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PHASE DIVISION MULTIPLEXING BASED ON BPSK

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ABSTRACT

Multiplexing enables multiple information streams to be transmitted over a shared communication medium and is traditionally achieved through Frequency Division Multiplexing (FDM), Time Division Multiplexing (TDM), or hybrid combinations of these techniques. All of these methods allocate communication resources by partitioning frequency or time. In contrast, this study investigates whether the phase parameter of a passband signal can also be utilized as a multiplexing dimension. To this end, a new BPSK-based physical-layer method, termed Phase Division Multiplexing (PDM), is introduced. The key idea behind PDM is to divide the phase domain into multiple non-overlapping regions, enabling several phase channels to operate in parallel over a single carrier frequency without increasing bandwidth or symbol duration.

The proposed structure—including the dual- and quad-channel PDM configurations—was implemented and simulated using MATLAB/Simulink. Constellation analyses and BER evaluations demonstrate that the signal phase can be effectively used as an additional multiplexing dimension and that PDM can successfully support simultaneous multi-channel transmission at the same carrier frequency. These results indicate that PDM may be suitable for low-rate or parallel communication scenarios where deterministic channel assignment, time independence, and bandwidth neutrality are required, and that it can serve as an additional multiplexing mechanism in such applications.

Keywords: Phase division multiplexing, PDM, BPSK, Multiplexing, Multichannel communication.

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1 INTRODUCTION

Technology is constantly evolving and, like in many other fields, continuously drives advancements in wireless communications. Socio-technical developments and emerging applications steadily increase the demand for communication resources, placing additional pressure on existing systems. This growing demand motivates researchers to explore new communication domains and to develop techniques that enable more efficient utilization of the available resources [1].

A communication system can be used more efficiently when multiple users are allowed to share the same communication medium simultaneously. Multiplexing is a technique used to enable such shared usage within a given communication resource. In general, the capacity of a communication link is much larger than the capacity required for two individual users to communicate [1], [2]. Allocating the entire link to a single user would therefore lead to resource underutilization and increased cost. For this reason, the capacity of the link is divided into smaller portions, forming independent communication channels. These channels are then assigned to different users, allowing multiple simultaneous communication sessions over the same physical medium [1], [3].

In conventional communication systems, multiplexing techniques typically rely on distributing signals across the frequency or time domains, as in Frequency Division Multiplexing (FDM), Orthogonal Frequency Division Multiplexing (OFDM), and Time Division Multiplexing (TDM), or operate in the code domain, as in Code Division Multiplexing (CDM). Although these approaches are well established and highly effective, they do not exploit the phase domain as an independent physical resource for multiplexing. The fundamental motivation of this study is the observation that electromagnetic signals inherently possess a phase parameter, which—despite being extensively used for modulation—has not been employed as a physical-domain multiplexing dimension. This work aims to explore this unused potential and to introduce a novel multiplexing technique, termed Phase Division Multiplexing (PDM), that enables simultaneous transmission of multiple data channels by utilizing predefined phase offsets of the same carrier signal.

The remainder of this paper is organized as follows. Section 2 provides a brief overview of existing multiplexing techniques and presents the conceptual foundation of the proposed phase-based approach. Section 3 describes the simulation setup and presents the performance evaluation of the PDM scheme. Section 4 discusses the obtained results and summarizes the main findings.

2 MULTIPLEXING

Any transmission line has a maximum bandwidth available within a given time interval. When an entire communication link is dedicated to only two endpoints, a substantial portion of its capacity remains unused, resulting in reduced system efficiency. To avoid this inefficiency, multiplexing is employed. Multiplexing enables multiple users to share an existing communication link, thereby reducing communication costs and improving resource utilization. Through multiplexing, multiple information streams can be transmitted over a single communication link, either simultaneously or in an alternating manner. In this approach, the link capacity is partitioned into smaller subchannels, each allocated to a different user.

Multiplexing in wireless communication is primarily achieved through FDM, TDM, or hybrid schemes that combine aspects of both techniques [4]. TDM divides the time domain by assigning the communication link to different users at different time intervals, whereas FDM divides the available frequency band into distinct subbands for multiple users. Both are considered physical-domain division techniques. In addition, OFDM—an extension of FDM using orthogonal subcarriers—and CDM, a logical-domain multiplexing technique, are also employed in modern systems [2], [3].

FDM [5] is the earliest multiplexing technique and it is presently used in many areas such as radio, television broadcast, mobile phones [4]. The bandwidth of the communication path is segmented into a number of different frequency ranges in order to facilitate the formation of communication channels using this method. These created channels are allocated for different users during whole time. It is generally used for multiplexing analogue signals [6]. It is a quite frequently used type of multiplexing. As shown in Figure 1, a portion of the bandwidth of the existing communication path is allocated to each communication channel and this divided bandwidth is used in the whole time. To prevent interchannel interference the guard bands are used [1]–[6].



Figure 1. Frequency division multiplexing [1]

In TDM [5], communication channels are obtained by dividing the communication path into time slots. These created channels allow different users to access and use the same communication path at different times. This means that the more channels are created, the later the channel usage turn will come. It is generally used for digital communication. This technique is based on the allocation of existing communication channels to specific users at specific times [2], [3]. The TDM structure is shown in Figure 2.

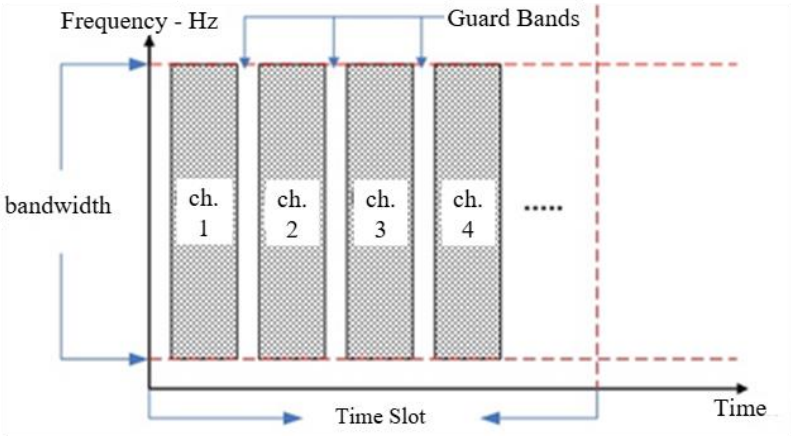


Figure 2. Time division multiplexing [1]

OFDM [7] is a multi-carrier transmission technique that divides the existing frequency spectrum into a series of orthogonal sub-carriers. Essentially, the basic feature that separates the OFDM technique which is a derivative of FDM from other multiplexing types, is that the subcarriers are orthogonal to each other. The orthogonal arrangement of the sub-carriers prevents both inter-carrier interference formation and provides a more efficient use of the transmission band [8], [9]. Today it is extensively used in wireless and mobile communications [8], [10]–[13]. Figure 3 shows how OFDM uses the band more efficiently than FDM.

