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Wireless Backhaul Optimization for 5G Internet Services in Smart Cities

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Abstract

The development of reliable smart cities falls under the functionalities 5G implementations offer: Wi-Fi, video surveillance, and sensor operations require the low-latency, rapid connections 5G offers. But cities require a wireless backhaul to support the desired functions. Evenly distributed, the city has a network of hidden cables within base stations and edge nodes, connecting to the core. In tested, dense, urban settings, we work to find an optimal balance of low space/heat/cost with data demand to maximize output within the wireless backhaul. The links' performance of three tested candidates, mmWave, sub-6 GHz, and free space optical, is analyzed to find optimal performance and trade-offs. Complex, real-time features constructed from the three candidates increase output data for requests and reduce latency, improving service under high demand. The simulations demonstrate the efficacy of the flexible, planned backhaul in minimizing latency and dropout rates and increasing data for high-demand applications such as smart grids, autonomous vehicles, and augmented/virtual reality displays. Taken as a whole, our work highlights a flexible, robust backhaul as the unseen backbone that will truly enable 5G-built smart cities to stand out and shine.

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1 Introduction

1.1 Definition and Importance of Wireless Backhaul Optimization for 5G Internet Services in Smart Cities

Wireless backhaul is that invisible wireless highway that links the leading network to scattered nodes, such as small cells or base stations, without a single strand of cable or fiber. For 5G, this link becomes crucial due to the high data speeds, near-zero latency, and rock-solid reliability that smart cities demand, which depend on it (Andrews et al., 2014). Unlike older networks, 5G packs many small cells into tight city blocks and blasts signals on high-frequency bands, such as millimeter-wave (mmWave) frequencies, which scatter easily and require finely tuned backhaul to stay steady (Ge et al., 2014; Del-Valle-Soto et al., 2020). Smart cities run on a web of connected services-autonomous cars, remote clinics, smart power grids, and live traffic apps-and all of them trade on real-time data. That means the backhaul links must be both fast and reliable. Tuning these wireless paths matters not just for better call quality or quicker downloads but also for ensuring a city can grow and adjust without its network crashing (Taleb et al., 2017; Kavitha, 2023). In crowded urban grids, digging trenches for fiber is often a budget-busting nightmare, so an agile wireless solution is usually the only practical choice.

1.2 Current Challenges and Limitations Facing Wireless Backhaul Technology

Wireless backhaul offers significant advantages to smart cities. Unfortunately, their deployment is considerably delayed. First, the greater the urbanization, the greater the competition for spectrum resources and the higher the level of interference. It is true that mmWave (millimeter-wave) links can support gigabit speeds, but their limited range, weak signal attenuation, and inefficient wall/tree penetration pose serious challenges (Rangan et al., 2014). This type of node arrangement is referred to as 'line of sight' geometry and, as node planners have discovered, it is often a greater challenge to realize in practice. The next barrier is scalability. The proliferation of sensors and mobile devices increases fragmentation in the backhaul, or in this case, radio links. If the routing protocols remain static, users will experience substantial slowdown and jitter. (Zhang et al., 2019; Beyene et al., 2023). Controlling rand usage is another contradiction and dichotomy to the fantasies of smart cities (Niu et al., 2015; Kenari, 2019). Beyond the technical challenges, the combination of bureaucracy and the costs of spectrum bandwidth, permits, and the associated mesh radios increases total spending considerably. The situation is aggravated, as well as straining, the overall metropolitan improvements; however, this is due to obsolete equipment and diverse sources of supply. (Checko et. al., 2014; Kavitha, 2024).

The wireless backhauls, shown in Figure 1(a), provide an elementary conduit between the 5G network core and the principal components of the smart city, enabling seamless citywide integration with 5G systems. As depicted in the figure, autonomous vehicles, CCTV systems, IoT devices, and smart infrastructure wirelessly communicate with the central 5G system through backhaul infrastructure. This configuration enables instantaneous data transmission, high-speed internet, and seamless smart-city functionality, all essential for permissioned city services. This figure also shows the requirement of strong and elastic backhaul systems, which are essential for meeting the 5G technology-integrated urban systems' low latency, high reliability, and dynamic interconnection requirements.

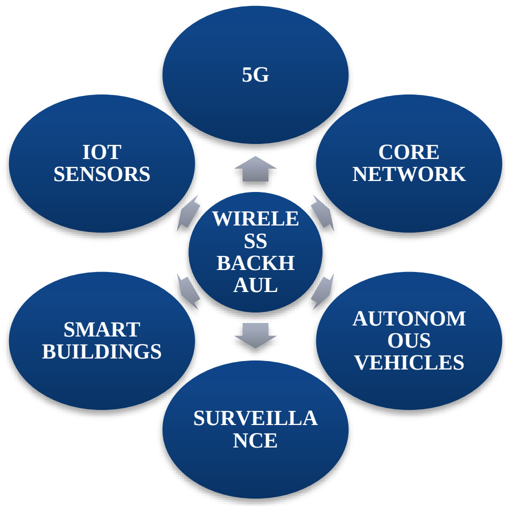

Figure 1(a): Role of wireless backhaul in 5g-enabled smart cities

The proposed system, which incorporates some Artificial Intelligence functionalities, is shown in Figure 1(b). Each of the proposed systems will have AI components that will determine traffic distribution, traffic congestion alleviation, and dynamic resource allocation. Each of these elements will be governed by a Software Defined Network (SDN), which will be responsible for monitoring the real-time updates and translating the AI components to data flow policies. An array of 5G base stations forms a mixed backhaul grid at the lowest level, preserving the speed and reliability of messages over any available route.

