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Application of Module to Coding Theory: A Systematic Literature Review

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Abstract
This research employs a systematic literature review methodology to comprehensively identify, assess, and interpret relevant findings pertaining to the correlation between module structure and coding theory. A meticulous literature search across Google Scholar, Dimensions, and Science Direct databases yielded 470 articles. Following a refined selection process, 14 articles were chosen for in-depth study, all published within the past decade (2012–2022). The investigation adopted the PRISMA analytical approach along with bibliometric analysis. A detailed overview of the PRISMA technique and the significance of bibliometric analysis is expounded upon. The review reveals several recurring trends, including the increasing emphasis on modular decomposition techniques and their impact on error correction capabilities. However, notable gaps remain in integrating algebraic frameworks with emerging coding standards. The study's outcomes are presented through concise summaries of the 14 selected articles, accompanied by research recommendations. Conclusively, this study offers insights into the advancement of code structures and highlights future research directions, especially in bridging theoretical models with practical coding implementations, thereby contributing to the optimization of communication systems.

Keywords: module theory, coding theory, linear code, bibliometric mapping, Prisma.

1. Introduction

A module over a ring is a commutative algebra over commutative ring. The study of commutative rings and related structures, particularly ideal and modules, is known as commutative algebra [1]. The module structure in the ring domain is the same as the multiplication and addition operations in the ring [2]. Module is an algebraic structure which means it also has submodules, bimodules, homomorphisms, and isomorphisms. Modules can be applied in coding theory, especially in linear code. Ring-linear coding theory is an area of algebraic coding theory where the underlying alphabet just carries the structure of a finite ring or, more broadly, a module rather than the structure of a finite field [3].

To create an efficient and ideal code word for transmitting a message, many other academics have studied the usage of module structures in coding theory. The module structures may be used as a coding framework for transmitting messages in a wide variety of ways. Ling

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& Sole Research [4, 5] explains about the structure of a quasi-cyclic codes which is a module structure accompanied by its use in life. Boucher et al. Research [6, 7] introduces skew-cyclic codes and skew-constacyclic codes in general, which are a module structure over fields. Cuadra, Garcia-Rubira, and Lopez-Ramos Research [8] describes a code which is a module structure over Hopf Algebras, where the Hopf Algebras is made up of a linear map S:H→H termed the antipode and a bialgebra H. A bialgebra is a vector space H with compatible unital algebra structure (m,u) and co-unital co algebra structure (Δ,ε) [9]. Climent et al. [10], Gluesing-Luerssen et al. [11], and Lally Research [12] describes about convolutional codes which is a module structures and its applications to design any systems, create a matrix from a single code, and determine the smallest distance between codes. Sun et al. research [13] introduces about Lattice Network Codes which is a module structure too, due to Eisenstein integers. Lam & Leroy research [14, 15] explains about Wedderburn polynomial over division ring, where Wedderburn polynomial is a minimum polynomial of an algebraic subset of a division ring [16]. Reed-Solomon codes introduced by Guruswami and Sudan [17], Koetter and Vardy [18, 19, 20], Lee and O'Sullivan [45], Alekhnovich [22], Zeh, Gentner, and Augot [23], Xing, Chen, and Bossert [24, 25], Chen et al. [26, 27] to solve coding problems such as decoding decision making, interpolation algorithm with Grobner Basis, solve polynomial of linear diophantine equations, low-complexity decoding problem, and algebraic chase decoding problem. The study involves bibliometric scrutiny and an in-depth examination of papers, including authorship, publication year, citations, module structure, research objectives, and outcomes. Research suggestions will be offered to authors for enhancing the quality of their results. The papers that are further analyzed in the systematic literature review are Ozbudak and Ozkaya Research [28], Shi et al. Research [29], Gorla and Ravagnani Research [30], Berger and Amrani Research [31], Boulagouaz and Leroy Research [32], Torrecillas et al. Research [33, 34], Xing et al. Research [25], Dyshko and Wood Research [35], Guneri and Ozkaya Research [36], Morales Research [37], Borello and Willems Research [38], Westerback Research [39], Garcia-Rubira and Lopez-Ramos Research [40], and how to select the paper will be explained further in the methods section.

