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Research Article

Low Latency 5G IP Transmission Backhaul Network Architecture: A Techno-Economic Analysis

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The steeply rising demand for mobile data drives the investigation of the transmission backhaul network architecture and cost for the fifth generation (5G) of mobile technologies. The proposed backhaul architecture will facilitate high throughput, low latency, scalability, low cost of ownership, and high capacity backhaul for 5G mobile technologies. This paper presents a transmission backhaul network architecture for 5G technology; the proposed internet protocol (IP) transmission backhauling architecture includes the data center, core network, distribution network, and access or IP random access network. A mathematical model for the data center IP core network, IP distributed network, and the IP access network for capital expenditure (Capex), operational expenditure (Opex), and the total cost of ownership (TCO) are presented, as well as a mathematical model for the entire backhauling architecture. The result shows that the increase in IP sites is positively proportional to the Capex and negatively proportional to the Opex. The selectivity analysis shows that the increase in bandwidth is directly proportional to the Capex, Opex, and TCO in the IP core network. The increase in data centers is directly proportional to the Capex, Opex, and TCO of the entire backhauling architecture.

1. Introduction

5G mobile cellular networks will address the need for increased data rates. Mobile access technology will connect billions of intelligent devices, supporting human- and machine-centric traffic. The backhaul network will bottleneck the 5G network architecture if not adequately dimensioned. Backhauling connects billions of devices to the central network. With the rise of 5G technology, the internet must adapt to meet various industries' quality requirements. A study by Hoeschele et al. [1] identifies 12 5G use case groups and examines their specific applications. The study concludes that using case groups such as video in 5G, health, and virtual and augmented reality will significantly affect traffic.

The shift from 4G to 5G is a big change for mobile network operators (MNOs). They need to adapt to avoid losing market share. One way to do this is to use scenario-based evaluation to measure future demand and supply uncertainty. A study using Britain as a case study found that technological advancements drive 90% of data growth between 2016 and 2030. Spectrum strategies can support baseline growth until around 2025, but new spectrum bands will be necessary to meet this demand. Small cell deployments offer significant capacity but come with higher costs [2]. The estimated 5G users will reach 37.340 million by the end of 2025. The projected data traffic growth is substantial, estimated to reach 342 PB by 2021 and 6,340 PB by 2025 [3]. 5G customers will account for 60% of subscriptions but generate 90% of traffic by 2025, driving data demand.

The traffic estimation provided in this study can help infrastructure providers, and policymakers to understand the anticipated impact of 5G on internet traffic.

Between 2018 and 2025, video streaming will rise from 48% of the total traffic to 82% of mobile traffic, with peruser monthly traffic rising from 1.8 to 13.39 GB.

Because of this enormous traffic demand, the 5G network will deploy more heavy traffic cells (small cells, microcells, and macrocells). The new technology will require backhaul with ultralow latency, high bandwidth, and the ability to support heavy core network traffic at a lower total cost of ownership (TCO) for the MNO.

This discussion will cover the technological and economic aspects of implementing 5G backhauling. This includes various forms of transmission backhauling such as microwave, fiber optics, optical switching networks, wavelength-division multiplexing (WDM), dense WDM, optical transport networks (OTN), and multiprotocol label switching (MPLS). We will also propose a 5G backhaul network architecture. Additionally, we will delve into the 5G IP backhaul network design model that consists of capital expenditure (Capex), operational expenditure (Opex), and TCO. This discussion is structured as follows: Section 2 covers relevant research, Section 3 delves into 5G IP backhauling architecture, Section 4 discusses IP backhauling network techno-economic model development, and Section 5 covers model formulation, result verification, and SA.

2. Related Work

2.1. Software-Defined Networking and Network Functions Virtualization. Mobile backhaul (MBH) networks must be reliable, high-capacity, and available to fulfill customer demand. MNO is always seeking new ways to boost customer bandwidth and reduce operational infrastructure costs. SDN and NFV improve bandwidth, reliability, availability, monitoring, and end-to-end management.

New software techniques like SDR and AI are being used to optimize wireless communication systems. This involves a self-management system that adjusts to the location of nodes, improving connectivity and extending coverage. With the help of AI-guided decisions, the placement of nodes is optimized, resulting in a significant increase in the number of subscribers served [4].

The difficulties of merging fronthaul and backhaul transportation in 5G networks were investigated. The study considers the different requirements for bandwidth and latency that may arise from new functional splits. Various solutions were proposed to address these challenges and tested using precommercial equipment. The research has proven that our proposed transportation solution, "Cross haul," efficiently fulfills the requirements of 5G front and backhaul at a reasonable cost [4]. WizHaul software is an excellent tool for optimizing the functional split of your 5G network. It can help with network planning, automation, and adaptation, making network management efficient and effective [5].

Introducing the Layback architecture—a system for wireless operators and technologies to share resources. The RAN resources are organized in layers, with a coordination point behind gateways implemented through SDN. A central SDN orchestrator manages communication and computation resources to facilitate cooperation among operators and technologies. Our case study on fluid CRAN function split demonstrated increased efficiency through sharing function blocks [6]. Matryoshka is a resource scheduling solution that uses rounding and decomposition to create an approximation algorithm that runs efficiently. It outperforms existing solutions like CSPP and Octopus by up to 52% [7].

An optimization framework was introduced to promote sharing backhaul network resources between multiple operators and wireless platforms. The proposed architecture, known as Layback, features a centralized SDN orchestrator at the wireless network backhaul. This is where traffic streams from different operators converge. The research also introduces a scalable decomposition approach, which addresses the resource allocation problem across multiple layers and time scales [8].

The most effective way to tackle the issues of heightened data traffic, diminished latency, and elevated expenses in 5G packet core architecture is through the utilization of SDN-based hierarchical design. The focal point of this study is the development of an access cloud within this structure. This cloud provides speedy and adaptable Ethernet-like support to MTC devices and terminals while also managing mobility and maintaining low latency. Delegating nonscalable tasks and network management procedures to the SDN local controllers [9] is necessary for the optimal benefits.

Self-organizing networks (SONs) running on LTE technology utilize programmability in both control and data planes to enable automation and optimize network performance. By leveraging SDN and radio, these networks become programable and reconfigurable. To further enhance the SON-based architecture, combining the control plane of SDN with the data plane of SDR is crucial. Our proposed management framework for SON prioritizes an open and extensible protocol interface, incorporating the most important features from existing protocols [9]. The open networking foundation advocates SDN adoption, which provides exceptional automation and control for administrators. SDN is crucial for reducing 5G latency, and Google has successfully improved resource consumption through its implementation. Oughton and Frias [10] clearly states that CORONET implemented SDN to promptly and effectively restructure network and data allocation in case of any malfunction or network enhancement [10].

Using an SDN-based algorithm has significantly enhanced the performance and reduced packet loss of an optical fiber network. This algorithm dynamically determines the optimal backhaul route, wavelength, and placement of the local baseband unit, thereby optimizing the mobile backhauling network performance. Multiple operators and technologies must collaborate to maximize resource efficiency. With RAN bandwidth depleting, MBH networks that connect mobile consumers to content face mounting pressures. These networks have diverse architectures, technologies, equipment, and topologies. Advanced network timing and synchronization, operations, administration, maintenance, provisioning, quality of service (QoS) prioritization, and protection features are in place to guarantee a good user experience [11].

2.2. Multiprotocol Label Switching Technology and Unified Multiprotocol Label Switching. For optimal 5G backhauling connectivity, a network must possess ultralow latency, an ultradense structure, high availability, and adequate capacity. The architecture should support 10 times the bandwidth per link and provide 100% coverage. Moreover, it must support enhanced mobile broadband, connected vehicles, AR/VR, S-UHD/3D video, haptics/sensing, enormous IoT, remote machine control, mission-critical services, and fixed-wireless access. These requirements are nonnegotiable for any network aiming to achieve optimal 5G backhauling connectivity.

Meeting these requirements requires the utilization of MPLS [12], a high packet switching technology. MPLS, developed by the internet engineering task force (IETF), facilitates Layers 2 and 3 protocols. Its primary objective is to optimize the management of internet-related matters, including the core network, access network, and routing performance [13].

The MPLS network's control plane is solely responsible for exchanging routing information and distributing labels among devices. The primary standard routing protocols used for MPLS are OSPF, IS–IS, and BGP. These protocols effectively support IP and label forwarding while also facilitating the exchange of routing information with other routers [14].

