

# Entanglement Quantification and Classification: A Systematic Literature Review

Amirul Asyraf Zahir<sup>1</sup>, Mohd Ilias M Shuhud<sup>3</sup>  
Faculty of Science and Technology  
Universiti Sains Islam Malaysia  
Negeri Sembilan, Malaysia

Siti Munirah Mohd<sup>2\*</sup>  
Genius Insan College  
Universiti Sains Islam Malaysia  
Negeri Sembilan, Malaysia

Bahari Idrus<sup>4</sup>  
Center for Software Technology and Management, Faculty of  
Information Science and Technology  
Universiti Kebangsaan Malaysia, Selangor, Malaysia

Hishamuddin Zainuddin<sup>5</sup>  
Department of Physics, Faculty of Science  
Universiti Putra Malaysia  
Selangor, Malaysia

Nurhidaya Mohamad Jan<sup>6</sup>  
Genius Insan College  
Universiti Sains Islam Malaysia  
Negeri Sembilan, Malaysia

Mohamed Ridza Wahiddin<sup>7</sup>  
Cybersecurity & Systems Unit  
Universiti Sains Islam Malaysia  
Negeri Sembilan, Malaysia

**Abstract**—Quantum entanglement is one of the essences of quantum mechanics and quantum information theory. It is a physical phenomenon in which entangled particles remain correlated with each other regardless of the distance between them. Quantum entanglement plays a significant role in areas such as quantum computing, quantum cryptography, and quantum teleportation. Quantifying entanglement is important for determining the depth of the entanglement level and has an impact on quantum information tasks performance. Entanglement classification is critical in quantum information theory for determining the class of states in a quantum system. The entanglement classification of two qubits as separable or entangled has been established. The classification of multiqubit entanglement is more challenging, especially in higher-qubit systems. The goal of this study is to identify different established measurements for entanglement quantification and entanglement classification methods through a systematic literature review. Indexed articles between 2017 and 2021 were selected as secondary resources from several sources based on specific keywords. This study presents a conceptual framework of entanglement quantification and classification based on previous studies.

**Keywords**—Entanglement quantification; quantum entanglement; entanglement classification; quantum measurement

## I. INTRODUCTION

Quantum entanglement is one of the most studied features in quantum mechanics that is critical to quantum information processing [1] in areas such as quantum teleportation, quantum cryptography, and quantum computing. In quantum computing, quantum entanglement plays a vital role in demonstrating the superiority of a quantum computer over its classical counterpart [2]. Although interest in quantum entanglement has grown over the years, knowledge of the

phenomenon is still limited, especially in higher-dimensional systems [3].

Entanglement quantification is a process of determining the level of entanglement and the intactness of a system and characterizing it. It is a fundamental problem in quantum information theory, especially in multipartite settings where the complexity increases with the number of subsystems involved [3, 4]. Some known entanglement quantification measurements are concurrence [5], Schmidt decomposition [6], negativity [7], and entanglement of formation [8].

The most well-known protocols in entanglement classification are local unitary (LU), local operations and classical communication (LOCC), and stochastic local operations and classical communication (SLOCC). The process of entanglement classification is an open problem in quantum information theory. Entanglement classification is established as either separable or entangled in a two-qubit system. The classification becomes more complex as the number of qubits in the system grows. For example, the classification in a three-qubit system is one separable, three biseparable, and two genuinely entangled states (GHZ and W) under SLOCC [9]. The classification for  $n$ -qubit  $\geq 4$  is understudied and it is even more complicated due to the infinite number of classes under SLOCC [10-12].

Entanglement classification is used to categorize the class for complex structures starting from  $n = 3$  qubits. It will be complemented with quantification because the measure that has been by quantification determines the degree of entanglement of each state.

This study followed a set of guidelines to identify existing entanglement quantification and classification methods, and propose a framework for the methods. The paper is organized

\*Corresponding Author.

as follows. The research methodology is detailed in Section II. Section III covers the results and discussions. Section IV concludes the study.

## II. METHODOLOGY

This section discusses the publication standard used in this study, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The following topics are thoroughly discussed: (1) PRISMA review protocol, (2) research question formulation, (3) systematic searching strategy, (4) quality appraisal, and (5) data extraction and analysis.

