Reliable low-latency networking: many radios, many paths

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Fig. 1. Multi-radio networking

Abstract- Including multiple radios on a single device provides the potential for improved reliability and reduced latency in the network. The cost of using this technology includes higher energy consumption and increased networking overhead. This research aims to investigate and evaluate the trade-offs between using multi-radio networking and single-radio networking, with emphasis on determining the optimal circumstances for both approaches. This research will makes use of the One simulator environment to evaluate the performance of both multi-radio and single-radio networks, with emphasis on important factors such as energy efficiency, delivery probability and throughput. By comparing the results of the simulations, this research aims to identify when the network benefits most to employ either multi-radio networking or single-radio networking, while keeping in mind what the desired quality of service is. The findings of this study will give us valuable information on decision-making regarding the selection of networking technologies for different situations, optimizing the energy consumption, reliability and throughput.

Additional Key Words and Phrases: multi-radio networking, trade-off, communication technologies, the One simulator, quality of service, redundancy, latency, energy consumption, network overhead, simulation

1 INTRODUCTION

Wireless communication systems have experienced explosive growth in recent years, and this trend is expected to continue in the future. As you can see in figure 2, the number of IoT and smartphone users have increased drastically over the years[1]. To meet the increasing demand for wireless communication systems, it is crucial to ensure that these systems can meet specific performance requirements such as reliability, latency, energy consumption, and networking overhead. Multi-radio networking[2, 5, 9] is a type of communication that uses different communication technologies, and it has gained considerable attention due to its potential to improve system throughput and performance. However, designing an efficient multi-radio networking system requires careful consideration of various factors and trade-offs.

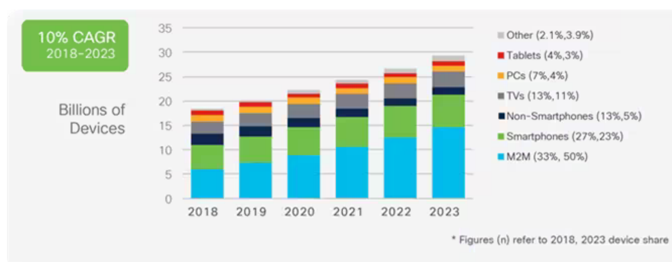

Fig. 2. Growth of devices globally.

Each Radio interface works on a different frequency or wireless technology, this allows for simultaneous communication on multiple channels. Using multi-radio networking offers several benefits and is already being used in various applications in today's world.

One of the benefits of using multi-radio networking is that it enhances the network reliability. If one of the channels or interfaces experiences congestion or interference, other interfaces can continue to operate and ensure a uninterrupted connectivity. It can also improve the overall network throughput by allowing multiple channels to transmit and receive. This enables higher data rates and increased capacity. Load balancing and Network optimization is also big reason why multi-radio networking is preferred as it distributes traffic across different radio interfaces which helps preventing congestion and efficiently utilizes available network resources if used correctly. Multi-radio networking makes seamless roaming between different wireless notworks possible. By utilizing multiple radio

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interfaces and channels on different frequencies or technologies, devices can more easily switch between networks and maintain connectivity during the transition.

This research aims to investigate the trade-offs between multi-radio networking and single-radio networking approaches, with the focus on determining the optimal solution by optimizing factors such as reliability, latency, energy consumption and networking overhead. This will be done to identify the scenarios where each approach is most beneficial.

In conclusion, this research will provide valuable insights into the design of efficient multi-radio networking systems. The findings of this study could be useful for researchers and practitioners in the field of wireless communication systems and contribute to the development of more reliable, efficient, and cost-effective multi-radio networking systems.

