Volume 1, 2025, Pages 253-262
| Regular Article | Open Access
Elaris Computing Nexus

Systematic Analysis and Goal-Based Categorization of Cross Layer Approaches in Ad Hoc Networks

Alfreda Nowak
Faculty of Environmental Engineering and Energy, Cracow University of Technology, Krakow, Poland.
alfreda256@gmail.com

Article Info
Elaris Computing Nexus
https://elarispublications.com/journals/ecn/ecn_home.html

Received 16 August 2025
Revised from 30 October 2025
Accepted 28 November 2025
Available online 24 December 2025
Published by Elaris Publications.

https://doi.org/10.65148/ECN/2025023

Corresponding author(s):
Alfreda Nowak, Faculty of Environmental Engineering and Energy, Cracow University of Technology, Krakow, Poland.
Email: alfreda256@gmail.com

Abstract – Cross-layer design is a highly significant method of maximizing ad hoc network performance. Optimization may be made more challenging in particular situations with traditional tiered designs due to the possibility of a large gap between the stages. This may create throughput, latency and energy consumption issues. In that regard, this paper will critically review 69 articles published since 2002 based on cross-layer techniques in ad hoc networks. We consider the use of the combinations of the layers of the Open Systems Interconnection (OSI) model, its purpose, and the methodology to be applied. Secondly, we employ an algorithm known as Frequent Pattern Growth (FPG) to analyze the frequency of various sets of layers that are chosen and optimize the sets. Our proposal introduces a new goal-based categorization model that identifies 10 overarching issues that are resolved by cross-layer solutions that comprise MIMO and beamforming, routing optimization, cooperative transmission, random access, resource reservation and multi-layer joint optimization.

Keywords – Cross-Layer Design, Ad Hoc Networks, OSI Model, Frequent Pattern Growth, MIMO, Beamforming, Resource Reservation, Cooperative Transmission, Routing Optimization, Energy Efficiency.

I. INTRODUCTION

A sensor network consists of a few miniature sensors, which are capable of detecting such things as sound, pressure, temperature, and vibrations in the environment. Each gadget is outfitted with a compact processor, a wireless communication antenna, and is powered by a battery, resulting in significant resource constraints. In Wireless Sensor Networks (WSNs), sensors often interact directly with a centralized controller or satellites, resulting in single-hop communication between sensors and controllers. Currently, WSNs may consist of autonomous nodes or terminals that interact by establishing a multi-hop ad hoc network. Such WSNs may alter their topology periodically due to node mobility.

In [1], Gopal and Jaffe assert that the broadcast characteristics of wireless communications, in contrast to the point-to-point condition of wired connections, fundamentally limit the efficacy of the layered structure in this context. Additionally, in [2], Trivedi et al. delineates cross-layering as the sole design option for MANETs (Mobile Ad Hoc Networks) and introduces a standardization proposal consisting of four components: the MANET subnetwork interfaces and layers, a cross-layer approaches, hierarchical addressing methods, and a heterogeneous routing protocol.

Ad hoc networks are essential in the advancement of wireless radiocommunications. Self-organized laptops or PDAs ad hoc networks are employed in combat scenarios, conferences, and disaster assistance. These systems inherit the conventional challenges of mobile and wireless communications, including power regulation, bandwidth enhancement, and transfer quality improvement. Moreover, they share properties of multi-hop and may lack having a specific architecture bring new study challenge such as device identification, network design, self-routing, ad hoc addressing and topology maintenance.

The cross-layer protocols are not based on the layered architecture of the typical Open Systems Interconnection (OSI) system. The cross-layered approach treats the protocol stack as an integrated system as opposed to isolated, individual layers. Cross-layer approach to WSNs is more efficient in comparison to the traditional one. Multilayer optimization has been suggested as the way to maximize the profit and minimize the costs [3]. Enhancement of process is complicated further when we consider the different factors, which include multiple technologies, layer analysis, accurate modelling of traffic, and realistic hierarchy of cost. Finding an almost optimal solution to highly complex multi-layer optimization problems has become a major issue. Networking protocols are defined guidelines of communication between connected computers.

The layered paradigm has been complexed in affecting its use in networking protocol formulations and implementations. Traditional protocol stack designs are monolithic, such that the design and implementation of one protocol can make the assumption that other protocols exist and have specifics, in the stack. With a layered protocol stack implementation, every protocol is developed and executed independently, with explicit specifications of any assumptions regarding other protocols; the protocols are then built into a protocol stack in order [4]. Layered implementations offer flexibility in employing component protocols to create specialized protocol stacks, simplify development and debugging by allowing isolated protocol testing, and are typically more comprehensible than monolithic implementations due to the explicit dependencies among protocols.

The fundamental premise of cross-layer design (CLD) is to ensure that data is accessible to all layers of the protocol stack. It permits the specification of processes or protocols that do not conform to OSI model isolation layers. Cross-layer integration and design strategies substantially enhance energy conservation in WSNs. Numerous studies commenced by concentrating on cross-layer interactions and approach to formulate novel communication protocols.

