Energy-Efficient Hybrid Algorithm using Single-Path, Anypath, and Collaborative Broadcasting Routing

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Abstract

Wireless mesh networks are essential for providing high-performance and reliable connectivity in various applications. Anypath routing algorithms have shown promise in improving the packet delivery rate (PDR) and overall network performance. However, energy efficiency remains a challenge in these networks. In this paper, we propose an optimized anypath-based collaborative broadcast routing algorithm that balances PDR and power consumption. We compare its performance with Dijkstra's algorithm, the anypath routing algorithm in [1], and the anypath-based collaborative broadcast algorithm under different network conditions and densities. The results show that our proposed algorithm outperforms Dijkstra's algorithm and has a higher PDR than the anypath routing algorithm in [1] under most conditions. However, power consumption increases significantly under good network conditions, indicating a need for more energy-efficient strategies in such scenarios. This research contributes to the understanding of anypath routing algorithms and their potential in wireless mesh networks, shedding light on the trade-offs between performance and power consumption..

1.Introduction:

Wireless networks have become an important part of modern network communications systems, playing a critical role in machine collaboration and wireless data exchange. The two important metrics of such wireless network, power consumption and performance are highly determined by the routing algorithm employed, which decides what path should a node took to reach the destination node. Conventional routing algorithms such as single-path algorithm and any-path algorithms, have been widely studied and employed in various network scenarios. However, both of these approaches have their own limitations when it comes to achieving a balance between network performance and energy consumption.

Single-path routing algorithms, such as Dijkstra's, which is also a shortest path algorithm that finds the path from the source to destination based on specific criteria, such as shortest distance value or minimal ETX value in wireless network. While these algorithms can provide satisfactory performance in certain situation, they may not always result in the path that provide best performance since they typically consider only one path at a time.

On the other hand, anypath routing algorithms, such as shortest-anypath-first in [1], aim to exploit the broadcast nature of wireless communications by providing data packets with multiple forwarding options, which in turn helps increase the probability of successful delivery. Taking this a step further, collaborative broadcasting routing forwards packets along multiple paths simultaneously. These methods have the potential to enable a node to have multiple paths as the next hop, improving network performance, particularly in packet delivery ratio (PDR). However, this approach can also lead to a significant increase in power consumption due to the utilization of multiple paths.

In this paper, we propose a novel hybrid routing algorithm that combine the method and strengths of both single-path, anypath routing algorithms and collaborative boardcasting routing, aiming to achieve an improved network performance while maintaining a good energy-efficiency. Our approach dynamically adjusts the routing strategy based on the network conditions, seeking to balance the trade-off between PDR and power consumption while reaching a network with stable status. We present a detailed description of our algorithm and provide an extensive evaluation through simulations, demonstrating its effectiveness in various network scenarios.

By addressing the limitations of existing routing algorithms, our proposed hybrid routing algorithm has the potential to enhance the performance and energy efficiency of wireless networks, ultimately contributing to more sustainable and reliable communications systems.

2. Related Work

The paper "Multirate Anypath Routing in Wireless Mesh Networks" [1] proposes a novel routing approach that combines the advantages of anypath routing with the benefits of multirate adaptation in wireless mesh networks. Multirate adaptation allows nodes to choose different transmission rates depending on the channel quality and the distance between nodes, which can significantly improve network throughput and efficiency. The authors of this paper aim to optimize end-to-end throughput by jointly considering anypath routing and multirate adaptation.

The proposed multirate anypath routing algorithm in [1] is designed to leverage the broadcast nature of wireless transmissions by exploiting the opportunities for opportunistic reception and retransmission. The algorithm selects a set of candidate next-hop nodes, considering both the transmission rate and the expected number of transmissions (ETX) needed to reach the destination. By doing so, the algorithm is able to adapt to varying network conditions and efficiently route packets in a wireless mesh network.

In [2], the authors conducted a performance comparison of various single-path routing algorithms, including DSDV, AODV, and DSR, in the context of mobile ad hoc networks. They discovered that under specific network density conditions, particularly when the number of nodes ranged from 40 to 100, the packet delivery ratio (PDR) of AODV and DSR exhibited a high degree of similarity. This observation raises the possibility that a similar situation may exist when comparing single-path routing algorithms, such as Dijkstra's algorithm, and anypath routing algorithms [1]. Consequently, this finding suggests that employing dynamic adjustments to enhance energy efficiency could be a viable approach for optimizing routing performance in wireless networks.