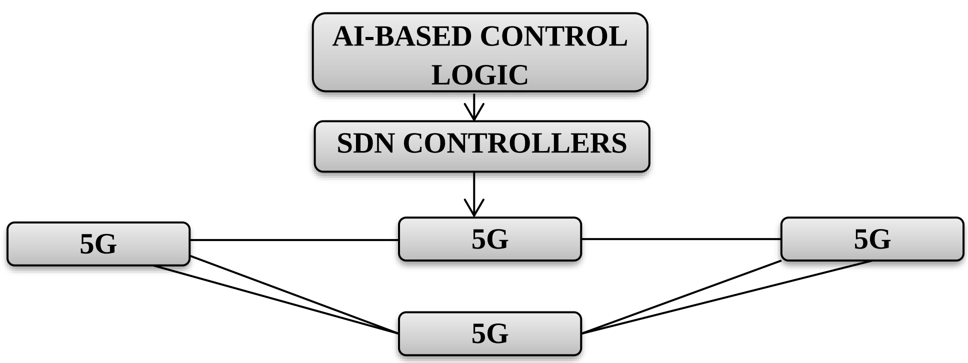

Figure 1(b): Architecture of the proposed 5g wireless backhaul optimization framework

1.3 Purpose and Objectives of the Research Study

This research aims to test and optimize wireless backhaul links for 5G smart city networks to increase speed, reliability, and scalability. It seeks novel tools, concepts, and methods to transcend existing boundaries and ensure uninterrupted service as urban functionalities expand. More specifically, the team aims to:

- Contextually juxtapose mmWave, sub-6 GHz, and Free-Space Optics (FSO).
- Understand the extent of delay reduction achievable from AI-automated innovative resource management and routing.
- Analyze realistic load performance of multi-hop and integrated wireless-blended wired systems.
- Evaluate performance in synthetic smart city emulations.

- Generate systems designs for network integration with existing infrastructure in streets, poles, and rooftops.

Completing these tasks will inform the development of stealthy, anticipatory networks that meet emergent 5G smart city requirements.

The remainder of this document proceeds as follows. For Section II, the explanation related to the Evolution of Wireless Backhaul Systems to Smart City Systems Optimizations. Section II contains the explanation of the proposed Research Methodology, the Research Design, the Data Collection Instruments, the Data Collection Procedures with the Evaluation Criteria, and the New Network Optimizations formulated as Novelties. Section IV contains the explanation of the Output/Outcome of the Work and the description of the Performance Comparison and/or Analytical Evaluation of the Methods. Section V contains the explanation of the Results, outlining the Findings, the Limitations, and the Recommendations for Future Work. Section VI is the Conclusion, where the author outlines his key contributions and provides recommendations to Policy Makers, Practitioners, and Researchers.

2 Literature Review

2.1 Evolution of Wireless Backhaul Technology in the Context of 5G Internet Services

A combination of rising mobile data demand and the need for reliable mobile services in the 5G era has created a challenging environment for backhaul infrastructure. In the 3G and 4G era, a straightforward interfacing of macro cells to fiber lines sufficed. 5G calls for interfacing a dense constellation of small cells and edge nodes, while the costs of installing fiber optics in metropolitan areas escalate rapidly (Wang et al., 2022; Turan & Ergenler, 2023). The industry relies more on wireless backhaul, including millimeter-wave, sub-6 GHz, and Free-Space Optics (FSO) links (Dang et al., 2020). Millimeter-wave technology is usually preferred due to the high throughput achievable. While Speed is always an important factor, its short range and absolute zero-tolerance for obstacles effectively limit its operational speed on roads (Boccardi et al., 2014; Kumar et al., 2023). The lower sub-6 GHz band can span greater distances, provided there are no excessive obstacles and no significant connectivity drops, and the band is streaming at a lower rate (Farhang & Rashidi, 2015). When multi-access edge computing (MEC) is implemented in conjunction with software-defined networking (SDN), wireless backhaul gains greater adaptability, allowing network managers to reallocate network resources on the fly and optimize to instantaneous network requirements (Kafetzis et al., 2022; Jassim & Ridha, 2022). The flexible, adroit architecture of the systems reduces the economic and resource costs of deployed hardware while simultaneously enabling them to reach higher operational levels in systems already deployed and running 5G.

2.2 Past Work on Fine-Tuning Wireless Backhaul for Smart Cities

Several projects have tested ways to fine-tune backhaul for the special needs of connected cities, for example, laying out a Cloud-RAN (C-RAN) design that pools baseband tasks and shortens round-trip time in city networks. (Taleb et al., 2017) took a different tack, using MEC to process data near the edge and reduce overall transport load. Research has focused on artificial intelligence and machine learning for real-time route selection and bandwidth steering. (Tang et al., 2020) demonstrated that reinforcement learning agents select optimal backhaul paths in real time as traffic changes. (Mohajer et al., 2022), on the other hand, emphasized the need for power-efficient routing in dense urban environments with low power available. (Akyildiz et al, 2020) emphasized that no one radio technology fulfills all requirements, so they advocated for a hybrid backhaul incorporating mmWave and sub-6 6GHz bands for both higher capacity and reliability. Such a hybrid solution works well in dense urban areas with glass-and-steel towers and high-speed traffic, which scatter and weaken coverage (Muller & Romano, 2024).