We present an in-depth study of CLD strategies on the ad hoc network, in terms of interaction among various layers on OSI and their objectives in optimization. Through the analysis of the applicable literature, the paper aims to unravel the common combinations of layers and optimization goals, categorize them in terms of the purpose, and suggest an enhanced goal-directed classification scheme that will help create more efficient and goal-oriented cross-layer protocols in the future.

The remainder of this study has been organized in the following manner: Section II describes CLD principles, describing concepts such as OSI reference model, motivation for CLD, and CLD classification. Section III gives a summary of other works, which have some relationship with CLD in ad hoc networks. Section IV describes the data and methods, highlighting (i) literature gathering and selection, (ii) data coding and analytical model and (iii) FPG analysis and categorizing. Section V provided a thorough discussion of the results. Finally, Section VI wraps up the study by outlining the importance of CLD methods in ad hoc networks.

II. CLD PRINCIPLES

Cross-layer refers to all methods that improve, combine, or optimize across several levels. To comprehend the standards of CLD, we initially provide in Section II(A) the OSI reference model, which established tiers to standardize communications. CLD fundamentally contravenes this rigid tiered architecture. Section II(B) elucidates the rationale behind cross-layer architectures. Section II(C) presents a comprehensive taxonomy of cross-layer designs.

OSI Reference Model

The International Organization for Standardization (ISO) established the OSI reference system. The primary goal of the paradigm is to control how interrelated systems interact. The internal operation and organization of every Open System (OSs) is not governed by the system; nonetheless, the exterior behavior of the open system must adhere to the OSI architecture.

Fig. 1 illustrates that the model categorizes all jobs essential for operating a communication model into 7 tiers. The categorization into levels is based on analogous features. Comprehensive details regarding the functionalities of each layer are available in [5]. Every layer delivers services to the subsequent higher layer. Independence of the layers is ensured by delineating the services without specifying the methods of their delivery. One or more entities deliver the services of a layer through an endpoint to the interfaces of the subsequent higher layer. Interfaces within two OSs, which function at a similar layer are referred to as peer interfaces. Different protocols facilitate the communications between peer interfaces.

Howser [6] enumerates thirteen points that substantiate the seven-layer framework. The objectives of the tiers include, among others:

- Establishing a boundary at a juncture where the service description is minimal and inter-layer interactions are reduced,
- Facilitating modifications of protocols or functions within a tier without impacting adjacent tiers, and
- Designing interfaces for each layer that interact solely with its immediate upper and lower tiers.

Motivation for CLD

The OSI system is widely known and the purpose of its layering is clear and logical. The question is about the reasons behind violating this well-defined structure, like performing interactions between layers or making the layers such that the functions or protocols of a layer require to change because of the changes in the functions or protocols of another layer. The answer lies in the inherently different nature of wireless/wired communication. The OSI system was originally wired communication. There are unique characteristics of wireless communication compared to cable communication. **Table 1** outlines four key areas and unique characteristics of wireless and wired communications.

Whereas the layering as per the OSI system simplifies the system design, it is characterized by inflexibility. The highly increased heterogeneity of wireless networks with regard to link mobility, medium access control, power management, and connections require more flexible framework. Due to the influence of mobility on many layers concurrently, coordination and adaptation among these layers is necessary to respond to rapid changes in the wireless network. Interaction across layer borders can facilitate the coordination of adjacent levels. However, the distinct properties of wireless connectivity have created novel dependencies between non-adjacent levels, necessitating the establishment of new interfaces between these layers.

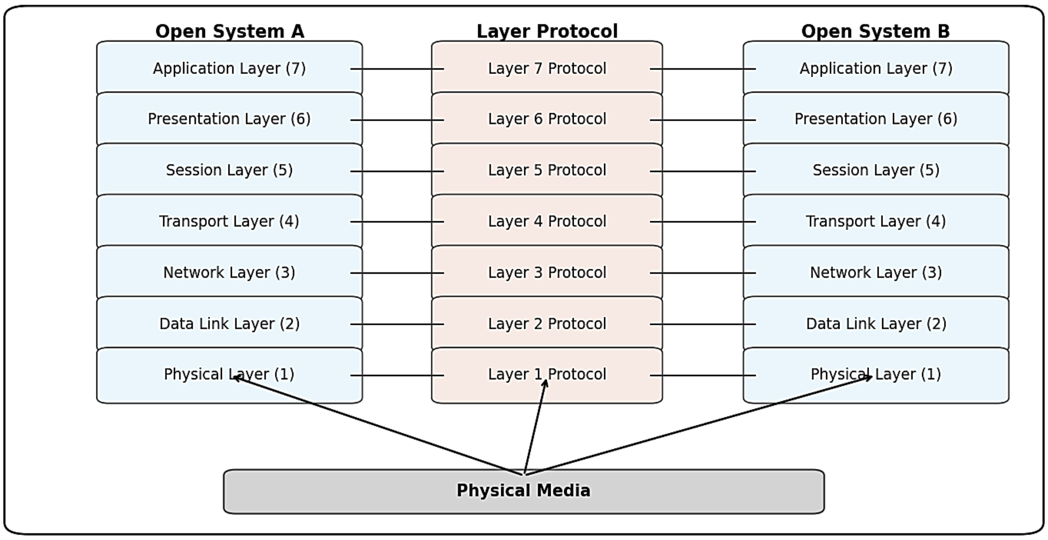

Fig 1. Two Oss Structured in Accordance with the OSI Reference System's Layering.