Additionally, in [3], the authors compare the energy consumption of single-path routing algorithms, such as OLSR, with multipath algorithms like AOMDV and M-CML, considering the number of nodes, which can also be related to network density. The differences in energy consumption vary based on different network densities. However, this study only evaluates the energy consumption for some protocols other than Dijkstra's and anypath routing algorithms presented in [1]. Furthermore, the evaluation is limited to cases with node numbers ranging from 10 to 30. It would be interesting to investigate how performance and performance metrics, such as PDR, change as the number of nodes in the network increases significantly, in order to study different algorithms' behavior in massive wireless networks. This understanding could be beneficial in developing a hybrid algorithm that takes advantage of both single-path and multipath routing strategies.

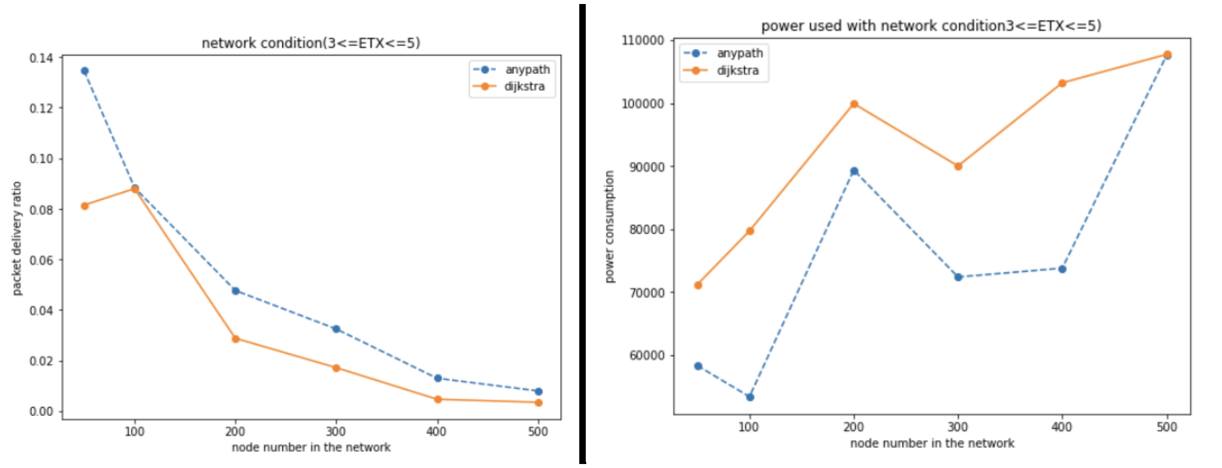
Our project is inspired by the work presented in [1], [2],[3] and seeks to further explore the performance of anypath routing in comparison to traditional single-path routing algorithms, such as Dijkstra's algorithm. By studying the performance of these routing algorithms under different network conditions and sizes, we aim to develop an understanding of the trade-offs between any-path and single-path routing.

3. Our Contribution:

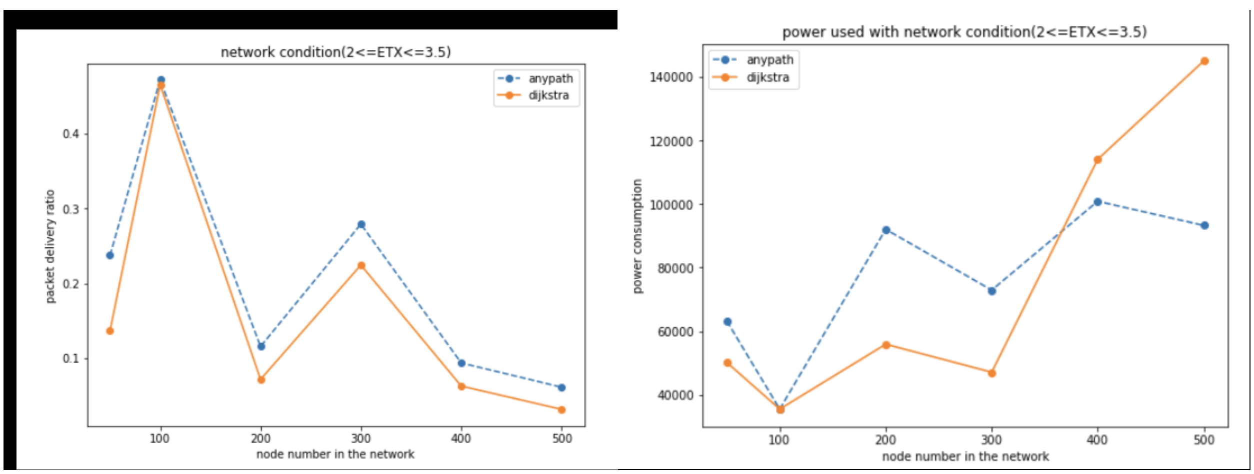
3.1 Evaluation of performance and power consumption between Dijkstra's algorithms and shortest first anypath routing