### A. PRISMA Review Protocol

PRISMA [13] was used as the review protocol in this systematic literature review. This review protocol served as a guideline for conducting a systematic literature review by formulating research questions, identifying the inclusion and exclusion criteria in a systematic searching strategy, conducting a quality appraisal of selected articles, and critical data extraction and analysis over a specified period. The scope of this study is entanglement quantification and classification.

### B. Research Question Formulation

The systematic literature review is guided by the research questions developed during the preliminary phase. The following research questions were formulated in accordance with the research objective of presenting a conceptual framework of entanglement quantification and classification: (1) What are the established methods of entanglement quantification? (2) What are the established methods for classifying quantum entanglement? (3) What is the preferred alternative method of entanglement quantification and classification?

### C. Systematic Searching Strategy

The systematic searching strategy of this study consists of three steps: identification, screening, and eligibility.

1) *Identification*: Identification is an important process as it determines which articles are relevant to the review. The articles for the study were primarily drawn from the databases of two powerful multidisciplinary search engines, Scopus and Web of Science (WOS), as well as an additional database, Google Scholar. A comprehensive search was conducted using the field tags “TITLE-ABS-Key” (title, abstract, and keywords) in Scopus and “TS” (topic) in WOS with the keywords entanglement quantification, quantum entanglement, entanglement classification, and quantum measurement.

The search strings were created to search for related articles in both databases. The searches were conducted from November to December 2021 (see Table I). A manual search was conducted using Google Scholar, with handpicked related articles derived from the same keywords as in Scopus and WOS. Based on the systematic searching of Scopus and WOS, a total of 13,659 potential related articles were identified and 1,934 articles were downloaded. Additionally, 8 articles were selected from Google Scholar for further analysis. The search results from Scopus and WOS are displayed in Fig. 1.

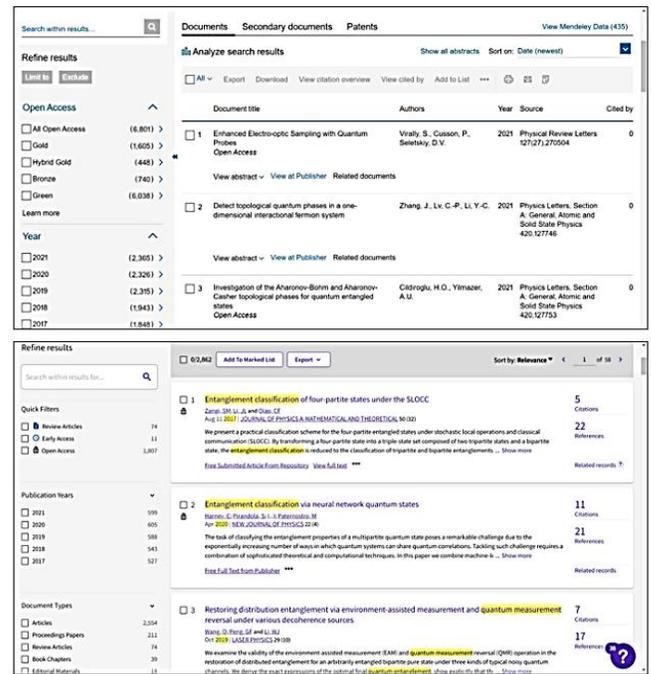


Fig. 1. Search Results in Scopus and WOS.

2) *Screening*: This systematic literature review examined indexed articles on entanglement quantification and classification published between 2017 and 2021. The five-year period was chosen because of the maturity of the subject [14]. 1,847 of the total 1,942 downloaded articles were excluded due to duplication by title review and abstract review. During the screening stage, the remaining 95 articles were validated to ensure they met the inclusion and exclusion criteria. The inclusion and exclusion criteria are the subject matter, literature type, language of the article, and year of publication (see Table II). Articles that are unrelated to entanglement quantification and classification were excluded from this study. As a precaution against misunderstanding and mistranslation, only articles written in English were considered. After this stage, 62 articles met the inclusion and exclusion criteria.