Table 1. Wireless Vs. Wired Communication Characteristics

Characteristic	Description
Link Connectivity	In wireless, nodes can communicate based on SINR; link quality varies with space, time, and interference.
Power Control	Transmit power affects link quality, data rate, number of neighbors, and network topology.
MAC	Due to wireless broadcast nature, issues like hidden/exposed nodes occur; MAC efficiency impacts QoS (delay, throughput).
Mobility	Node mobility alters network topology, routing, and link quality over time.

Cross-Layer Design Classification

Clearly, multiple options for implementing cross-layer architectures are available. Babber and Randhawa [7] categorize cross-layer designs based on the extent to which they contravene the initial OSI reference system. They identify six categories of CLD illustrated in **Fig. 2**.

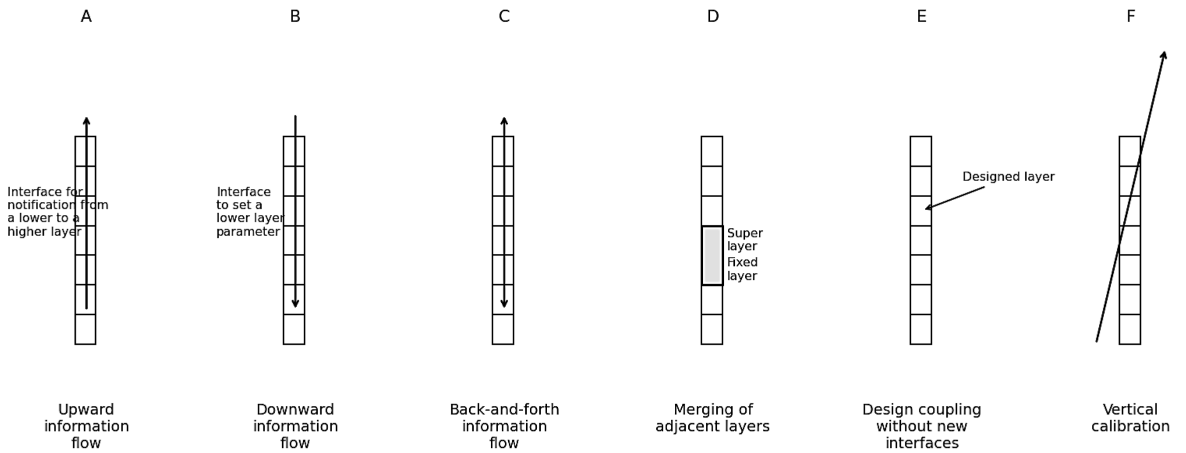

Fig 2. Categories of Cross-Layer Design Suggestions.

In models shown in Examples A–C, completely new interfaces are created. Transmission of data from the lowest to a higher layer (A) may cause this, as seen in [8]. Video communications across wireless channels may be made easier using a bottom-up approach, which involves communicating information about the equivalence classes of operational terminals from the physical layer up to the higher layers. In [10], Böhringer [9] presents the polar opposite of a bottom-up method—a top-down technique. A SINR request is sent to the physical layer for each client service class that specifies QoS needs at the application layer.

The PHY layer accomplishes **Fig. 3**, which describes MAC and LLC sub-tiers of the data connection layer. The need for an enhanced spatial analysis method. Novel interfaces are constructed by transmitting information from a higher to a lower layer, as shown by class B in **Fig. 2**. Class C encompasses all methodologies in which novel interfaces are established by bidirectional data exchanges between two levels. Unlike classes A-C, which generate new interfaces, class D integrates nearby levels. Two or more interconnected layers' services are consolidated in the resulting super layer.

There are no newly-created interfaces. An example of a collaborative PHY-MAC CLD that may ape this super layer is one that reduces interference from multiple access. Class F will be outlined before class E is explained. Every stratum is vertically calibrated in Class F. It adjusts the parameters continuously during runtime in reaction to changes in network or channel conditions, or it statically sets all layers during design depending on a given measure. Neither Class E nor any of the subsequent classes add new interfaces nor alter the OSI reference model's structure by merging layers.

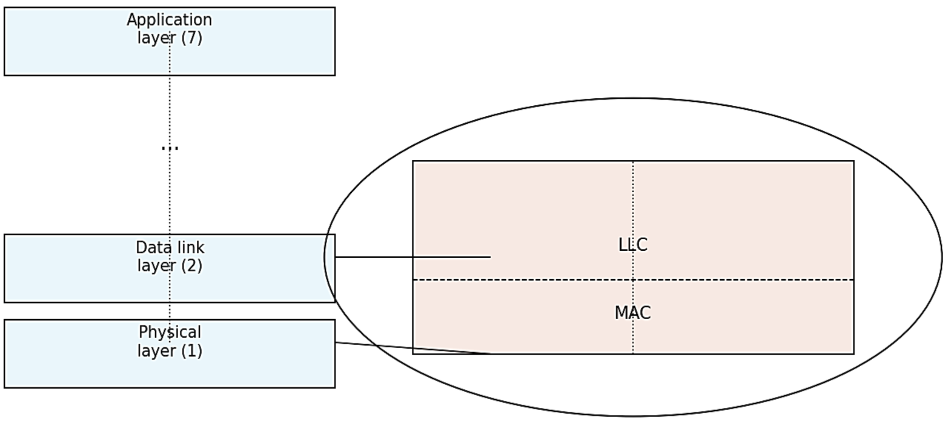

Fig 3. LLC and MAC Data Connection Layer Sublayers.

