Ben-Gurion University of the Negev

Faculty of Engineering Science

School of Electrical and Computer Engineering

Dept. of Communication System Engineering

Fourth Year Engineering Project

Final Report

# Practical solutions for fault-tolerant networks

| | |
|---|---|
| **Project number:** | **p-2023-012** |
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| **Supervisor:** | Prof. Michael Segal |
| **Submitting date:** | 10.07.2023 |

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# 1. Abstract

## 1.1 English abstract

**Practical solutions for fault-tolerant networks**

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Adviser name: Prof. Segal Michael

Wireless communication is increasingly being employed to transfer highly sensitive information. Wireless networks lack fixed topology, with changing node disposition. Temporary network structure depends on node distribution and transmission range, forming a communication graph. Energy efficiency is a primary objective due to limited device energy supplies.

The aim of the project is to design an algorithms that achieves cost-effective wireless network that satisfies specific properties, such as graph diameter demands, pairwise connectivity demands and network lifetime, while minimizing total power consumption.

Five methods were developed and evaluated:

- Method 1: Clustering and adjusting power based on distance from the center node.
- Method 2: Clustering and adjusting power based on MST structure of center nodes.
- Method 3: Clustering and assigning power based on MST of border nodes.
- Method 4: Creating K edge-disjoint paths and adjusting power incrementally.
- Method 5: Creating K node-disjoint paths and adjusting power incrementally.

Findings showed trade-offs: Methods 1 and 2 have the best time complexity, while Methods 4 and 5 have poorer running times. Methods 1, 2, and 3 prioritize low graph diameter, while Methods 4 and 5 emphasize network resilience. Methods 2 and 3 achieves the lowest power consumption among all methods. There is a trade-off between minimizing power consumption, graph diameter, and node failure resilience.

This project offers practical wireless network optimization solutions, considering power consumption, graph diameter, and network resilience. Trade-offs should be considered when choosing the appropriate method.

**Keywords:** wireless network, clustering, graph diameter, pairwise connectivity, network lifetime, energy efficiency, communication graph.

## 1.2 Hebrew Abstract

**<u>פתרונות מעשיים לרשתות עמידות לנפילות</u>**


שמות הסטודנטים: מוסקוביץ' שניר, מולאי דור

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מנחה: פרופ' סגל מיכאל



תקשורת אלחוטית משמשת יותר ויותר להעברת מידע רגיש במיוחד. רשתות אלחוטיות חסרות טופולוגיה קבועה, כאשר מיקום הצמתים משתנה. מבנה הרשת הזמני תלוי במיקום הצמתים במרחב ובטווח השידור. פרמטרים אלה קובעים גרף תקשורת. מכשירים אלחוטיים מצוידים בדרך כלל באספקת אנרגיה מוגבלת, מה שהופך את יעילות ניצול האנרגיה לאחת היעדים העיקריים בתכנון הרשת.

מטרת הפרויקט היא לתכנן אלגוריתמים הבונים רשת אלחוטית על ידי השמת הספקים לכל מכשיר בגרף, כך שהרשת תהיה חסכונית ותספק מאפיינים ספציפיים, כגון דרישות קוטר גרף, דרישת קישוריות בין זוגות צמתים ומשך חיי הרשת, תוך מזעור צריכת האנרגיה הכוללת.

פיתחנו ובדקנו חמש שיטות:

- שיטה 1: חלוקה לקבוצות (לפי מיקום) והשמת הספק לפי מרחק מהצומת המרכזי.
- שיטה 2: חלוקה לקבוצות והשמת הספק על בסיס מבנה MST של צמתים מרכזיים.
- שיטה 3: חלוקה לקבוצות והשמת הספק על בסיס מבנה MST של צמתי גבול.
- שיטה 4: יצירת K מסלולים זרים בקשתות והעלאת ההספק בהדרגה.
- שיטה 5: יצירת K מסלולים זרים בצמתים והעלאת ההספק בהדרגה.

הממצאים הראו שקלול תמורות: לשיטות 1 ו-2 יש את סיבוכיות הזמן הטובה ביותר, בעוד שלשיטות 4 ו-5 יש זמני ריצה ארוכים יותר. שיטות 1, 2 ו-3 נותנות עדיפות לקוטר גרף נמוך, בעוד ששיטות 4 ו-5 שומרות על עמידות הרשת לנפילת צמתים. שיטות 2 ו-3 השיגו את סכום ההספקים הנמוך ביותר מבין כל השיטות. קיים שקלול תמורות בין מזעור צריכת האנרגיה, קוטר הגרף עמידות הרשת לנפילות.