The MPLS system comprises the data plane and the control plane. The data plane's essential function is to forward labels, which is done without using any routing or distribution protocols. This distinction of duties empowers routers to make intelligent routing decisions. Each packet contains a 32-bit header and a label affixed to it for routing purposes. By virtue of this label, the packet can be directed to its intended destination without considering the original packet information [15]. The organization of labels in MPLS follows a last-in, first-out approach, ensuring that information is transported and distributed efficiently. MPLS switching takes place when the label field contains the required information for forwarding. The MPLS virtual network is a popular application in the MNO industry, offering a virtual private network that operates over both natural IP networks and specifically designed MPLS networks [16]. The MPLS network plays a crucial role in packaging data packets into IP tunnels. Once an MPLS network's label-switched path is established, it follows the inner gateway protocol's best path to reach the intended destination network. This is done by using IGPs like OSPF or IS–IS to communicate routing information to all MPLS routers, thereby determining the most efficient path to the target network. The MPLS core network then forwards packets based on the label, not IP, until the last label switch, where the label is removed, and IP forwarding resumes.

NR technology is an absolute game-changer for 5G. It provides new capabilities such as virtualized capacity, which is essential for the profitable operation of massive machine-type communication and new ultrareliable low-latency communication applications. Furthermore, it enables closer coordination between local server farms, relevant registers, and system endpoints, leading to more efficient operations. By implementing the segment routing technique in a packet network, the backhauling design becomes more flexible, effective, cost-efficient, adaptable, reasonable, and perceptible. It is no wonder that many MNOs prefer to use the unified MPLS solution as their transport technology, extending the IP network on a high-capacity optical infrastructure [17, 18].

The unified MPLS can establish a robust framework that can seamlessly support TDM services, 2G, and packet services such as 3G and 4G. Its network design is highly pliable and can cater to the operators' needs from the core to the access layer. This solution offers a cost-effective and efficient infrastructure that optimizes the control and forwarding plane of the network equipment to make it more practical and economical [19, 20].

In a network with extensive MNO coverage, unified MPLS is essential. The segmentation of the core, aggregation, and access networks of the data center and transport network, with each domain operating on its own IGP, is critical. Communication between domains is enabled using BGP. In large-scale networks such as 5G, which involve thousands of devices, the implementation of unified MPLS is an incredibly complex undertaking that cannot be ignored [21].

2.3. Segment Routing Techniques (SRTs). The IETF presents SRTs. An SRT is an important routing technique that simplifies control plane operation. SRT implementation is achieved by putting the information of the shorter root and the destination node in a header (the segment list), so that traffic will flow in that direction to the destination.

The segment list is the same as the MPLS data plane plus the segment list where the traffic is ordered to use to the destination. In SRT, signaling protocols are unnecessary; the starting node makes all the decisions about the segment list. Where, we have equal cost multipath (ECMP) operation, the traffic is automatically load-balanced on a perflow basis. A study proposed a segment list management algorithm for the longest match relay push for dynamic traffic recovery and traffic engineering in a multi-domain network [22]. The system was tested based on the segment routing and an SDN. The outcome of the test shows that the algorithm can make multiple links share the same segment list according to the initial forwarding information base [23].

The combination of SRT and SDN techniques (SDNT) has become the conventional network architecture for SDNT. SRT provides an improved service level agreement (SLA), network availability, network flexibility, and scalability of the systems. Because the segment list is needed only at the entrance, the node and all other nodes only need to forward the traffic according to the segment list without knowing the packet information [24]. A model for simplifying and combining the ECMP was proposed for weight restriction with segment list simplification. SRT helps to achieve efficient resource utilization by overcoming the network scalability issues of MPLS-TE [25, 26].

2.4. 5G Transport Topology. MBH can be based on three main topologies, ring, hub, and spoke, and daisy chain, with their unique limitations and merits [27]. The unified MPLS may build a foundation for TDM, 2G, and packet services like 3G and 4G. It simplifies and lowers the cost of network equipment's control and forwarding plane.

Ring topology has reduced maintenance costs, speedy sub-50 ms service restoration, and a faster return on investment. Ring topology provides logical network connectivity options such as point-to-point (P2), point-to-multipoint, and multicast. Optimizing mobile network traffic increases network efficiency. The ring architecture may readily scale to numerous interconnected nodes (macrocells, microcells, and picocells) accessed through high-bandwidth ethernet over fiber. It collects all the small cells at a macrocells site and sends the data to the mobile core network via fiber. Daisy chains are utilized when backhaul circuits from each site to an aggregation hub are too expensive or impracticable. Besides network topology, physical transport media like wired or wireless are used [28].

Navarro-Ortiz et al. [29] discusses the characteristics of 5G, requirements, radio interface deployment, and performance evaluation standards. The study compiles references from four major standards development organizations (SDOs): The International Telecommunication Union (ITU), The 3rd Generation Partnership Project (3GPP), The Institute of Electrical and Electronic Engineers (IEEE), and The World Interoperability for Microwave Access (WIMAX). Additionally, the study includes information about industry associations (IA), such as 5GPPP (METIS, FANTASTIC-5G, mm MAGIC, SPEED-5G, and 5G NOMA), NGMN, and AIT. It is important to note that the SDOs and IAs show no major differences between radio interface deployment and traffic model scenarios, which are thoroughly summarized in the study.

2.5. Fiber Optics for 5G Backhauling. For MBH, fiber optics is the recommended primary wireline to use in 5G network architecture. Among available media options like microwave, digital subscriber line (DSL), and mmWave, fiber-based backhaul links are considered the highest standard for MBH networking. They boast the highest potential bandwidth capacity [30]. Fiber optics offer unparalleled flexibility, with the ability to cover vast distances while providing top-level resiliency and protection. This technology can be deployed using an array of topologies, including point-to-point, ring, hub-spoke, and daisy chain. To cut down on the cost of time division multiplexing (TDM), the introduction of a fronthaul aggregation method managed with wavelength division multiplexing passive optical network (WDM-PON) architecture has been the way forward [31]. It offers a balanced solution between simplicity and adding a level of adaptability and dynamic flexibility from the WDM architecture. TDN-PON systems can be GE-PON and GPON, which can be deployed as Fiber to the Home (FTTH) to contribute 1 Gbps and can be advanced to XG-PON and 10G-EPON [32]. GPON technology is used for FTTH for residential and small business customers, yielding much success for the MNO in Ghana and Africa. Of all the FTTH technology, including P2P active ethernet, GPON, 10GE-PON, 40G-PON, and WDM-PON, GPON is a leading technology in the last-mile network because of it simple architecture and low cost. TDM-PON can be used for 5G fronthaul owing to its capacity and cost-effectiveness. However, its major drawback is latency on the upstream and complex architecture that obstructs easy and dynamic adaptability and scalability, thus limiting resource pooling [21]. Techniques such as WDM can be enabled so that multiple optical signals can be conveyed in parallel, with each signal carried on a different wavelength or color of light [33]. WDM can be divided into DWDM, which uses close channel spacing to deliver even more throughput per fiber, and CWDM, which provides eight channels using eight wavelengths. Currently, DWDM can handle up to 160 signals, each having a bandwidth of 10 Gbps, which is the total capacity of 1.6 Tbps per core of a fiber [30]. However, this places a limitation on the availability, architectural design, and cost of deployment. The use of WDM-PON will solve all the issues facing TDM-PON, it allows physical sharing of fiber medium by several optical network units while providing virtual P2P architecture with P2P wavelength realization. WDM-PON is dynamic, adaptive resource allocation at low latency and enables scalability [14]. All these advantages translate directly to a potential reduction in fiber links and lower capital expenditure owing to resource sharing and pooling. The main disadvantages of WDM-PON are the high cost of maintenance and deployment of transceivers and multiplexers/demultiplexer [34].

2.6. Capital Expenditure, Operational, and Total Cost of Ownership. Smail and Weijia [35] conducted a study analyzing the Capex, Opex, TCO, and network capacity of a distributed antenna system (DAS) and femtocell. The study took into account crucial factors such as antenna expansion, intercell interference, and energy efficiency. Additionally, Bouras et al. [36] thoroughly examined different financial models; Capex and Opex for small cells and DAS through a techno-economic analysis.

Assessing new communication technologies through techno-economic evaluations are common among engineers. However, there is limited comprehensive research on 5G's techno-economics. With 5G deployment underway, it is an opportunity to understand its achievements for ongoing research on 6G. This survey looks at emerging trends in 5G's techno-economic literature and provides five recommendations for future 6G technologies [37]. The paper introduces a Python simulator called pysim5G that combines engineering and cost analysis for 5G networks. It includes radio interference and deployment cost analysis. A case study shows that 5G infrastructure sharing can reduce costs by up to 50%. The open-source simulator enables integrated techno-economic assessments within a geospatial context [38]. The goal of 5G networks and edge computing is to enable high-device connectivity, leading to innovative services in various industries. Economic feasibility is crucial for their success, and effective techniques must be used to assess it. This paper analyzes immersive media services provided at crowded events through a cloud-enabled small cell network owned by a neutral host and offered to multiple MNOs [39].