2 RELATED WORK

The use of multiple radios on a single device to improve communication reliability and reduce latency has been a topic of interest in the field of wireless communication systems[6]. Previous studies have investigated the performance of multi-radio networking, including channel assignment algorithms[10], routing techniques[5], and interference mitigation. Additionally, some studies have focused on exploring the potential of multi-access edge computing (MEC) architecture[4, 9] and low complexity solutions for maximizing network utility by leveraging the multi-link aggregation capability of users in the network[2, 7, 8]. There is still a need for further research to determine the optimal solution for balancing the trade-off between energy consumption and network performance when we compare the utilization of multi-radio networking and single-radio networking technologies. This research aims to investigate the advantages and disadvantages of using multi-radio networking and identifying the optimal circumstances for using either approach.

While multi-radio networks offer improved performance, they often require significant energy consumption, which can limit their practicality for IoT(internet of things) devices. Therefore, investigating the trade-off between energy consumption and network performance in multi-radio networking is essential to determine the optimal solution that can maximize network performance while minimizing energy consumption. It's worth noting that even with multiplex, which enables multiple radios to share the same frequency band and reduce the energy consumption of each radio, the overall energy consumption may not necessarily be lower than a single-radio network. This is because the overhead associated with managing multiple radios may offset the energy savings achieved through multiplexing[3]. Therefore, investigating the trade-off between energy consumption and network performance in multi-radio networking is critical to determine the optimal solution that can balance the various factors.

Research has also been conducted on the use of different communication technologies in wireless communication systems, such as cognitive radio networks and multi-channel MAC protocols. However, there is still a need for further investigation into the performance of different communication technologies in a multi-radio environment and the optimal trade-off between these technologies to balance the various factors, including energy consumption.

To address this research gap, this study aims to investigate the trade-offs between multi-radio networking and single-radio networking technologies and determining the optimal solution to balance reliability, energy consumption and throughput. The research assesses the performance of both the close-range high-speed interface and the long-range low-speed interface to compare the results of multi-radio and single-radio technologies. The simulations are done using 'The One' simulator based on java. By comparing the results obtained from the simulations, this research aims to provide a conclusion into the optimal use of multi-radio and single-radio networking in multiple scenarios, with the ultimate goal to optimize network performance with energy consumption kept in mind.

3 METHODOLOGY

This study will utilize simulations to evaluate the effects of multi-radio and single-radio networking. The network nodes will have high-speed short-range interface (Interface 1, as shown in Table 1) and a low-speed long-range interface (Interface 2, as shown in Table 2). All the nodes remain stationary throughout the simulation and the traffic generation is created to converge at a single sink node. All sources of randomness are removed from the simulation to ensure reliable and consistent results. This approach makes sure that repeating the same simulation with the same configuration twice yields the same results, enhancing our understanding and providing dependable results for this study.

3.1 The One

The Opportunistic Network Environment(The One) simulator is used in this study. The One is a software tool used for simulating and evaluating networks. It provides a platform to study communication protocols, routing algorithms and a good alternative to test applications in case the traditional network infrastructure is absent or unreliable. The One simulator focuses on Delay-Tolerant Networking(DTN) and opportunistic networking. This allows researchers to investigate the performance and behaviour of various DTN protocols and algorithms in dynamic and challenging environments.

Table 1. Interface 1 parameters

Interface 1	**Value**
Type	InterferenceLimitedInterface
Transmit Speed	1MB/s
Transmit Range	120 meters

Table 2. Interface 2 parameters

Interface 2	**Value**
Type	InterferenceLimitedInterface
Transmit Speed	250kB/s
Transmit Range	480 meters

3.2 Settings

The simulations run for 10000 seconds, which is equivalent to approximately 2.8 hours. This duration allows us to observe relevant patterns and conclusive results. Both interfaces that are created use the "interferenceLimitedInterface"(figure 1 and 2) class. This interface class dynamically updates the bit-rate based on the number of other nodes that transmit within range. If there is no other node transmitting within range, the maximum speed is achieved.