This study aims to address challenges in understanding related papers, identify diverse perspectives on coding and module structure, and provide a comprehensive analysis with recommendations for researchers. Although many studies have explored module-based coding techniques, a critical gap remains in synthesizing these approaches into a coherent framework. Existing literature often presents fragmented insights, lacking a unified analysis that clarifies the relationships among various module structures, coding strategies, and mathematical tools. Therefore, this systematic review is necessary to fill this void by mapping key developments, analyzing research patterns, and guiding future investigations. The study involves bibliometric scrutiny and an in-depth examination of papers—including authorship, publication year, citations, module structure, research objectives, and outcomes—while offering research suggestions for enhancing result quality.

2. Materials and Methods

The literature that focuses on the use of the module structure in coding theory was identified. The data used in this study are articles obtained from three database sources, namely Dimensions, Science Direct, and Google Scholar. The articles considered in the literature are journal articles, preprint, and proceedings from 2012 to 2022. Article searches were carried out using Publish or Perish software to get article data from google scholar and using database website to get article data from Dimensions and Science Direct. Article searches are limited to a maximum limit of 1000 articles on the Publish or Perish software. The keywords used by researchers to selected articles are "Module Structure", "Coding Theory" and "Algebra".

The Selection process for paper selection is divided into two stages, namely semi-automatic selection and manual selection. Semi-automatic selection was carried out with the help of the

Jabref application to remove existing duplication from the three journal sources. Manual selection is made to read duplicates that are not detected by the Jabref application. The application is not detected due to the different file types of each journal source. Additionally, the selection of article abstracts, accessibility, and material that satisfies the author's search criteria is done manually. The manual selection process aids researchers in accurately representing research results and ensures that no studies are missed as a result of machine errors, while the semi-automatic selection process speeds up the search for duplications or increases researchers' efficiency when con-ducting literature searches.