A study analyzed the cost of deploying 5G networks with different frequencies and network densities in Central London. Results showed that multiple technology options could achieve high speeds, but millimeter-wave technology and 802.11ac access points are necessary to exceed 100 Gbps/km^2 in capacity. The cost of high-capacity networks is estimated to be 4–5 times higher than LTE networks. The study provides insights into the cost considerations of 5G rollout [40].

In [41], a comprehensive and general techno-economic framework is presented for evaluating the TCO and economic viability of a HetNet deployment. The framework is then applied to a case study focused on a backhaul-based transportation segment. The study's results emphasize the importance of making informed decisions regarding technology and deployment strategies to preserve the potential financial benefits of HetNet deployment. Furthermore, the findings demonstrate that the deployment solution with the lowest TCO may not always lead to the highest profits. The demand for mobile traffic and IoT poses challenges for 4G networks. Operators must transition to 5G after 2020. A mathematical modeling approach and techno-economic analysis suggest a new pricing model to accommodate growth. Comparing expenses and revenue, 5G has lower costs than 4G LTE and can support increased data consumption and more users. Reusing existing sites reduces costs when deploying a denser macro network. However, small-cell solutions have limitations in capacity and coverage constraints [35]. 5G networks' high-density cell architectures pose technical and financial challenges, leading to over-provisioning and increased operational costs. Existing planning solutions fall short of meeting the multitenancy and network slicing requirements of 5G networks. To address this, a new algorithm utilizing Voronoi Tessellation has been proposed. Backhauling-as-*a*-service (BHaaS) and traffic profile-as-*a*-service (TPaaS) approaches can increase project benefits by 22% compared to the traditional models. BHaaS emphasizes a "pay-only-for-what-you-use" framework, while TPaaS leverages yearly traffic profiles [42].

Bouras et al. [43] presented a techno-economic analysis for 5G architecture for DAS and MIMO. Bouras et al. [44] and Gedel and Nwulu [44] used an ordinary annuity model to predict the future annual repeating payment of the principal amount invested in Capex, Opex, and TCO. Verbrugge et al. [45] stated that the principal cost for operations includes the running and backhaul costs, whereas the principal invested capital amount comprises the eNodeB and the EPC, as well as the transmit and receive antennas. Habibi et al. [46] illustrates that the reconstruction of a new architecture will improve performance, enhance energy efficiency, and decrease Capex, Opex, and TCO.

Although much has been written on the techno-economic model and sensitivity analysis of some essential variables in literature, researchers have not considered the assessment of 5G IP backhauling network architecture and the techno-economic model for IP backhauling. The studies by Oughton and Frias [10], Smail and Weijia [35], and Bouras et al. [36, 44, 47] present techno-economic models and sensitivity analysis for DAS, MIMO, macrocells, and small cells, but models for transmission backhaul architecture for the 5G mobile network, and the key transmission technology MPLS, WDM, DWDM, and OTN were not presented. From the said literature, no study has concurrently assessed the key contributions of this study, which are highlighted below:

(1) Reviews will be done on various type of transmission topology recommended for 5G deployment, types of transmission media including guided and unguided media and routing technique (MPLS, WDM, DWDM, and OTN).

(2) We propose a transmission backhaul architecture for the 5G mobile network. This will include the data center elements, core network, distribution network, and access or IP RAN.

(3) A mathematical model for the Capex, Opex, and TCO for the data center, core network, distribution network, and the IP RAN will be presented.

(4) We will test the model using cost data from the MNO and National Communication Authority (NCA), and an SA of key variables in backhauling.

3. Unified MPLS 5G Backhauling Architecture

The proposed arrangement in Figure 1, is to evolve the IP transport networks control and data plane toward segment routing orientated around SDN to form a unified MPLS.

Combining SRT and SDN (SDNT) is the standard network design, SDNT improves SLA, network availability, flexibility, and scalability. Because the segment list is only needed at the entry, the node and all other nodes can forward traffic based on the segment list without knowing packet details [22–24].

The architecture is made up of three main transport domains, the core network, aggregation network, the access or IP network, IP reflectors, and the main transport data center. The core network will have an OSPF routing protocol while the aggregation network and the access run on IS–IS routing the will reduce latency, improve network security, and high level of network protection [48, 49]. All interdomain communications are possible with implementing BGP and enabling P2P communications. This IP transport infrastructure is fit for covering a wide scope of service technologies with a related IP-based SLA. BGP-based VPN advancement (EVPNs and VPNv4/v6) and rising SD-WAN VPN technology simultaneously maintain scalability and reduce latency. The proposed arrangement will support all the TDMA services in 2G and CDMA services in 3G and 4G by P2P communication. These arrangements will spread from fully distributed implementation to crossbreed style, where the SDNT controller and the routers' usefulness are separated. The 5G industry has three main ways to deal with parting the radio capacities between different segments of the e-RAN. These include the low-level splits, where the physical element of the radio is part of the radio unit or the radio equipment at the cell site.

4. Economic Mathematical Modeling

Economic models are tools used to analyze the risk in financial investment in various businesses. The models include the present value, the net present value (NPV), profitability index, and the internal rate of return, which are used for analysis of large projects. The project is good only if the

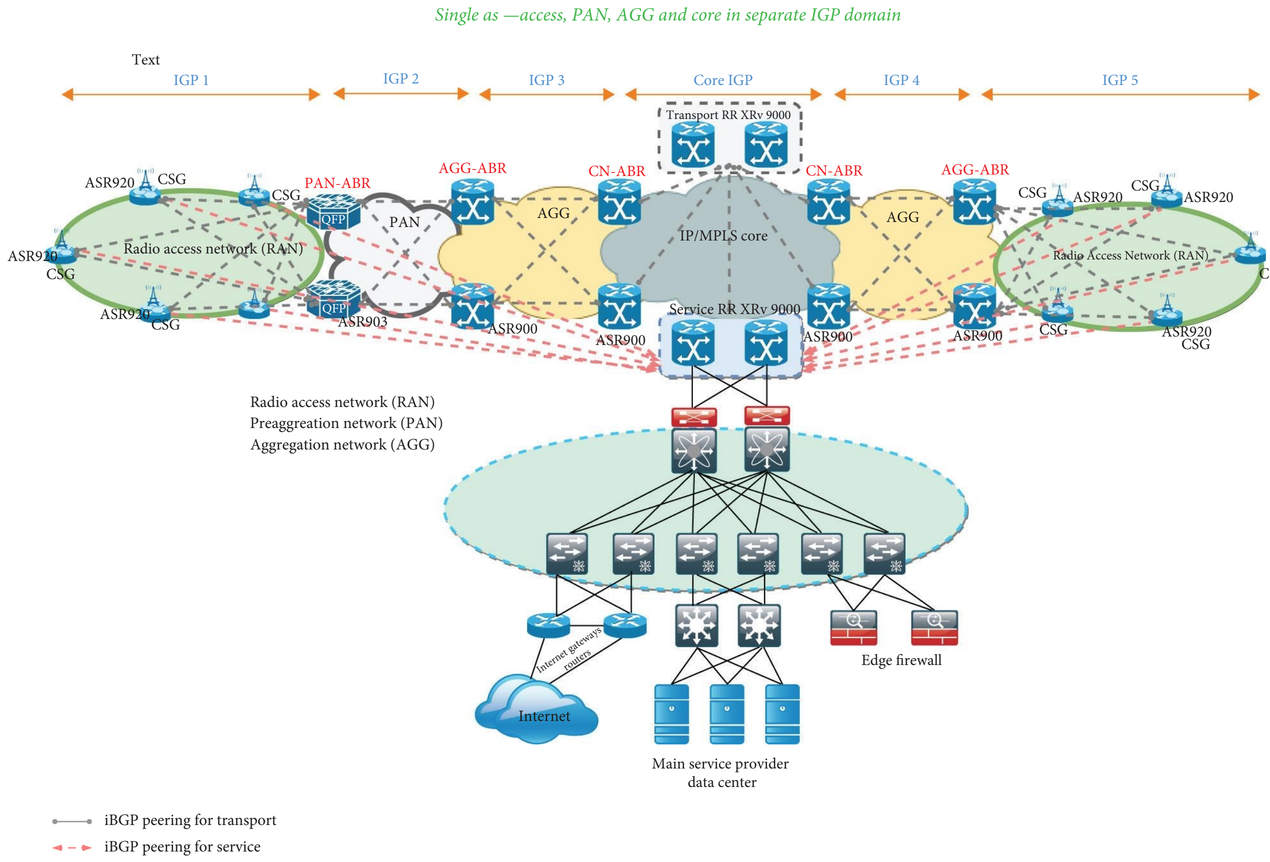

Figure 1: Proposed unified MPLS backhauling architecture for 5G technology.

present value is greater than the initial cost of the investment. The profitability index must be greater than one. The economic model depends on the Capex, Opex, and TCI.