To evaluate the performance of anypath routing in the context of wireless mesh networks, we utilize Python to model the network as a graph, denoted G=(V, E), where V represents the set of vertices or nodes, and E signifies the set of edges or links connecting these nodes. Each edge in E is characterized by its power consumption and Expected Transmission Count (ETX) values. To ensure that our graph-based model closely resembles real-life network conditions, we first assign positions to the nodes within a specified distance range (500 m). Subsequently, we use the distances between nodes and an input parameter representing network conditions to calculate the ETX values for each edge. As for power consumption values, we assign random values ranging from 1 to 5 to simulate variations in power costs across different edges.

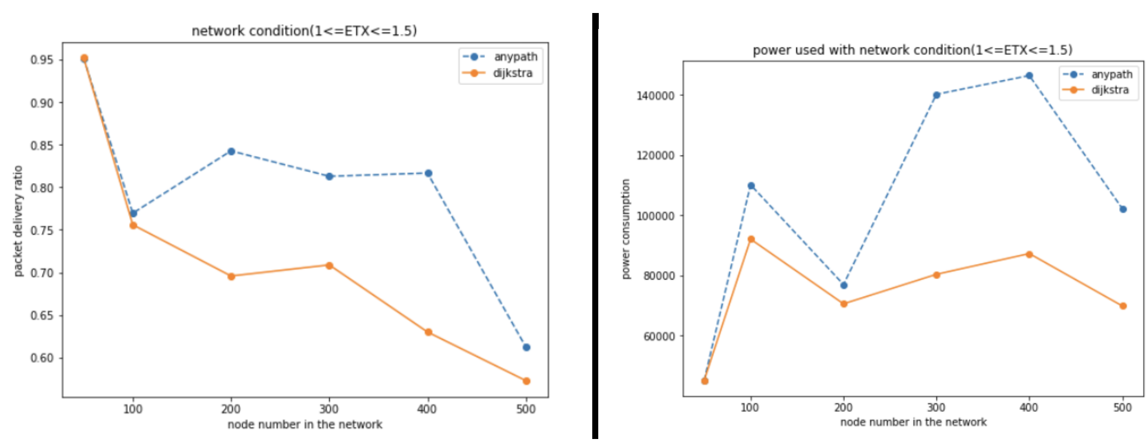
Wireless networks are known for their dynamic nature, which can lead to a wide range of network conditions, such as good, average, or poor. Additionally, an increase in the number of nodes within a network can also affect the performance and power consumption of various routing algorithms. To better understand these dynamics, we first implement the anypath algorithm from [1] for a single-rate case and compare it with Dijkstra's algorithm under different network conditions and node numbers in a random network based on the previously mentioned graph topology.



a. PDR and total power consumption under bad network conditions sending 10000 packets.



b. PDR and total power consumption under average network conditions sending 10000 packets.



c. PDR and total power consumption under good network conditions sending 10000 packets

Fig. 2. Routing decision comparison between Dijkstra’s routing algorithm and anypath routing.

As observed, the performance of anypath routing in [1] outperforms single-path routing, specifically Dijkstra's algorithm, across different network conditions and densities. Interestingly, under poor network conditions (3 <= ETX <= 5), the power consumption of Dijkstra's algorithm is significantly higher than that of the anypath algorithm. However, in most other cases, anypath routing generally consumes more power than Dijkstra's algorithm, especially when network conditions improve.

Despite anypath algorithms outperforming Dijkstra's algorithm in various scenarios, the performance differences are not substantial under poor and average network conditions. For instance, in Fig. 1(b), the PDR differences between the two algorithms under node numbers of 200 and 300 are less than 5%, while anypath routing consumes considerably more energy. This observation raises the question of whether it is possible to develop a routing method that offers better performance than the anypath routing presented in [1], while maintaining acceptable energy efficiency.