Changes to the functionality of one layer cause another layer to modify its operations. The Mud-MAC system is an instance of a CLD. Assuming that the fundamental physical layer is MUD-compatible, this protocol is intended to improve spatial reuse with the right MAC protocol setup. In the OSI reference design, the data link layer consists of two sub-layers, the MAC layer and the LLC (Logical Link Control) layer, as shown in **Fig. 3**. When many users try to access common media at the same time, it sets up the access mechanism to avoid multiple access interference.

III. RELATED WORK

As mentioned by Lin, Kwok, and Wang [11], the most possible way to come up with energy-efficient communication protocols is through cross-layer design. Conventional means of communication have a high overhead, and this aspect results in high inefficiencies. The cross-layer optimizations in WSNs aim at reducing energy, maximizing routing effectiveness, guaranteeing QoS (quality of service) and optimum scheduling. CLD holds the opinion that the parameters at numerous levels can be accessed and/or changed to achieve targeted goals.

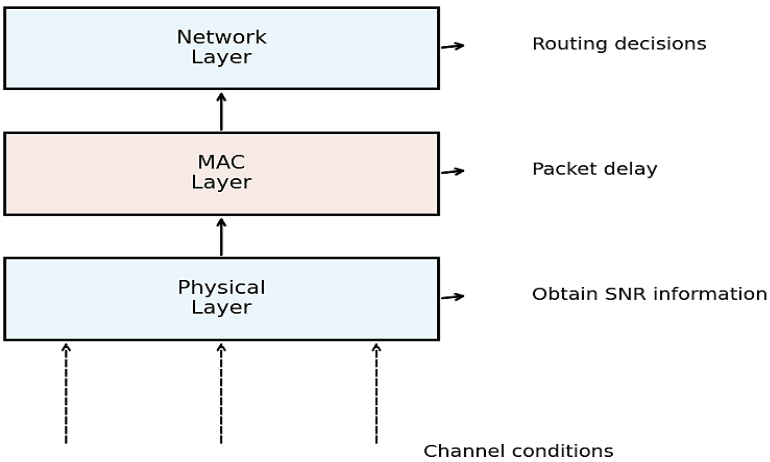

Fig 4. Cross- Layer Communication for Routing.

The study of efficient routing was provided in detail by Nakas, Kandris, and Visvardis [12]. The basic premise behind CDN is that when the control and data delivery in a large number of levels are simultaneously optimized, there is the possibility of achieving significant performance improvements by utilizing the interactions between different protocol stack levels. Nonetheless, a disadvantage of this design is the possibility of undermining the modularity of the whole system. **Fig. 4** depicts the cross-layer concept for routing.

As discussed by Lv and Luo [13], channel estimation at the physical layer provides the real-time SNR (signal-to-noise ratio) of a connection, which is utilized to ascertain the information rate, hence affecting the transfer delay. The routing algorithm identifies the ideal route based on the delay of each connection, hence ensuring equitable distribution of the network load across the available connections. Thus, cross-layering improves the efficacy of the subordinate levels.

Jiang et al. [14] studied the maximum multi-hop massively parallel ad hoc network capability. Multi-Input Multi-Output (MIMO) is an important method of increasing the capacity of the wireless networks. Although much research has been conducted on MIMO at the link and physical levels, limited research has been conducted on MIMO at the network level, namely with rules of capacity scaling in multi-hop MIMO ad hoc networks. In [15], Bolcskei et al. focus on the principles of capacity grading of MIMO ad hoc networks. They are aimed at figuring out the achievable output of each node as the number of nodes decreases in the network. Their system architecture was a MIMO system which includes IC (interference cancellation), and SM (spatial multiplexing).

The seven-layered OSI model provides a conceptual model of network communication by defining the activities like data transfer, routing and session management. New et al. [16] state that the tiered approach of the model allows easier comprehension and troubleshooting; however, its strict division of the levels puts pressure on the modern wireless networks. This includes an increase in latency and resource consumption of processing per layer, limited adaptability to the changing wireless conditions, and difficulties with dealing with emerging technologies such as MIMO and beamforming.

Su and Lim [17] show that cross-layer design solutions get around these problems by making it easier for layers to talk to each other and work together to improve network performance, security, and efficiency by allowing levels to work together in real time based on the situation. This strategy makes resource management and flexibility better than what the standard OSI model can do. This is why cross-layer designs are so important for modern wireless communication systems.