TABLE I. SYSTEMATIC REVIEW PROCESS SEARCH STRING

Database	Search string
Scopus	TITLE-ABS-KEY (“entanglement quantification” OR “quantum entanglement” OR “entanglement classification” OR “quantum measurement”)
WOS	TS= (“entanglement quantification” OR “quantum entanglement” OR “entanglement classification” OR “quantum measurement”)

TABLE II. INCLUSION AND EXCLUSION CRITERIA

Inclusion	Exclusion
Articles on the subject matter of “entanglement quantification” and “entanglement classification”	Articles written in languages other than English
Indexed journal articles	Articles published before 2017

3) *Eligibility*: In the third stage of the systematic searching strategy, the remaining 62 articles from the screening stage were reviewed again for suitability for this study. After a thorough examination, 27 articles were removed since their research direction or theme did not focus on entanglement quantification and classification. The remaining 35 articles were then prepared for a quality appraisal (see Fig. 3).

*D. Quality Appraisal*

The 35 selected articles were sent to an expert in the field for quality appraisal to ensure that only high-quality articles were used in the review. According to [15], the remaining articles should be ranked as high, moderate, or low quality, with only high and moderate-quality articles being included in the review. To meet the quality standard, the expert concentrated on specific elements such as the theme, objective, and results of the articles. Following the appraisal, the expert determined that all 35 articles were suitable for the review.

*E. Data Extraction and Analysis*

In-depth analysis was used to extract relevant data from the articles by first analyzing the abstract, then the discussion and conclusion, and finally the body for any other relevant

information. The extracted data were tabulated in Microsoft Word. The articles were divided into five categories based on the year they were published (see Fig. 2). There are 8 articles published in 2017, 8 articles in 2018, 3 articles in 2019, 5 articles in 2020, and 11 articles in 2021.

The main themes in the articles from the extracted data are entanglement quantification and entanglement classification. In the following section, we will go over a few of the methods that were discovered.

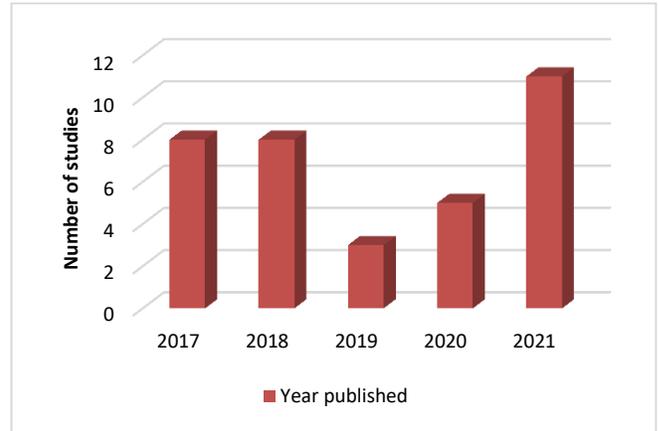


Fig. 2. Articles Group by Year Published.