פרויקט זה מציע פתרונות מעשיים לאופטימיזציה של רשת אלחוטית, תוך התחשבות בצריכת האנרגיה, קוטר הגרף ועמידות הרשת. יש לבחור העדפות בעת בחירת השיטה המתאימה.



**מילות מפתח:** רשת אלחוטית, חלוקה לקבוצות, קוטר גרף, קישוריות בין זוגות צמתים, חיי רשת, נצילות אנרגיה, גרף תקשורת.

# 2. Introduction

## 2.1 Project's goal

The project's main goal is to design algorithm that assign power $a_v$ for every node so that message transmission between all nodes will work properly with minimum power as possible, while saving battery life as much as possible and satisfy a given property.

## 2.2 Approaches and methods

we extensively reviewed articles covering relevant topics, focusing on features that align with our properties demands. By merging these concepts with our own insights, we developed a new algorithms specifically tailored to address our problem. We conducted a comparative analysis of the methods, classifying them based on their suitability for different network topologies, including wide and small networks. This evaluation enabled us to identify the most effective method for each scenario, facilitating efficient problem-solving within diverse network structures.

## 2.3 Methodology

Our working method throughout the project is divided into three stages.
In the first stage we will design algorithm that combines several algorithms for solving the power assignment problem.
In the second stage, we analyzed our efficiency of our algorithms compared to the optimal solution on **simple** topologies.
In the third stage, we examined our algorithms on wide and complicated topologies and compared the results between the different methods.

# 4. Our approach

## 4.1 Method 1

We employed the KMeans algorithm to cluster the nodes in a graph G. Each cluster is represented by a center node that is chosen based on its proximity to other nodes in the cluster. To determine the center node, we calculate the mean coordinates of the nodes in the cluster and select the node closest to this mean position. This ensures that the chosen center node is representative of the cluster's overall location.

After clustering, we assign power to each individual node based on its distance from its respective center node. Nodes closer to the center node are allocated less power, while nodes farther away receive higher power assignments. This power adjustment scheme optimizes energy consumption and enhances the network's overall efficiency.

Additionally, we assign power to the center nodes in a way that ensures connectivity among them. By distributing power appropriately, we guarantee that all the center nodes are connected, forming a reliable communication backbone for the network.

The time complexity of this method is $O(k \cdot n)$, where $\boldsymbol{k}$ represents the number of clusters and $\boldsymbol{n}$ represents the number of nodes in the network. This approach provides an effective solution for optimizing power consumption in wireless networks while maintaining low graph diameter.

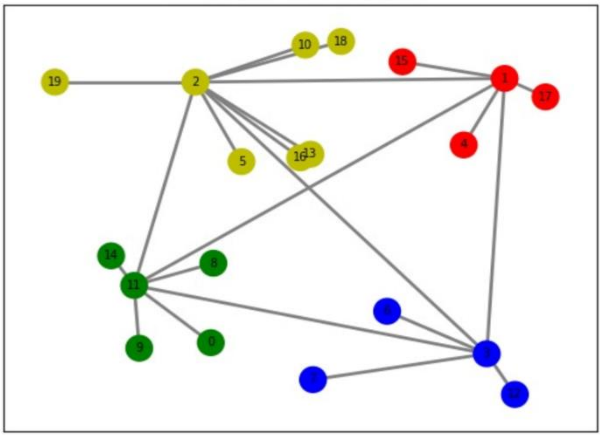


*Figure 1: running example of method 1*

## 4.2 Method 2

We employed the KMeans algorithm to cluster the nodes in a graph G. Each cluster is represented by a center node that is chosen based on its proximity to other nodes in the cluster. To determine the center node, we calculate the mean coordinates of the nodes in the cluster and select the node closest to this mean position. This ensures that the chosen center node is representative of the cluster's overall location.

After clustering, we assign power to each individual node based on its distance from its respective center node. Nodes closer to the center node are allocated less power, while nodes farther away receive higher power assignments. This power adjustment scheme optimizes energy consumption and enhances the network's overall efficiency.

In addition, we establish connectivity among the center nodes by constructing a Minimum Spanning Tree (MST) based on their relationships. This ensures that all center nodes are connected, forming a resilient communication backbone within the network.

The time complexity of this method is $O(k \cdot n)$, where $\boldsymbol{k}$ represents the number of clusters and $\boldsymbol{n}$ represents the number of nodes in the network. This approach provides an effective solution for optimizing power consumption in wireless networks while maintaining low graph diameter.