4.1. Mathematical Model Formulation. In this section, we develop an improved economic model for an annual repeating payment for the telecom infrastructure and the TCO. The new model will be an improvement on the models in Equations (1–3) [35, 36, 44, 47].

$$A = P\frac{r(1+r)^n}{(1+r)^n - 1}, \tag{1}$$

$$A = \frac{1}{1-(1+i)^{-n}}C, \tag{2}$$

$$C_{\text{macro}}^{\text{TCO}} = (1+f_m)N(C_{\text{eNB}} + C_{\text{EPC}})\frac{r(1+r)^n}{(1+r)^{n-1}} + \text{N}C_{\text{st}} + f_{\text{BW}}\text{BW}. \tag{3}$$

Equation (1) is a repeating payment model where A is the annual settlement, r symbolizes the interest rate, P is the individual present value, and n is the years of repayment. In Equation (2), A is the annual repayment, C is the total present value, i is the interest rate, and n is the number of years of repayment. Equation (3) is the TCO for a macrocell with parameters including N is the number of eNodeB, C_{eNB} is the capital cost for a single BS, C_{EPC} is the capital cost of deploying the core network of a single eNB. f_{BW} is the backhaul bandwidth expressed in €/Gbps, C_{st} is site costs apart from maintenance cost, backhaul BW for a site's interconnection and f_m site maintenance costs. Equations (1) and (2) both have a limitation of repayment that always comes to the investor at the end of the investment; there is no preinstalment. The parameter used in this model did not clearly consider this passive infrastructure cost. The tower company or the MNO has no assurance of payment. Investment using this model is risky if the MNO defaults in payment. The model used will require a longer repayment period of at least 10 years. The model does not take into account the time value for money; tower companies will lose owing to interest rate and inflation fluctuation. Equation (3) is the TCO for a macrocell, and does not take into consideration the infrastructure capital cost and the infrastructure operational cost. In Equation (3), TCO does not consider if the tower infrastructure is owned by the MNO or rented. The model does not factor in the height of the tower, which is a principal cost element in tower building. The limitations of the model above show numerous gaps in the result, which will be addressed in the proposed model.

4.2. Conventional Model Formulation. The aim of the study is to develop a risk-free, economical model that will mitigate all the limitations of the models used in [35, 41, 43, 44, 47,]. The new model will include Bs (new 5G radio), fronthaul, remote radio modules, and an antenna. Tower height will affect capital and operational costs. The model is an annuity due; thus, the state will pay the tower company's investment. The new model addresses the limitations of Equations (1) and (2) on time value interest rate declines and inflation. This model's TCO is $(1+\mathrm{m})$ times the prior model's, making it more resilient and risk-free for tower and MNO companies. Initial investment cost exceeds NPV, resulting in strong NPV and ROI. Initial capital expenditure includes tower supply, land purchase, AC power, backup power solution, hybrid solution (power hybrid or solar hybrid), generator, air-conditioning, rectifier systems or DC power plant, fiber infrastructure, construction, and installation costs. Initial operational expenditures include site management, security, energy (fuel, commercial electricity charges), salaries, and office and apartment rent. The capital and operational cost model will be utilized to represent the total cost of ownership or initial investment, and an NPV model will be built for the tower company. The study will outline all the passive infrastructure elements for 5G implementation. A mathematical model for Capex, Opex, and TCO will be presented for 5G infrastructure sharing. The paper will also present a mathematical model for the NPV. This study will investigate the Capex, Opex, the TCO and the NPV with cost data from the MNO, Tower Company of Ghana, and NCA. Finally, an SA is used to assess the effect and influence of a key variable element of 5G passive infrastructure sharing.

4.3. Capex for IP Transmission Backhaul 5G Technology Deployment. Capex is spent on new infrastructure and equipment, data center solutions, core network, distribution network, and access network comprising Capex (the IP RAN network). We considered leaf and spine architecture for this IP data center solution due to its deterministic bandwidth, low latency, GBE infrastructure, and scalable service insertion. The spine links to the IP core network, whereas the leaf and mobile core nodes connect to the leaf. This design is particularly flexible during updates; a leaf is inserted for service and a spine for bandwidth. Service nodes readily transition. The leaf layer has 10 GE, 25 GE, and 100 GE ports. The spine handles north-south, east-west, and data/storage traffic. The data center nodes, including the spine router, comprise a tree topology to display 5G traffic with low predictable latency and outstanding efficiency. In our 5G design, we adopt a leaf-and-spine architecture. Cisco recommends the Nexus 9000, 5K/7K leaf routers, Cisco ISR router 4331 for the internet, and Cisco ASA Firewall (ASA 5585) for network security.

The IP core network is an MPLS core network (CN), which in this backhaul configuration requires ASR-900X routers for the core that are directly connected to the mobile core network through the spine and the provider end router PE, which is also ASR900X, and XRv-9000 route reflectors for all routing tables. The IP core network has four main routers, eight PE routers, and four reflectors. IP network's next layer is distribution or aggregation. Four ASR907 routers form a ring. This component of the network interacts with the CN through the CN-ABR, which consists of two ASR900s, one active and one protecting. The IP-RAN links to the aggregation network through the preaggregation network (PAN). The IP-RAN connects all services to the network; 2G and 3G cell sites connect via VLAN, and 5G cell sites connect via IP. Transport application design uses QoS, flexible application placement, strong reliability, high scalability, low latency, and MPLS segment routing. Cost determines the optimum IGP path to a packet's destination. The lower cost route will get many packets, causing congestion and packet drop.

To overcome this problem, we implement segment routing in MPLS [11]. SR-TE optimizes the network by overriding IGP default behavior. Segment routing secures the network, speeds rerouting and minimizes network costs. It optimizes network utilization by employing traffic engineering to assign load while ensuring bandwidth to mission-critical applications, reducing network complexity, and making it easy and less expensive to manage. SR-TE is SDN-enabled and real-time [33, 50, 51].

SDN will improve latency, bandwidth, reliability, availability, monitoring, and end-to-end management. SDN isolates the control interface from each device, creating a dynamic, manageable, cost-effective, and adaptive architecture for administrators. SDN reduces 5G latency. SDN controls ports, routers, switches, and optical devices. The high-bandwidth optical network infrastructure will be used, despite the backhauling architecture [52].

An OTN layer underlying an IP network adds efficiency, flexibility, and programmability over pure optics and deterministic characteristics where needed. OTN can send data farther than MPLS. In our suggested 5G backhauling architecture, OTN runs beneath IP [32]. The capital expenditure for this architecture will only consider the IP network elements, which will include the IP data center, the IP core, the aggregation network, the preaggregation, IP-RAN network, the MPLS/segment routing traffic engineering, the SDN solution and deployment.

Suppose C_{InvMNO} is the initial Capex, α is the interest for the cost of capital, C_{cxmc} is the repayment amount, then reference from Equations (1) and (2):

$$C_{\mathrm{cxIPN}} = C_{\mathrm{InvIP}}(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right]. \tag{4}$$

The main advantages of this this model over what is being used are that the TCI value will be $(1+m)$ times that of the previous model, making this kind of investment more profitable, the risk level is very low and any increase in the interest rate will have no effect on the return value of the investment. Assuming, that the MNO owns the data, centers were all the backhauling routers are deployed, consider the Capex of the data center as follows:

$$C_{\mathrm{cxdata}} = \left(2R_{\mathrm{sp}} + 6R_{\mathrm{leaf}} + 2R_{\mathrm{isr}} + 2R_{\mathrm{firewall}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right], \tag{5}$$

where R_{sp} is the spine router, we propose the Nexus 9000 router for the application; where R_{leaf} is the leaf router, we proposed the nexus 7000 router; where R_{isr} is the internet gateway router and in the work we propose the ISR 4331 router; R_{firewall} is the firewall router and the proposed router for this application is the ASA 5585-X.