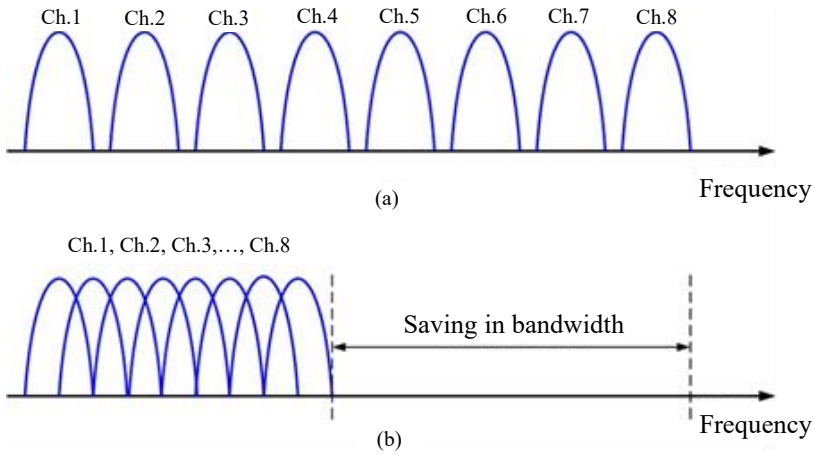


Figure 3. (a) FDM (b) OFDM [14]

CDM [15] is a logical division technique, not a physical division operation such as FDM, TDM. Figure 4 shows the CDM, FDM and TDM structures. In this multiplexing technique, users can use the entire frequency bandwidth of the transmission path during whole time. Division operation is done by assigning each user a unique code and users having code can get the information from the communication environment. All the data in the communication environment is coded and the users receive their own information according to the key code they have. That is, the information signal to be transmitted is encoded and converted into another signal, and all that signals are transmitted from the same medium. With this method, the encoded data is transmitted with high security. Also the user who has the code to decode this encoded signal is able to access the data. This technique has been used especially in third generation (3G) mobile technologies [16]–[19].

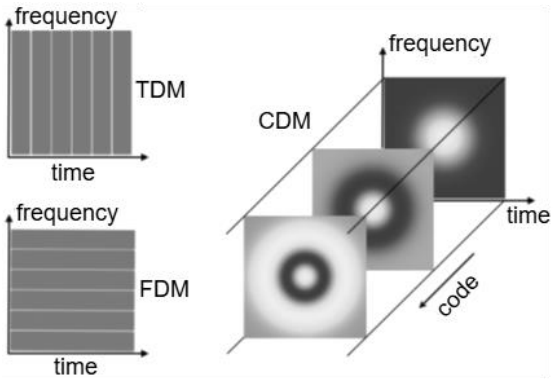


Figure 4. TDM, FDM and CDM [20]

CDM, unlike other multiplexing methods, operates as a logical multiplexing technique based on code sequences, whereas FDM and OFDM perform multiplexing in the frequency domain and TDM in the time domain. As summarized above, conventional schemes distinctly rely on frequency and time as the primary physical resources for separating multiple users or data streams. However, communication signals inherently possess another fundamental physical parameter, as a passband signal can generally be expressed as:

$$s(t) = A\cos(2\pi ft + \theta) \tag{1}$$

where A, f, t, and θ represent amplitude, frequency, time, and phase, respectively. These parameters are routinely used for modulation—such as in ASK, QAM, FSK, and PSK—while frequency and time are also extensively used for multiplexing. This naturally raises an important question: if amplitude, frequency, and phase are all fundamental components of a communication signal, and if frequency and time are already used for multiplexing, why has the phase parameter not been employed as a multiplexing dimension as well?

Motivated by this question, the present study investigates how the phase parameter of a passband communication signal can be structured and utilized as a physical multiplexing domain, and introduces a new physical-layer technique termed Phase Division Multiplexing (PDM). In the proposed approach, multiple physical phase channels are created by assigning distinct phase offsets of the same carrier signal. These phase-separated branches (phase channels) act as independent physical transmission paths, enabling simultaneous data transfer without requiring separate frequency bands or time slots. The following subsection provides a detailed description of the proposed PDM method and its operational principles.

2.1 Phase Division Multiplexing based on BPSK

In the proposed PDM structure, multiplexing is achieved by separating the phase domain into multiple phase channels. Since the technique is fundamentally based on assigning BPSK-like symbol pairs to distinct phase offsets, it is useful to begin by briefly reviewing the structure of conventional PSK [21], [22] modulation schemes. For this purpose, commonly used BPSK, QPSK, and 8PSK constellations are illustrated in Figure 5 to build the conceptual background for phase-domain channel formation modulation constellation diagrams for better understanding;

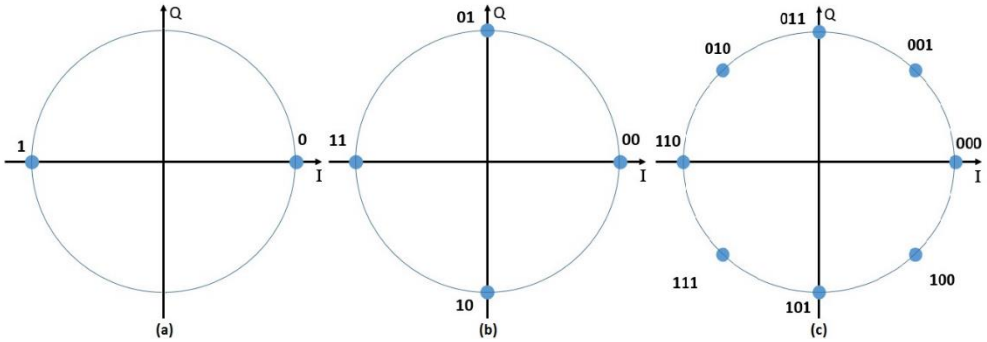


Figure 5. BPSK, QPSK and 8PSK constellation diagrams

Figure 5 shows the constellation diagrams of BPSK, QPSK, and 8PSK, respectively. In BPSK, one bit of information is mapped to one of two symbols that differ by 180°, corresponding to logical “1” and “0”. In QPSK, two bits are mapped to four symbols, each separated by 90°, whereas in 8PSK, three bits are represented by eight uniformly spaced phases. In all PSK schemes, the receiver determines the transmitted data by identifying the phase of the received symbol within the constellation [23]. These modulation structures demonstrate how discrete phase values can represent digital information.

Building on this principle, PDM forms a physical multiplexing structure by distributing BPSK symbol pairs across different phase offsets of the same carrier. Instead of using a single pair of antipodal phases (0° / 180°) as in conventional BPSK, PDM assigns multiple pairs of antipodal phases (e.g., 0°/180°, 90°/270°, 45°/225°, etc.) to create multiple phase channels within the same phase plane. Each phase channel carries its own BPSK symbol, enabling several users—or several data streams—to be transmitted simultaneously over the same carrier frequency. This concept is illustrated in Figure 6, which shows the placement of individual phase channels on the I–Q plane.

As seen in the figure, each phase channel consists of a pair of antipodal symbol points representing the logical values “1” and “0”. These symbol points correspond to two BPSK symbols separated by 180°, ensuring that each channel can independently convey one bit of information within a symbol period. The mathematical representation of the symbol signals associated with each phase channel can be expressed as follows.

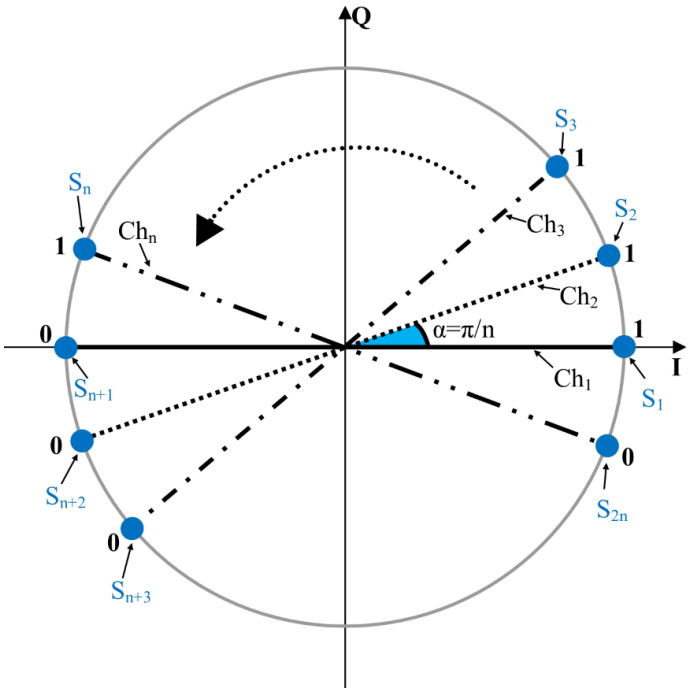


Figure 6. Phase channel placement

Let

- *A:* signal amplitude
- *n:* number of phase channels
- *α:* phase separation between adjacent channels
- $i = 1,2,\ldots, 2n$ symbol index