2.3 Comparison of Different Optimization Techniques and Their Effectiveness

Advancing techniques to optimize backhaul networks, along with new advantages and trade-offs, have since emerged. AI-based techniques can analyze historical traffic data; however, they require substantial training data, substantial computational resources, and heavy computational processing (Jiang et al., 2021; Myoa et al., 2023). Software-defined techniques allow the entire system's data to be computed in one central unit, enabling faster computations and routing. However, the computed routes fail if there is no central controller or if the network visualization is lost (Li et al., 2018; Huang et al., 2019). Taking the network's physical topology into account will enhance its reliability, coverage, and robustness. However, this method will add a few milliseconds of latency (Sattar et al., 2019; Farhang & Rashidi, 2015; Meymari et al., 2015). The energy-first paradigm, in contrast, lowers operational expenditure and increases the network's battery longevity, with the trade-off being reduced peak throughput when network pathways are restricted or the speed decreased (Akyildiz et al., 2020; Moreau & Sinclair, 2024). The example of building a smart city illustrates this: there is no method to rule them all, and building one specific to the smart city will depend solely on its unique intentions. Currently, planners prefer a hybrid scheme that incorporates AI, SDN, MEC, and multiple links, since these provide the scalability, resilience, and rapid wireless backhaul that 5G neighborhoods require (Dang et al., 2020; Arvinth, 2024).

3 Methodology

3.1 Research Design and Approach for Studying Wireless Backhaul Optimization

This study examines unlocking the discrete 5 G backhaul smart links in a smart city architecture through a quantitative simulation-driven methodology. Employing tools like MATLAB and the NS-3 network simulator, and carrying out simulations of various backhaul scenarios, researchers can conduct simulations in a virtual lab, designed to replicate real-world challenges, such as interference, user surges, geography of the sites, and stability of the links, to ensure that the experiment's results can be applied to real-world situations outside the lab; this virtual lab setting allows the researchers to carry out various simulations under controlled settings. The project proceeds with a set of predetermined steps. Initially, researchers represent urban blocks as virtual grids, filled with base stations, small cells, and user terminals. Subsequently, each grid incorporates a specific optimization layer, such as load balancing, energy-optimised routing, or real-time bandwidth slicing. Engineers progress to recording and evaluating the primary metrics (throughput, delay, packet loss, and power consumption) and performing a rank comparative analysis. In parallel with these simulations, the team develops a novel hybrid model that integrates linear programming and graph-theoretic routing to determine optimal routes efficiently. The synergetic model of these complementary disciplines aims to optimize each radio link for energy efficiency, thereby sustaining low operational costs.

The incremental and stage-based Do Logic Framework (Model 1) is stratified as follows: the first component is model design, a stage in which necessary components and calibration concepts related to the wireless backhaul link are engineered. The second component is data collection, a stage where the necessary datasets and simulation parameters for analysis are gathered. The third component is simulation, a phase where the group undertakes many instances of empirical testing to evaluate the model and its responses to the different environments. This is followed by performance, a subdivision of the model that focuses on the specific parameters of throughput, latency, jitter, and packet delivery ratio to make sense of the system. The last component is results interpretation, where the optimization techniques are studied by the modelers to understand the magnitude of the impact. The sequencing of the above stages is to enhance the reliability of the research and its reproducibility.

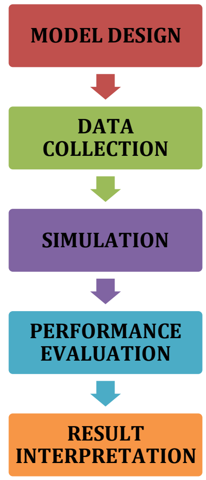

Figure 2: Research methodology flowchart

3.2 Data Collection Methods and Tools Used for Analysis

To analyze how different modifications to the wireless backhaul perform, the investigated trade-offs build a set of data that is used: the trade-offs undergo hypothesis testing in a controlled computer simulation environment that the researchers have complete control over, in a model smart city. These simulations occur in NS-3/MATLAB as previously discussed, in which the researchers attempt to model real city blocks (with varying numbers of towers, small cells, and handsets in the streets). Each of these scenarios contains a set of moving users, concrete and glass obstacles, and traffic surges. The results obtained reflect the real-world chaos that operational systems undergo. Within this simulation, the researchers change routing strategies and resource controllers (to determine the optimal conditions to obtain the fastest and most reliable network). In order to achieve results within a reasonable time, the team optimizes the given simulation, collecting a set of metrics (as a reward for the optimization). The metrics of interest include the measure (in Mbps) of link throughput, the latency (in ms) of round-trip, % of lost packets, the energy (in joules) to transmit a bit, and several others that serve to diminish the proxy reputation of reliability and energy efficiency. The simulation results were screened and cleaned (to improve the quality of the data available) and transformed to a state where the data could be formalized into standard statistical procedures.

By relying on these statistics, the authors are able to evaluate each method on a level playing field and maintain the validity of their conclusions.

3.3 Criteria for Evaluating the Performance of Different Optimization Strategies

Engineers are able to utilize three important criteria to determine the effectiveness of the wireless backhaul fixes:

First of which is the `Throughput Maximization`, which is evaluated based on the amount of completed data flow for a particular plan: As expressed in this equation:

$$Maximize\ T = \sum_{i=1}^{n} B_i \qquad (1)$$

Here, B_i is how much bandwidth the link I actually use, and n tells us how many backhaul links are running at the moment.