The Capex for the IP core network is as follows:

$$C_{\text{cxlPCore}} = \left(4R_{\text{CNR}} + 4R_{\text{reflect}} + 8R_{\text{PE}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right], \tag{6}$$

where $4R_{CNR}$ is the core network router, we propose ASR-900x; where $4R_{\text{reflect}}$ is the route reflector, we propose XRv-9000; $8R_{\text{PE}}$ is the provider edge router and the proposed router is ASR-900x. Looking at the above equation, the core router is the same as the provider edge router

$$C_{\text{cxlPCore}} = \left(12R_{\text{ASR}} + 4R_{\text{reflect}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right]. \tag{7}$$

Aggregation network, preaggregation and access or IP RAN network.

$$\begin{aligned} C_{\text{cxAGNPANIPRAN}} = {} & \left(8R_{\text{AGN}} + 2R_{\text{PAN}}\right. \\ & \left. +16R_{\text{lPRAN}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right]. \end{aligned} \tag{8}$$

The above equation is the Capex for the aggregation network, preaggregation and access or IP RAN network; R_{AGN} is the aggregation network router, the proposed report is ASR-900x. R_{PAN} is the preaggregation router; the proposed router is ASR-900x. R_{lPRAN} is the access or IP RAN router and the proposed router is ASR 9000v.

$$C_{\text{cxAGNPANIPRAN}} = \left(10R_{\text{ASR}} + 16R_{\text{ASR9000v}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}-1}{(1+\alpha)}\right]. \tag{9}$$

SDN, configuration, implementation and others are calculated below:

$$\begin{aligned} C_{\text{cxSDN,lmpl,others}} = {} & \left(C_{\text{SDN}} + \left(C_{\text{rent}} + C_{\text{energy}}\right.\right. \\ & \left.\left. + C_{\text{impl}}\right)(1+\alpha)\right)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right], \end{aligned} \tag{10}$$

where C_{SDN} is the cost of software, C_{rent} the cost of renting or procuring of the land, C_{energy} and C_{implem}.

4.4. Total Capital Expenditure.

$$C_{\text{cxIPN}} = C_{\text{cxdata}} + C_{\text{cxIPCore}} + C_{\text{cxAGNPANIPRAN}} + C_{\text{cxSDN,lmpl,others}}, \tag{11}$$

$$\begin{aligned} C_{\text{cxIPN}} = {} & \left(2R_{\text{sp}} + 6R_{\text{leaf}} + 2R_{\text{isr}} + 2R_{\text{firewall}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right] + (4R_{\text{CNR}} + 4R_{\text{reflect}} \\ & + 8R_{\text{PE}})(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right] + \left(10R_{\text{ASR}} + 16R_{\text{ASR9000v}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right] \quad , \\ & + \left(C_{\text{SDN}} + \left(C_{\text{rent}} + C_{\text{energy}} + C_{\text{impl}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right]\right. \end{aligned} \tag{12}$$

$$\begin{aligned} C_{\text{cxIPN}} = {} & \left(2R_{\text{sp}} + 6R_{\text{leaf}} + 2R_{\text{isr}} + 4R_{\text{RR}} + 2R_{\text{firewall}}\right. \\ & +24R_{\text{ASR}} + 16R_{\text{ASR9000v}} + C_{\text{SDN}} + C_{\text{rent}} \\ & \left. +C_{\text{energy}} + C_{\text{impl}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right] \end{aligned} \; . \tag{13}$$

4.5. Opex for IP Transmission Backhaul 5G Technology Deployment.

Opex is the amount of money invested for the costs concerning the day-to-day operation of the system depending on the type of operations, cost of rent, vehicle maintenance cost, salaries and wages, etc.

$$C_{\text{oxIPN}} = C_{\text{InvoIP}}(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right], \tag{14}$$

$$C_{\text{oxIPN}} = \left(C_{\text{EC}} + C_{\text{co}} + C_{\text{sec}} + C_{\text{sitepm}} + C_{\text{rent}}\right)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right], \tag{15}$$

where C_{EC} is the monthly energy cost that includes the genset, national power and hybrid, C_{cooling} is the system for backhauling to improve the QoS of the routers and other systems,C_{urity} is required because the data center is sensitive enough to warrant security on site, C_{sitepm} is the cost of maintenance to repair faults and replace faulty equipment (fiber cut, radio, interface cards replacement and preventive maintenance on the site, site janitorial services, etc.), and C_{rent} refers to rent for the site space depending on whether the MNO is sharing with a tower company or if the infrastructure is owned by the MNO.

4.6. Total Cost of Investments for IP Transmission Backhaul 5G Technology. TCO or TCI is a single value that represents the life span of a capital purchase. It is a financial estimate that helps in determining the direct and indirect costs of a product or services. It is the sum of the operational cost and the capital cost.

$$\mathrm{TCI}_{\mathrm{IPN}} = \mathrm{TCI}_{\mathrm{cxIPN}} + \mathrm{TCI}_{\mathrm{oxPN}}, \tag{16}$$

$$\begin{aligned}\mathrm{TCI}_{\mathrm{IPN}} = {} & \big(2R_{\mathrm{sp}} + 6R_{\mathrm{leaf}} + 2R_{\mathrm{isr}} + 4R_{\mathrm{RR}} + 2R_{\mathrm{firewall}} \\ & + 24R_{\mathrm{ASR}} + 16R_{\mathrm{ASR9000v}} + C_{\mathrm{SDN}} + C_{\mathrm{rent}} + C_{\mathrm{energy}} \\ & + C_{\mathrm{impl}}\big)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right] + \big(C_{\mathrm{EC}} + C_{\mathrm{cooling}} \\ & + C_{\mathrm{security}} + C_{\mathrm{sitemanagement}} + \\ & C_{\mathrm{rent}}\left[(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right]\right]\big).\end{aligned} \tag{17}$$

Simplifying Equation (17),

$$\begin{aligned}\mathrm{TCI}_{\mathrm{IPN}} = {} & \big(2R_{\mathrm{sp}} + 6R_{\mathrm{leaf}} + 2R_{\mathrm{isr}} + 4R_{\mathrm{RR}} + 2R_{\mathrm{firewall}} \\ & + 24R_{\mathrm{ASR}} + 16R_{\mathrm{ASR9000v}} + C_{\mathrm{SDN}} + C_{\mathrm{rent}} + C_{\mathrm{energy}} \\ & + C_{\mathrm{impl}}\big)(1+\alpha)\left[\frac{\alpha(1+\alpha)^{\Psi}}{(1+\alpha)-1}\right]\big(C_{\mathrm{EC}} + C_{\mathrm{cooling}} \\ & + C_{\mathrm{security}} + C_{\mathrm{sitepm}} + C_{\mathrm{RENT}}\big).\end{aligned} \tag{18}$$

5. Model Verification

This section will test the model using MNO in Ghana and the NCA [53–55]. The Tema metropolitan area of 565 km^2 with a population of about 292,773 was considered. The population of the Tema metropolis is entirely urban. The model's economic performance will be verified based on the assumptions below. We assume that the MNO owns the infrastructure and the SDN is not activated on the IP network when we have one data center in an area of 565 km^2 and when we have two, three, four, or five data center to assist in the reducing latency. The situation is assessed when the MNO rents the infrastructure, with SDN activated, again with one data center in an area of 565 km^2, with two, three, four, or five data center to assist in the reducing latency. The model will help us to compare which method is cheaper and easier to deploy at the reduced latency. Finally, an SA assesses the effect and influence of a key variable element of the 5G backhauling. SA will be performed on upgrading the backhauling from 10 to 100 GHz with SDN activated, the effect of the interest rate will be analyzed, as will the Capex, Opex, and TCO, and the number of the data center. We will also test segment routing protocol with Opex, Capex, and TCO.

Table 1: TCO parameter indispensable variables for IP backhauling.

Parameter	Cost descriptions	Values
α	Annual interest rate	(2.5–7.5) %
ψ	Repayment pan of a site in years	(2–20) Annually
R_{sp}	Cost of spine router (NCS 6k)	\$(3,000–5,000)
R_{isr}	Cost of ISR router 4331	\$(1,000–7,000)
R_{firewall}	Cost of firewall router (NCS 500)	\$5,000
R_{CNR}	Core network router (ASR920)	\$9,000
R_{reflect}	Cost of leaf router (Nexus9000)	\$5,000
R_{ASR}	Cost of Cisco ASR9001	\$ 3,500
R_{AGN}	Cost of the agg. router (ASR903)	\$3,000
R_{PAN}	Cost of PAN router (ASR 920)	\$9,000
R_{IPRAN}	Cost of IP RAN router (ASR900x)	\$3,000
R_{ASR9000v}	Cost Cisco ASR9000v	\$2,950
C_{SDN}	Software defined	\$12,000
C_{energy}	Cost of energy for IP network	\$900
C_{impl}	Site implementation cost	\$(200–1,200)
C_{EC}	Energy cost for the core network	\$[(800 to 1,200)
C_{co}	Operations cost	\$(1,000–2,100)
C_{secu}	Cost of site security	\$(100 −500)
C_{sitepm}	Site preventive maintenance	\$(100–300)
C_{rent}	Cost of renting	\$(100–1,500)

Table 2: Analysis of backhauling Capex, Opex, and TCO per site.