3.2 Integration of Anypath Routing Algorithm and Collaborative Broadcasting Routing

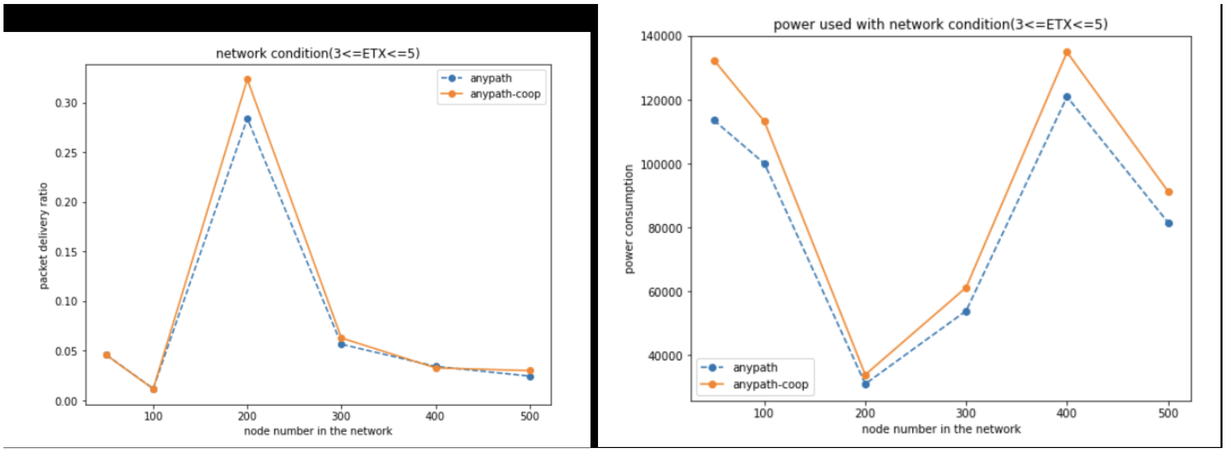
Collaborative broadcasting routing is a well-known routing strategy employed to enhance network performance. However, applying this strategy to every node in the network can result in significantly higher power consumption compared to anypath routing, despite potentially offering substantial improvement in PDR. Interestingly, the forwarding set calculated by the algorithm in [1] effectively filters nodes that are worthy of forwarding based on the probability of successful transmission. By incorporating collaborative broadcast routing based on the forwarding set, it may be possible to reduce unnecessary power consumption while achieving a substantial performance improvement. In our code implementation, packets are forwarded to every node in the forwarding set, as opposed to transmitting to only one node in the forwarding set based on priority.

With this implementation, we can conduct simulations to analyze the differences between the anypath-based collaborative broadcasting routing algorithm and the anypath algorithm presented in [1]:

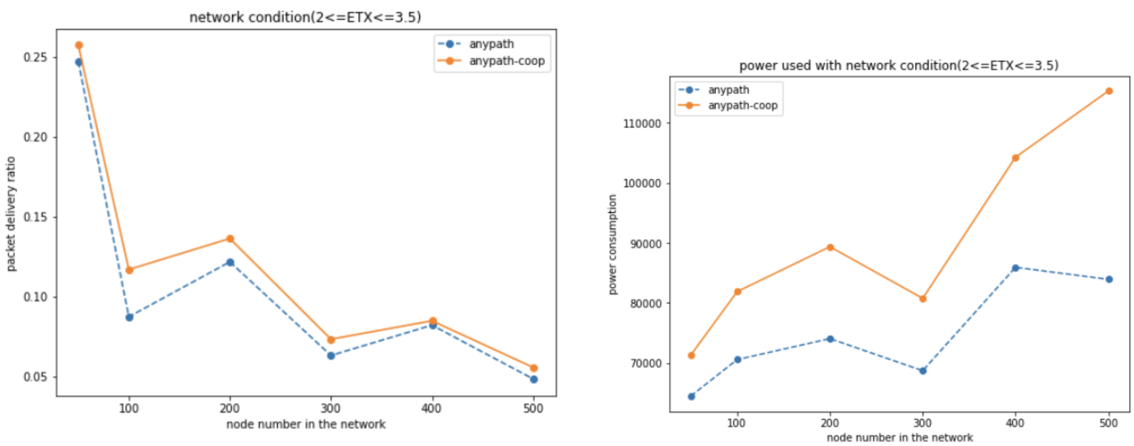
```
for node in forwarding_table:
    node.transmit()
```

```
for node in forwarding_table:
    if successfully transmit:
        node.transmit()
        break
```