For the movement model of these networks, the "StationaryMovement" is chosen which makes sure that the nodes remain stationary while the simulation is running, removing another source of randomness. The "EpidemicRouter" is used for routing as it was the most suited for stationary nodes that only transfer data to connected nodes.

The time-to-live(TTL) of the messages is set to 5 hours, which surpasses the simulation run time. This allows for potential congestion among nodes and prevents messages from disappearing. Finally, the "rng seed" from the movement model class and "randomize update order" from the optimization class are both disabled to remove any potential randomness in the simulation. This approach ensures clear and dependable results, as mentioned earlier.

Table 3. Simulation Parameters

Parameter	Value
Buffersize	5MB
Event class	MessageEventGenerator
Message interval	25 to 35 seconds
Message size	500kB to 1MB

3.3 Network

For the simulations multiple network configurations have been made, differing in the amount of nodes and whether they use the battery functionality (Table 4). The initial energy variable shows how much energy is stored in every node. The scan energy variable indicates the energy that is consumed when nodes establish a connection with each other, this occurs at the beginning of the simulation for data transmission and reception. The scan response energy variable stands for the energy consumed in responding to the device discovery message from other nodes. Finally, the transmit energy reflects the energy that is consumed while nodes are in the "sending" state.

All nodes in the network are given random locations within a specified maximum range, which, in our research, is set to 250m in all the network configurations. This ensures that the maximum distance between any two nodes does not exceed the maximum range. By using the same maximum range for all network configurations, we ensure consistent and reliable results. This approach also guarantees that each node has at least one other node within range to establish a connection. Figure 3 shows the topology of one of the network configurations consisting of 25 nodes.

Each network configuration starts with only the sink node using the multi-radio technology. As the percentage of multi-radio nodes needs to increase, the nodes that need to be changed from single to multi-radio are randomly selected using a python script. For the network configurations that use the battery functionality, we make use of the energy model provided by the ONE simulator. (Table 4). The initial energy is set in a way that when a node utilizes both interfaces, it depletes approximately 80 percent into the simulation. Nodes making use of multi-radio networking have their energy usage doubled, as both interfaces consume a comparable amount of energy when you look at the transmit speed and range. The reasoning behind this is that the difference in speed and range between the interfaces is a factor of 4, which results in a comparable energy usage. By keeping the same initial energy level in the batteries for all simulations, we can observe whether multi-radio networking can actually bring any improvements to the network without upgrading the batteries.

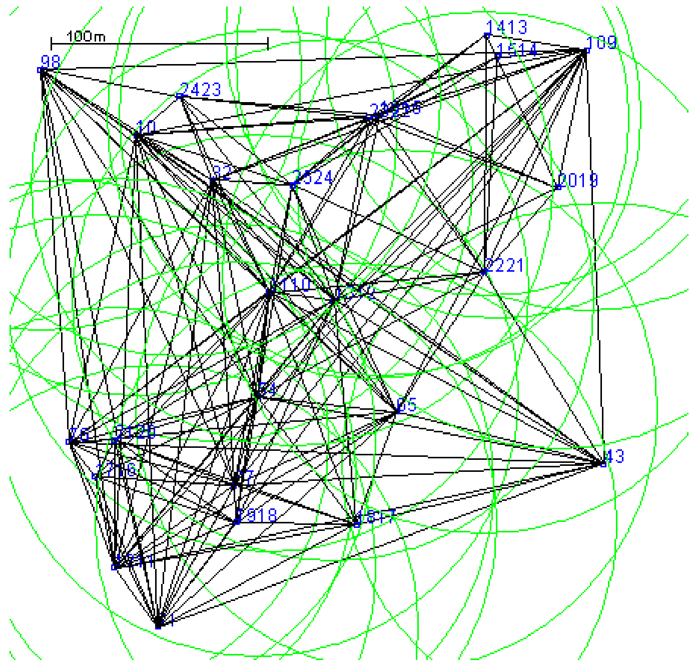

Fig. 3. Topology of the network with 25 nodes (50 percent multi-radio)

Finally, the simulations are also done again without batteries to evaluate performance improvements without battery limitations. This enables us to assess the extent of improvement that is achievable without energy constraints.

