low latency values imply that the elements that participate in the communication chain must imply very low individual latencies, specifically several orders of magnitude below the total latency. Therefore, the future 6G constellations challenge, especially in the demappers, lies in the design of low complexity constellations/demappers that do not imply an increase in system latency.

Finally, another network characteristic where a large increase is expected and affects the design of constellations is the device density. In particular, it is expected to grow from 10^6 to 10^7 device/km^2. In order to be able to cope with that demand, very high values of spectral efficiency and capacity are required. What is more, techniques such as MIMO or new generation multiplexing schemes might not be enough, and thus, the design of high order constellations is once again critical.

VI. CONCLUSION AND FUTURE RESEARCH

Concepts such as 5G/6G communications, IoT systems, or ultra-high-quality multimedia systems might be regarded as the future paradigm, but in the upcoming years, society will undoubtedly face a digital evolution of these technologies. In this context, the modulation of such a large amount of information data poses a daunting challenge for communication system designers.

In this survey, a detailed clarification of the different constellation schemes is shown to facilitate a better understanding of constellation design techniques. State-of-the-art works referring to constellation design are well covered through a deep study of the existing techniques via theoretical studies and real-world use cases. This survey focuses on the main wireless communication systems that implement and consider the advances in modulation theory, e.g., satellite communications, DTT, and mobile communication systems. Moreover, the section of desirable properties contributes to the efficient design of such system blocks, proposing the key features that the modulation design should fulfill.

Although an important investigation effort has been carried out to date, in order to enhance the performance of constellation designs, there are still challenges that the researchers must face up to be prepared for the future of digital communications. The authors of this paper propose research threads that may be key for successfully deploying future communication systems. First, the design of massive order constellations for the high SNR range should be in the scope. This sort of constellation is of particular importance to facilitate high data rate services. However, the existing massive order constellations are far away from Shannon's limit for high SNR values. Moreover, new modulation techniques based on another sort of orthonormal basis functions such as the proposed in [158]–[162] should be investigated. Following with the design of constellation schemes and focusing on IoT and industrial applications, there are two research fields of interest. The first one is about the combination of GS and PS design methods. There will be sensors with an equal and unequal bit probability distribution in an IoT environment with a huge number of sensors with different properties. Therefore, constellations designed using a joint combination of GS and PS may provide better system performance than the single method design. The second one implies sensors with a predefined pattern of bits. The transmitter could send a reduced number of constellation points via pattern coding in such cases. Another thread of research is the intelligence of the communication system. The advent of Machine Learning (ML) techniques applied in standard hardware devices makes it possible to create intelligent demappers that adapt to several reception characteristics, e.g., propagation scenario, coding and modulation, or return channel.

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