Number of sites	Capex k\$	Opex k\$	TCO k\$
1	251.5	128.	379.82
2	251.5	129.42	380.92
3	251.5	132	383.5
4	251.5	135	386.5
5	501.15	132.73	633.88
6	501.15	141	642.15
7	501.15	144	645.15
8	501.15	148.56	649.71
9	750.81	151.5	902.31
10	750.81	153.3	904.11
11	750.81	155.4	906.21
12	750.81	140.5	891.31
13	1,000.46	141.61	1,142.07
14	1,000.46	142.72	1,143.18
15	1,000.46	143.83	1,144.29
16	1,000.46	144.94	1,145.4
17	1,250.11	146.05	1,396.16
18	1,250.11	147.16	1,397.27
19	1,250.11	148.27	1,398.38
20	1,250.11	149.38	1,399.49

5.1. Simulation Result for Transmission Data Center and IP Backhauling. Table 1 above shows the crucial variable for the IP backhauling network architecture, its consist of several routers and some cost variables obtain from the MNO and NCA in Ghana. Table 2 above shows the cost relationship between Capex, Opex, and TCO for IP transmission network backhauling. The result shows that Capex is the same for all four IP sites, but Opex is 8.8% for the first site, but reduces to 2% and 2.2% for the second and third sites. Capex is said to increase by 50% after the first four sites and reduce Opex

Table 3: Analysis of backhauling Capex, Opex, and TCO and gigabits per site.

Data in GB	Capex k$	Opex k$	TCO k$
1	250	128	378
2	374	277	651
3	624	387	1,011
4	874	469	1,343
5	871	469	1,340
6	981	469	1,450
7	1,102	469	1,571
8	1,123	469	1,592
9	1,219	469	1,688
10	1,330	469	1,799

Table 4: Comparison of number of data center CAPEX, OPEX, and TCO.

Data center	Capex k$	Opex k$	TCO k$
1	249.65	128.32	377.97
2	499.3	276.64	775.94
3	748.96	377.62	1,126.58
4	998.61	398.37	1,396.98
5	1,248.26	445.4	1,693.66
6	1,411.4	492.4	1,903.8

further to an average of 1.9%. when the sites move from eight to the third and fourth, the Capex increases further to 66.6% at a drastic reduction in average Opex of 0.8%. Again, from 12 and 16 to 20 sites, Capex increases to 75% and 80%, respectively, at the same Opex of 0.8%. In summary, we can say that for every four new IP sites, Capex will increase by an average of 73% at an average reduction of 1.56% Opex.

In Table 3 we tested the module and compared the increase in the bandwidth in Gigabyte (GB) and Capex, Opex, and TCO. The result shows an average increase of 12% in Capex for every 1 GB increase in bandwidth in the IP core network, a 10% increase in Opex for every 1 GB increase in bandwidth and an 11% increase in TCO for every 1 GB increase in bandwidth. This shows that the bandwidth increase is directly proportional to the Capex, Opex, and TCO. Table 4 compared the increase in data centers and Capex, Opex, and TCO. The result shows an average increase in Capex for every additional data center is 27.9%, associated with an average increase of 21% in Opex and 26% in TCO. It is also evident from the SA that the Capex and Opex keep reducing for every additional data center. The increase in the number of data centers is directly proportional to the increase in Capex, Opex, and TCO.

5.2. Sensitivity Analysis

5.2.1. Key Findings of Sensitivity Analysis and Future Work. Figure 2 depicts the SA of the data center. The SA is said to compare the Capex, Opex, and TCO of the data center and the bandwidth. When the bandwidth is increased to 2 GB, the cost will increase by 12% and to 3 GB by 11%; a move to 4 GB will cause a 10% increase in Capex, followed by a 5, 6, 7, 8, 9 or 10 GB increase in bandwidth increasing Capex by 9%, 3%, 11%, 8%, 5%, respectively, and Opex will increase by 12%, 11%, 1%, 9%, and 3%. In summary, increasing the data center's bandwidth by 1 GB will raise Capex by 9%, Opex by 7%, and TCO by 8.5%. When doing SA on the IP core network, we compared Capex, Opex, TCO, and bandwidth.

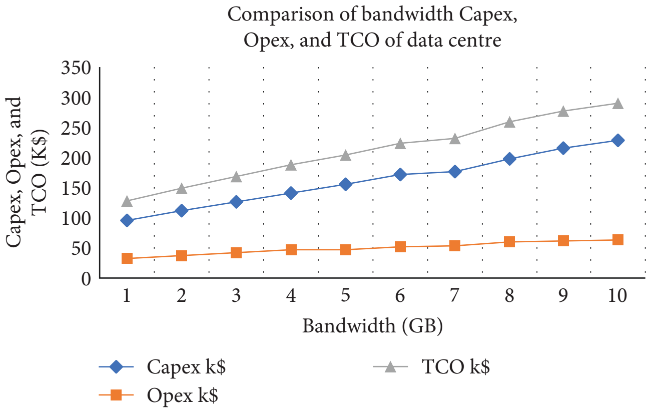

Figure 2: Sensitivity analysis of Capex, Opex, and TCO on data centre with bandwidth.

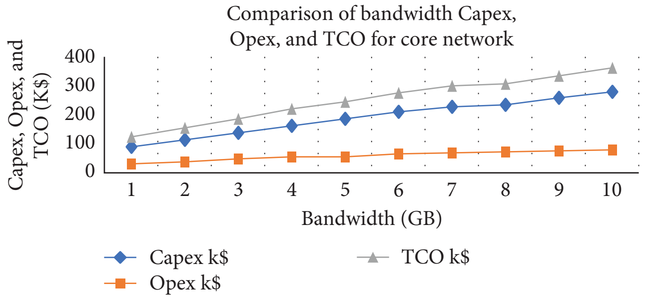

Figure 3: Sensitivity analysis of Capex, Opex, and TCO on IP core network with bandwidth.

The SA reveals that Capex will increase by 21% when IP core network bandwidth is extended from 1 to 2 GB and by 17%, 13%, 11%, 8%, 3%, 9%, and 7% when bandwidth is increased to 3, 4, 5, 6, 7, 8, 9, and 10 GB, respectively. 2, 3, 4, 6, and 7 GB have the same Opex increase, however, 5 and 8 GB have 1% and 5%, respectively, and SAme for TCO.

In summary, we have an average increase of 12% in Capex for every 1 GB increase in bandwidth in the IP core network, a 10% increase in Opex for every 1 GB increase in bandwidth, and an 11% increase in TCO for every 1 GB increase in bandwidth. This shows that the increase in bandwidth is directly proportionate to the Capex, Opex, and TCO.

Figure 3 is the sensitivity analysis of the IP core network. We compared the bandwidth increase with the capital, operational expenditure, and total cost of ownership for the IP core network.

Increasing the capacity from 1 to 4 GB results in corresponding increases of 30%, 40%, and 30% in the capital expenses.

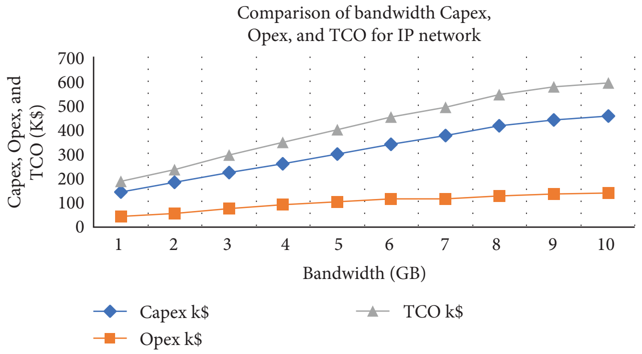

Figure 4: Sensitivity analysis of Capex, Opex, and TCO on IP access network with bandwidth.

The Capex will increase by 2% for a bandwidth of 5 GB, while a bandwidth of 6, 7, 8, 9, and 10 GB will have a 10% increase in Capex each.

As the bandwidth increases from 2 to 10 GB, the Opex will rise proportionally. The corresponding increases for each bandwidth are 29%, 17%, and 40%. However, there will be no additional increase in Opex when bandwidth increases from 5 to 10 GB.