- θ_i: phase offset of the i-th symbol
- f_c: carrier frequency
- T_s: symbol duration
- $S_i(t)$: symbol waveform

The phase offsets are given by

$$\alpha = \frac{\pi}{n}; \qquad \theta_i = (i-1)\alpha \tag{2}$$

Thus, each symbol waveform in the passband can be written as;

$$S_i(t) = A\cos(2\pi f_c t + \theta_i) \tag{3}$$

This signal can be expressed using the following orthonormal basis functions:

$$\emptyset_1(t) = \sqrt{\frac{2}{T_s}}\cos(2\pi f_c t), \qquad \emptyset_2(t) = \sqrt{\frac{2}{T_s}}\sin(2\pi f_c t) \quad 0 \le t \le T_s \tag{4}$$

The in-phase and quadrature components of the *i*-th symbol are;

$$I_i = A\sqrt{\frac{T_s}{2}}\cos\theta_i \qquad\qquad Q_i = -A\sqrt{\frac{T_s}{2}}\sin\theta_i \tag{5}$$

Accordingly, the symbol signal can be written in vector form as;

$$S_i(t) = I_i\emptyset_1(t) + Q_i\emptyset_2(t) \tag{6}$$

This formulation provides the complete symbol set for any chosen number of phase channels *n*, and forms the basis of the PDM symbol structure.

In the proposed PDM architecture, all phase channels operate at the same carrier frequency, and each channel transmits its corresponding BPSK symbol simultaneously during the same symbol interval. This means that, unlike conventional PSK modulation—where only a single symbol is transmitted per symbol period—PDM enables the transmission of as many simultaneous symbols as the number of available phase channels.

Since each phase channel occupies a distinct phase offset but uses the same frequency and the same symbol duration, the symbol waveforms overlap in space and time, leading to a composite received signal. This composite (superposed) waveform is the vector sum of all

simultaneously transmitted channel symbols. In other words, a PDM symbol represents the superposition of multiple BPSK symbols transmitted through different phase channels.

Let the transmitter activate *n* phase channels in a given symbol period. The received signal can then be written as a linear combination of the basis signals corresponding to these channels. This vectorial superposition forms a single PDM symbol, which encodes an n-bit data group—one bit from each active phase channel. Hence, the logical data associated with each channel is embedded in a distinct phase component of the composite signal. This superposed symbol can be write as:

$$S_{PDM}(t) = \sum_{j \in B} S_j(t) \tag{7}$$

where *B* denotes the set of active phase channels and $S_j(t)$ is the j-th symbol waveform defined in Equation (3).

During demodulation, the receiver aims to separate and recover the individual bits carried by each phase channel. Since each channel corresponds to a unique phase offset, the receiver isolates the projection of the composite signal onto the basis associated with that channel. In this manner, the bit carried by the first phase channel "k_1" has the highest significance within the resulting data group, while the remaining bits "k_2 … k_n" follow the predefined channel order. Each user—assigned to a specific phase channel—retrieves its own bit by extracting the decision result located at its corresponding position within the received data group [24].

Another important aspect of the PDM structure concerns the status of inactive channels. Unlike PSK and other modulation schemes, PDM incorporates a third state, denoted as "–", indicating that a particular phase channel does not transmit a symbol during that symbol interval. Thus, the input alphabet of each channel becomes: {1, 0, -} which corresponds to transmitting "1", transmitting "0", or leaving the channel inactive. For an n-channel PDM system, this results in a total of 3^n possible combinations of symbol states. Therefore, the PDM modulator must be capable of generating and processing 3^n distinct composite symbol configurations arising from the superposition of active and inactive phase channels. The demodulation process can be expressed as follows:

$$r(t) = S_{PDM}(t) + n(t) \tag{8}$$

where S_{PDM} is the superposed PDM symbol defined in Equation (7) and $n(t)$ is the noise component added by the AWGN channel.

The receiver mixes the noisy passband signal with the orthonormal carrier functions to extract the in-phase and quadrature components:

$$r_I(t) = r(t)\cos 2\pi f_c t, \qquad r_Q(t) = -r(t)\sin 2\pi f_c t \tag{9}$$

The baseband components are integrated over one symbol duration:

$$R_I = \int_0^{T_s} r_I(t)\, dt, \qquad R_Q = \int_0^{T_s} r_Q(t)\, dt \tag{10}$$

These values form the received vector:

$$R = [R_I, R_Q] \tag{11}$$

Let

$$C_m = [I_m, Q_m], \;\; m = 1, \ldots, 3^n \tag{12}$$

denote the reference constellation points precomputed during initialization.

Symbol detection is performed using the minimum-distance rule:

$$\hat{m} = \underset{m}{argmin} \|R - C_m\| \tag{13}$$

Finally, the detected bit group is obtained as:

$$(\hat{k}_1, \hat{k}_2, .., \hat{k}_n) = SymbolToBits(\hat{m}) \tag{14}$$

For clarity, the following subsections analyze dual-channel and quad-channel PDM configurations, demonstrating how phase channels are allocated and how the resulting composite (superposed) PDM symbol emerges from their superposition.

Dual Channel PDM Model: Dual-channel PDM represents the simplest configuration of the proposed phase-domain multiplexing technique.

In this structure, the 360° phase plane is partitioned symmetrically to form two phase channels. Each channel is assigned a pair of antipodal phase values separated by 180°, enabling the transmission of one BPSK symbol per channel within each symbol period. For the dual-channel case, the selected phase values are (0°, 180°) for Channel-1 and (90°, 270°) for Channel-2, as illustrated in Figure 7.

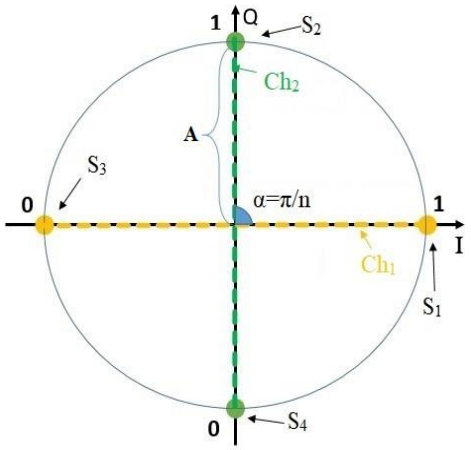


Figure 7. Symbol and phase allocation for Dual Channel PDM

Using the symbol definitions obtained from Equations (2) and (3), the four channel-specific symbols—denoted as S_1, S_3 for Channel-1 and S_2, S_4 for Channel-2—are shown in Figure 7. Here, S_1 and S_3 correspond to the logical values "1" and "0" of Channel-1, while S_2 and S_4 represent the same for Channel-2.

During transmission, both phase channels operate at the same carrier frequency and transmit their symbols simultaneously. As a result, the waveform observed at the receiver is the vector sum of the active channel symbols, forming the superposed symbol (S_{PDM}) of the dual-channel PDM system. This superposition produces $3^2=9$ possible output states, corresponding to all input combinations formed from the set {1, 0, −}. Table 1 lists these composite (superposed) symbols along with their vector representation, amplitude, and phase values. The inactive state "–" indicates that the corresponding channel does not transmit a symbol during that symbol interval.