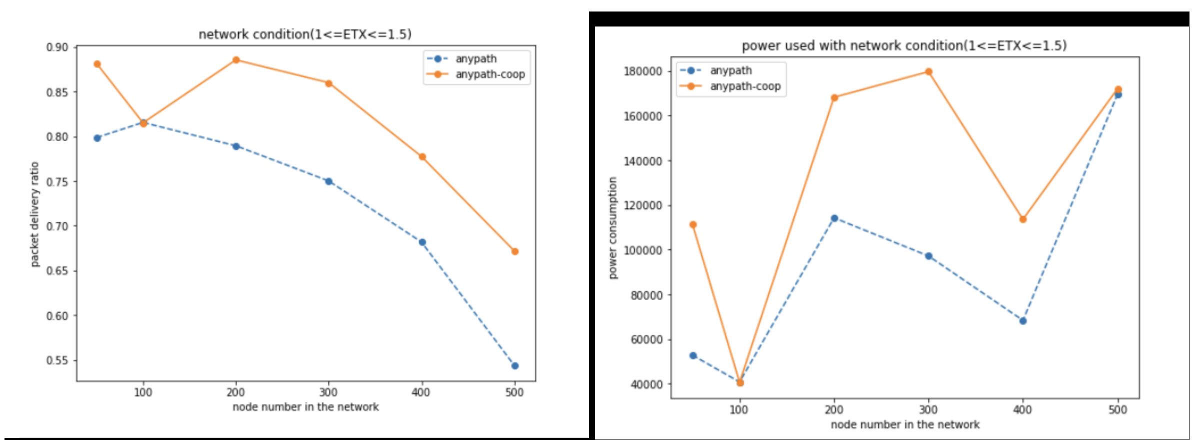
Fig 2. Routing decision of collaborative broadcast routing and anypath routing



a. PDR and total power consumption under bad network conditions sending 10000 packets.



b. PDR and total power consumption under average network conditions sending 10000 packets.



c. PDR and total power consumption under good network conditions sending 10000 packets

Fig. 3. Performance and power analysis via simulation of anypath-based collaborative broadcasting algorithm and anypath algorithm.

Based on the simulation results, the performance of the anypath-based collaborative broadcasting algorithm outperforms the anypath routing presented in [1]. Furthermore, the performance differences increase as network conditions improve. From a power consumption perspective, the energy usage difference is minimal when network conditions are poor, but the anypath-based collaborative broadcasting algorithm consumes more energy than the anypath algorithm as network conditions improve.

Although applying the anypath routing forwarding table in conjunction with the collaborative broadcasting algorithm already helps to eliminate some paths with low energy efficiency, power consumption remains substantial, while sometimes providing only a small performance increase.

3.3 Energy Reduction Method

3.3.1 Hierarchy Optimization

In [1], the authors calculate the distance from each node to the destination using weights based on transmission probability and the distance of neighbors. However, the algorithm does not account for power values, which are essential for energy efficiency considerations. To further reduce power consumption, we adapt the anypath algorithm from [1] to consider energy consumption

Suppose **Dist(d)** represents the shortest anypath routing algorithm in [1], and **d** denotes the distance from every node to its neighbor. The **Dist()** algorithm returns a list of forwarding sets as the shortest anypath based on **d**, where **d** is a set containing the dij value representing the distance from node **i** to node **j**. To account for power consumption, we define a new parameter **dx**, where **dx** is a set containing

$\mathbf{dxij = dij + \mathcal{E}pij}$, with **pij** representing the power consumption from node **i** to node **j**, and **Ɛ** is a small parameter ensuring $\mathbf{dxij - dij + \mathcal{E}pij} < 0.01$ to maintain the shortest anypath as the primary priority:

```
SHORTEST-ANYPATH-FIRST-Power-Second(G, d, P)
for each node i in V
   do Di ← ∞
Fi ← Ø
Dd ← 0
S ← Ø
Q ← V
while Q != Ø
   do j ← EXTRACT-MIN(Q)
   S ← S ∪ {j}
   for each incoming edge (i, j) in E
       do J ← Fi ∪ {j}
       if Di+Ɛ*pi from P > Dj+Ɛ*pj from P
          then Di ← diJ + DJ+Ɛ*pj
          Fi ← J
```