Keeping the delay as low as possible between the starting node and the target node is one of our main goals. The delay L along a chosen route is found by using the formula shown here:

$$L = \sum_{j=1}^{m} \left(\frac{D_j}{R_j} + Q_j \right) \qquad (2)$$

Where D_j stands for the size of the data packet, R_j is how fast that packet travels, and Q_j shows how much time it waits in the queue at hop j.

Energy Efficiency: The goal of any smart tweak is to cut down the overall power used while the information is on the wire. We measure that power with the formula E, given here:

$$E = \frac{\sum_{i=1}^{n} P_i \cdot t_i}{\sum_{i=1}^{n} D_i} \qquad (3)$$

In the formula, P_i stands for how much power link i uses, t_i gives the period the data is on that link, and D_i shows the total bits sent over it. The new mixed model mixes Dijkstra's quick path-finding to pick the fastest route and a tighter planner to share bandwidth, so the whole network stays speedy yet reliable.

Utilizing the approach described earlier, this part of the text will pinpoint elements of concordance and progress pertaining to this research and previous works.

Methods and Approaches Comparison

This research considers the wireless backhaul technologies mmWave, sub-6 GHz, and Free-Space Optics (FSO) and the optimization of these technologies through AI-driven dynamic routing, multi-hop relays, and adaptive bandwidth slicing within the 5G smart city context. This approach will be compared to other works in the following aspects:

- Routing Strategies: Most previous works concentrated on fixed routing strategies and the static optimization of wireless backhaul networks. These works utilized, to some degree, the Cloud-RAN, Multi-Edge Computing (MEC), and Software Defined Networks (SDN) to enhance the network, but did not incorporate real-time, dynamic, and adjustable optimization.
- AI-based Dynamic Routing: This study utilizes intelligent dynamic routing, building on previous works on reinforcement learning for dynamic routing in 5G networks. Unlike others, this study incorporates AI with SDN, which allows for central, real-time backhaul optimization through more effective adaptive, multi-tiered management in smart city environments.
- Hybrid Backhaul Networks: Earlier research proposed hybrid backhaul networks that combine mmWave and sub-6 GHz technology to improve urban coverage and capacity.

The studies mentioned above do not use adaptive techniques in routing. Inversely, this study differs from those in incorporating AI-based dynamic routing adaptive to a hybrid backhaul configuration to improve both spectral efficiency and reliability in varied network conditions.

4 Results

4.1 Analysis of the Current State of Wireless Backhaul Technology in Smart Cities

Today's wireless backhaul in smart cities looks great on paper, but in real life, the gear is spread unevenly across the tech stack. Highly capable mmWave connections only exist in prime geolocation commercial centers where laying-in fiber is unfeasible, whereas slower sub-6 GHz radio gear is applied to fringe and side areas. Such uncoordinated geolocation settings create flow multiplexing hotspots, render several connections dormant, and send Quality-of-Service measurement metrics into disarray. Combine with erratic user mobility, and the backhaul becomes queueing unstable, triggering excessive transfers and more pronounced lag. A significant pain point is that the majority of networks are designed with unchanging heuristics in mind: every routing path and bandwidth allocation are predetermined in a static, unresponsive manner. During peak traffic intervals, such a configuration under load dispersion causes traffic flows to be unevenly distributed, driving particular routing paths to and over the functional limits of the queue, and dropping packets when queueing delay interferes. Because no single controller oversees the mix of microwave, millimeter-wave, and wire, the system cannot fix itself after a link vanishes or jams.

4.2 Comparison of Different Optimization Techniques and Their Impact on 5G Internet Services

In considering the various solutions, academics evaluated metrics beyond speed and delay, focusing on those that all customers can appreciate daily. One notable metric of interest is Spectral Efficiency (SE), which can be described as:

$$SE = \frac{C}{B} \tag{4}$$

The maximum number of bits a link can transmit per second is called its channel capacity. Consequently, engineers tend to link that number to the bandwidth B, measured in Hertz. Software-defined networks driven by AI demonstrated the ability to shift bandwidth to busy networks. In contrast to older, fixed schemes that let bandwidth sit idle in quieter regions, these defined networks can transmit more bits per hertz.

$$PDR = \frac{P_{received}}{P_{resent}} \tag{5}$$

In the analysis conducted by the researchers, the definition of $P_{received}$ is the total number of packets successfully delivered, whereas P_{resent} is the total number of packets dispatched during the experiment. Dynamic routing achieves and maintains a packet delivery rate over 95%; however, during network congestion, the static variants of the routing algorithms' delivery rates plummet to below 85%. The researchers also analyzed jitter, a phenomenon characterized by undesirable delays that frustrate video calls. The researchers were able to analyze the jitter in the static routing algorithms using a simple formula:

$$J = \frac{1}{n-1}\sum_{i=1}^{n}|D_i - \overline{D}| \tag{6}$$

The delay for packet i is shown as D_i, while the average delay is $\overline{D}$. Routes guided by AI cut jitter sharply, so voice calls and video meetings felt smoother even on busy streets. The extra figures reveal that each method helped a bit, yet the mix of adaptive algorithms running on a central brain yielded steady gains across every area we looked at.