Table 4. Energy Model parameters

Parameter	Value
Initial energy	6000
Scan energy	0.5
Scan response energy	0.2
Transmit energy	0.1

4 RESULTS

The delivery probability of messages in the network in each simulation is mainly what is being measured. It refers to the likelihood that a message will be successfully delivered from a source node to its intended destination which in our case always is the sink node. The chance that the message will reach its destination depends on factors such as network connectivity, routing protocols, node mobility and communication constrains.

The delivery probability will be expressed as a value between 0 and 1, where 1 stands for a guaranteed message delivery and 0 represents no chance of delivery.

Network designers and researchers analyze the delivery probability to evaluate the effectiveness and performance of routing models, mobility models and other factors influencing message delivery. In our case we will be using it to evaluate the performance of both multi-radio networking and single-radio networking.

4.1 Performance

As you can see in Figures 4, 6, and 7, the delivery probability decreases a bit, for the networks with batteries, when only a small percentage of multi-radio nodes are used, but it increases progressively as the percentage of multi-radio nodes jumps up. Nodes without battery generally have a higher delivery probability compared to the nodes with a battery. You can also see that in all the networks with and without batteries the message delivery rate in the network does increase when a significant percentage multi-radio nodes is being used.

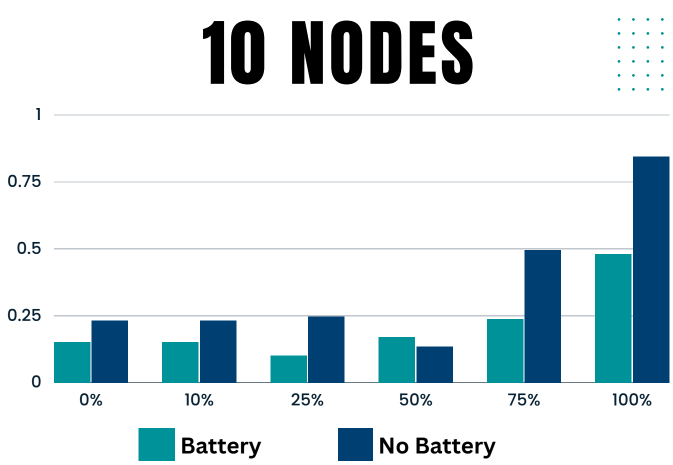

Fig. 4. Simulations with 10 nodes

4.2 Impact transmit-range and transmit-speed

Another important point to consider is finding the key properties of the second interfaces connection that can be changed to establish the optimal configuration. To achieve this, a network configuration of 25 nodes with 50 percent of these nodes being multi-radio was used. Figure 9 shows that the best transmit speed for this configuration is