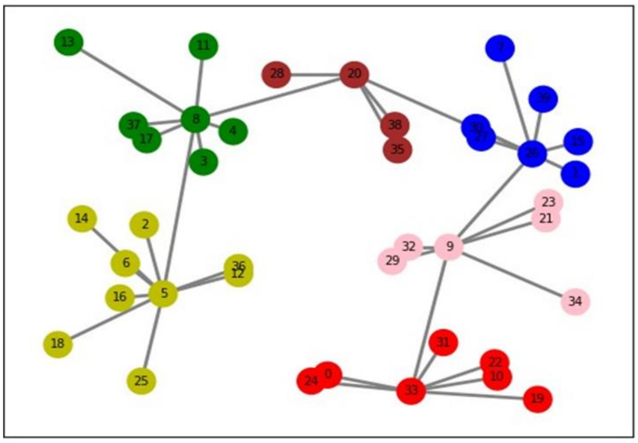

*Figure 2: running example of method 2*

## 4.3 Method 3

we employed the KMeans algorithm to perform clustering on a graph G, grouping nodes into clusters. Subsequently, we identified border nodes by determining the closest node from each cluster to every other cluster.

Next, we constructed the Minimum Spanning Tree (MST) using the border nodes. Power allocation was performed according to the MST, ensuring efficient utilization of energy resources. For each cluster, we connected each node to the closest border node and assigned power levels based distance between them.

The time complexity of this method is $O(k \cdot n^2)$, where $\boldsymbol{k}$ represents the number of clusters and $\boldsymbol{n}$ represents the number of nodes in the network. This approach optimizes power consumption while maintaining network connectivity and resilience.

By combining clustering, border node identification, MST construction, and power assignment, we achieve an effective solution for wireless network optimization. The method considers both inter-cluster and intra-cluster connectivity, resulting in improved performance and energy efficiency.

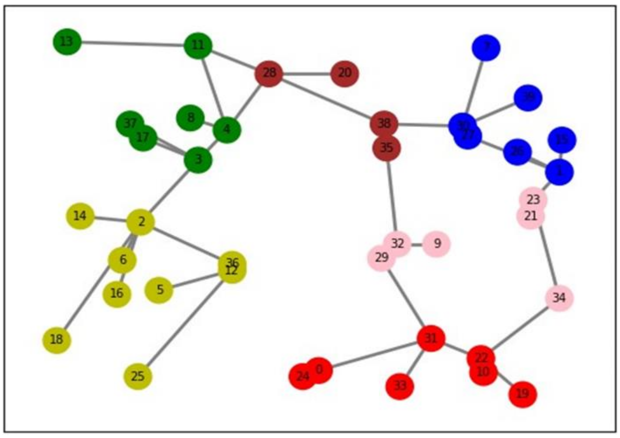


*Figure 3: running example of method 3*

## 4.4 Method 4

we developed a methodology for wireless network optimization by creating K edge-disjoint paths. Initially, we assigned power levels to each node, facilitating communication with its two closest neighbors. Additionally, we connected the connected components in the graph in the most efficient manner possible, starting with the closest pair of components and iteratively extending the connections.

To ensure network connectivity, we verified the existence of K edge-disjoint paths between each pair of nodes. This approach ensured the availability of multiple independent paths, enhancing reliability in communication.

If the desired network property was not initially achieved, we iteratively adjusted the power levels until the desired outcome was met. This iterative process allowed for fine-tuning power allocation and optimizing overall network performance.

The time complexity of this method is $O(n^3 \cdot n!)$, where $\boldsymbol{n}$ represents the number of nodes in the network. This complexity arises from the exhaustive search required to identify the optimal set of K edge-disjoint paths.

By employing this approach, we achieved improved network resilience and efficiency. Through power allocation and the creation of independent paths, we enhanced the network's reliability while minimizing power consumption.