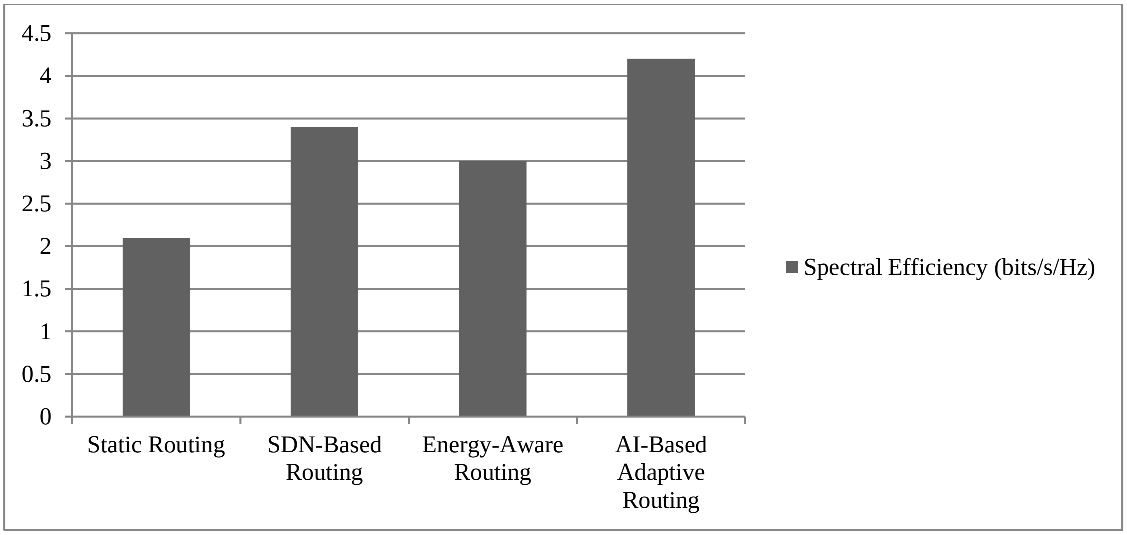

Figure 3: Spectral efficiency vs. optimization technique

Figure 3 displays a bar chart comparing spectral efficiency across five different routing methods. AI adaptive methods score best with 4.2 bits and claim the first place, with the only method offering dynamic, real-time, responsive bandwidth allocation. Following the SDN method comes the Software Defined Networking method with 3.4 bits. Centralized SDN architecture pays the price of slower reaction time and decision speed due to the AI model's slower response time. Next came energy-aware routing with a 2.1 bits/sec latency score. Energy-aware routing calculates the benefit of energy spent versus energy saved. Static routing was the worst method at 2.1 bits owing to a lack of demand or demand... All the other numbers suggest otherwise... The winner of adaptive and learning networks versus other networks hands down.

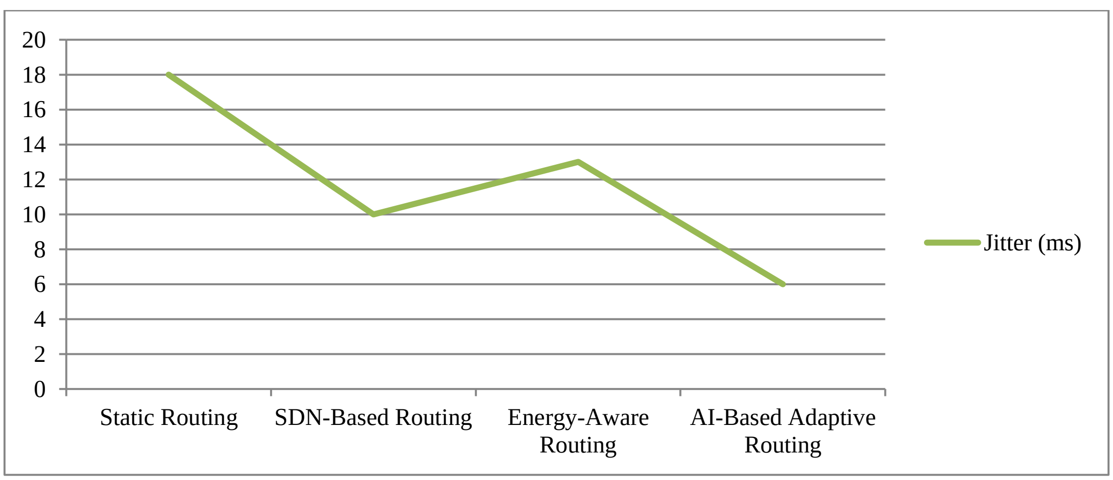

Figure 4: Jitter across optimization strategies

The line chart in Figure 4 tracks jitter for each routing method, spotlighting how much delay the packets experience during transit. For video calls, online games, or any time-critical service, lower jitter is simply a must. The AI-driven adaptive pathing kept jitter to 6 ms, the clear winner in delivering steady packet flow. SDN routing followed close behind at 10 ms, rerouting packets on the fly as links grew congested or shaky. Energy-aware paths climbed to 13 ms; the green routing maintained power savings but sometimes paused before picking a new hop. Static paths arriving at 18 ms precisely demonstrate why workloads struggle under inflexible rules. The image clearly shows the service provided through intelligent adaptive systems to smooth 5G in the future metropolitan areas.