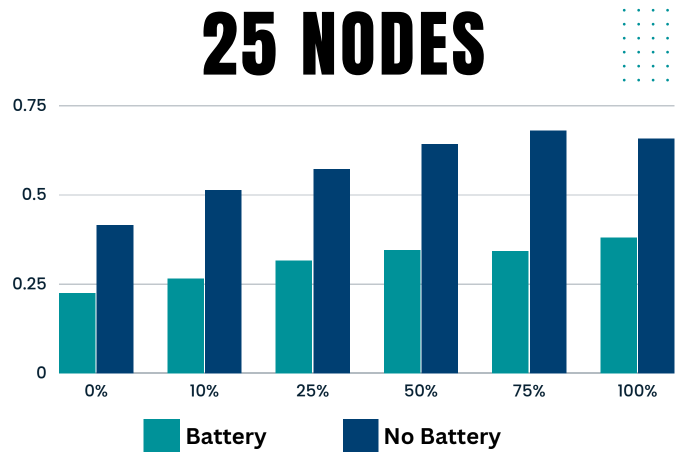

Fig. 5. Simulations with 25 nodes

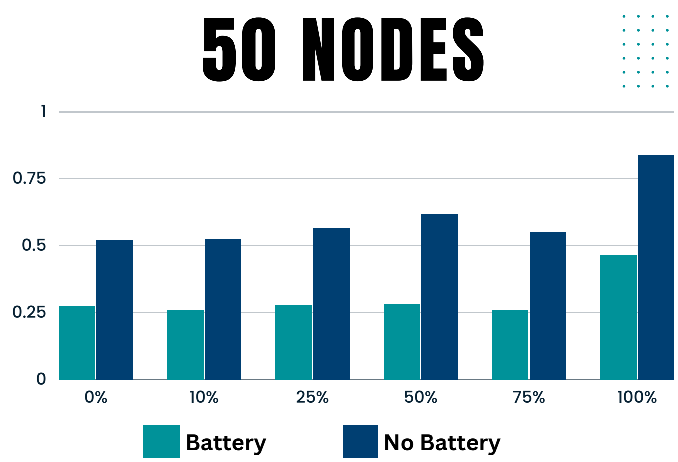

Fig. 6. Simulations with 50 nodes

125kB/s and increasing the speed actually leads to a slight decrease in delivery probability. However, it is worth noting that the message delivery probabilities across all the tested transmit speeds are quite close to each other, this could indicate that the differences are not statistically significant. Figure 8 illustrates that a range of 360 meters yields the best results in this configuration, and reducing the range below this value drastically affects the delivery probability.

5 ANALYSIS AND DISCUSSION

In this section, an explanation will be given for the results that we gained from the simulations.