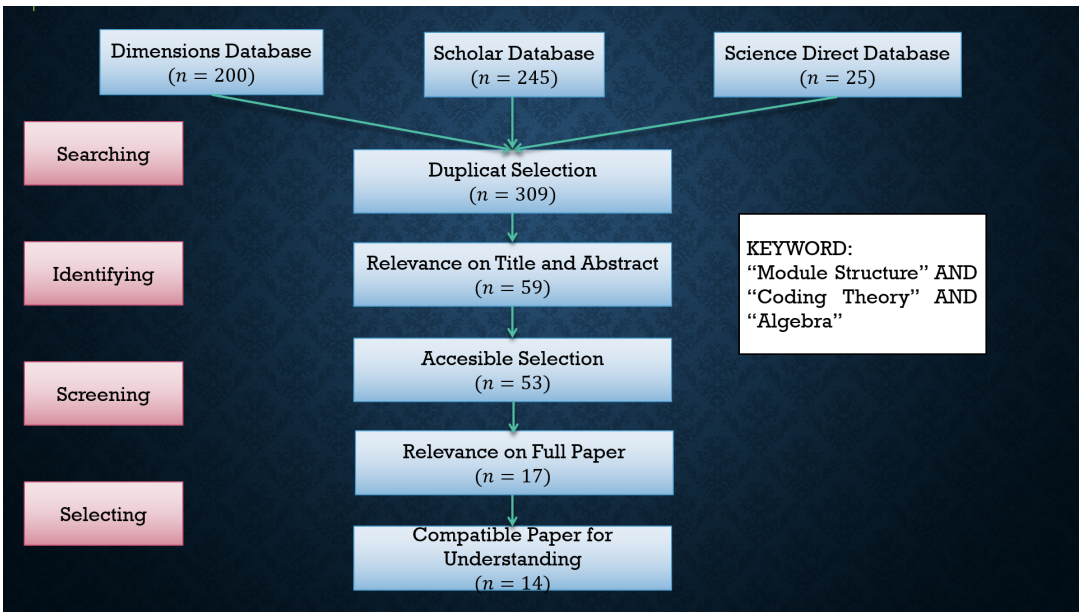

FIGURE 1. Flowchart of literature selection process

First, the literature is searched using publish or perish software by entering keywords, year of publication, and maximum article limit. Second, the literature obtained was 245 articles from the Publish or Perish software which were selected by eliminating literature in the form of books and other topics that were not relevant to this research. The selected literature is journal articles, preprint, and proceedings whose topics are relevant to module structure in coding theory. Third, open the dimensions website and search for literature by entering keywords, year of publication, and removing literature in the form of books in literature search. Findings from a literature search on the Dimensions website revealed up to 200 article that were pertinent to the issue. Fourth, open the science direct website and search for literature by entering keywords, year of publication, and removing literature in the form of books in literature search. The results of a literature search on the Science Direct Website found as many as 25 article that were relevant to the topic being searched. Fifth, obtained total 470 articles from dimensions, google scholar, and science direct which were then identified in all of these articles to eliminate duplicate articles from the three databases. Sixth, after deleting duplicate articles, 309 articles were acquired. These articles were chosen using the Jabref application and manual selection was done for data with various file extensions. Seventh, obtained 59 articles whose titles are relevant to the keyword entered. Reading the abstracts and titles from the previous results, then choosing the ones that come the closest to the topic's appropriateness, is how titles and abstracts that are pertinent to the topic are chosen. Eighth, with accessible selection, obtained 53 articles that can be accessed for free by researchers. Searching for open sources paper, fully accessible articles is how the accessibility selection process is carried out. Nineth, read the 17 articles and select the relevant articles in full paper. Full paper selection is done

by reading research results and research conclusions from previously obtained articles. Last, select compatible articles for further understanding by researchers and obtained 14 compatible articles which were selected in a systematic literature review for massive understanding. This selection is carried out by reading the paper from the introduction to conclusion and choosing those with a good research index. The research topics mapping is shown in Figure 2.