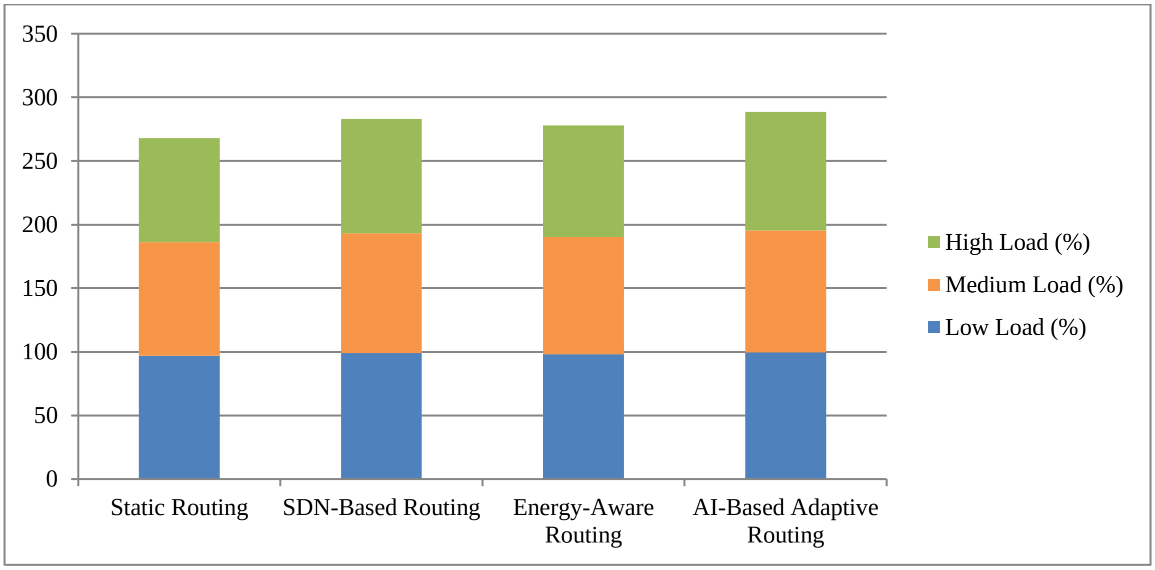

Figure 5: Packet delivery ratio (PDR) under load conditions

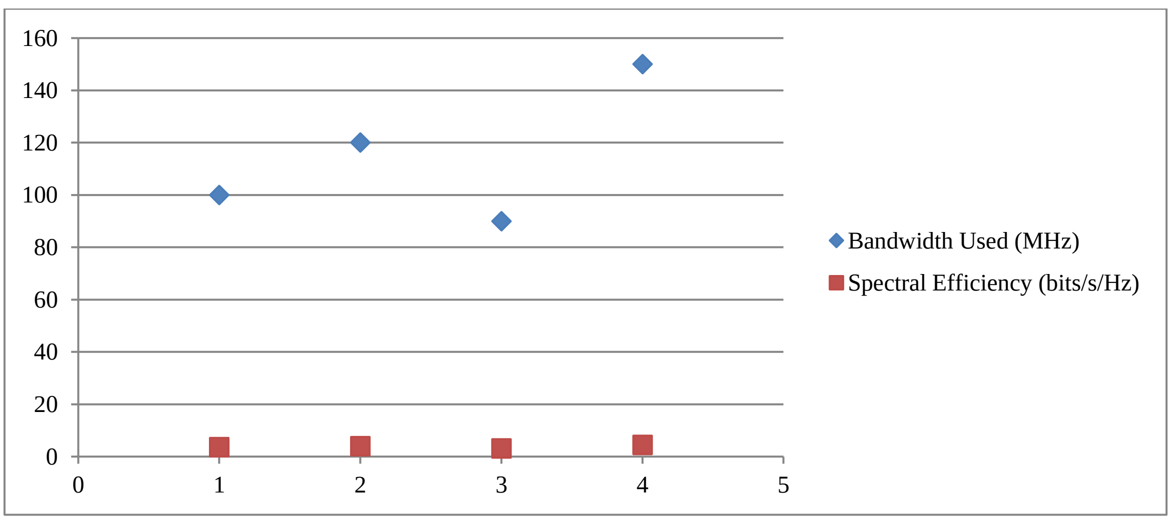

Figure 6: Spectral efficiency vs. bandwidth usage in hybrid backhaul

The PDRs for all examined routing strategies at light, medium, and high traffic volumes are juxtaposed in the stacked column chart in Figure 5. All strategies demonstrated PDRs above 95% at light traffic volumes, with the AI routing strategy leading at 99.5%, followed by the static routing strategy at 97%. However, as the network's user base grew, the gaps in PDR achievement widened. AI routing maintained a leading position in medium and high load conditions, with PDRs of 96% and 93%, respectively, demonstrating its ability to detect and avoid congestion. SDN-driven and green energy routing strategies also performed well, losing only a few percentage points in PDR during high traffic volumes.

In contrast, static routing tumbled the most, reaching 82 per cent when traffic peaked. Taken together, the results show that adaptive, brainy schemes deliver packets far more steadily, no matter how busy the radio spectrum becomes. Figure 6 shows a scatter plot of bandwidth use versus spectral efficiency for several hybrid backhaul mixes. The top-performing link trio-mmWave, Sub-6 GHz, and FSO reached 4.5 bits/s/Hz by steering traffic across channels and cutting cross-talk. A second pairing, mmWave plus FSO, came in close at 3.9 thanks to strong line-of-sight and roomy capacity. The Sub-6 plus FSO combo lagged at 3.1 because its lower frequency is easily blocked by rain or foliage. Meanwhile, mmWave with Sub-6 averaged 3.6 but missed the robustness a third link can offer. Together, these results confirm that smart, multi-technology backhaul boosts spectral efficiency by matching each link to real-time demand.