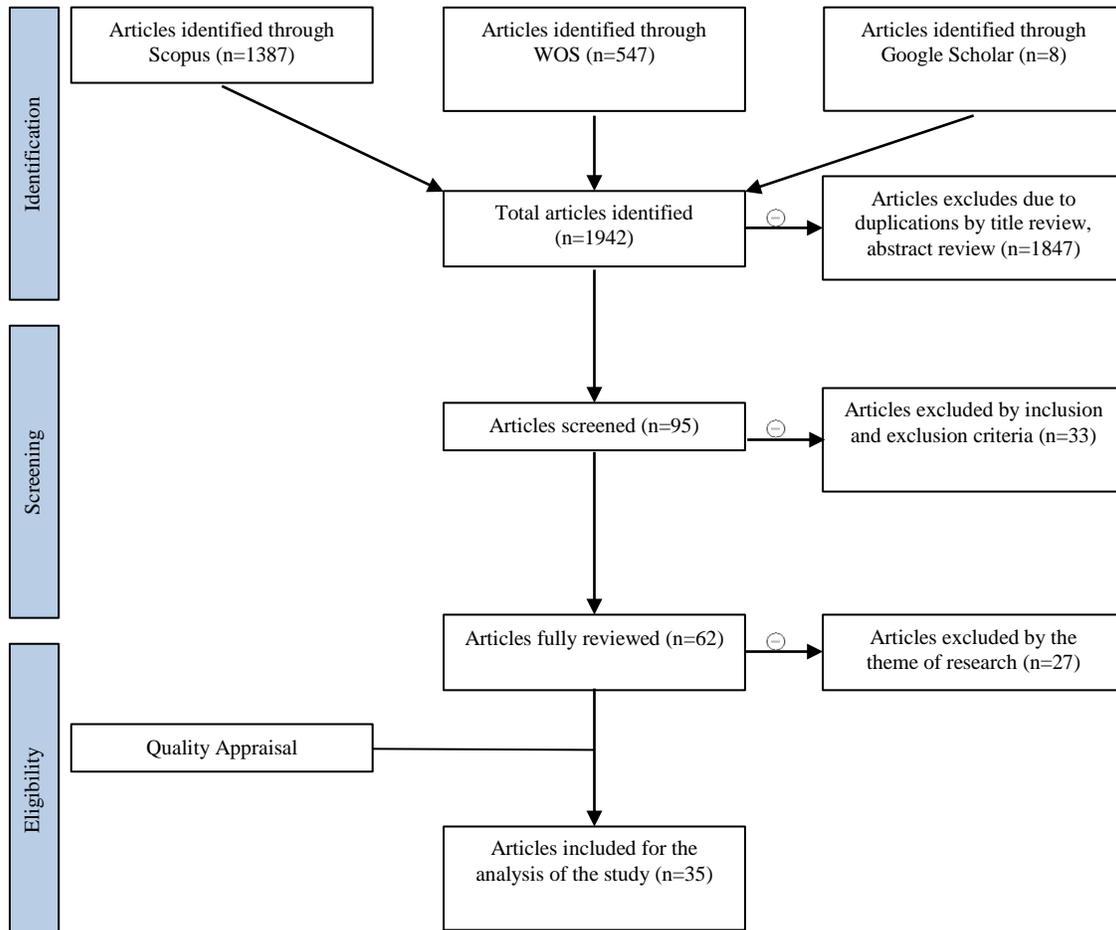


Fig. 3. Article Selection Process.

### III. RESULT

This section discusses the identified themes, entanglement quantification, and entanglement classification in previous studies (see Table III and Table IV). A proposed conceptual framework of entanglement quantification and classification has been developed and is presented as a reference for future work (see Fig. 6).

#### A. Entanglement Quantification and Entanglement Classification Methods

There are 19 entanglement quantification methods established from previous studies, as shown in Table III. Some of these methods are compounded (additional variables or adaptation) such as base or compounded concurrence [4, 5, 8, 16-19], base or compounded negativity [4, 7, 8, 19], base or compounded entanglement of formation [4, 5, 8, 20], base or compounded convex-roof measures [6, 8, 21], base or compounded tangle [4, 5, 17], base or compounded entanglement witness [22, 23], relative entropy of entanglement [20, 21], and Schmidt decomposition [6, 20]. Other established entanglement quantification methods are: (1) Tsallis-q entanglement measure, (2) k-entanglement measure, (3) entanglement of assistance, (4) supervised machine learning, (5) linear entropy of entanglement, (6) an extension of an entanglement measure for the mixed state from the measure of a pure state, (7) global nonselective projective measurement, (8) Gramian operators, (9) exact PPT entanglement cost, (10) operational entanglement monotone approach, and (11) entanglement of formation.

These methods were grouped into the following clusters: Cluster 1: Concurrence; Cluster 2: negativity; Cluster 3: Entanglement of formation; Cluster 4: Convex-roof measures; Cluster 5: Tangle; Cluster 6: Entanglement witness; Cluster 7: Relative entropy of entanglement; and Cluster 8: Schmidt decomposition. Fig. 4 depicts the clusters of entanglement quantification methods. Concurrence is the most commonly used entanglement quantification method, followed by negativity. Base or compounded concurrence and negativity are widely regarded as simple and direct measures of entanglement compared to other listed methods in this research.

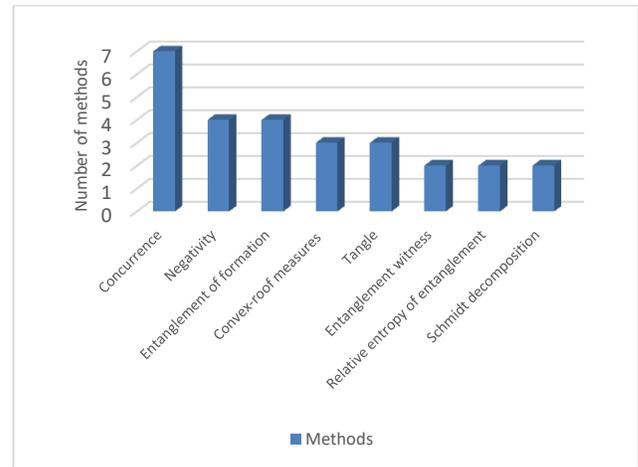


Fig. 4. Entanglement Quantification Methods Cluster.