Table 1. Composite (superposed) symbol states for Dual Channel PDM

Transmitted Data	**Transmitted Signal**		**Received Signal**		
k_1 from Ch1 k_2 from Ch2	Ch_1 Symbol	Ch_2 Symbol	Composite PDM Symbol (S_{PDM})	Amplitude (V)	Phase
$k_1 = –$, $k_2 = –$	0	0	0 + 0	0	0°
$k_1 = –$, $k_2 = 0$	0	S_4	0 + S_4	1	270°
$k_1 = –$, $k_2 = 1$	0	S_2	0 + S_2	1	90°
$k_1 = 0$, $k_2 = –$	S_3	0	S_3 + 0	1	180°
$k_1 = 1$, $k_2 = –$	S_1	0	S_1 + 0	1	0°
$k_1 = 0$, $k_2 = 0$	S_3	S_4	S_3 + S_4	1.4142	225°
$k_1 = 0$, $k_2 = 1$	S_3	S_2	S_3 + S_2	1.4142	135°
$k_1 = 1$, $k_2 = 0$	S_1	S_4	S_1 + S_4	1.4142	315°
$k_1 = 1$, $k_2 = 1$	S_1	S_2	S_1 + S_2	1.4142	45°

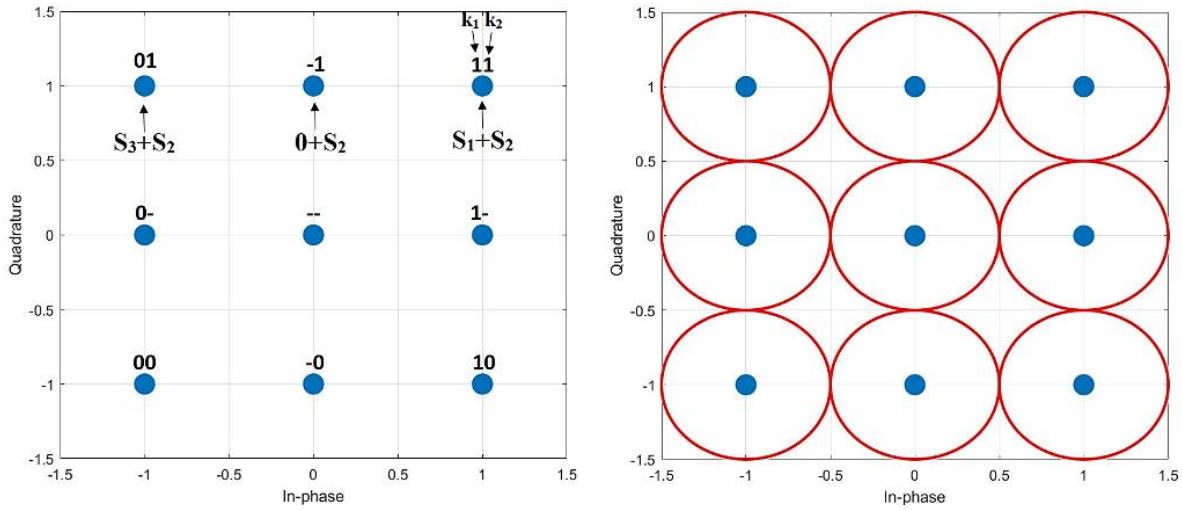


Figure 8 . (a) Constellation diagram of Dual Channel PDM (b) receiver tolerance ranges

Figure 8(a) shows the resulting constellation diagram for the dual-channel PDM system, where each blue point corresponds to a composite PDM symbol (S_{PDM}). Each composite symbol encodes a two-bit data group (k_1k_2), where the first bit belongs to Channel-1 (k_1) and the second bit belongs to Channel-2 (k_2). During demodulation, the receiver determines the region in which the received vector lies and extracts the bits of each channel accordingly. The tolerance regions shown in Figure 8(b) are used to make reliable symbol decisions in the presence of noise.

This dual-channel configuration demonstrates the fundamental operation of PDM: by assigning distinct phase offsets to each channel and summing their simultaneously transmitted BPSK symbols, multiple bits can be conveyed within a single symbol period over a single carrier frequency.

Quad Channel PDM Model: The Quad-channel configuration represents the generalization of the PDM principle to four independent phase channels. In this structure, the 360° phase plane is divided into eight equal angular intervals, and each channel is assigned a pair of antipodal phase values separated by 180°. This provides one BPSK-like symbol per channel, resulting in four simultaneously transmitted symbols during every symbol period.

For the quad-channel case, the selected phase offsets are typically chosen as shown in Figure 9:

- Channel-1: 0° and 180°
- Channel-2: 45° and 225°
- Channel-3: 90° and 270°
- Channel-4: 135° and 315°

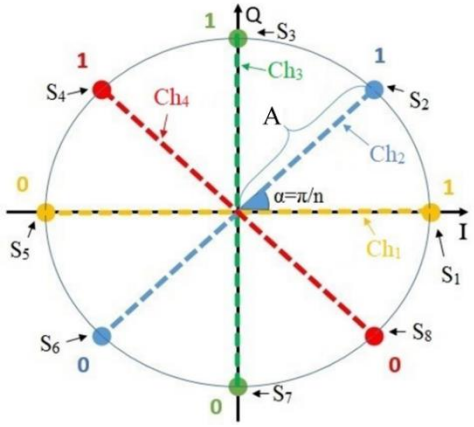


Figure 9. Symbol and phase allocation for Quad Channel PDM

Using the symbol definitions obtained from the PDM symbol Equations (2) and (3), each channel produces one of two antipodal symbols—denoted as (S_1, S_5), (S_2, S_6), (S_3, S_7), and (S_4, S_8)—corresponding to the transmitted bit ("1", "0", or the inactive "–" state). These eight symbols occupy distinct positions on the I–Q plane.

Since all channels operate at the same carrier frequency and transmit their symbols simultaneously, the waveform observed at the receiver is the superposed PDM symbol, obtained as the vector sum of the four channel symbols. Unlike conventional PSK, which produces a single symbol per symbol period, quad-channel PDM produces one composite symbol derived from up to four active phase channels. Because each channel can independently take the values {1, 0, −}, the total number of possible input states is 3^4=81. Each of these 81 combinations corresponds to a unique superposed symbol with distinct amplitude–phase characteristics.

Table 2. Per-channel symbol mapping for Quad Channel PDM

Transmitted Data	**Ch_1 Symbol**	**Ch_2 Symbol**	**Ch_3 Symbol**	**Ch_4 Symbol**
1	S_1	S_2	S_3	S_4
0	S_5	S_6	S_7	S_8
-	0	0	0	0

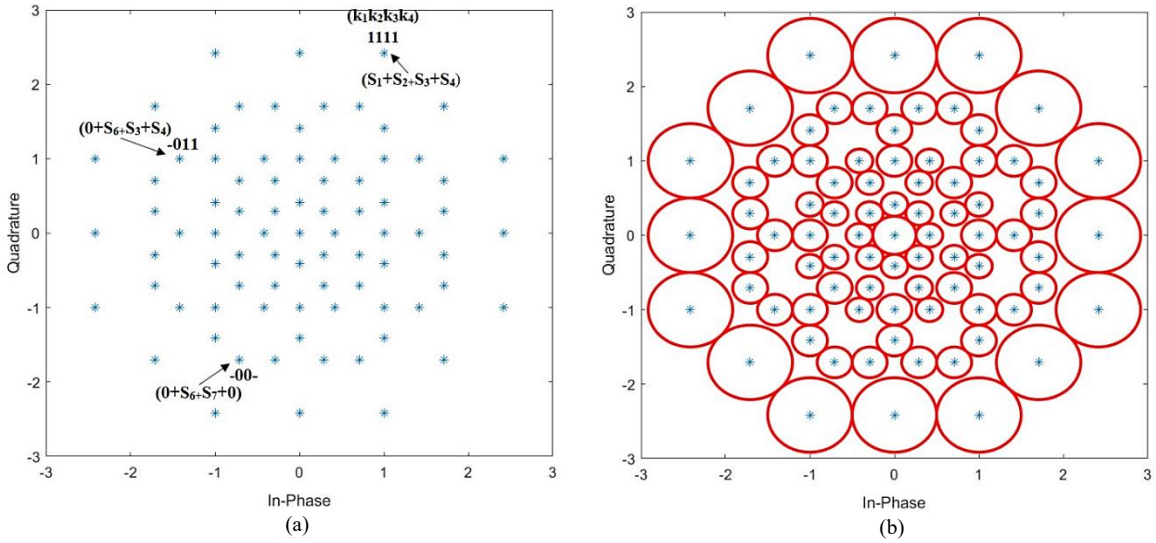


Figure 10. (a)Constellation diagram of Quad Channel PDM (b) tolerance ranges for the receiver