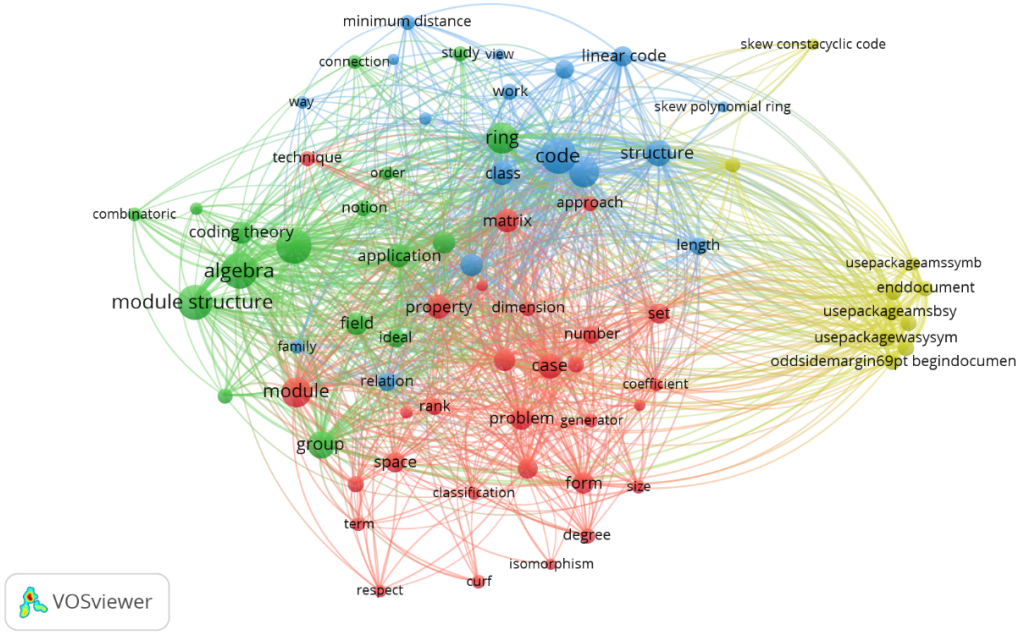

FIGURE 2. Research topics mapping using VOSviewer

Bibliometrics are the process counting and analyzing many aspects of written communication, as well as the nature and path of development of a field (to the extent that this is reflected through written communication), mathematical and statistical approaches are used to books and other forms of communication [41, 42]. The literature review was analyzed using three research indicators: word cooccurrence, number of citations, and number of publications [43]). The author using VOSviewer to identify the mapping of the study issue in question, specifically "module structure", "algebra", and "coding theory". Figure 2 shows the bibliometrics of the module structure research topic on coding theory. Figure 2 depicts four hues that represent a cluster of terms that appear often in study, notably red, blue, green, and yellow. The red color indicates keywords that have a strong relationship with the keyword "module". The blue hue represents important terms that have a strong association with the word "code structure" and explain the code's categorization. The green hue indicates the link between a term and the keywords sought by the author, which are "module structure", "coding theory", and "algebra". The yellow hue denotes a coding package, which is represented by a latex-shaped file and is interpreted as a "use package" statement. Clusters between colors also suggest a link between the colors red, blue, green, and yellow, but it is weak connection, which means that words in the red cluster seldom appear together with words in the blue, green, and yellow clusters, and vice versa.

The articles obtained from the selection process were explored further to explain about the authors, title, years of research, method used in research, code structures, and the result of the research. Additionally, this analysis of the literature looks at the variations between the fourteen papers evaluated, as well as the benefits and drawbacks of each, and the structure of the code utilized in the form of modules. We learn more about the main results discussed in this

article and suggestions for research. Finally, we re-view the research findings from these papers in order to share discoveries in future work, critique the research findings and the application of the code structure, and offer ideas to researchers in order to explain the direction of research development.

3. Results and Discussion

After going through the article selection procedure stated in the research method, the researcher has a better grasp of the fourteen publications that were chosen. The researcher examined the whole content of the paper, including the author of the article, the year of publication, the title of the study, the number of citations, the method used, the structure of the code mentioned, and the article research results. Further analysis was carried out by the researcher in order to obtain a summary of the data about the article in Table 1.

The first article [32] addresses the aforementioned issues by applying the concept of pseudo-linear transformation to cyclic codes and more broadly to (σ,δ)-codes. The transformative idea is utilized to yield research results in the form of constructing generic matrices and control matrices for cyclic codes, skew cyclic codes, and (σ,δ)-codes. In the second article [33], the concept of separable extension is employed in the context of rings and ideal codes, exemplified by the application to cyclic convolutional codes. Article [32] addresses the issues by applying pseudo-linear transformations to cyclic and (σ,δ)-codes, resulting in the construction of matrices for various code types. The second article [33] applies separable extensions to rings, exemplified with cyclic convolutional codes.

Article [36] applies the Concatenated Structure to demonstrate the asymptotic goodness of multidimensional quasi-cyclic codes. It utilizes convolutional codes to find the minimum distance of these codes, establishing non-catastrophicity requirements for the encoder code. The sixth article [30] employs module codes, submodule codes, and submodule distance to determine the minimum distance of codes in algebraic networks. This approach generates submodule codes, minimizes encoding errors, and expedites submodule distance calculations.