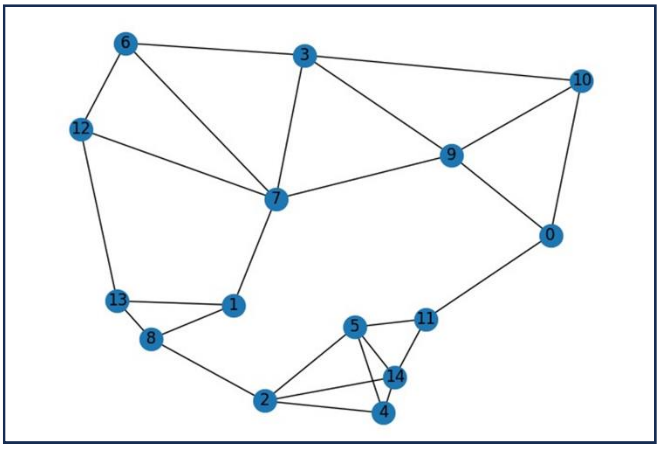


*Figure 4: running example of method 4*

## 4.5 Method 5

we developed a methodology for wireless network optimization by creating K node-disjoint paths. This involved a multi-step approach. Firstly, we constructed the Minimum Spanning Tree (MST) of the wireless network, capturing the connectivity among the nodes, and assign power for each node according to his distance from is farthest neighbor.

Next, for every pair of connected nodes u and v, we established connections between every neighbor of u and every neighbor of v (and assign power accordingly). This step ensured multiple independent paths between different pairs of nodes, enhancing network reliability.

To achieve the desired network property, we incrementally adjusted the power levels, if necessary. This iterative process allowed us to fine-tune power allocation until the desired outcome was satisfied, optimizing network performance.

The time complexity of this method is $O(n^3 \cdot n!)$, where $\boldsymbol{n}$ represents the number of nodes in the network. This complexity arises from the exhaustive search required to find the optimal set of K node-disjoint paths.

Through this approach, we achieved enhanced network resilience and efficiency by creating multiple independent paths and optimizing power allocation. This methodology provides an effective solution for wireless network optimization, meeting the desired network requirements.

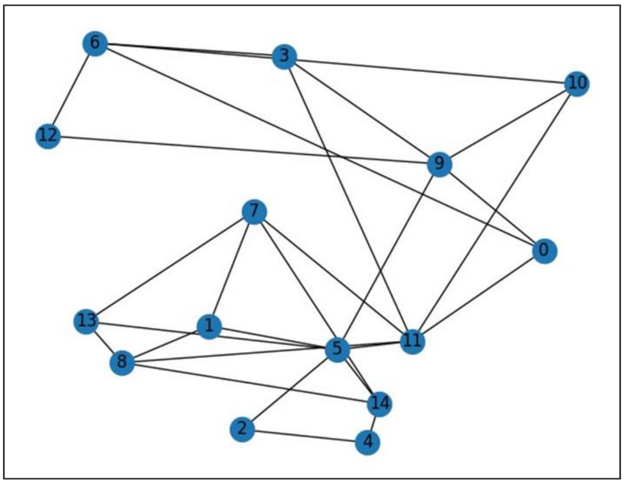


*Figure 5: running example of method 5*

## 5. Tests and verification

In our project, we conducted extensive testing on our algorithms to assess their performance. Initially, we focused on the algorithms that utilize clustering, specifically methods 1, 2, and 3, and compared these results with the outcomes obtained from the MST graph, which serves as the benchmark for the optimal solution in terms of the total power sum. We investigated the impact of varying the number of clusters while keeping the number of nodes fixed.
During the tests, we compared three essential parameters:

- The total power consumption, which directly affects energy efficiency.
- The diameter of the generated graph, which indicates the network's overall size and efficiency in transmitting messages.
- The number of broadcast messages that can be transmitted in the graph, providing an important measure of the network's lifetime and its ability to sustain long-term communication.

Through these rigorous tests and parameter comparisons, we gained valuable insights into the strengths and weaknesses of the clustering-based algorithms. These results allowed us to make informed decisions about which method best suits the specific requirements of our wireless network optimization project.

Furthermore, in the second phase of our testing, we examined and compared the performance of all the methods we previously presented. During this stage, we varied the number of nodes while keeping the number of clusters constant. Through these tests, we evaluated the effectiveness of each method using the same key parameters: total power consumption, graph diameter, and the number of messages transmitted, indicating network lifetime.

Our comprehensive analysis also involved comparing the results of each method against the MST solution, which represents the optimal benchmark for minimizing the total power sum in the network. By doing so, we obtained a comprehensive understanding of the relative strengths and weaknesses of each method and their ability to approximate the optimal solution.

By conducting these tests and comparisons, we gained valuable insights into the efficiency and practicality of each approach, allowing us to make well-informed decisions in selecting the most suitable method for various network configurations and requirements. These results serve as a solid foundation for our project's aim of providing practical approximation algorithms for wireless network optimization.

# 6. Results & Explanations

## 6.1 Cluster methods

We will now present the results of the comparison between the methods that are based on clustering.