Table 2 summarizes the mapping between input states and their corresponding per-channel symbols. Figure 10(a) illustrates the resulting constellation diagram for the quad-channel PDM system. Compared with the dual-channel case, the constellation becomes denser and exhibits multiple amplitude levels due to the vectorial superposition of four phase-offset symbols. Each composite symbol represents a four-bit data group ($k_1k_2k_3k_4$), where the bit positions correspond to Channels 1 through 4. For example, for the input state

$$(k_1k_2k_3k_4) = (1{-}0{-})$$

The resulting superposed symbol is;

$$S_{PDM} = S_1 + S_7$$

Figure 10(b) illustrates the decision regions used by the receiver. During demodulation, the received signal is mapped to the nearest region in the PDM constellation, and the corresponding ($k_1k_2k_3k_4$) values are extracted in accordance with the predefined phase-channel ordering.

This four-channel structure demonstrates the scalability of PDM: by increasing the number of phase channels, more bits can be transmitted per symbol without requiring additional bandwidth, frequency slots, or time slots.

3 SIMULATIONS AND RESULTS

In this study, all PDM modulators and demodulators were implemented and tested in the MATLAB/Simulink environment [25] to evaluate the performance of the proposed technique. The complete PDM transceiver model was constructed using Simulink blocks together with custom functions developed specifically for the PDM structure. The performance of the system was assessed through simulations conducted over an Additive White Gaussian Noise (AWGN) channel, and the bit-error-rate (BER) behavior was examined for dual-channel and quad-channel PDM configurations.

3.1 Simulation Initialization and Parameters

In the simulation setup, alongside the standard Simulink blocks, several custom functions were developed to represent the specific structure of the proposed PDM technique. These functions are executed only once at the beginning of the simulation through the model's InitFcn (Initialization Function). When the simulation starts, the InitFcn computes all initialization routines and transfers the resulting variables to the model workspace, making them available to all modulator, AWGN channel, and demodulator components. The variables and functions defined in the InitFcn are summarized below:

- ch_number, A, f: Define the number of channels, signal amplitude, and carrier frequency used in the model. For dual-channel simulation, ch_number = 2.
- modulation_type: Specifies the modulation scheme as 'BPSK' or 'QPSK'. For PDM-BPSK simulations, modulation_type = 'BPSK'.
- avgPower = mean(abs(sig_mat).^2): Calculates the average power of all generated symbol signals. This value depends on the amplitude and the number of phase channels and is used by the AWGN channel block to represent the input signal power.
- comb = comb_mat(ch_number, modulation_type): This function generates all possible input-state combinations according to the number of phase channels and the selected modulation type. The resulting combination matrix is stored in the variable comb and made available to the Simulink model through the workspace.
- reff = ref_point(comb, A, f, ch_number, modulation_type): Computes the reference constellation points associated with each input-state combination by using the

amplitude, carrier frequency, number of channels, and modulation type. The resulting reference vectors (reff) are used for constellation visualization and decision boundaries.

- sig_mat = calculate_sig_mat(comb, A, f, ch_number, modulation_type): Generates the complex constellation points corresponding to all possible input-state combinations. The resulting vector sig_mat contains the superposed PDM symbols (S_{PDM}) and is also used to compute the average input signal power required by the AWGN channel.
- [tol_centers, tol_radius] = cal_tolere(ch_number, sig_mat, modulation_type): Determines the center coordinates and the enclosing radii of the tolerance regions by analyzing the geometric distribution of the superposed symbol points. The variables tol_centers and tol_radius represent, respectively, the constellation centers and the maximum tolerance radius of each cluster, and are used by the receiver to define symbol decision boundaries.

This initialization structure provides a flexible and reusable simulation environment for testing different PDM configurations without repetitive pre-processing.

3.2 Dual-Channel PDM Simulation Model

The simulation structure of the dual-channel PDM system is illustrated in Figure 11. The main functional blocks of the transmitter, channel, and receiver are shown, and their roles within the PDM transceiver are summarized in the block descriptions that follow.

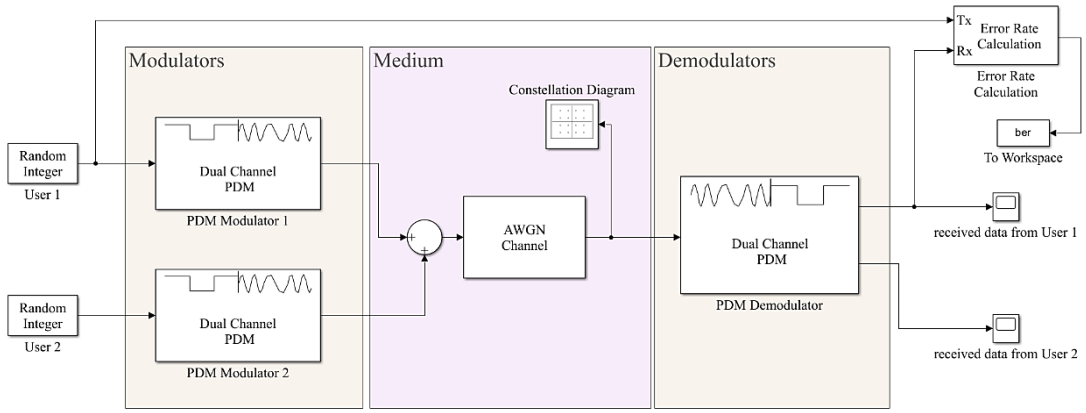


Figure 11. Simulation model of Dual Channel PDM

Random Integer Generator: Generates a sequence of uniformly distributed random integers in the range [0, 2], In the simulation, the three possible input-state values used by the PDM technique '0', '1' and '-' are represented numerically as 0, 1, and 2, respectively.

PDM Modulator: This block generates the phase-channel symbols corresponding to the input data produced by the Random Generator. For each phase channel, the modulator maps the input-state value (1, 0, or –) to its associated phase symbol using the predefined PDM phase assignments and the PDM symbol equations.

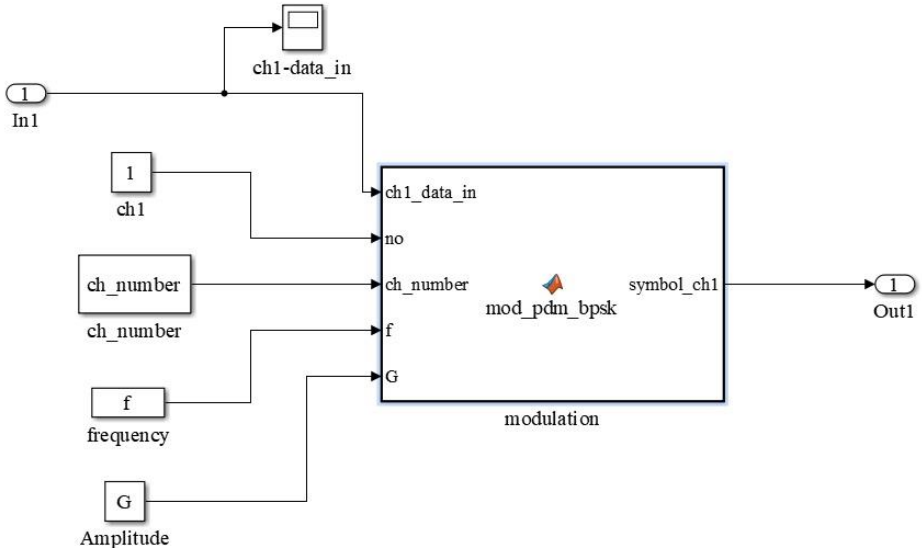


Figure 12. Subsystem structure of the PDM modulators

Each modulator block contains the subsystem shown in Figure 12. This subsystem is identical for all PDM-BPSK configurations. Within this subsystem, the function mod_pdm_bpsk takes the user data and, based on the number of channels, channel index, carrier frequency, and amplitude, generates the corresponding symbol waveforms as defined in Table3.