IV. DATA AND METHODS

Literature Acquisition and Selection

The research is based on a systematic and reproducible approach to the literature acquisition following the criteria of systematic reviews. We obtained publications from Wiley Online Library, ScienceDirect, SpringerLink, ACM Digital Library, and IEEE Xplore, all of which were published after 2002. The search was done with limited and free-text search phrases. These include, but are not limited to: cross-layer design AND ad hoc networks, multi-layer optimization AND wireless, and protocol adaptation AND cross-layer. Our initial number of publications was 482, and after eliminating the publications that did not satisfy the requirements, (i) must mention at least two OSI layers of the architecture, (ii) must be concerned with a wireless network that does not require an infrastructure, or is configured on the fly, and (iii) performance study must be performed by using real-world data, simulations, or theoretical techniques. After the screening process, 69 publications were retained.

Table 2. Literature Acquisition Summary

Stage	Count
Initial query results	482
After duplicate removal	398
After abstract-level screening	152
After applying inclusion rules	69

The meticulous filtering made sure that the dataset was both complete and a good example of cutting-edge research. **Table 2** shows how the process of narrowing down works, from the query output to the final inclusion.

Data Encoding and Analytical Framework

To make it easier to analyze the data, each publication was encoded in two orthogonal dimensions: layer involvement and optimization goals. The OSI layers were represented using Eq. (1) as a finite set.

$$\mathcal{L} = \{\mathrm{l}_1, \mathrm{l}_2, \mathrm{l}_3, \mathrm{l}_4, \mathrm{l}_5\}, \tag{1}$$

where l_1, l_2, l_3, l_4 and l_5 denote the physical, data link, network, transport, and application layers, respectively. For any publication p_i, its layer representation was captured as a binary vector using Eq. (2).

$$\mathrm{v}(p_i) = [x_1, x_2, x_3, x_4, x_5], \quad x_j \in \{0, 1\} \tag{2}$$

Here, $x_j = 1$ if layer l_j is employed in the study and $x_j = 0$ otherwise.

Similarly, optimization goals were formalized as Eq. (3).

$$\mathcal{G} = \{\text{throughput, latency, energy, stability, packet error rate, interference, overhead}\} \tag{3}$$

For each publication, a goal vector was encoded as Eq. (4).

$$g(p_i) = [y_1, y_2, \dots, y_m], \quad y_k \in \{0,1\}, \tag{4}$$

with $y_k = 1$ if optimization goal k is addressed. The dual-vector representation enabled unified analysis of structural (layer) and functional (goal) dimensions. **Table 3** shows a fragment of the coding scheme used.

Table 3. Example Encoding of Publications

Pub.	Physical	Data Link	Network	Transport	Application	Throughput	Latency	Energy	Stability	PER	Overhead
P01	1	1	1	0	0	1	0	1	0	0	0
P02	1	0	1	0	0	0	1	1	0	0	0
P03	1	1	1	1	0	1	0	0	1	1	0

FPG Analysis and Classification

To identify dominant combinations of layers and optimization goals, the Frequent Pattern Growth (FPG) algorithm was applied to the binary dataset. The frequency of occurrence of an itemset S (where $S \subseteq \mathcal{L} \vee S \subseteq G$) was defined using Eq. (5).

$$f(S) = \frac{|\{p_i \in D \mid S \subseteq v(p_i) \vee S \subseteq g(p_i)\}|}{|D|} \tag{5}$$

where D is the set of all reviewed publications. An itemset was considered frequent if Eq. (6):

$$f(S) \geq \theta, \tag{6}$$

with the support threshold set at θ = 0.05.

The FPG algorithm recursively constructs conditional FP-trees, compressing transactions into prefix structures and generating association rules of Eq. (7).

$$S_1 \Rightarrow S_2, \quad \text{with support } f(S_1 \cup S_2), \text{ confidence } \frac{f(S_1 \cup S_2)}{f(S_1)} \tag{7}$$

This made it possible to find co-optimization trends, like the common occurrence of throughput and energy efficiency or the connection of physical and data link layers. The frequencies that were taken out were put into layer combinations (**Table 4**) and optimization targets (**Table 5**).

Table 4. Layer Combination Frequencies

Combination	**Frequency $f(S)$**
(Physical, Data Link)	0.54
(Data Link, Network)	0.54
(Physical, Network)	0.40
(Physical, Data Link, Net)	0.31

Table 5. Optimization Goal Frequencies

Goal Combination	**Frequency $f(S)$**
(Line Throughput)	0.36
(Power Consumption)	0.21
(Path Throughput)	0.33
(Path Stability)	0.13
(Latency + Throughput)	0.06

The developed association rules allowed for the change from purely structural categorization (by OSI layers) to goal-oriented categories. For example, a protocol that spans the physical, MAC, and network layers and aims to minimize interference is clearly labeled as an “interference-driven design” instead of being vaguely labeled as “three-layer interaction.”

V. RESULTS AND DISCUSSION

A total of 69 articles were examined from 2002 to 2023. The annual publication release is shown as a histogram. The examined papers indicate that CLD use various OSI model tier integration. The FPG (frequent pattern growth) method was used to determine the frequency of various layer combinations in the analyzed publications. The channel, network, and physical layers are the most often used cross-layer techniques (see **Table 6**). Ad hoc networks cannot exist without the initial 3 tiers, which have the most significant effect on them.

