The Component Structure: An Alternative Mesoscopic Representation for Complex Networks

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Abstract: We introduce the "component structure," a mesoscopic representation that differentiates between a network's dense and sparse global components. Unlike its alternatives (community structure, core-periphery), the representation offers a straightforward definition, captures a broader spectrum of mesoscopic features, and supports hierarchical analysis, allowing for a multilevel network examination of networks' organizational principles and functional behaviors.

Complex networks are prevalent in various scientific disciplines, representing systems as diverse as social interactions [1-3], pandemics [4-7], and technological infrastructures [8-9]. Traditional network analysis often focuses on microscopic (node-level) or macroscopic (network-level) properties. However, these approaches can miss critical mesoscopic structures, such as communities, motifs, and other intermediate-scale features. This work introduces the concept of the component structure as an alternative mesoscopic representation, highlighting its potential to provide deeper insights into the organizational principles and functional behaviors of complex networks [10-16].

Complex networks are characterized by intricate patterns of connectivity among their elements. Two scales of analysis have traditionally dominated the study of these networks: the microscopic scale, focusing on individual nodes and edges, and the macroscopic scale, which examines global properties such as degree distributions, network diameter, and overall connectivity. While these approaches have yielded significant insights, they often overlook the importance of mesoscopic structures that play a crucial role in the functionality and evolution of complex networks. Mesoscopic structures, such as communities, clusters, motifs, and core-periphery structures, provide an intermediate level of organization that bridges the gap between a network's local and global properties. These structures are critical for understanding the network's modular organization, resilience, and dynamics. For instance, in social networks, communities may represent groups of individuals with shared interests or activities, while in biological networks, motifs can indicate recurring functional subunits.

Communities are groups of nodes that are more densely connected than the rest of the network. Detecting and analyzing communities can reveal hierarchical organization and functional modules within networks, providing insights into their structural and functional properties. Motifs are small, recurring subgraphs that appear more frequently in a network than would be expected by chance. They are fundamental building blocks that can give insights into the network's underlying principles and functions. For example, certain motifs in transcriptional regulatory networks correspond to specific biological functions. Core-periphery structures consist of a densely connected core and a sparsely connected periphery. Nodes in the core are highly interconnected, often forming the backbone of the network, while peripheral nodes are connected primarily to the core rather than to each other. This structure is prevalent in social,

economic, and infrastructure networks. The multi-core-periphery model extends the core-periphery concept to networks with multiple dense cores, each with its periphery. This representation captures the presence of several central hubs within the network, each surrounded by less-connected nodes, reflecting a more complex and realistic organizational pattern in many real-world networks.

The component structure of a network is proposed as an alternative mesoscopic representation, emphasizing the role of cohesive subgroups within the network. The component structure differentiates between dense local components and sparse global components. Local components represent cohesive subgroups within the network, whereas global components capture the interactions between these subgroups. This dual-component approach provides a more nuanced understanding of network organization. A component in a network is defined based on its density and connectivity. Local components are densely connected subgraphs, representing clusters of closely interacting nodes. Global components, on the other hand, are sparser structures that connect these dense local components, capturing the broader interaction patterns within the network. To identify these components, algorithms can be adapted to distinguish between high-density clusters (local components) and their sparser connections (global components). Techniques such as modularity optimization for community detection and connectivity analysis for global interactions can be employed.

The component structure approach offers several advantages:

1. It has a clear and straightforward definition, avoiding the ambiguities that often arise with community and core-periphery structures.
2. It captures a broader spectrum of mesoscopic features than traditional community, motif, or core-periphery-based methods.
3. Each component in the component structure is itself a network. This allows using standard network analysis tools and techniques on these sub-networks, facilitating deeper and more flexible analyses [17].
4. The component structure inherently supports hierarchical analysis. Researchers can recursively identify components within components until no significant density inhomogeneities remain, providing a comprehensive multilevel view of the network's organization.
5. Analyzing the distribution and properties of components can reveal insights into the network's robustness, vulnerability, and functional organization.

By integrating this perspective with traditional microscopic and macroscopic analyses, researchers can achieve a more nuanced understanding of complex networks,

Demonstrating this concept, Figure 1 illustrates the component structure of global transportation networks [18-20]. It identifies seven locally defined geographical clusters and a global component that includes international airports and their interconnections. This differentiation deepens our understanding of how the network is organized and interconnected on regional and interregional scales. The degree centrality reported in Table 1 of the various components allows us to distinguish the regional and international roles of the airports worldwide [21]. It offers an alternative to the community-aware centrality approach [22-23].