Table 3. Output signals for dual channel model

Input Data	Output Signal		
	Random Generator	Modulator Ch_1	Modulator Ch_2
1	1	S_1	S_2
0	0	S_3	S_4
-	2	0	0

All active channel symbols are generated simultaneously and summed to form a single composite PDM symbol, representing the vector superposition of the per-channel contributions. The resulting waveform is then passed to the AWGN channel for transmission.

AWGN Channel: This block adds additive white Gaussian noise to the composite PDM waveform in accordance with the specified E_b/N_0 value. The block uses the average input signal power (avgPower)—computed during initialization—to properly scale the noise variance.

During each symbol period, the AWGN channel receives the superposed PDM symbol and injects Gaussian noise with a two-sided power spectral density of $N_0/2$, ensuring consistency with theoretical BER expressions. The parameters 'E_b/N_0 (dB)' and 'Number of bits per symbol' are configured according to the PDM configuration: 2 bits per symbol for the dual-channel case and 4 bits per symbol for the quad-channel case. The noisy output of this block is forwarded directly to the PDM demodulator, where symbol decisions and bit recovery are performed.

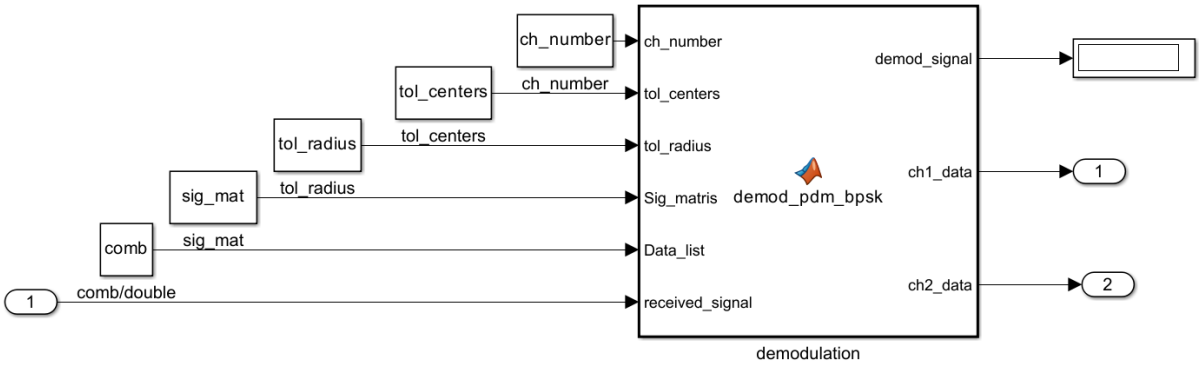


Figure 13. Subsystem structure of the PDM demodulators

PDM Demodulator: This block receives the noisy composite waveform from the AWGN channel and performs symbol detection for each phase channel. The demodulator determines the transmitted data by applying the decision logic based on the constellation reference points and tolerance regions computed during initialization. Under each demodulator block, the subsystem structure shown in Figure 13 is used.

Inside this subsystem, the function demod_pdm_bpsk processes the received noisy composite symbol in complex baseband form (equivalent to its in-phase/quadrature representation), extracts its amplitude–phase (or I–Q) coordinates, and compares it with the predefined constellation reference points. Based on this comparison and the associated tolerance regions, the demodulator decides which PDM symbol has been received and then separates the corresponding per-channel data values according to the symbol–bit mapping of the PDM scheme. This demodulator subsystem is identical for all PDM-BPSK variants; only the number of output data channels changes depending on the configured number of phase channels.

Thus, the PDM demodulator reconstructs the data transmitted through each phase channel by exploiting the predefined phase assignments and tolerance regions. The recovered bit groups are then forwarded to the BER calculation block for performance evaluation.

Error Rate Calculation: The Error Rate Calculation block computes the bit error rate (BER) by comparing the transmitted bit sequence with the bit sequence recovered by the PDM demodulator. In the simulation, the transmitted data used as the reference input corresponds to the per-channel bit values generated by the Random Generator, while the second input receives the reconstructed bit stream obtained at the output of the PDM demodulator.

For each simulation run, the block counts the total number of bit errors and divides this value by the total number of processed bits, producing an empirical BER that reflects the performance of the PDM system under the selected E_b/N_0 conditions. The block is configured to operate in "Entire frame" mode so that BER is computed over the full simulation duration.

Since each PDM symbol carries one bit per active phase channel,

- 2 bits per symbol are evaluated for the dual-channel configuration,
- 4 bits per symbol are evaluated for the quad-channel configuration.

The BER output provided by this block is used to generate the BER vs. E_b/N_0 performance curves presented in the Simulation Results section.

3.3 Quad-Channel PDM Simulation Model

The simulation model of the quad-channel PDM system is shown in Figure 14.

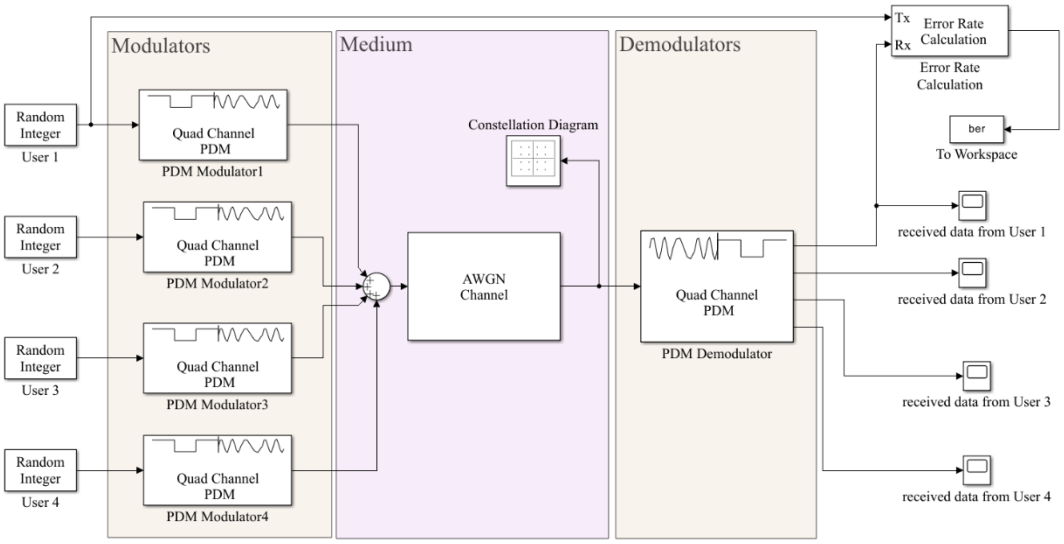


Figure 14. Simulation model of Quad Channel PDM

Similar to the dual-channel case, the transmitter, AWGN channel, and receiver blocks work together to generate, transmit, and decode the quad-channel PDM signal. In this

configuration, four phase channels are used, enabling each PDM symbol to represent a four-bit data group.