Fig 4. Shortest-anypath-first-power-second algorithm

All parameters are the same as those in the shortest-anypath-first algorithm in [1], except for **pi** and **pj**, which are derived from the power value set **P** representing the power consumption of each link. By employing this hierarchical optimization strategy in the algorithm, the forwarding set return will have a better decision when a node considers two nodes with the same distance, it will prioritize the one with lower power consumption. This approach can help reduce power consumption, especially in cases where many nodes have the same Distance **Dj** calculated in [1].

3.3.2 Forwarding Set Filter based on shortest path of Dijkstra's algorithm

One potential reason for the increased power consumption in collaborative broadcasting is the presence of nodes in the forwarding set that may not be energy-efficient for broadcasting packets. Eliminating these nodes could further reduce power consumption while only causing a minimal drop in performance metrics such as packet delivery rate.

Upon examining the forwarding set returned by the algorithm in [1], we observed that, in most cases, the shortest path calculated by Dijkstra's algorithm is one potential path within the anypath set returned by the anypath algorithm. Consequently, we propose a rating algorithm that evaluates each node in the shortest path produced by Dijkstra's algorithm based on the transmission success probability between the node in the shortest path and its neighbors if the neighbors are in the forwarding set generated by the anypath algorithm. The algorithm assigns a numerical grade to each node. Using these grades, we calculate an average grade for the entire shortest path as sum(grade for each node) / (length of the shortest path). For nodes in the shortest path with grades below this expected value, their forwarding set will only contain the next-hop node in Dijkstra's shortest path. Otherwise, the forwarding set will remain as produced by the anypath algorithm in [1].

```
#grading algorithm
def grading(node, Forwarding_set):
    #grade are set as 0 since the smaller the
    grade = 0
    #for node i in node's forwardng set
    for i in Forwarding_set[node]:
        #grade = sum of all etx value from no
        grade = grade - get_neighbor_power(gr


    #have a average value
    return grade/len(Forwarding_set[node])
```

```
    #for node in shortest path expect the desti
    for j0 in range(0,len(path)-1):
        #gd = current node's grade
        gd = grading(j0,Fi)
        #accmulate all grade of node in it's f
        grade = grade + gd
        g.append(gd)
    #expected grade for the entire shortest pa
    grade = grade/(len(path)-1)
    #for node in shortest path
    for i1 in range(len(path)-1):
        #if grade of current node < expected g
        if g[i1] <= grade:
            #forwarding set only contain next
            Combined[path[i1]] = {path[i1+1]}
```

Fig 5. Grading algorithm

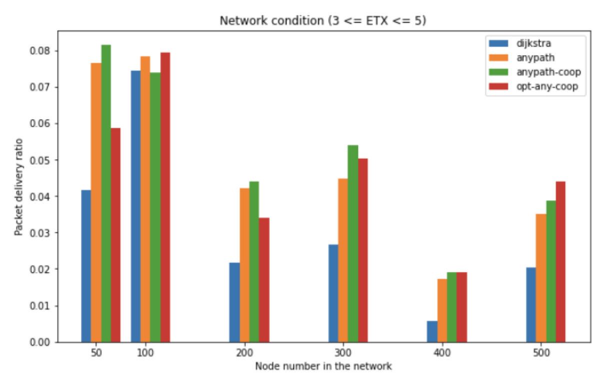
The grade of the entire shortest path is determined by the probability of each node in the forwarding set of those in the shortest path successfully reaching the next hop. By employing this strategy, the forwarding set is filtered, resulting in a new forwarding set that only contains nodes with high energy efficiency. This approach aims to strike a balance between performance and power consumption, ensuring optimal network operation.

3.3.3 Optimized Anypath-Based Collaborative Broadcasting Routing Algorithm

By integrating the hierarchical optimization strategy presented in Section 3.3.1 and the forwarding set filter technique discussed in Section 3.3.2 with the anypath routing algorithm and collaborative broadcasting routing combination from Section 3.2, we propose an optimized anypath-based collaborative broadcasting routing algorithm. This algorithm aims to achieve a balance between high packet delivery rate (PDR) and reduced power consumption, resulting in a more energy-efficient and high-performing routing solution for wireless networks.