By integrating FPG to the objectives of the methodologies in the examined papers, we recorded these findings (see **Table 7**). The enhancement of line constraints is more prevalent than the enhancement of path measures. This mostly occurs because optimizing path measures requires a comprehensive understanding of the system, which is more challenging and entails more service information overhead than acquiring localized expertise. The two predominant characteristics are line consumption and throughput of energy, with their combined frequencies above 0.571. It occurs because all other line constraints affect and determine output.

Table 6. Frequency of Layer Use in Analyzed Publications

Frequency	Layer Combination
0.07	(3 4 5)
0.07	(1 3 4 5)
0.07	(2 3 4 5)
0.07	(1 2 3 4 5)
0.07	(1 2 3 5)
0.09	(4 5)
0.09	(1 3 4)
0.09	(1 2 3 4)
0.09	(1 4 5)
0.09	(2 4 5)
0.09	(1 2 4 5)
0.09	(2 3 5)
0.1	(1 2 5)
0.12	(1 4)
0.12	(1 2 4)
0.12	(1 3 5)
0.13	(2 5)
0.15	(3 4)
0.15	(2 3 4)
0.15	(1 5)
0.21	(3 5)
0.24	(4)
0.24	(2 4)
0.25	(5)
0.31	(1 2 3)
0.4	(1 3)
0.54	(2 3)
0.54	(1 2)
0.63	(1)
0.7	(3)
0.84	(2)

Optimizing line output inherently enhances other metrics. Path constraints are contingent upon line characteristics and energy usage. When the power unit is exhausted, the route associated with that node is interrupted. The analyzed literature categorizes cross-layer approaches into two primary types: first, methods that focus on a single layer while using other levels, and second, approaches that emphasize the joint enhancement of many layers. Within these two overarching groups, 10 objectives for using a CLD are evident: Resource reservation, cooperative transmission, unpredictable channel access, MIMO, overlay networks, application information flow adaptability to network condition, routing metrics, and protocols. Simultaneous optimization of various layers.

In [18], cross-layer methodologies were categorized based on the combinations of layers used. This categorization is comprehensive but inadequately represents the fundamental nature of cross-layer approaches. In alignment with the objective of using the cross-layer strategy, we formulated a novel categorization of CLD approaches in decentralized networks (see **Fig. 5**) based on the intended outcomes of utilizing multiple layers. The suggested categorization may facilitate the simplification of objective-driven CLD protocol design.

The main aims of network management protocols are latency, packet error rate, and throughput. These goals stay the same no matter how many levels are involved in the process of making things better. At the same time, there may be several ways to reach these aims. The proposed taxonomy helps to organize various strategies.

When creating a new CLD protocol, there is often a specified goal to reach, such a channel access protocol or a routing protocol. Since the standards in these releases have already been sorted using the specified taxonomy, **Fig. 6** can help choose the articles that will be the basis for research on new cross-layer protocols. The proposed classification is goal-oriented, unlike traditional combination-oriented categorizations. Classifications based on combinations may be confusing. For instance, allowing a CLD to use the channel, physical, and network levels. This approach may be classified as a routing protocol, a channel access protocol, or a protocol characterized by separate layers and data exchange.

Table 7. Frequency Of Goals in the Examined Publications

Frequencies	Goal Integration
0.01	(line packet error rate, energy usage)
0.01	(path stability, line latency)
0.01	(line throughput, line delay, path stability)
0.01	(power usage, line latency, line throughput)
0.01	(route packet error rate - RPER, power usage, route throughput)
0.01	(RPER, interference)
0.01	(power consumption, interference)
0.01	(route throughput, RPER, interference)
0.01	(interference, RPER, power consumption)
0.01	(energy consumption, path throughput, interference)
0.01	(power consumption, path throughput, RPER, interference)
0.01	(path stability, path throughput)
0.01	(path latency, RPER)
0.01	(path stability, path latency)
0.01	(path latency, line throughput)
0.01	(path throughput, path latency, RPER)
0.01	(path stability, path latency, line throughput)
0.01	(data overhead, path stability)
0.03	(power consumption, line latency)
0.03	(RPER, power consumption)
0.03	(path throughput, interference)
0.04	(line throughput, line latency)
0.04	(path throughput, RPER)
0.04	(interference, line throughput)
0.04	(path stability, line throughput)
0.06	(line delay)
0.06	(path throughput, energy usage)
0.06	(path throughput, path latency)
0.09	(interference)
0.09	(path latency)
0.09	(information overhead)
0.1	(RPER)
0.13	(path stability)
0.21	(energy consumption)
0.33	(path throughput)
0.36	(line throughput)