4.3 Identification of Best Practices and Recommendations for Improving Wireless Backhaul Optimization

After side-by-side tests, a clear list of best practices appeared for tuning wireless backhaul in 5G smart cities. First on the list is an adaptive routing system that never stops watching the radio airwaves and shifts links on the fly. That watchful engine needs to add congestion alerts and machine-learning traffic guesses so heavy bursts get stopped before users see them. Next, do not fine-tune only speed; treat jitter, spectrum use, and drop rates equally so each app gets the service it was promised. Joint models should swap loads, cut power, and trim delay simultaneously. Finally, cities should place their faith and dollars in programmable gear like SDN and NFV, bringing together cables of different ages and protocols under a single control panel. When that panel also runs AI at the edge, every router, switch, and microwave link is tuned in the moment. In short, any city network that mixes mmWave, sub-6 GHz, and free-space optics should decide which component goes where based on street layout and who uses the service, while local policies keep it scalable and resistant to outages.

4.4 Delay CDF and Implementation According to Routing Strategies

Figure 7 shows the Cumulative Distribution Functions (CDFs) of delays for the four routing strategies of the wireless backhaul networks: Static Routing, SDN-Based Routing, Energy-Aware Routing, and AI-Based Adaptive Routing. CDF is the probability that a randomly selected score falls below a specific value. In this study, the x-axis is latency (measured in milliseconds), and the y-axis is the total probability that packets experience latency below a given threshold.

Each routing strategy is displayed as a curve to accommodate the network latency targets. The spacing and steepness of the curves indicate how well each routing strategy minimizes network latency.

- Blue line Static Routing exemplifies a fundamental Routing Strategy that has predetermined FIXED routes. Despite it not being dynamic, this is a routing strategy associated with lower latencies. This is confirmed by the gradual low inclination of the curve signifying that a great number of packets encounter considerable latencies. Static Routing is not equipped to deal with heavy traffic conditions and network changes. This results in inefficiencies that are only made worse during congestion or interference.
- The SDN Based Routing in the green line is characterized by the implementation of Software Defined Networking in Routing SDN that is capable of dynamically altering and optimizing routing in real time. When comparing Static Routing and SDN-Based curves, the SDN-Based Routing curve outperforms Static Routing, with larger increases and steeper rises, indicating that larger Packets encounter lower latencies. SDN is able to perform better than Static methods. Emphasis is

placed on the fact that SDN is still used greatly in more advanced methods. AI in comparison to these static methods.

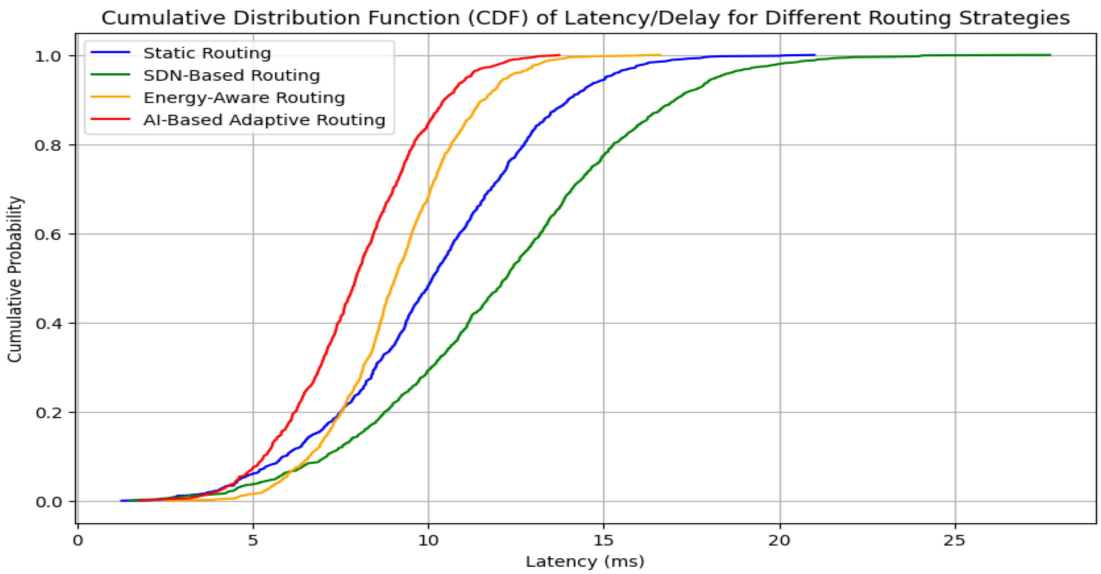

Figure 7: Cumulative distribution function background ālatency/delay of different techniques routing strategies

- Energy Aware Routing (orange line) attempts to optimize routes not only for latency but also for energy expenditure; in this case, in addition to delay, energy-efficient routing paths are considered. This strategy lies between SDN-Based Routing and AI-Based Adaptive Routing in terms of performance. Even though this approach attempts to reduce power and latency, unlike SDN or AI-based methods, it does not guarantee attaining the lowest latency. This is because in certain situations, the routes along which energy would be saved may not necessarily be the fastest routes, though there is a significant improvement relative to Static Routing.
- AI-Based Adaptive Routing (red line) is the last and most sophisticated approach in which AI (Artificial Intelligence) programs modify routing tactics in a flexible manner to the current state of the network in real time and rationally take into account the existing state of the network including the volume of traffic, sources of interference, and the availability of resources. The curve for AI Based Adaptive Routing is the steepest, demonstrates that this method achieves the most pessimistic latency. The AI Based Adaptive Routing curve is indicative of the lowest latency, the steepness of the curve demonstrates that most packets undergo very low latencies as opposed to the other methods. This enables the approach to subject packets to minimal delay under a variety of congestion scenarios because predictive models and machine learning methods are used to optimize routes and control congestion.