TABLE III. ENTANGLEMENT QUANTIFICATION METHODS FROM PREVIOUS STUDIES

Source	Methods	Qubit system		Quantum state			Remarks
		BP	MP	PU	MX	AR	
[5]	Concurrence, tangle, Tsallis-q entanglement measure, entanglement of formation, squared concurrence	⊗			⊗		N-qubit = 2 High dimensional system
[22]	Witness operator	⊗			⊗		N-qubit = 2 High dimensional system
[6]	Ent (PU – Schmid decomposition; MX – Convex roof extension)	⊗	⊗	⊗	⊗		N-qubit = 2, 3, n MX - Not applicable for n-partite and above
[4]	Negativity tangle, entanglement of formation tangle, concurrence tangle		⊗	⊗	⊗		N-qubit = 3, 4, n
[16]	Ent-concurrence	⊗	⊗	⊗	⊗		N-qubit = 2, 3, 4 Detects entanglement in reduced and full states
[24]	Entanglement of assistance		⊗	⊗			N-qubit = 3
[3]	Supervised machine learning		⊗	⊗			N qubit ≤ 8
[17]	A family of multipartite entanglement - concentratable entanglements (n-tangle, concurrence, linear entropy of entanglement)		⊗	⊗			N-qubit = 3
[25]	An extension of an entanglement measure for the mixed state from the measure of pure state	⊗		⊗	⊗		N-qubit = 2
[7]	Negativity/global nonselective projective measurement	⊗		⊗	⊗		N-qubit = 2
[20]	Fidelity based distance (relative entropy, entanglement of formation, and Schmidt decomposition)	⊗	⊗	⊗	⊗		N-qubit = 2, 3

[26]	Ent Detector – computational toolbox (Gramian operators)	✳		✳	✳		N-qubit = 2
[23]	Quantitative measurement-device-independent entanglement witness (MDI-EW)	✳				✳	N-qubit = 2 Extendable to multipartite (n-qubit)
[27]	Operational entanglement monotone approach	✳		✳	✳		N-qubit = 2
[21]	Axiomatic approach - Convex roof entanglement measures (the relative entropy of entanglement, the negativity, the logarithmic negativity, and the logarithmic convex-roof extended negativity)	✳		✳	✳		N-qubit = 2
[18]	Concurrence		✳	✳			N-qubit = 7
[19]	Concurrence of assistance and negativity of assistance	✳	✳	✳			N-qubit = 2, 3, n
[8]	Concurrence, negativity, convex-roof extended negativity, entanglement of formation	✳	✳	✳	✳		N-qubit = 2, 3
[28]	k-entanglement measure and exact PPT entanglement cost	✳	✳	✳		✳	N-qubit = 2, 3

BP = Bipartite, MP = Multipartite, PU = Pure State, MX = Mixed State, AR = Arbitrary State