We investigated the impact of varying the number of clusters for fixed number of nodes.

The findings and outcomes of our tests are visually represented in the following graphs:

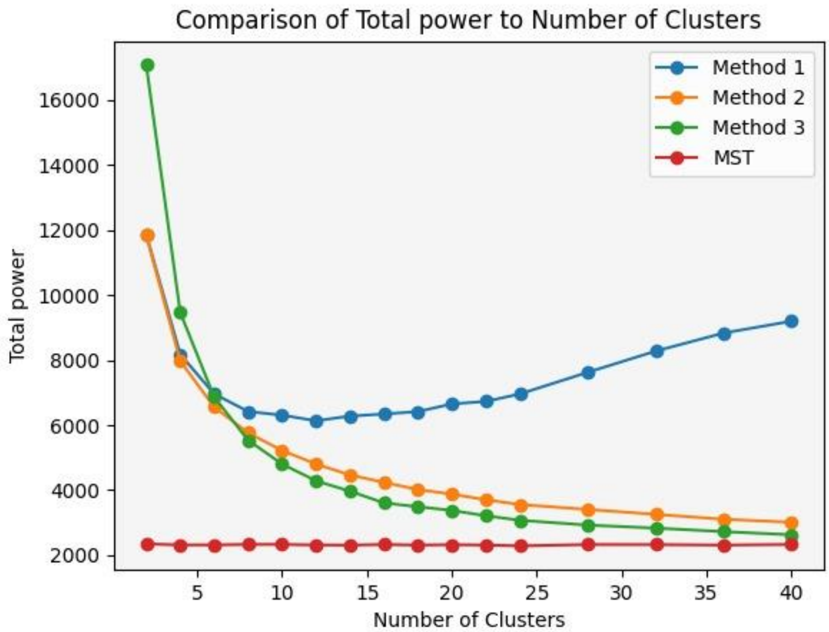


*Figure 6: comparison of total power to number of clusters*

Based on the graph, it is evident that as the number of clusters increases, methods 2 and 3 closely approximate the optimal solution (MST) in terms of the total power sum. Similarly, method 1 behaves similarly up to a certain threshold, but beyond that point, it starts to deviate from the optimal solution, resulting in an increase in the total power sum.

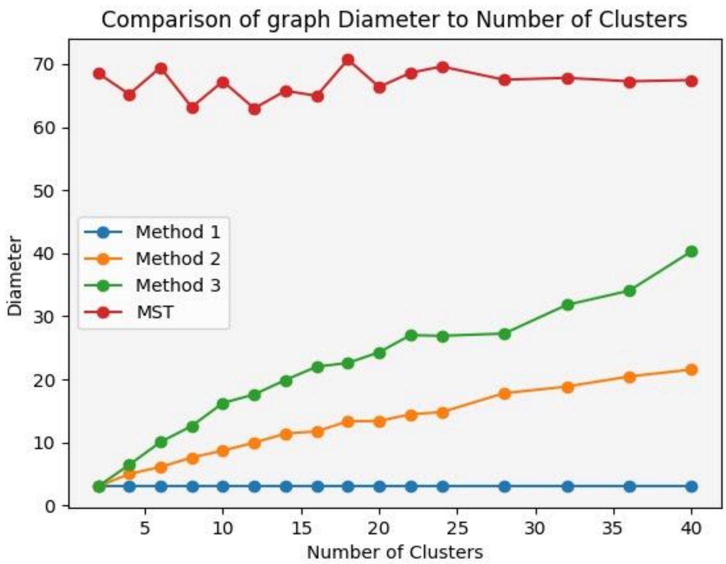


*Figure 7: comparison of graph diameter to number of clusters*

From the graph, it is evident that method 1 consistently maintains a constant graph diameter regardless of the number of clusters. In contrast, methods 2 and 3 exhibit a gradual increase in the graph diameter as the number of clusters increases. This observation highlights the distinct behavior of each method concerning the graph's size and connectivity in response to varying cluster configurations.