Finally, the TCO increased from 1 to 2 and 3 GB by 42%, 36%, and 25%, respectively. Moving from 3 to 4 GB does not result in a higher TCO. However, a rise of 8% is seen in TCO when transitioning from 4 to 5 and 6 GB. For 7 GB, there is only a 1% increase in TCO, while there is a 6% increase for 8, 9, and 10 GB.

It is important to note that there is a significant rise in Capex, Opex, and TCO when increasing bandwidth from 1 to 3 GB, resulting in an average increase of 33% for Opex and 34% for Capex and TCO. However, the expenses are significantly reduced for bandwidths of 4 to 10 GB, with an average of 0 for Opex, 7% for Capex, and 5% for TCO.

In Figure 4, we analyzed the Capex, Opex, and TCO in relation to the bandwidth of the IP network. Our study revealed that when the bandwidth is increased from 1 to 2 GB, the Capex will increase by 21%. Similarly, the increase in Capex for 3 GB bandwidth will be 18%, while for 4, 5, 6, 7, 8, 9, and 10 GB, the increase will be 15%, 13%, 11%, 10%, 9%, 5%, and 3%, respectively. The Opex will also increase proportionately for each of the corresponding bandwidths, i.e., 21%, 30%, 15%, 13%, 11%, 9%, 5%, and 3%. The changes in TCO due to the increase in bandwidth will be 21%, 15%, 13%, 11%, 8%, 9%, 8%, and 3% for 2, 3, 4, 5, 6, 7, 8, 9, and 10 GB bandwidths, respectively. Therefore, on average, there will be a 12% increase in Capex, Opex, and TCO for every 1 GB increase in bandwidth. To sum up, our analysis indicates that the Capex, Opex, and TCO in the IP network are directly proportional to the bandwidth.

In Figure 5, we compared the number of data centers with the Capex, Opex, and TCO. Our findings show that increasing the number of data centers reduces the transmission latency. However, it also leads to an increase in Capex, Opex, and TCO. Specifically, the increase in Capex, Opex, and TCO for the second data center will be 50%, 53%, and 51%, respectively, of those of the first data center. For the third data center, the increase in Capex will be 33%, in Opex 53%, and in TCO 31%. Similarly, there will be an increase in Capex, Opex, and TCO for the fourth and fifth data centers. The fourth data center will experience a 19% increase in Capex, 10% in Opex, and 17% in TCO, while the fifth data center will have an increase of 11.5%, 9.5%, and 11% in Capex, Opex, and TCO, respectively.

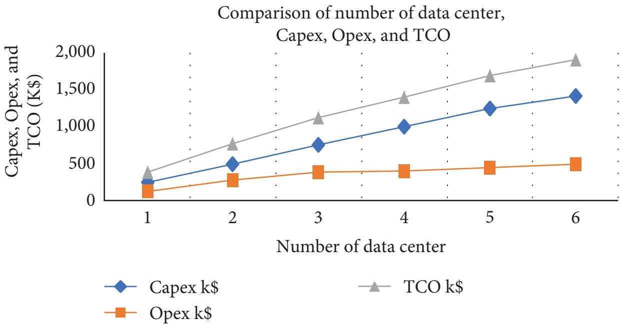

Figure 5: Sensitivity analysis comparison of number of data centres with Capex, Opex, and TCO.

To sum up, adding another data center leads to an average 27.9% increase in Capex, a 21% increase in Opex, and a 26% increase in TCO. The research also shows that Capex and Opex decrease with each additional data center. It is apparent that the more data centers there are, the higher the costs of Capex, Opex, and TCO.

6. Conclusion

IP backhauling architecture is an essential segment in the implementation of 5G mobile technology. It is important for the backhaul architecture to have high bandwidth, low latency, and low TCO. In the paper, we present the low-latency IP backhauling architecture, which comprises an IP data center, IP core network, IP aggregation network, and IP access network managed by an SDN. In this paper, we presented and tested a mathematical model for Capex, Opex, and TCO for IP backhauling architecture. The test was performed using numerical data from the MNO. We also performed SA to investigate the effects of Capex, Opex, and TCO on the number of data centers and the bandwidth. MNO must be heedful of increasing the number of data centers and bandwidth to reduce latency; this is critical to the TCO. Future research could consider working on IP front-hauling network architecture with MPLS running on segment routing and an SDN. A techno-economic analysis comparison of Capex, Opex, and TCO could also be undertaken.

Data Availability

The data used to support the findings of this study were supplied by the National Communication Authority (NCA) of Ghana under license and so cannot be made freely available. Requests for access to these data should be made to +233 (0) 302 776621/302 771701, info@nca.org.gh/www.nca.org.gh.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

I.A.G contributed in the conceptualization, methodology, software, formal analysis, investigation, and writing—original draft preparation. NIN contributed in the supervision. I.A.G and NIN contributed in the writing–review and editing and visualization. Both authors have read and agreed to the published version of the manuscript.

References

[1] T. Hoeschele, C. Dietzel, D. Kopp, F. H. P. Fitzek, and M. Reisslein, "Importance of internet exchange point (IXP) infrastructure for 5G: estimating the impact of 5G use cases," *Telecommunications Policy*, vol. 45, no. 3, Article ID 102091, 2021.

[2] E. Oughton, Z. Frias, T. Russell, D. Sicker, and D. D. Cleevely, "Towards 5G: scenario-based assessment of the future supply and demand for mobile telecommunications infrastructure," *Technological Forecasting and Social Change*, vol. 133, pp. 141–155, 2018.

[3] H. Shin, J. Jung, and Y. Koo, "Forecasting the video data traffic of 5 G services in South Korea," *Technological Forecasting and Social Change*, vol. 153, Article ID 119948, 2020.

[4] S. Gonzalez-Diaz, A. Garcia-Saavedra, A. de la Oliva et al., "Integrating fronthaul and backhaul networks: transport challenges and feasibility results," *IEEE Transactions on Mobile Computing*, vol. 20, no. 2, pp. 533–549, 2021.

[5] J. X. Salvat, A. Garcia-Saavedra, X. Li, and X. Costa-Perez, "WizHaul: an automated solution for vRAN deployments optimization," 2018, [Online]. Paper submitted in WSA 2018: 22nd International ITG Workshop on Smart Antennas, Bochum: IEEE. Available: https://core.ac.uk/download/pdf/288499735.pdf.

[6] P. Shantharama, A. S. Thyagaturu, N. Karakoc, L. Ferrari, M. Reisslein, and A. Scaglione, "LayBack: SDN management of multi-access edge computing (MEC) for network access services and radio resource sharing," *IEEE Access*, vol. 6, pp. 57545–57561, 2018.

[7] M. Sun, L. Pu, J. Zhang, and J. Xu, "Matryoshka: joint resource scheduling for cost-efficient MEC in NGFI-based C-RAN," in *ICC 2019—2019 IEEE International Conference on Communications (ICC)*, pp. 1–7, IEEE, Shanghai, China, May 2019.

[8] L. Ferrari, N. Karakoc, A. Scaglione, M. Reisslein, and A. Thyagaturu, "Layered cooperative resource sharing at a wireless SDN Backhaul," in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*, pp. 1–6, IEEE, Kansas City, MO, USA, May 2018.

[9] C. Ramirez-Perez and V. Ramos, "SDN meets SDR in self-organizing networks: fitting the pieces of network management," *IEEE Communications Magazine*, vol. 54, no. 1, pp. 48–57, 2016.

[10] E. J. Oughton and Z. Frias, "The cost, coverage and rollout implications of 5G infrastructure in Britain," *Telecommunications Policy*, vol. 42, no. 8, pp. 636–652, 2018.

[11] G. Brown, "New transport network architectures for 5G RAN," *Fujitsu*, 2018.

[12] "Use of MPLS in mobile backhaul networks introduction," *Broadband Forum*, 2012, https://www.yumpu.com/en/document/view/6670209/use-of-mpls-in-mobile-backhaul-networks-broadband-forum.

[13] P. Lowden, *5G-Ready Data Centers the Cisco Way*, Cisco Systems, Inc, 2019.

[14] G. A. Zhang, J. Y. Gu, Z. H. Bao, C. Xu, and S. B. Zhang, "Joint routing and channel assignment algorithms in cognitive wireless mesh networks," *Transactions on Emerging Telecommunications Technologies*, vol. 25, no. 3, pp. 294–307, 2014.

[15] D. S. Spraggs and D. Hagarty, *Cisco Converged 5G xHaul Transport*, p. 25, Cisco Systems, Inc, 2018.

[16] Cisco, *Cisco Catalyst 6500 Series and Cisco 7600 Series Network Analysis*, pp. 1–11, Cisco Systems, Inc., Figure 1, 2010.