PDM Modulator (Quad Channel): The modulator structure is similar to the dual-channel case; however, it generates four phase-channel symbols simultaneously. Using the symbol definitions given in Table 4, the modulator maps the input data values (1, 0, −) to their corresponding phase symbols and produces the associated waveform components for all four channels. These four symbol waveforms are summed to obtain the composite PDM symbol, which is then passed to the AWGN channel.

Table 4. Output signals for Quad Channel PDM model

Input Data	Output Signal				
	Generator	Ch_1 Modulator	Ch_2 Modulator	Ch_3 Modulator	Ch_4 Modulator
1	1	S_1	S_2	S_3	S_4
0	0	S_5	S_6	S_7	S_8
-	2	0	0	0	0

PDM Demodulator (Quad Channel): Using the defined functions, the demodulator receives the noisy composite symbol from the AWGN channel. Based on the tolerance intervals, it determines which PDM symbol has been received, separates the four channel data values, and sends them to the output.

3.4 Simulation Results

This section presents the simulation results obtained for both the dual-channel and quad-channel PDM configurations. In the following subsections, constellation diagrams observed under different E_b/N_0 values, the BER curves obtained for both PDM models using MATLAB's Bit Error Rate Analysis Tool (BERTool), and a comparative evaluation with conventional modulation schemes are provided and discussed.

3.4.1 Constellation Diagrams under Different E_b/N_0 Values

The dual-channel and quad-channel PDM models were simulated using the parameter set given in Table 5. For each configuration, the system was evaluated at the E_b/N_0 values specified in the table, and the resulting constellation diagrams were generated. The obtained symbol clusters for the dual-channel PDM are presented in Figure 15, while those for the quad-channel PDM are shown in Figure 16.

Table 5. Simulation parameters

Parameters	Dual Channel PDM	Quad Channel PDM
Amplitude (A)	1 V	1 V
Carrier frequency (f)	100 Hz	100 Hz
Sample time	1µs	1µs
Symbol period	1µs	1µs
Run time	1s	1s
Input signal power (referenced to 1 ohm)	1.3333 W	2.6667 W
Number of bits per symbol	2	4
E_b/N_0 Values	9 dB, 11 dB, 13 dB, 15 dB	11 dB, 15 dB, 19 dB, 23 dB

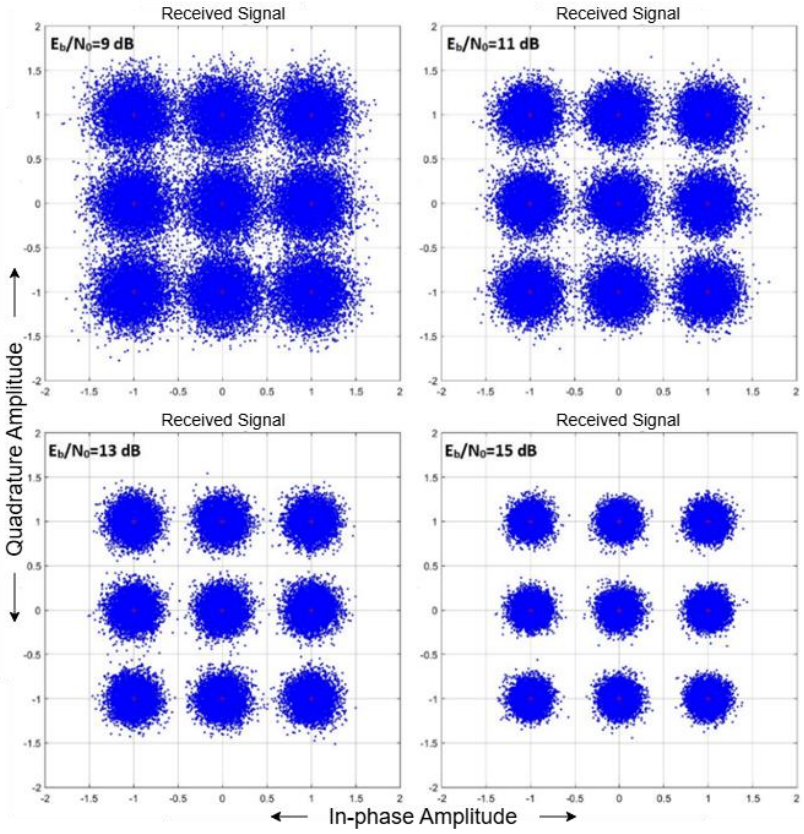


Figure 15. Constellation diagrams of Dual Channel PDM for various E_b/N_0 values

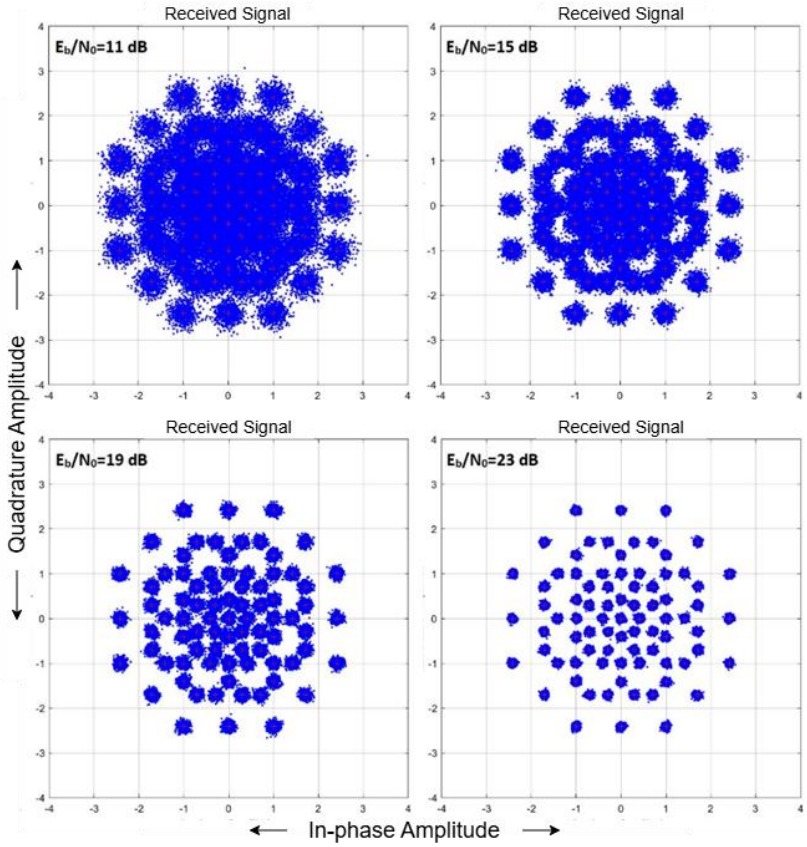


Figure 16. Constellation diagrams of Quad Channel PDM for various E_b/N_0 values

The constellation diagrams obtained for the dual-channel and quad-channel PDM models clearly illustrate how the symbol clusters evolve as the E_b/N_0 value increases.