The seventh article [25] utilizes Kotter's iterative polynomial construction algorithm, Grobner basis of a module, and Low-Complexity Chase Basis Reduction (LCC-BR) algorithm to address low-complexity and low-latency features. The LCC-BR method simplifies calculations, while the progressive LCC-BR method, although complex, yields higher message quality. This article, overall, is concise and captures the essence of the content. The eighth article [28] applies the new concatenated structure and the trace representation concept to address research problems, including calculating the minimum distance bound for QnDC codes and the lower bound for 2D convolutional codes.

The ninth article [29] applies module structure construction and basis theory concepts, resulting in a specific class of quasi-cyclic codes. The article provides insights into their structures and includes numerical examples. In the tenth article [38], the study utilizes the concept of algebraic descriptions for quasi-cyclic codes and the full group of permutations. This approach yields intrinsic descriptions of quasi-group codes and reveals some code structures. The eleventh article [34] employs bilinear forms, finite rings, and MacWilliams identities. These concepts are subsequently used to address research problems, including constructing codes with the Frobenius alphabet and exploring literature. The article also introduces a method for creating new Frobenius algebras from existing ones, based on skew polynomials, and explains how to build new finite Frobenius rings from old ones. The general findings on bilinear forms

defined on modules over non-projective Frobenius algebras, discovered in preceding sections, are utilized to establish major conditions.

TABLE 1. Identification on articles

Author, Year of Research	Title	Cited	Method used in research	Code Structures	Results of the research
Boulagouaz & Leroy, 2013	(σ,δ)-codes	18	Pseudo-linear transformations	Cyclic codes, skew cyclic codes, and (σ,δ)-codes	The generic matrices and control matrices of (σ,δ)-codes, cyclic codes, and skew cyclic codes.
Gomez-Torrecillas et al., 2017	Ideal Codes Over Separable Ring Extensions	14	Separable extension of rings and ideal codes	Cyclic convolutional codes	A more in-depth grasp of σ-cyclic convolutional codes including examples and computations in computer programs.
Morales, 2016	On Lee Association Schemes Over $\mathbb{Z}_4$ and Their Terwilliger Algebra	10	Terwilliger algebra of Hamming association schemes.	$\mathbb{Z}_4$-codes of length n and Lee association schemes	Proof of the three major theorems of the algebraic structure of $\mathbb{Z}_4$-codes with length n.
Berger & El Amrani, 2014	Codes Over Finite Quotients of Polynomial Rings	7	Polynomial Euclidean division from the structure of $\mathbb{F}[x]$	Quasi-cyclic codes	The basis of divisors for quasi-cyclic codes, generalize to the case $\left(\frac{\mathbb{F}[x]}{f(x)}\right)^l$, where $f(x)$ is a monic polynomial, and the canonical generator matrix.
Guneri & Ozkaya, 2016	Multidimensional Quasi-Cyclic and Convolutional Codes	7	The Concatenated Structure to show that multi-dimensional quasi-cyclic codes are asymptotically good.	Multidimensional quasi-cyclic codes	Proof $QnDC$ codes are asymptotically good, conditions of noncatastrophicity of encoders, and determining the free distance of convolutional codes.
Gorla & Ravagnani, 2018	An Algebraic Framework for End-to-End Physical-Layer Network Coding	7	Construction submodule codes and submodule distance	Module codes and submodule codes	Get distribution of information loss and errors in module transmissions and get the minimum-distance decoding in algebraic framework.