[17] Cisco, *Cisco Data Center Spine-and-Leaf Architecture: Design Overview*, pp. 1–32, Cisco Systems, (USA) Pte. Ltd., 2020.

[18] J. Cheng and K. Grinnemo, *Telco Distributed DC with Transport Protocol Enhancement for 5G Mobile Networks*, Karlstad, 2017.

[19] H. Feb, *Make 5G Backhaul Feasible Everywhere*, Vol. M3023985, HUAWEI TECHNOLOGIES CO, 2019.

[20] R. G. Kaduskar and A. D. Kavishwar, "Mobile backhaul network," in *2011 International Conference on Information and Network Technology, IPCSIT*, vol. 4, pp. 211–216, IACSIT Press, Singapore, 2011.

[21] H. T. Co, *OTC304101 OptiX Metro 6100 Hardware Description*, no. 1, pp. 1–44, Huawei Technologies Co.

[22] V. Eramo, A. Cianfrani, T. Catena, M. Polverini, and F. G. Lavacca, "Reconfiguration of cloud and bandwidth resources in NFV architectures based on segment routing control/data plane," in *2019 21st International Conference on Transparent Optical Networks (ICTON)*, pp. 1–5, IEEE, Angers, France, July 2019.

[23] J. Zhou, Z. Zhang, and N. Zhou, "A segment list management algorithm based on segment routing," in *2019 IEEE 11th International Conference on Communication Software and Networks (ICCSN)*, pp. 297–302, IEEE, Chongqing, China, November 2019.

[24] A. Giorgetti, A. Sgambelluri, F. Paolucci, F. Cugini, and P. Castoldi, "Segment routing for effective recovery and multi-domain traffic engineering," *Journal of Optical Communications and Networking*, vol. 9, no. 2, pp. A223–A232, 2017.

[25] L. Davoli, L. Veltri, P. L. Ventre, G. Siracusano, and S. Salsano, "Traffic engineering with segment routing: SDN-based architectural design and open source implementation," in *2015 Fourth European Workshop on Software Defined Networks*, pp. 111-112, IEEE, Bilbao, Spain, November 2015.

[26] P. Castoldi, A. Giorgetti, A. Sgambelluri, F. Paolucci, and F. Cugini, "Segment routing in multi-layer networks," in *2017 19th International Conference on Transparent Optical Networks (ICTON)*, pp. 1–4, IEEE, Girona, Spain, September 2017.

[27] X. Wang, *Application of Ethernet in Mobile Backhaul Network*, HUAWEI TECHNOLOGIES CO, 2010.

[28] W. Sagheer, S. Spraggs, and D. Hagarty, *Cisco '5G Ready' Transport*, Cisco Systems, Inc., 2018.

[29] J. Navarro-Ortiz, P. Romero-Diaz, S. Sendra, P. Ameigeiras, J. J. Ramos-Munoz, and J. M. Lopez-Soler, "A survey on 5G usage scenarios and traffic models," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 2, pp. 905–929, 2020.

[30] NGOF, "5G-oriented OTN technology white paper next-generation optical transport network forum 5G-oriented OTN technical white paper," *NGOFRUM*, pp. 1–39, 2018.

[31] *Timing and Synchronization Huawei Technologies Co*, pp. 17–20, Huawei Technologies Co, 2001.

[32] P. Introduction and C. N. Elements, *OptiX OSN Second Line Maintenance Training OptiX OSN*, pp. 0–185, Huawei Technologies Co, 2006.

[33] W. X. Requirements, "5G Requirements to wireless backhaul," *IMT 2020/5G*, 2020.

[34] T. L. Talarico, I. A. Casas, T. C. Chung, and W. J. Dobrogosz, "Production and isolation of reuterin, a growth inhibitor produced by Lactobacillus reuteri," *Antimicrobial Agents and Chemotherapy*, vol. 32, no. 12, pp. 1854–1858, 1988.

[35] G. Smail and J. Weijia, "Techno-economic analysis and prediction for the deployment of 5G mobile network," in *2017 20th Conference on Innovations in Clouds, Internet and Networks (ICIN)*, pp. 9–16, IEEE, Paris, France, April 2017.

[36] C. Bouras, V. Kokkinos, A. Kollia, and A. Papazois, "Analyzing small-cells and distributed antenna systems from techno-economic perspective," *International Journal of Wireless Networks and Broadband Technologies*, vol. 6, no. 1, pp. 45–64, 2017.

[37] E. J. Oughton and W. Lehr, "Surveying 5G techno-economic research to inform the evaluation of 6G wireless technologies," *IEEE Access*, vol. 10, pp. 25237–25257, 2022.

[38] E. J. Oughton, K. Katsaros, F. Entezami, D. Kaleshi, and J. Crowcroft, "An open-source techno-economic assessment framework for 5G deployment," *IEEE Access*, vol. 7, pp. 155930–155940, 2019.

[39] P. Paglierani, I. Neokosmidis, T. Rokkas et al., "Techno-economic analysis of 5G immersive media services in cloud-enabled small cell networks: the neutral host business model," *Transactions on Emerging Telecommunications Technologies*, vol. 31, no. 2, Article ID e3746, 2020.

[40] D. Wisely, N. Wang, and R. Tafazolli, "Capacity and costs for 5G networks in dense urban areas," *IET Communications*, vol. 12, no. 19, pp. 2502–2510, 2018.

[41] C. Bouras, A. Kollia, and A. Papazois, "Dense deployments and DAS in 5G: a techno-economic comparison," *Wireless Personal Communications*, vol. 94, pp. 1777–1797, 2017.

[42] N. Haddaji, A. Bayati, K.-K. Nguyen, and M. Cheriet, "BackHauling-as-a-service (BHaaS) for 5G optical sliced networks: an optimized TCO approach," *Journal of Lightwave Technology*, vol. 36, no. 18, pp. 4006–4017, 2018.

[43] C. Bouras, S. Kokkalis, A. Kollia, and A. Papazois, "Techno-economic analysis of MIMO & DAS in 5G," in *2018 11th IFIP Wireless and Mobile Networking Conference (WMNC)*, pp. 1–8, IEEE, Prague, Czech Republic, September 2018.

[44] I. A. Gedel and N. I. Nwulu, "Infrastructure sharing for 5G deployment: a techno-economic analysis," *International Journal of Interactive Mobile Technologies*, vol. 15, no. 2, pp. 137–156, 2021.

[45] S. Verbrugge, S. Pasqualini, F.-J. Westphal et al., "Modeling operational expenditures for telecom operators," in *Conference on Optical Network Design and Modeling, 2005*, pp. 455–466, IEEE, Milan, Italy, 2005.

[46] M. A. Habibi, M. Nasimi, B. Han, and H. D. Schotten, "A comprehensive survey of RAN architectures toward 5G mobile communication system," *IEEE Access*, vol. 7, pp. 70371–70421, 2019.

[47] C. Bouras, V. Kokkinos, and A. Papazois, "Financing and pricing small cells in next-generation mobile networks," in *Wired/Wireless Internet Communications. WWIC 2014. Lecture Notes in Computer Science*, A. Mellouk, S. Fowler, S. Hoceini, and B. Daachi, Eds., vol. 8458, pp. 41–54, Springer, Cham, 2014.

[48] D. Bercovich, L. M. Contreras, Y. Haddad, A. Adam, and C. J. Bernardos, "Software-defined wireless transport networks for flexible mobile backhaul in 5G systems," *Mobile Networks and Applications*, vol. 20, pp. 793–801, 2015.

[49] V. Jungnickel, K. Habel, M. Parker et al., "Software-defined open architecture for front- and backhaul in 5G mobile networks," in *2014 16th International Conference on Transparent Optical Networks (ICTON)*, pp. 1–4, IEEE, Graz, Austria, July 2014.

[50] Cisco, *Cisco's Massively Scalable Data Center Network Fabric Design and Operation*, pp. 1–20, Cisco Systems, Inc., 2020.

[51] A. Kodjo, "Design and optimization of wireless backhaul networks To cite this version: Docteur en Sciences réseaux de collecte sans fil," 2015.

[52] P. Analyst and H. Reading, "5G transport networks: heavy reading operator survey & analysis".

[53] E. Norty, "National analytical report 2010 population and Housing censes," ACCRA, 2013.

[54] O. F. S. NCA Ghana Tests, "National communications authority telcos sanctioned GHC 34 million for failing quality," no. 6, pp. 4–7, 2018.

[55] National Communication Authority, "Quarterly statistical bulletin on communications in Ghana," *National Communication Authority*, vol. 2, no. 3, pp. 1–36, 2017.