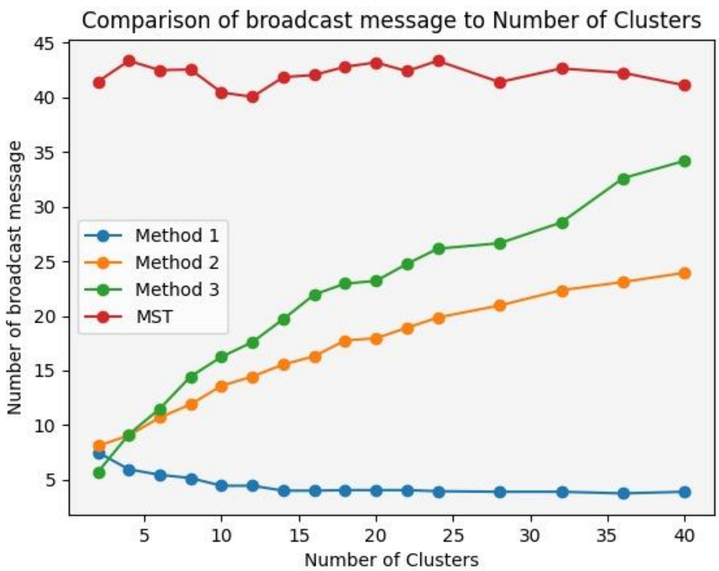


*Figure 8: comparison of number of broadcast message to number of clusters*

Based on the graph, method 1 exhibits behavior opposite to methods 2 and 3. In method 1, the number of broadcast messages that can be sent decreases as the number of clusters increases, indicating a shorter network life with more clusters. Conversely, in methods 2 and 3, the number of broadcast messages increases as the number of clusters increases, implying a longer network life with higher cluster numbers. This observation underscores the contrasting impact of cluster configurations on network lifetime across the different methods.

## 6.2 Comparing all the methods

We will now present the results of the comparison between all the methods. We investigated the impact of varying the number of nodes (for fixed number of clusters).

The findings and outcomes of our tests are visually represented in the following graphs:

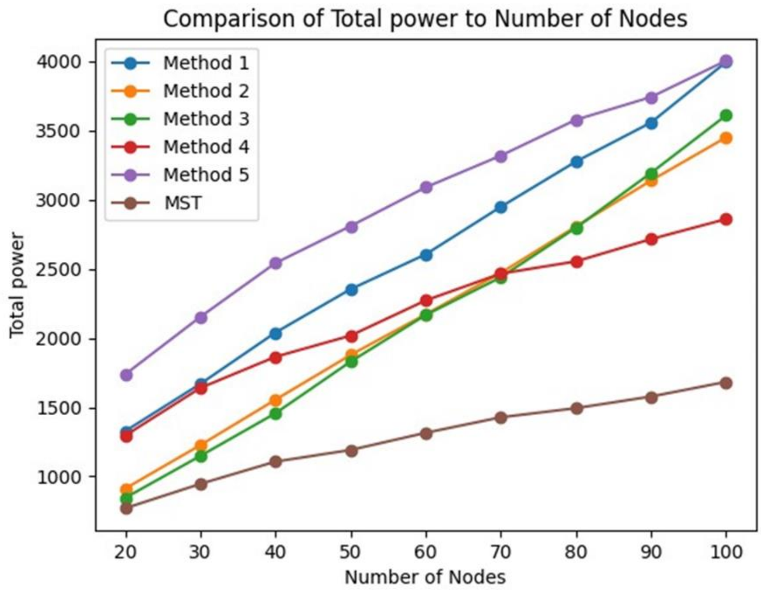


*Figure 9: comparison of total power to number of nodes*

Based on the graph ,in smaller networks, Methods 2 and 3 exhibit performance closest to the optimal solution. However, as the network size grows larger, Method 4 achieves the closest approximation to the optimal solution. Interestingly, Method 5 prioritizes increased network durability, but this comes at the cost of higher power consumption.

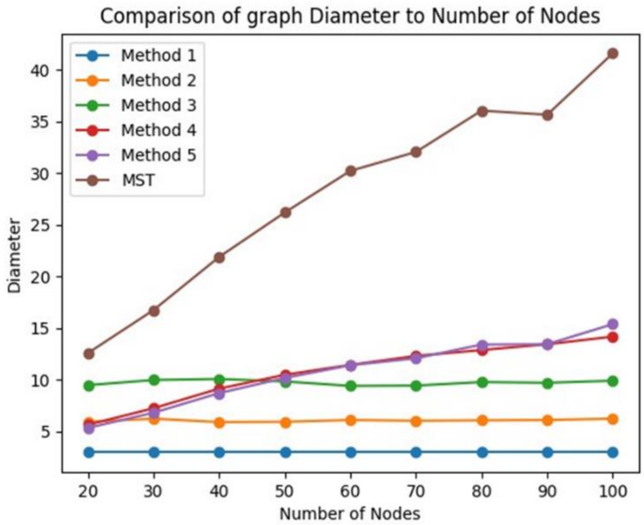


*Figure 10: comparison of graph diameter to number of nodes*

The graph clearly illustrates that in Methods 1, 2, and 3, the graph diameter is solely determined by the number of clusters and remains unaffected by changes in the network size. In contrast, for Methods 4 and 5, the graph diameter exhibits a slow and gradual increase with the network size, indicating a proportional expansion relative to the network's dimensions. This observation highlights the distinct behaviors of these methods concerning the graph's size and connectivity in response to varying network configurations.