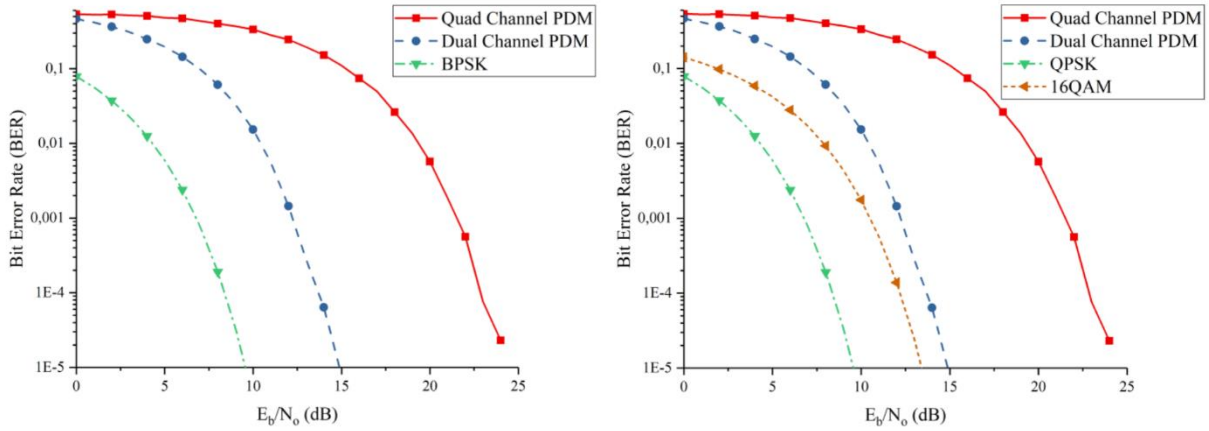
For the dual-channel PDM system, which consists of nine distinct symbols, the clusters appear relatively dispersed at E_b/N_0 levels of 9–11 dB. As the noise decreases, the constellation becomes more structured, and by E_b/N_0 = 13 dB the individual symbol groups begin to separate distinctly. At E_b/N_0 = 15 dB, the symbol clusters are tightly packed and well-separated, indicating that symbol decisions can be made reliably.

In contrast, the quad-channel PDM structure features a much denser constellation with 81 symbols. Due to this high symbol density, the clusters heavily overlap at lower E_b/N_0 values, as seen at 11 dB and 15 dB. As the SNR increases, the geometric separation improves; at E_b/N_0=19 dB, the clusters start to form distinguishable regions, and at E_b/N_0 = 23 dB, all 81 symbols become clearly isolated, forming well-defined decision boundaries.

These results demonstrate that as the number of phase channels increases, the symbol density grows significantly, requiring higher E_b/N_0 values for adequate symbol separation. Consequently, quad-channel PDM demands a substantially larger SNR than the dual-channel configuration to achieve comparable decision reliability.

3.4.2 BER Analysis with Conventional Modulation Schemes

To evaluate the error performance of the proposed PDM architecture, BER curves were obtained for both the dual-channel and quad-channel PDM configurations using MATLAB's BERTool. The results were then compared with well-known conventional modulation schemes. Since PDM employs BPSK symbols within each phase channel, the first comparison is made against standard BPSK to assess the degradation caused by phase-domain multiplexing. A second comparison is conducted with QPSK and 16-QAM to examine the spectral-efficiency perspective, where the bit-per-symbol capacities match those of dual- and quad-channel PDM, respectively. These two complementary analyses provide a comprehensive view of how PDM behaves relative to established modulation formats in terms of BER performance and noise resilience.



(a) Comparision with BPSK (b) Comparision with QPSK and 16QAM

Figure 17. BER performance comparison of PDM with conventional modulation schemes

The BER curves presented in Figure 17 clearly illustrate the relative performance of the proposed PDM configurations compared with conventional modulation schemes. In Figure 17(a), both Dual Channel and Quad Channel PDM are benchmarked against BPSK, which uses a single phase symbol per symbol period. As expected, the increased number of simultaneously transmitted phase-channel symbols in PDM leads to higher required E_b/N_0 values to achieve the same BER level as BPSK. Specifically, achieving a BER of 10^{-5} requires approximately 9 dB for BPSK, 15 dB for Dual Channel PDM, and 24 dB for Quad Channel PDM.

Figure 17(b) provides a higher-order symbol-rate comparison, where Dual Channel PDM is compared with QPSK (both carrying 2 bits per symbol), and Quad Channel PDM is compared with 16-QAM (4 bits per symbol). The results show that although PDM requires a higher E_b/N_0 relative to QPSK and 16-QAM, it achieves multi-bit transmission without

increasing bandwidth or requiring additional frequency or time resources. This highlights the fundamental trade-off in PDM: improved spectral compactness at the cost of increased power requirements for reliable detection.

Table 6. Summary comparison of PDM and conventional modulation schemes in terms of spectral efficiency and required E_b/N_0 (for BER = 10^{-5})

Modulation Scheme	Bits per Symbol	Required E_b/N_0 (BER = 10^{-5})	Number of Channels	Constellation Size (Symbols)
BPSK	1	9 dB	1	2
QPSK	2	9 dB	1	4
16-QAM	4	12 dB	1	16
Dual Channel PDM	2	15 dB	2	9
Quad Channel PDM	4	24 dB	4	81

Table 6 presents a numerical comparison between PDM and conventional modulation schemes. Although PDM requires higher E_b/N_0 values compared to conventional schemes with the same bits-per-symbol level, it enables simultaneous multi-channel transmission without increasing bandwidth, time slots, or carrier frequency. This inherent capability highlights the distinct operational advantage of the PDM approach.

4 DISCUSSION AND CONCLUSION

The increasing number of users and the growing diversity of communication requirements continually raise the question of how existing physical-layer resources can efficiently support parallel data transmission. Motivated by this challenge, this study introduced and examined Phase Division Multiplexing (PDM), a physical-layer approach that allocates distinct phase regions to create multiple phase channels over a single carrier frequency.

Unlike conventional multiplexing strategies such as FDM and TDM, which separate users in frequency or time, PDM operates by dividing the phase domain itself. The dual- and quad-channel PDM models developed in this work demonstrate that multiple phase channels can be operated simultaneously without requiring additional bandwidth, symbol duration, or carrier resources. The resulting composite symbols naturally become denser as the number of phase channels increases, which leads to a corresponding increase in the E_b/N_0 required for reliable symbol detection. In this respect, PDM trades power efficiency for simultaneous multi-channel transmission, offering a complementary—not competing—approach to existing multiplexing techniques.

Because PDM is fundamentally based on BPSK-type antipodal signaling, its operational range is inherently limited to cases where the required number of phase channels remains moderate. Nevertheless, the ability to transmit multiple symbols in parallel without time slicing (as in TDM) or frequency partitioning (as in FDM) suggests that PDM may be suitable for scenarios in which low data volume, parallel communication capability, and deterministic channel assignment are desirable. Such characteristics may offer potential advantages in application domains such as IoT systems, low-rate wireless sensor networks, real-time control links, or environments where minimizing switching delays and reducing additional synchronization overhead could be beneficial.

The simulation results obtained using MATLAB/Simulink validate the theoretical foundations of the PDM structure. The constellation diagrams and BER characteristics confirm that phase-space segmentation can reliably support multi-channel communication under sufficient SNR conditions. Although PDM requires higher E_b/N_0 than conventional modulation schemes with the same bits-per-symbol rate, its ability to provide time-independent, bandwidth-neutral, and frequency-neutral multichannel operation presents a unique operational benefit. Furthermore, PDM can be combined with FDM or TDM to form hybrid structures, where the number of overall communication channels may increase exponentially.

In summary, this work establishes the theoretical basis and simulation-level validation of the PDM concept. The results highlight that phase-domain partitioning can be used to form multiple phase channels over a single carrier and that these channels can be demodulated reliably under appropriate SNR conditions. Future work may further explore hardware implementation, performance under fading channels, and integration with existing multiplexing frameworks to assess the full practical potential of PDM.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

In this study, artificial intelligence (AI) tools were used solely for the purpose of improving the grammatical accuracy and linguistic clarity of the English text. All scientific content, including data analysis, figures, and the structural composition of the manuscript, was entirely generated by the authors without any AI assistance.

Contributions of the Authors

Munip Geylani: Developed the proposed method, derived the mathematical formulations, implemented and executed the simulations, analyzed the data, and wrote the manuscript.

Musa Çıbuk: Contributed to the development of the methodology, participated in data analysis, and provided final supervision and critical review.

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