References

[1] K. A. Qureshi, R. A. S. Malick, M. Sabih and H. Cherifi," Complex Network and Source Inspired COVID-19 Fake News Classification on Twitter," in IEEE Access, vol. 9, pp. 139636-139656, 2021.

[2] Khubaib Ahmed Qureshi, Rauf Ahmed Shams Malick, Muhammad Sabih, Hocine Cherifi, Deception detection on social media: A source-based perspective, Knowledge-Based Systems, Volume 256, 2022, 109649, ISSN 0950-7051, https://doi.org/10.1016/j.knosys.2022.109649.

[3] Eeti, A. Singh and H. Cherifi, "Centrality-Based Opinion Modeling on Temporal Networks," in *IEEE Access*, vol. 8, pp. 1945-1961, 2020
[4] M. Arquam, A. Singh and H. Cherifi," Impact of Seasonal Conditions on Vector-Borne Epidemiological Dynamics," in IEEE Access, vol. 8, pp. 94510-94525, 2020,
[5] M. Kumar, A.Singh, and H.Cherifi An Efficient Immunization Strategy Using Overlapping Nodes and Its Neighborhoods. In Companion Proceedings of the The Web Conference 2018
[6] Chakraborty, D., Singh, A., Cherifi, H. Immunization Strategies Based on the Overlapping Nodes in Networks with Community Structure. In: Nguyen, H., Snasel, V. (eds) Computational Social Networks. CSoNet 2016. Lecture Notes in Computer Science, vol 9795. Springer
[7] N. Gupta, A. Singh, and H. Cherifi, Community-based immunization strategies for epidemic control, 7th International Conference on Communication Systems and Networks (COMSNETS), Bangalore, India, 2015, pp. 1-6, doi: 10.1109/COMSNETS.2015.7098709.
[8] Ghalmane, Z., Cherifi, C., Cherifi, H. et al. Extracting backbones in weighted modular complex networks. SciRep 10, 15539 (2020). https://doi.org/10.1038/s41598-020-71876-0.
[9] Ghalmane, Z., Cherifi, C., Cherifi, H. et al. Extracting modular-based backbones in weighted networks, Information Sciences, Vol 576, 2021, Pages 454-474,
[10] Diop, I.M., Cherifi, C., Diallo, C., Cherifi, H. (2022). Targeted Attacks on the World Air Transportation Network: Impact on Its Regional Structure. In: Pacheco, D., Teixeira, A.S., Barbosa, H., Menezes, R., Mangioni, G. (eds) Complex Networks XIII. Springer Proceedings in Complexity. Springer, Cham.
[11] Diop, I.M., Cherifi, C., Diallo, C., Cherifi, H. (2022). Targeted Attacks on the World Air Transportation Network: Impact on Its Regional Structure. In: Pacheco, D., Teixeira, A.S., Barbosa, H., Menezes, R., Mangioni, G. (eds) Complex Networks XIII. Springer Proceedings in Complexity. Springer, Cham. https://doi.org/10.1007/978-3-031-17658-6_1
[12] I. M. Diop, C. Cherifi, C. Diallo and H. Cherifi, "Robustness of the Weighted World Air Transportation Network Components," *2022 IEEE Workshop on Complexity in Engineering (COMPENG)*, Florence, Italy, 2022, pp. 1-6, doi: 10.1109/COMPENG50184.2022.9905439.
[13] Issa Moussa Diop, Cherif Diallo, Chantal Cherifi, Hocine Cherifi," Robustness Analysis of the Regional and Interregional Components of the Weighted World Air Transportation Network," Complexity, vol. 2022, Article ID 6595314, 17 pages, 2022.
[14] Diop, I.M., Cherifi, C., Diallo, C., Cherifi, H. (2023). Targeted Attack of the Air Transportation Network Global Component. In: CSoNet 2022. Lecture Notes in Computer Science, vol 13831. Springer, Cham. https://doi.org/10.1007/978-3-031-26303-3_11
[15] Diop, I.M., Cherifi, C., Diallo, C., Cherifi, H. (2023). Targeted Attacks Based on Networks Component Structure. In: CompleNet 2023. Springer Proceedings in Complexity. Springer, Cham. https://doi.org/10.1007/978-3-031-28276-8_6
[16] Hmaida, S., Cherifi, H. & El Hassouni, M. A multilevel backbone extraction framework. Appl Netw Sci 9, 41 (2024). https://doi.org/10.1007/s41109-024-00645-z
[17] Diop, I.M., Diallo, C., Cherifi, C., Cherifi, H. (2024). On the Hierarchical Component Structure of the World Air Transport Network. In: Studies in Computational Intelligence, vol 1142. Springer, Cham. https://doi.org/10.1007/978-3-031-53499-7_19
[18] Diop, I.M., Cherifi, C., Diallo, C. et al. Revealing the component structure of the world air transportation network. Applied Network Science 6, 92 (2021).
[19] Issa Moussa Diop, Cherif Diallo, Chantal Cherifi, Hocine Cherifi," Exploring the Regional Structure of the Worldwide Air Traffic and Route Networks," Complexity, vol. 2023, Article ID 3411799, 29 pages, 2023. https://doi.org/10.1155/2
[20] Diop, I.M., Diallo, C., Cherifi, C., Cherifi, H. (2024). Weighted and Unweighted Air Transportation Component Structure: Consistency and Differences. Studies in Computational Intelligence, vol 1142. Springer, Cham. https://doi.org/10.1007/978-3-031-53499-7_20