The graph shows that AI-Based Adaptive Routing achieved utmost control on the lowest achievable latency with the least amount of variance in the performance compared to other strategies. It’s then evident from the sharp shift in the CDF graph that the number of packets experiencing delay are in a large proportion. This is not the case with Static Routing which has the least performant graph which is flat and in primary colors which means the total number of packets are experiencing more delay. The other strategies of SDN Based Routing and Energy Aware Routing are the mid-tier performers with SDN Routings dynamic network condition responsiveness outpacing the Energy Aware Routing in the more efficient latency to energy spent drop.

From the above chart, it is possible to understand the effect that the proposed methodologies and routing strategies have on the latency in the 5G WWBN and the varying methodologies that come with the adjustment of the latency vs the performance, responsiveness, and the overall energy efficient.

5 Discussion

5.1 Implications of the Research Findings for the Deployment of 5G Internet Services in Smart Cities

This study offers pivotal lessons for rolling out 5G in future smart cities. Because modern urban life leans so heavily on quick, round-the-clock data-sharing-smart traffic lights, IoT sensors, security cameras, and even self-driving cars-the backbone wireless link has to stay quick and steady. Side-by-side tests show that older, fixed single-path routes simply cannot deliver the low delay and large data volume that new 5G applications demand. Instead, the gains seen with AI and SDN tools point to a clear path: backhaul networks need a smart control layer that can tweak settings on the fly. Cities should therefore build systems that read traffic loads, watch moving devices, and reroute or reshape links whenever an outage or spike occurs. Blending mmWave, sub-6 GHz, and free-space optics into one hybrid mesh also smooths coverage and reliability across different neighborhoods and weather. In summary, a responsive, developing, and integrated technology infrastructure will constitute the foundation of a 5G-enabled smart city.

5.2 Challenges and Limitations of Implementing Wireless Backhaul Optimization Strategies

While earlier trials may yield favorable results, the transition from lab concepts to field application involves several significant challenges. Most notably, the price of high-end wireless backhaul technology such as mmWave radios, free-space optics, and powerful AI servers required to run the SDN may be unaffordable for mid-sized cities or metro areas still developing essential network infrastructure. A considerable degree of network complexity will also be added as the incorporation of AI and SDN transforms a rudimentary radio overlay into a multi-tiered structure, necessitating the engagement of AI and SDN network management specialists to monitor, troubleshoot, and fine-tune the system. In addition, the integration of equipment from multiple vendors can be very challenging. When micromanagement of a system becomes necessary, its architecture is prone to severe limitations. Most complex metro areas will quickly grind to a halt without blazing fast decision-making processes. When obstacles such as antennae, rain, and extended free-space optics come into play, the network becomes a high-stakes gamble. There are more privacy and security issues as central control systems consolidate and analyze vast quantities of data from users and devices. Ensuring those systems are compliant with data privacy regulations entails additional burdens and obstacles.

5.3 Future Research Directions and Opportunities for Further Study

With the continuous evolution of 5G networks and smart-city technologies, there remains a growing list of potential research opportunities. One area of particular interest is the development of small, edge-centric tuning algorithms that prioritize local nodes over a remote server. This approach is likely to reduce latency and minimize the strain on the system’s core. Integrated with edge AI or federated learning, those algorithms could perform real-time decision-making while abstracting sensitive data. Another prospect is the combination of quantum computing and blockchain for backhaul routing algorithms. Ultra-fast quantum computers are likely to solve critical traffic management problems, while blockchain technology secures the data between nodes. Self-healing backhaul systems that autonomously detect and circumvent blockages should also be a focus. Finally, interdisciplinary teams with expertise in urban design, energy systems, and wireless communications should optimize backhaul to improve connectivity between devices while achieving targets for renewable energy and universal accessibility.

6 Conclusion

The analysis puts forward the repositioning of the wireless backhauls as a necessary condition for effective and trustworthy 5G rollouts in smart cities. The team empirically compared routing for mixed use of spectrum and delivery by fixed, real-time, and intelligent, AI updating schemes to find that smart mixed models are optimal across multiple outcomes of spectrum and delivery. The results obtained from the research incentivise cities to make an initial investment in flexible, AI, and software-driven systems that adapt to traffic. Predictably, Policymakers are to provide frameworks that stimulate investment in such advanced systems and collaboration between the public and private sectors. Industry actors are to furnish backhaul systems that integrate multiple forms of technology and fund adaptable, smart infrastructures. Researchers too must pursue the effective tuning of AI for simple systems, integrate it with alternative advanced systems such as blockchains and quantum chips, and address the need for smart, backhaul systems as urban living becomes denser and increasingly dependant on data. The results of the research will meet the immediate demand for 5G whilst reducing the chances of urban networks strangulation during the rollouts of 6G. The results will ensure the equitable sustainment of urban networks and will provide for the effective deployment of the digital services.

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