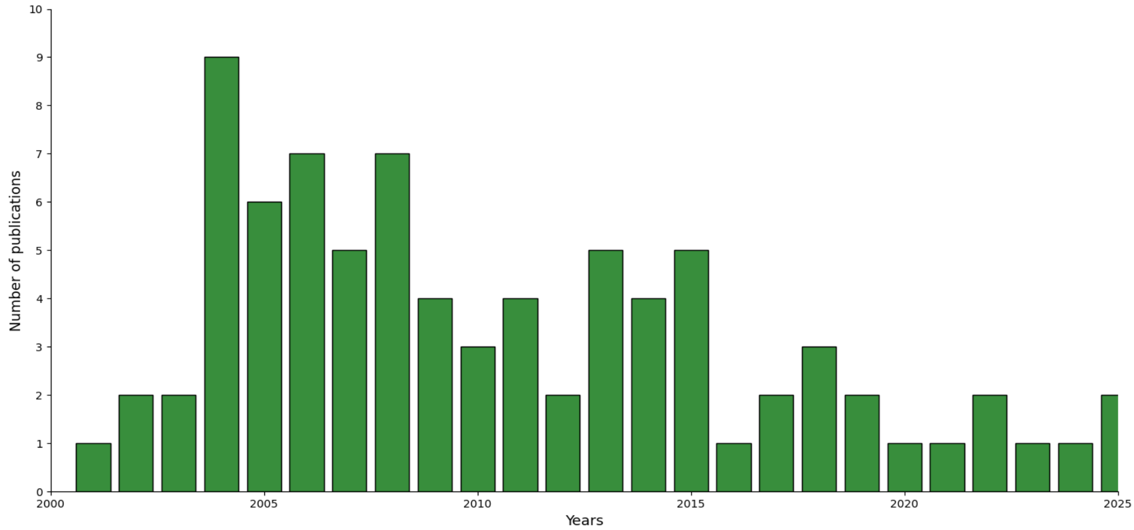

Fig 5. Publication Activity on CLD for Decentralized Networks.

The suggested classification provides a clear reason for the technique that was looked at. This condition makes the suggested categorization more useful. We were able to find the 10 problems that a CLD could help with thanks to the categorization. There are ten problems listed above. Before, these problems were fixed in a single matching layer.

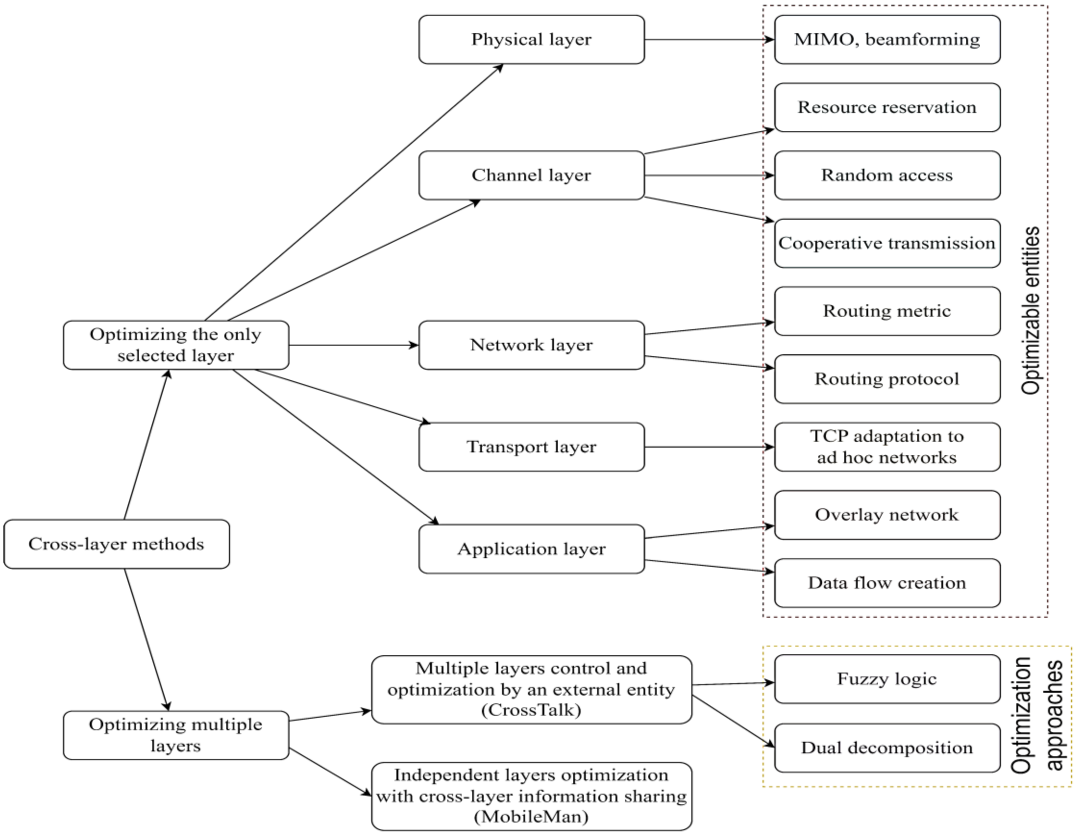

Fig 6. CLD Approaches for the Categorization of Ad Hoc Networks.

VI. CONCLUSION

We have studied the CLD methods in ad hoc networks and found that there are significant disclosures about the prevalent OSI layer combinations and optimization objectives in existing studies. Using the FPG algorithm, we were able to discover strong patterns and correlations between layers and optimization goals, focusing on energy usage and throughput. The proposed goal-based classification model is better than the traditional layer-combination classification, which gives a better insight into the intent of cross-layer designs. Such new framework helps to formulate superior protocols because it helps to make a better distinction among different procedures and their purposes. Future studies can use this classification to advance cross-layer procedures, therefore, enhancing the functionality of ad hoc networks and optimizing resource usage.