[21] Diop, I.M., Diallo, C., Cherifi, C., Cherifi, H. (2024). On Centrality and Core in Weighted and Unweighted Air Transport Component Structures. In: Studies in Computational Intelligence, vol 1142. Springer, Cham. https://doi.org/10.1007/978-3-031-53499-7_22
[22] Rajeh, S., Savonnet, M., Leclercq, E. et al. Comparative evaluation of community-aware centrality measures. Qual Quant 57, 1273–1302 (2023). https://doi.org/10.1007/s11135-022-01416-7
[23] Rajeh S, Cherifi H Ranking influential nodes in complex networks with community structure. PLoS ONE 17(8): e0273610. https://doi.org/10.1371/journal.pone.0273610

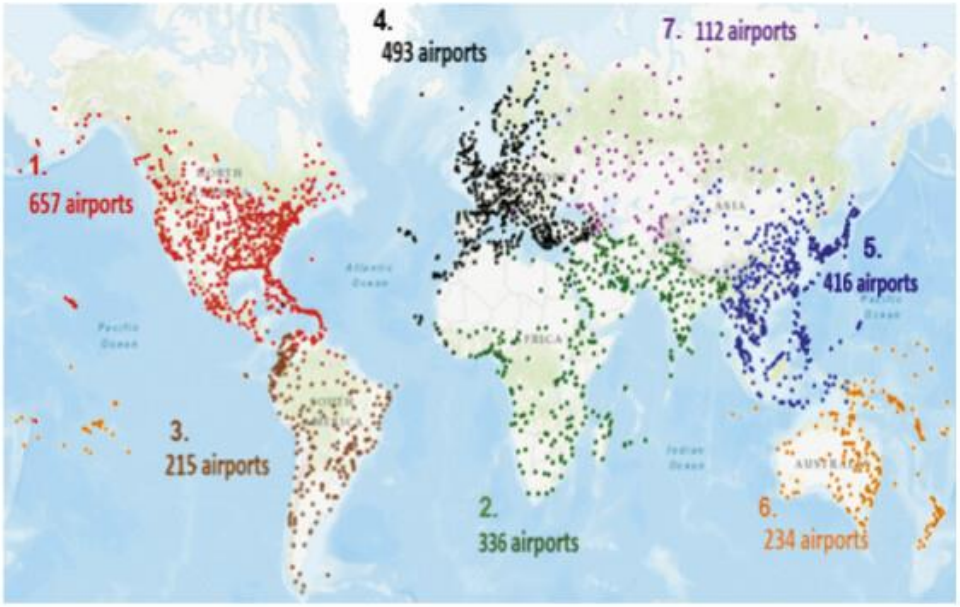


Figure 1 (a) **The large local components of the unweighted network.** Each color is associated with a component. The North and Central America-Caribbean component is red (1). The Africa-Middle East-India component is green (2). South American component is brown (3). Europe is in black (4). East and Southeast Asia is blue (5), and Oceania is orange (6). Russia is in purple (7)



Figure 1 (b) The airports in the **large global component** of the unweighted network are distributed all over the world

Table 1 (a) **Degree Centrality in the seven large local components.** The top five hubs for each large local component are reported. ID is the internal degree. It measures the number of connections of an airport with airports located in its large local component. LR is the airport's local rank in its component by decreasing internal degree. CP is the cumulative fraction of connected airports and represents the proportion of airports that the top x local hubs can reach in their components