TABLE IV. ENTANGLEMENT CLASSIFICATION METHODS FROM PREVIOUS STUDIES

Source	Methods	Protocol	Qubit system		Quantum state			Remarks
			BP	MP	PU	MX	AR	
[3]	Supervised machine learning	LOCC		✳	✳			N-qubit ≤ 8
[17]	A family of multipartite entanglement - concentratable entanglements (n-tangle, concurrence, linear entropy of entanglement)	LOCC		✳	✳			N-qubit = 3
[25]	An extension of an entanglement measure for the mixed state from the measure of the pure state	LOCC	✳		✳	✳		N-qubit = 2
[7]	Negativity / Global nonselective projective measurement	LOCC	✳		✳	✳		N-qubit = 2
[26]	Ent Detector – computational toolbox (Gramian operators)	LU	✳		✳	✳		N-qubit = 2
[23]	Quantitative measurement-device-independent entanglement witness (MDI-EW)	LOCC	✳				✳	N-qubit = 2
[27]	Operational entanglement monotone approach	LOCC	✳		✳	✳		N-qubit = 2
[21]	Axiomatic approach - Convex roof entanglement measures (the relative entropy of entanglement, the negativity, the logarithmic negativity, and the logarithmic convex-roof extended negativity)	LU	✳		✳	✳		N-qubit = 2
[28]	K-entanglement measure and exact PPT entanglement cost	LOCC	✳	✳	✳		✳	N-qubit = 2, 3
[29]	A set of operators (contains only Pauli matrices)	SLOCC		✳	✳	✳		N-qubit = 3
[9]	Witness operator	SLOCC		✳	✳			N-qubit = 3
[10]	Algebraic geometry (SLOCC invariants – secant varieties) – k-secants and ℓ-multiranks	SLOCC		✳	✳			N-qubit = 5
[30]	Entanglement polytope	LU		✳	✳			N-qubit = 3
[31]	Maximal Schmidt rank	SLOCC		✳	✳			N-qubit = 3
[11]	Singular value decomposition	SLOCC		✳	✳			N-qubit = 4
[32]	Grover’s algorithm, Shor’s algorithm, Quantum Fourier Transform	SLOCC	✳	✳	✳			N-qubit = 2, 3, 4
[33]	Inductive classification approach	SLOCC		✳	✳			N-qubit = 4
[34]	Invoking the proportional relationships for spectrums and standard Jordan normal forms	SLOCC	✳	✳	✳			N-qubit = 2, 3, 4
[35]	Pauli z-operators	SLOCC		✳	✳			N-qubit = 3
[36]	Bell inequalities	LU		✳	✳			N-qubit = 3
[37]	Special unitary group	LU		✳	✳			N-qubit = 3
[38]	Algebraic geometry	SLOCC	✳	✳	✳			N-qubit = 2, 3, 4
[39]	Separable neural network quantum state	LOCC		✳		✳		N-qubit = 3
[40]	Integer partitions	SLOCC		✳	✳			N-qubit = 4
[41]	Single polynomial entanglement measure	SLOCC		✳	✳			N-qubit = 4

BP = Bipartite, MP = Multipartite, PU = Pure State, MX = Mixed State, AR = Arbitrary State, LU = Local unitary, LOCC = Local operations and classical communication, SLOCC = Stochastic local operations and classical communication

Table IV lists 25 published entanglement classification methods. The protocols used in the studies were emphasized instead of the methods. The LU, LOCC, and SLOCC protocols were identified in the articles. As shown in Fig. 5, it was found that SLOCC is the most utilized protocol. This may be due to the fluidity of the SLOCC protocols in classifying entanglement. The protocols were classified into three clusters, as depicted in Fig. 5.

**B. Conceptual framework of entanglement quantification and classification**

Methods for quantifying and classifying entanglement established in previous studies were thoroughly examined to comprehend the essence of both concepts. The purpose of this research is to develop a conceptual framework of entanglement quantification and classification in bipartite and multipartite systems. The framework was developed following the specifications established in previous studies on the

quantum qubit system and state for entanglement quantification, as well as entanglement classification protocols.

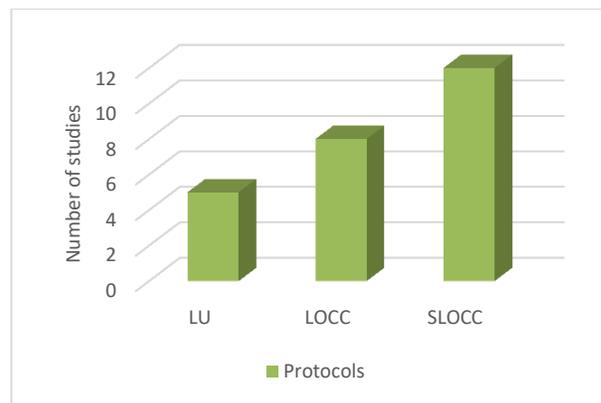


Fig. 5. Entanglement Classification Protocols Clusters.