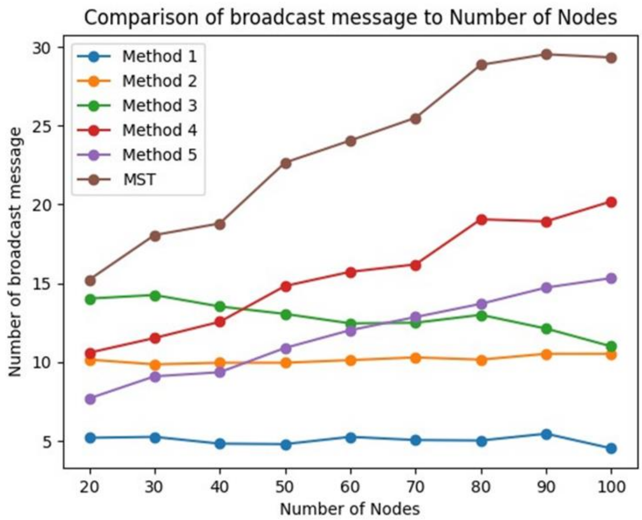


*Figure 11: comparison of number of broadcast message to number of nodes*

As depicted in the graph, the number of broadcast messages passing through the network serves as a representative measure of the network's lifespan. In methods 1, 2, and 3, the number of broadcast messages is primarily determined by the number of clusters and remains unaffected by changes in the network size. Conversely, in methods 4 and 5, the number of broadcast messages exhibits a gradual increase as the network size grows. This observation underscores the differing effects of network configurations on the network's longevity across the various methods.

# 7. Conclusions and recommendations

## 7.1 Summery

Our project on wireless network optimization has been a comprehensive and enlightening endeavor. We covered various stages, from academic research to algorithm development and network analysis. We explored multiple methods, including clustering-based approaches (Methods 1, 2, and 3), and K node-disjoint paths (Method 5) and K edge-disjoint paths (Method 4) methodologies.

Throughout the project, we gained valuable insights into power consumption, graph diameter, and network resilience. Our in-depth analysis involved extensive testing, and we compared the performance of the methods against the Minimum Spanning Tree (MST) solution, representing the optimal benchmark for total power sum.

Overall, this project equipped us with essential skills in wireless network optimization, algorithm development, and experimental testing. Despite encountering various challenges, we successfully navigated through them, enriching our problem-solving abilities and preparing us for real-life scenarios in network design and optimization.

## 7.2 Conclusions

Based on our comprehensive analysis and comparison of the methods for wireless network optimization, we have derived valuable conclusions. For scenarios where the primary objective is to achieve the minimum total power consumption, the Minimum Spanning Tree (MST) method stands as the optimal choice.

When seeking a balance between minimum total power consumption and minimum graph diameter, two methods have proven to be highly effective. Method 2, which centers on creating a clique based on clustering, and Method 3, employing a border MST approach, both demonstrate excellent performance in these conditions.

On the other hand, when the focus is on attaining minimum total power consumption while adhering to a given graph diameter, Method 1, which centers MST based on clustering, outperforms the other methods.

Lastly, for situations demanding minimum total power consumption and fault-tolerant networks, Method 4, with its k-edge disjoint paths approach, and Method 5, utilizing k-node disjoint paths, prove to be the most suitable choices.

Our findings provide valuable insights into selecting the appropriate method for specific wireless network configurations, ensuring energy efficiency, graph connectivity, and network resilience are optimally balanced.

## 7.3 Schedule vs planning

The task management attached in appendix (Task management).

We had some delays between the task management to Gantt chart. Firstly, at the beginning of our project, we did not estimate properly how much each part would take us due to our lack of experience. Secondly, this delay did not detract from the results and submissions since according to the Gantt chart we were supposed to finish everything ahead of time, which in practice did not happen.