Author, Year of Research	Title	Cited	Method used in research	Code Structures	Results of the research
Xing et al., 2020	Low-Complexity Chase Decoding of Reed-Solomon Codes Using Module	7	Kotter's iterative polynomial construction algorithm, the concept of Grobner basis of a module and Low-Complexity Chase Basis Reduction (LCC-BR) algorithm	Reed-Solomon Codes	Analysis of the low-complexity and low-latency features of LCC-BR algorithm and the numerical results of Reed-Solomon Codes with LCC-BR interpolation technique.
Ozbudak & Ozkaya, 2016	A Minimum Distance Bound for Quasi-nD-Cyclic Codes	6	The new concatenated structure and the trace representation.	Multidimensional quasi-cyclic ($QnDC$) codes and nD convolutional codes	A minimum distance bound for multidimensional quasi-cyclic codes and a lower bound on the free distance of certain 2D convolutional codes.
Shi et al., 2017	A Special Class of Quasi-Cyclic Codes	5	The construction of module structure of quasi-cyclic codes	The special class of quasi-cyclic codes	Obtain the image of cyclic codes over an extension field with a basis and the theory of special class of quasi-cyclic codes.
Borello & Willems, 2022	On The Algebraic Structure of Quasi-Group Codes	4	The concept of algebraic description of quasi-cyclic codes and the full group of permutation	Quasi group codes	Get an intrinsic description of quasigroup codes of their permutation automorphism groups and some structural properties.
Gomez-Torrecillas et al., 2019	Some Remarks on Non Projective Frobenius Algebras and Linear Codes	3	The concept of bilinear forms, finite ring, and MacWilliams identities	Non Projective Frobenius Algebras and Linear Codes	Get a code with a frobenius alphabet and a literature of non-projective Frobenius Algebras.

Author, Year of Research	Title	Cited	Method used in research	Code Structures	Results of the research
Wester-back, 2017	Parity Check Systems of Nonlinear Codes Over Finite Com-mutative Frobenius Rings	1	The concept of parity check systems, Fourier analysis, and MacWilliams identities	Non linear codes over commutative Frobenius rings	The connection between parity check systems and codes and get a minimal distance distribution of codes.
Garcia-Rubira & Lopez-Ramos, 2013	Tensor Products of Ideal Codes Over Hopf Algebras	0	Tensor product of simple codes and The Hamming distance	Indecompo-sable ideal codes in Radford Hopf algebras	Get a behavior of tensor products of indecomposable ideal codes in Radford Hopf algebras.
Dyshko & Wood, 2021	Mac-Williams Extension Property for Arbitrary Weights On Linear Codes Over Module Alphabets	0	MacWilliams extensions property, The Hamming weight, and the Fourier Transform	Linear codes over module alphabets	Get special matrices of linear codes and the symmetrized weight compositions of linear codes.

In the twelfth article [39], the concepts of parity check systems, Fourier analysis, and MacWilliams identities are applied to explore the relationship between parity check systems and codes. The focus is on achieving minimal distance and understanding distance distribution through the use of parity check systems, along with their connection to characters. The thirteenth article [40] employs the concept of the tensor product of simple codes and Hamming distance to analyze the behavior of ideal codes that are not decomposed in Radford Hopf algebras. In examining the family of Radford Hopf algebras, it is highlighted that the semisimplicity of the tensor product of simple ideal codes is lost. The last article [35] addresses the aforementioned issues by applying the concept of the MacWilliams extensions property, Hamming weight, and Fourier Transform. These three concepts, particularly a specific matrix of linear codes and their symmetrical weight composition, are utilized to generate research findings.

4. Conclusions

This systematic literature review examined 470 articles obtained from Google Scholar, Dimensions, and Science Direct, filtered by the research period from 2012 to 2022. After a rigorous screening process, 14 articles were selected for detailed analysis. The review revealed several consistent themes, including the increasing adoption of module structures in linear and non-linear coding frameworks, and the application of algebraic tools such as rings, fields, and homomorphisms in the development of codes. However, the analysis also uncovered notable gaps in the literature—specifically, a lack of comparative studies across different module structures and limited integration between theoretical constructs and practical coding implementations. These limitations highlight the need for a more unified framework that bridges theory and application in coding theory. As a result, this study contributes by mapping current

research trends, identifying methodological approaches, and outlining unresolved issues. Future research should focus on developing optimized code structures based on a deeper synthesis of existing models and validating their effectiveness in real-world communication systems.

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