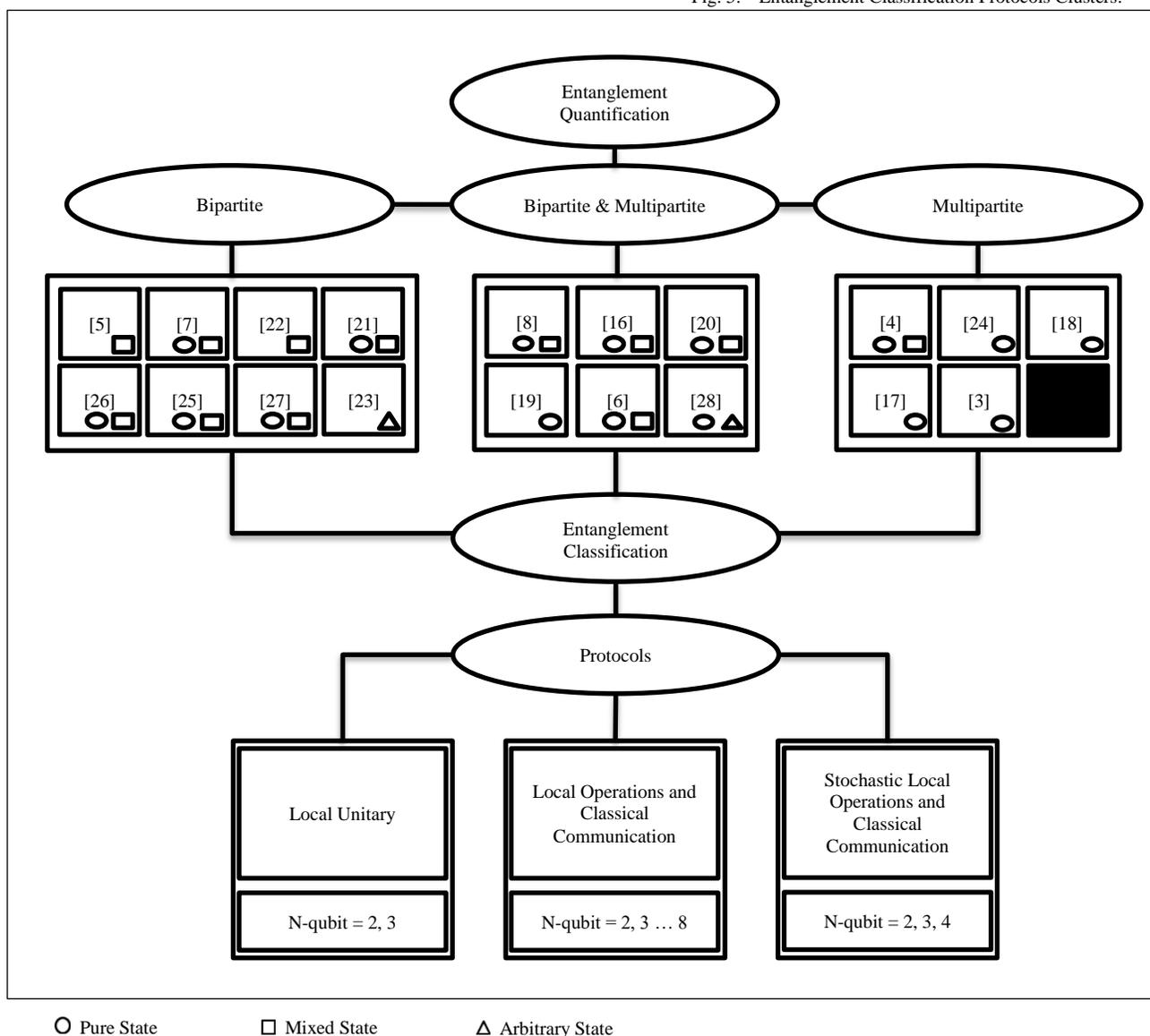


Fig. 6. Proposed Conceptual Framework of Entanglement Quantification and Classification.

#### IV. CONCLUSION

Even though significant progress has been achieved, entanglement quantification and classification remains a challenging and open problem in quantum information processing, especially in mixed quantum state and when there are many particles (qubits) involved, i.e.,  $n$ -qubit  $\geq 4$ .

This study presents several established methods for quantifying and classifying entanglement that have been identified in previous studies. In addition, a conceptual framework of entanglement quantification and classification in bipartite and multipartite systems was developed and presented as a guidance or reference for future work based on one's specific requirements, namely measurement methods, qubit system, quantum state and protocols.

The understanding of the entanglement measures and classification is still considered insufficient. Therefore, further study on entanglement quantification and classification methods based on the proposed conceptual framework is needed to produce a universal quantification measurement and precise classes or families for classification in a higher-qubit and higher-dimensional system.

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