## 7.4 Recommendations for a future work

In future endeavors related to wireless network optimization, several recommendations can pave the way for further advancements. Firstly, exploring advanced clustering techniques could significantly improve the efficiency of clustering-based methods (Methods 1, 2, and 3). Investigating state-of-the-art algorithms and machine learning approaches can lead to better clustering solutions, optimizing power consumption, graph diameter, and network resilience.

Secondly, there is ample room for refinement in power allocation algorithms. Developing more sophisticated methods for power allocation can yield enhanced energy efficiency and network longevity. Fine-tuning power distribution and management strategies can further minimize power consumption while ensuring optimal network performance.

Additionally, for practical implementation in real-life scenarios, future research should consider the incorporation of real-world constraints, such as hardware limitations, environmental factors, and interference. Addressing these real-world challenges will result in more reliable and robust wireless network designs suitable for long-term deployment.

Lastly, expanding the scope of investigation to include dynamic network topologies and adaptive algorithms would be worthwhile. Considering the dynamic nature of wireless networks, developing adaptive optimization approaches that can dynamically adjust power levels and network configurations based on changing conditions will lead to more resilient and adaptable networks.

By focusing on these recommendations, future work in wireless network optimization can unlock new possibilities for efficient and reliable communication, addressing the growing demands of wireless communication in the modern world.

## 8. References

[1] - Z. Nutov. Approximating minimum-power k-connectivity. Ad Hoc & Sensor Wireless Networks, 9(1-2):129– 137, 2010.

[2] - Y. Lando and Z. Nutov. On minimum power connectivity problems. J. Discrete Algorithms, 8(2):164–173, 2010.

[3] – Z. Nutov. Survivable network activation problems. Theoretical Computer Science, 514:105–115, 2013.

[4] - M. Goemans, A. Goldberg, S. Plotkin, D. Shmoys, E. Tardos, and D. Williamson. Improved approximation algorithms for network design problems. In SODA, pages 223–232, 1994.

[5] - A. Frank. Connections in Combinatorial Optimization. Oxford University Press, 2011.

# 9. Appendices

## 9.1 Recommendation of a grade (by an academic supervisor) for a concluding report

**המלצת ציון (ע"י מנחה אקדמי) לדו"ח מסכם**

אם יש צורך, לכל סטודנט/ית בנפרד

מספר הפרויקט: p-2023-012

שם הפרויקט: פתרונות מעשיים לרשתות עמידות לנפילות.

שם המנחה החיצוני:

שם המנחה מהמחלקה: פרופ' מיכאל סגל

שם הסטודנט/ית: דור מולאי ת.ז.: 205870637

שם הסטודנט/ית: שניר מוסקוביץ' ת.ז.: 206293128

| % | | חלש<br>55-64 | בינוני<br>65-74 | טוב<br>75-84 | ט"מ<br>85-94 | מצוין<br>95-100 | |
|---|---|---|---|---|---|---|---|
| 20 | הצגת הגישה והתכנון ההנדסי | | | | | | |
| 20 | הצגת התוצאות וניתוח השגיאות | | | | | | |
| 20 | הסקת מסקנות | | | | | | |
| 10 | גילוי יוזמה וחריצות | | | | | | |
| 20 | פתרון בעיות, מקוריות ותרומה אישית (מעבר למילוי ההנחיות) | | | | | | |
| 10 | עמידה בלו"ז ורמת הביצוע המעשי | | | | | | |

אם יש כוונה לפרסם/ יפורסם מאמר, שם כתב העת ומועד משוער להגשה:

ציין אם יש כוונה לשקול המלצה כפרויקט מצטיין:

הערות נוספות:

## 9.2 Task management

| Start Date | End Date | Dor Moolay | Snir Moscovich | Task | Status |
|---|---|---|---|---|---|
| 10/10/2022 | 23/10/2022 | Yes | yes | Pre reading | |
| 23/10/2021 | 30/10/2022 | yes | yes | PDR | Done |
| 10/11/2021 | 30/12/2022 | yes | yes | Methods design | Done |
| 01/01/2021 | 10/04/2023 | yes | yes | Methods development | Done |
| 15/01/2023 | 18/01/2023 | yes | yes | PRE | Done |
| 11/04/2022 | 02/06/2023 | yes | yes | Testing and verification | Done |
| 13/03/2022 | 19/03/2023 | yes | yes | Progress | Done |
| 03/06/2022 | 10/06/2023 | yes | yes | Poster | Done |
| 10/06/2022 | 18/06/2023 | yes | yes | Presentation | Done |
| 20/06/2022 | 30/07/2023 | yes | yes | Final submission | Done |

*Table 1: Task management*