CRediT Author Statement

The author reviewed the results and approved the final version of the manuscript.

Data Availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interests

The authors declare no conflict of interest.

Funding

No funding agency is associated with this research.

Competing Interests

There are no competing interests.

References

[1]. Gopal and J. Jaffe, "Point-To-Multipoint communication over broadcast links," IRE Transactions on Communications Systems, vol. 32, no. 9, pp. 1034–1044, Sep. 1984, doi: 10.1109/tcom.1984.1096179.
[2]. H. Trivedi, P. Veeraraghavan, S. Loke, A. Desai, and J. Singh, "Routing mechanisms and cross-layer design for Vehicular Ad Hoc Networks: A survey," 2011 IEEE Symposium on Computers & Informatics, pp. 243–248, Mar. 2011, doi: 10.1109/isci.2011.5958921.
[3]. C. Rozic, D. Klonidis, and I. Tomkos, "A survey of multi-layer network optimization," 2016 International Conference on Optical Network Design and Modeling (ONDM), pp. 1–6, May 2016, doi: 10.1109/ondm.2016.7494053.
[4]. X. Gu, X. Fu, H. Tschofenig, and L. Wolf, "Towards self-optimizing protocol stack for autonomic communication: Initial experience," in Lecture notes in computer science, 2006, pp. 186–201. doi: 10.1007/11687818_15.
[5]. J. Borges, L. C. Rodrigues, R. L. Reis, and J. F. Mano, "Layer-by-Layer assembly of Light-Responsive Polymeric multilayer systems," Advanced Functional Materials, vol. 24, no. 36, pp. 5624–5648, Jul. 2014, doi: 10.1002/adfm.201401050.
[6]. G. Howser, "The OSI seven-layer model," in Springer eBooks, 2019, pp. 7–32. doi: 10.1007/978-3-030-34496-2_2.
[7]. K. Babber and R. Randhawa, "Cross-Layer designs in wireless sensor networks," in Studies in computational intelligence, 2018, pp. 141–166. doi: 10.1007/978-3-662-57277-1_7.
[8]. H. V. Poor, "Information and inference in the wireless physical layer," IEEE Wireless Communications, vol. 19, no. 1, pp. 40–47, Feb. 2012, doi: 10.1109/mwc.2012.6155875.
[9]. C. Böhringer, "The synthesis of bottom-up and top-down in energy policy modeling," Energy Economics, vol. 20, no. 3, pp. 233–248, Jun. 1998, doi: 10.1016/s0140-9883(97)00015-7.
[10]. V. Crespi, A. Galstyan, and K. Lerman, "Top-down vs bottom-up methodologies in multi-agent system design," Autonomous Robots, vol. 24, no. 3, pp. 303–313, Jan. 2008, doi: 10.1007/s10514-007-9080-5.
[11]. X. Lin, Y. Kwok, and H. Wang, "Cross-layer design for energy efficient communication in wireless sensor networks," Wireless Communications and Mobile Computing, vol. 9, no. 2, pp. 251–268, Feb. 2008, doi: 10.1002/wcm.608.
[12]. C. Nakas, D. Kandris, and G. Visvardis, "Energy Efficient routing in wireless sensor Networks: A Comprehensive survey," Algorithms, vol. 13, no. 3, p. 72, Mar. 2020, doi: 10.3390/a13030072.
[13]. C. Lv and Z. Luo, "Deep Learning for channel estimation in Physical Layer Wireless Communications: Fundamental, methods, and challenges," Electronics, vol. 12, no. 24, p. 4965, Dec. 2023, doi: 10.3390/electronics12244965.
[14]. C. Jiang, Y. Shi, Y. T. Hou, and S. Kompella, "On the Asymptotic Capacity of Multi-Hop MIMO Ad Hoc Networks," IEEE Transactions on Wireless Communications, vol. 10, no. 4, pp. 1032–1037, Feb. 2011, doi: 10.1109/twc.2011.020111.100528.
[15]. H. Bolcskei, R. U. Nabar, O. Oyman, and A. J. Paulraj, "Capacity scaling laws in MIMO relay networks," IEEE Transactions on Wireless Communications, vol. 5, no. 6, pp. 1433–1444, Jun. 2006, doi: 10.1109/twc.2006.1638664.
[16]. W. K. New., "A tutorial on fluid antenna system for 6G networks: encompassing communication theory, optimization methods and hardware designs," IEEE Communications Surveys & Tutorials, p. 1, Jan. 2024, doi: 10.1109/comst.2024.3498855.
[17]. W. Su and T. L. Lim, "Cross-layer design and optimisation for wireless sensor networks," International Journal of Sensor Networks, vol. 6, no. 1, p. 3, Jan. 2009, doi: 10.1504/ijsnet.2009.028021.
[18]. "Integrated approaches to enhancing Cross-Layer communication and antenna design for Next-Generation wireless networks," National Journal of Antennas and Propagation, vol. 7, no. 1, Jan. 2025, doi: 10.31838/njap/07.01.16.

ISSN (Online): 3105-9082