The proposed optimized anypath-based collaborative broadcasting routing algorithm combines the benefits of each individual technique, ensuring that the forwarding sets generated are energy-efficient and prioritize the shortest anypath. Moreover, by filtering the forwarding set based on the grades calculated using the shortest path of Dijkstra's algorithm, the algorithm can identify and utilize only the high energy-efficient nodes in the network. This comprehensive approach leads to an overall improvement in network performance while minimizing power consumption.

4. Evaluation:



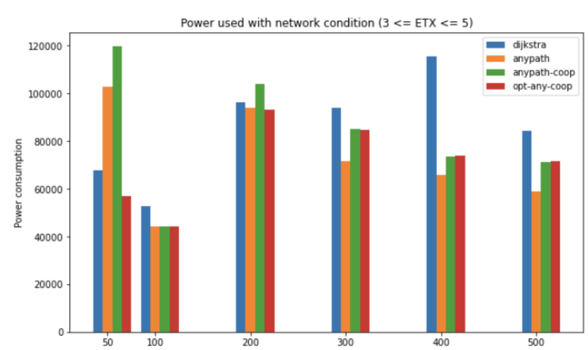


Fig 6. performance and power used comparison under network conditions(3<=ETX<=5)

Under adverse network conditions (3 <= ETX <= 5), the optimized anypath-based collaborative broadcast algorithm exhibits a relatively close packet delivery rate (PDR) compared to other algorithms. Specifically, the average PDR under different network densities for the optimized anypath-based collaborative broadcast algorithm is only 4.75%, lower than the anypath routing algorithm (4.89%) by 0.14%, lower than the anypath-based collaborative algorithm (5.18%) by 0.43%, while Dijkstra's algorithm only has a PDR of 3.17%.

Regarding power consumption, the optimized anypath-based collaborative broadcast algorithm has the lowest average power consumption for 10000 packets sent under various network density cases (70715). It has a 14.68% power consumption reduction compared to the anypath-based collaborative broadcast algorithm (82883), a 3.01% reduction compared to the anypath algorithm in [1] (72912), and a 16.91% power reduction compared to Dijkstra's algorithm (85116).

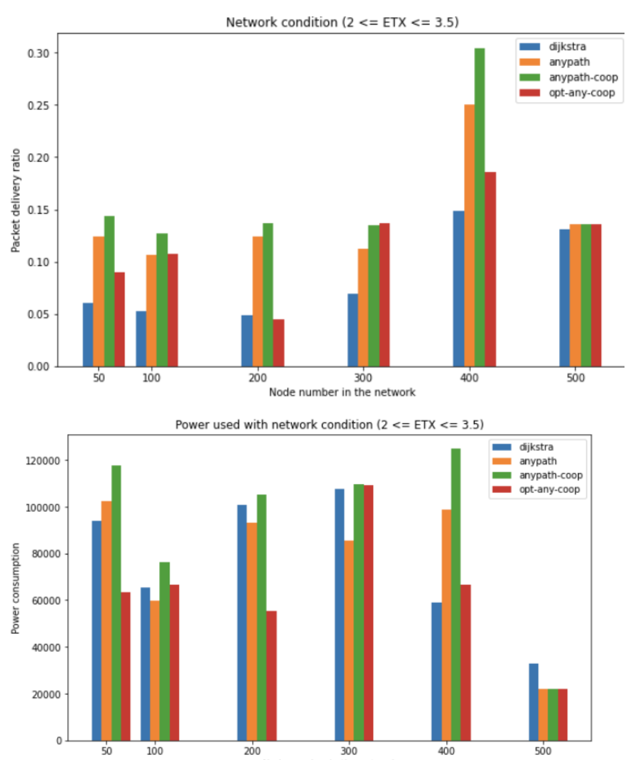


Fig 7. performance and power used comparison under network conditions(2<=ETX<=3.5)

Under average network conditions (2 <= ETX <= 3.5), the optimized anypath-based collaborative broadcast algorithm shows significant improvement compared to Dijkstra's algorithm and is slightly lower than the other two algorithms. Specifically, the average PDR under different network densities for the optimized anypath-based collaborative broadcast algorithm is 11.68%, only lower than the anypath routing algorithm (14.2%) by approximately 2.52% and the anypath-based collaborative algorithm (16.35%) by 4.67%, while higher than Dijkstra's algorithm by 3.2%.