Large Local Component	Airport	City	Country	ID	LR	CP (%)
North and central America Caribbean	Hartsfield J	Atlanta	USA	187	1	23,89
	Dallas Fort Worth	Dallas	USA	172	2	35,92
	Chicago O'Hare	Chicago	USA	172	3	40,18
	Denver	Denver	USA	161	4	47,64
	George B Houston	Houston	USA	146	5	49,77
Europe	Schiphol	Amsterdam	Netherlands	162	1	32,86
	Munich	Munich	Germany	145	2	40,36
	London Stansted	London	UK	142	3	51,72
	Barcelona	Barcelona	Spain	137	4	55,78
	Frankfurt	Frankfurt	Germany	132	5	56,79
East and Southeast Asia	Beijing Capital	Beijing	China	133	1	31,97
	Guangzhou Baiyun	Guangzhou	China	112	2	37,25
	Shanghai Pudong	Shanghai	China	112	3	41,34
	Chengdu Shuangliu	Chengdu	China	95	4	44,47
	Taiwan Taoyuan	Taipei	Taiwan	87	5	46,63
Africa Middle East-Southern Asia	Dubai	Dubai	U A E	78	1	23,14
	King Abdudaziz	Jeddah	Saudi Arabia	63	2	30,56
	Indira Gandhi	Delhi	India	60	3	39,76
	Chhatrapati Shivaji	Mumbai	India	58	4	42,13
	Addis Ababa Bole	Addis Ababa	Ethiopia	56	5	51,33
Oceania	Sydney K Smith	Sydney	Australia	55	1	23,5
	Brisbane	Brisbane	Australia	48	2	31,19
	Auckland	Auckland	New Zealand	36	3	38,46
	Melbourne	Melbourne	Australia	33	4	40,59
	Port M Jacksons	Port Moresby	P New Guinea	24	5	48,71
South America	G G A F Montoro	Sao Paulo	Brazil	48	1	22,42
	El Dorado	Bogota	Colombia	44	2	40,65
	Viracopos	Campinas	Brazil	42	3	45,32
	Jorge Newbery	Buenos Aires	Argentina	41	4	60,28
	P J Kubistschek	Brasilia	Brazil	36	5	64,48
Russia Central Asia-Transcaucasia	Domodedovo	Moscow	Russia	81	1	72,32
	Pulkovo	St Petersburg	Russia	49	2	82,14
	Sheremetyevo	Moscow	Russia	49	2	84,82
	Tolmachevo	Novosibirsk	Russia	32	4	85,71
	Koltsovo	Yekaterinburg	Russia	31	5	85,71

Table 1 (b) **Degree centrality in the large global component.** The top five inter-regional hubs in each region are reported. ED is the external degree. It measures the number of connections of an airport with airports located in the large global component. GRR is the global rank of the airport in its region. GRC is the global rank in the global component is the airport rank in the global component by decreasing external degree

Region	Airport	City	Country	ED	GRR	GRC
North and central America-Caribbean	John F Kennedy	New York	USA			9
	Lester B Pearson	Toronto	Canada			19
	Newark Liberty	Newark	USA	39	3	24
	Miami	Miami	USA	36	4	27
	Los Angeles	Los Angeles	USA	34	5	30
Europe	Frankfurt	Frankfurt	Germany	106	1	1
	Charles de Gaulle	Paris	France	104	2	2
	Atatürk	Istanbul	Turkey	99	3	3
	Heathrow	London	UK	89	4	4
	Schiphol	Amsterdam	Netherlands	80	5	7
East and Southeast Asia	Beijing Capital	Beijing	China	61	1	10
	Suvarnabhumi	Bangkok	Thailand	57	2	12
	Narita	Tokyo	Japan	56	3	13
	Incheon	Seoul	South Korea	48	4	15
	Hong Kong	Hong Kong	Hong Kong	47	5	16
Africa-Middle East-Southern Asia	Dubai	Dubai	U A E	89	1	4
	Hamad	Doha	Qatar	59	2	11
	Abu Dhabi	Abu Dhabi	U A E	42	3	22
	Cairo	Cairo	Egypt	34	4	30
	Indira Gandhi	Delhi	India	31	5	32
Oceania	Sydney K Smith	Sydney	Australia	26	1	41
	Melbourne	Melbourne	Australia	20	2	57
	Auckland	Auckland	New Zealand	13	3	96
	Perth	Perth	Australia	13	3	96
	Brisbane	Brisbane	Australia	12	4	106
South America	Guarulhos-G A F M	São Paulo	Brazil	36	1	26
	El Dorado	Bogotá	Colombia	30	2	36
	Jorge Chávez	Lima	Peru	22	3	53
	Ministro Pistarini	Buenos Aires	Argentina	19	4	61
	Rio G–T Jobim	Rio de Janeiro	Brazil	18	5	69
Russia-Central Asia-Transcaucasia	Sheremetyevo	Moscow	Russia	84	1	6
	Domodedovo	Moscow	Russia	77	2	8
	Pulkovo	St Petersburg	Russia	47	3	16
	Vnukovo	Moscow	Russia	31	4	32
	Heydar Aliyev	Baku	Azerbaijan	23	5	51

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