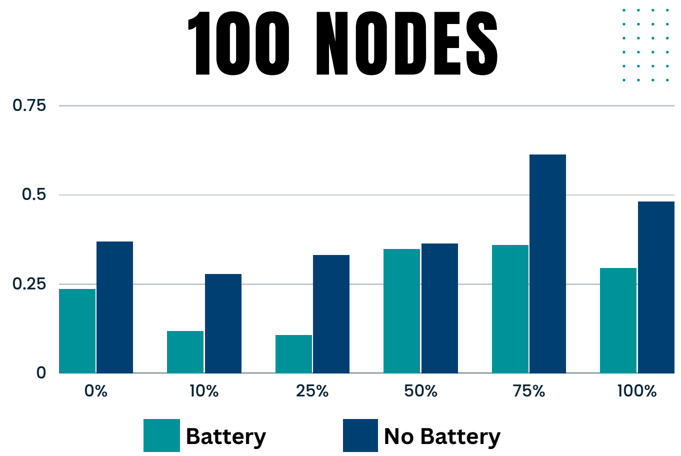

Fig. 7. Simulations with 100 nodes

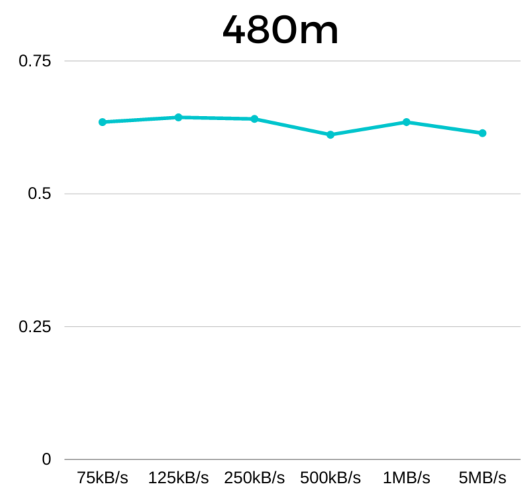

Fig. 9. Interface 2 with different transmit-speeds

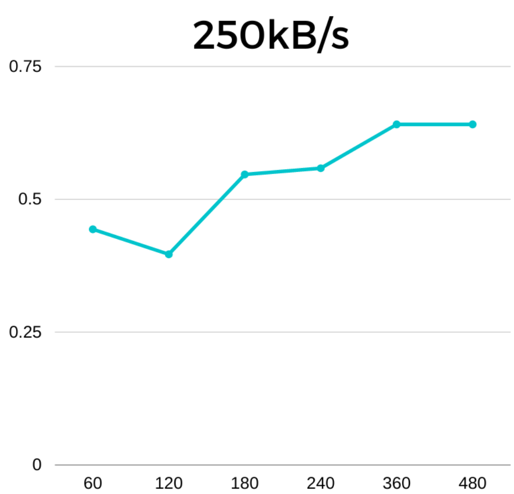

Fig. 8. Interface 2 with different transmit-ranges

5.1 Performance

In general, the delivery probability that is shown in Figures 4, 6, and 7 decreases when the percentage of nodes using multi-radio is small, but improves compared to the single-radio technology as the percentage of multi-radio nodes increases. This can be explained due to the fact that nodes using the second interface can only establish a connection with other nodes using the same interface. When the number of nodes with the second interface is low, the chance of finding a path from a specific node to the sink node decreases. This also explains the pattern shown in these figures.

When higher percentages of multi-radio nodes are used, there is a notable and significant improvement in the message delivery rate. This improvement is observed even when the nodes have the same battery capacity, indicating that the enhanced performance is not solely attributed to the battery capacity. The significant improvement is likely due to the increased range utilized by the second interface. This extended range enables the nodes to establish faster and more efficient paths to the desired destination node, particularly the sink node in our research. Consequently, as more nodes utilize this second interface, the process of establishing effective paths becomes even more efficient, leading to improved message delivery probabilities in our network configurations.

5.2 Impact transmit-range and transmit-speed

Simulations were done on a network with 25 nodes, with 50 percent of them being multi-radio nodes. As you can see in Figure 8, the ideal range for the second interface in this configuration was 360 meters. Going beyond this range did not result a significant increase in the message delivery probability, while reducing the range below this threshold resulted in a drastic decrease in the network's message delivery probability. This can be attributed to the fact that the second interface's extended range played a important role in improving message delivery. Decreasing the range would reduce this advantage, thereby reducing the overall performance of the network.

Figure 9 shows that a transmit-speed of 125kB/s is the optimal speed for this configuration and like we have mentioned before increasing the transmit speed leads to a slight decrease in message delivery probability. The delivery probability generally decreases as the transmit-speed increases. This is because using a higher transmit-speed results in a larger volume of data being sent to the nodes, leading to a faster rate of congestion and more packet loss as a result. Using slower a slower transmit-speed solves this issue. As mentioned before, it is worth noting that the message delivery probabilities across all the tested transmit speeds are quite close to each other. This could indicate that the differences are not statistically significant. As a result, the bandwidth might not be as important as the transmit range in this network.

6 CONCLUSION

In basic stationary networks, multi-radio technology improves the delivery probability of the network without an increase in battery capacity of the nodes. However, it is important to note that this improvement in message delivery is mainly observed when the network contains a substantial proportion of multi-radio nodes. Considering the significant enhancement even without upgrading the battery capacity, it may be worthwhile to consider upgrading the batteries. Such an upgrade could potentially lead to even greater significant improvements in message delivery rates compared to networks without batteries, as seen in our research. When we examined the optimal properties of the second interface for multi-radio networking, we discovered a specific range that yielded the best results. This range can be considered the 'sweet spot' where additionally increasing the range would not result in significant improvement, while reducing the range would significantly reduce the network's performance. In our network, this sweet spot was determined to be 360 meters, showing us that maintaining this range was important for achieving optimal network performance in our network. Finally, a slower transmit-speed for the second interface was found to be more beneficial in preventing congestion in the nodes and ensuring efficient packet delivery.

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