For power consumption, the optimized anypath-based collaborative broadcast algorithm has the lowest average power consumption for 10000 packets sent under various network density cases (63847), with a 31.03% power consumption reduction compared to the anypath-based collaborative broadcast algorithm (92575), a 16.96% reduction compared to the anypath algorithm in [1] (76891), and a 16.74% power reduction compared to Dijkstra's algorithm (76700).

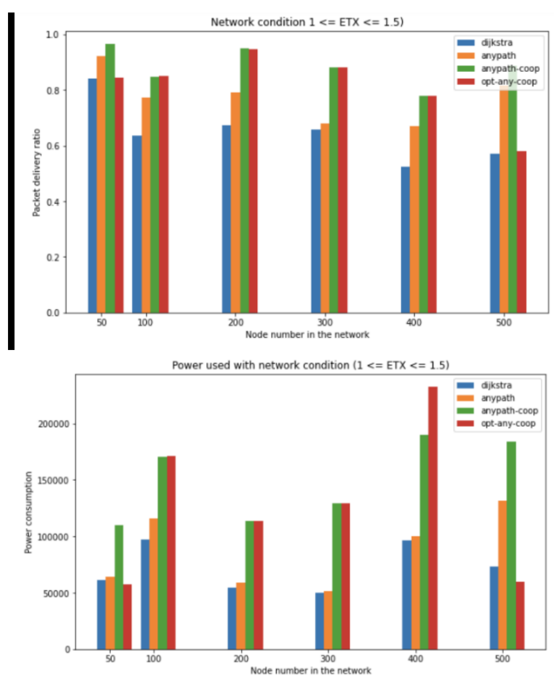


Fig 8. performance and power used comparison under network conditions(1<=ETX<=1.5)

Under good network conditions (1 <= ETX <= 1.5), the optimized anypath-based collaborative broadcast algorithm demonstrates better PDR than Dijkstra's algorithm and the anypath algorithm of [1]. Specifically, the average PDR under different network densities for the optimized anypath-based collaborative broadcast algorithm is 81.3%, only lower than the anypath-based collaborative algorithm (88.5%) by approximately 7.2%. Additionally, the optimized anypath-based collaborative broadcast algorithm has a 3.8% higher PDR than the anypath algorithm of [1] and a 16.36% higher packet delivery rate than Dijkstra's algorithm.

In terms of power consumption, the optimized anypath-based collaborative broadcast algorithm has the second-highest average power consumption for 10000 packets sent under various network density cases (127507), with a 14.82% power consumption reduction compared to the anypath-based collaborative broadcast algorithm (149646). It consumes 46.38% more power than the anypath algorithm in [1] (87117) and 76.87% more power than Dijkstra's algorithm (72116).

Based on these evaluations, the optimized anypath-based collaborative broadcast algorithm demonstrates outstanding performance and energy efficiency in the first two network condition scenarios. In the third scenario, under good network conditions, the performance of this algorithm remains very good, but the power consumption increases significantly. Therefore, the optimized anypath-based collaborative broadcast algorithm is a suitable choice for situations similar to the first two network conditions. However, under the third condition (good network conditions), there may be alternative strategies with better energy efficiency.

5.Conclusion

In this paper, we presented an optimized anypath-based collaborative broadcast routing algorithm that aims to balance packet delivery rate (PDR) and power consumption in wireless mesh networks. We evaluated the performance of the proposed algorithm under various network conditions and densities, comparing it with Dijkstra's algorithm, the anypath routing algorithm in [1], and the anypath-based collaborative broadcast algorithm. Our findings demonstrated that the optimized anypath-based collaborative broadcast algorithm outperforms Dijkstra's algorithm in all network conditions and has a higher PDR than the anypath routing algorithm in [1] under most conditions. However, the power consumption increases significantly under good network conditions, suggesting that alternative strategies may be more energy-efficient in such scenarios.

Our work contributes to the understanding of anypath routing algorithms and their potential in wireless mesh networks, providing insights into the trade-offs between performance and power consumption. Future research may focus on developing more energy-efficient strategies under various network conditions and investigating the potential of machine learning techniques in optimizing routing decisions.

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