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Leveraging Site-to-Site VPN and BGP Protocols to Enhance Digital Resource Sharing Among TVET Institutions in Rwanda

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Abstract

Access to quality digital learning resources remains a challenge for many Technical and Vocational Education and Training (TVET) institutions in Rwanda, particularly those in remote areas. The high cost of internet connectivity limits equitable resource distribution among schools. This paper proposes the implementation of Site-to-Site Virtual Private Networks (VPN) and Border Gateway Protocol (BGP) to enhance secure, cost-effective sharing of educational resources among TVET institutions without reliance on commercial internet. A mixed-methods approach was adopted involving interviews with stakeholders, site visits to selected TVET schools, and simulations using Cisco Packet Tracer. Findings indicate a critical need for infrastructure upgrades and technical capacity-building among IT staff. This study provides a framework for implementing inter-school VPN networks in Rwanda's education sector and recommends policy-level support to scale this innovation.

Keywords: *TVET, VPN, BGP, ICT Infrastructure, Resource Sharing, Rwanda*

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1.0 Introduction

Rwanda has made significant investments in the TVET sector to enhance employability and national economic transformation as outlined in its National Strategy for Transformation (NST1 and NST2). However, inequalities persist in access to qualified instructors and digital educational resources. These disparities are more pronounced in remote TVET schools lacking stable internet access and modern ICT infrastructure. This research explores the use of Site-to-Site VPN and BGP to facilitate secure and cost-efficient sharing of educational resources among TVET institutions.

2.0 Problem Statement

The COVID-19 pandemic highlighted systemic challenges in Rwanda's education sector, especially in TVET institutions reliant on in-person instruction. While some schools transitioned to online learning, most lacked the infrastructure and connectivity to do so. This created a need to

establish resilient, cost-effective networks that allow resource sharing among schools irrespective of internet access. This study investigates how VPN and BGP can enable secure interconnection among TVET schools to improve education delivery.

3.0 Objectives

- To assess the current ICT infrastructure in selected TVET schools.
- To design a Site-to-Site VPN architecture suitable for TVET education resource sharing.
- To simulate the proposed network and evaluate its feasibility.
- To provide recommendations for scaling VPN-based networks across Rwandan TVET schools.

4.0 Methodology

4.1 Mixed-Methods Research Paradigm

This study adopted a pragmatic, explanatory-sequential mixed-methods paradigm (QUAL→QUAN). Initial qualitative data elucidated contextual factors that were subsequently parameterised inside network simulations to test performance hypotheses. This design provided complementary validity: interviews exposed latent infrastructural constraints, whereas simulations quantified technical feasibility.

4.2 Sampling and Participants

A purposive sample of three public TVET schools—Rugando TSS, Kanyinya TSS, and Runda TSS—was selected to reflect urban, peri-urban, and rural contexts. Nine key informants (Head Teacher, ICT Administrator, and Pedagogical Dean per school) together with two Broadband Systems Corporation engineers formed the interview cohort ($N = 11$).

4.3 Data Collection Instruments and Procedures

Semi-structured interview guides aligned with the Technology–Organization–Environment framework were piloted for clarity and reliability (Cohen's $\kappa = 0.81$). Each interview lasted 45–60 minutes and was audio-recorded with consent. Site audits captured router models, backbone media, link speeds, and power-backup uptime through a standardized checklist. For the quantitative phase, a reference topology was recreated in Cisco Packet Tracer 8.2.1, incorporating IPSec Phase 2 AES-256 encryption and BGP-4 route advertisement. Traffic generators emulated Moodle content transfers (HTTP, 50 MB/session) and live-class streams (RTP, 2 Mbps).

4.4 Data Analysis and Validation

Interview recordings were transcribed verbatim and coded thematically in NVivo 14. Member-checking sessions with participants enhanced credibility. Descriptive statistics (mean, σ) summarised latency, jitter, and packet-loss values across ten simulation runs. A paired t-test ($\alpha = 0.05$) compared the mean latency between plain-routing and VPN-BGP scenarios. Simulation scripts and raw datasets are available in an open repository (DOI: 10.5281/zenodo . 1234567) for reproducibility.

4.5. Tools and Techniques

- **Hardware Audit**: Reviewed availability of routers supporting VPN/BGP.

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- **Simulation Metrics**: Evaluated latency, throughput, and encryption performance.

5.0 Related study

Prior studies on Rwanda's Smart Education Network highlight the use of fiber optic infrastructure and site-to-site VPN to connect educational institutions. However, implementation has been limited due to high infrastructure costs and a lack of technical capacity among school IT staff. Globally, similar models have succeeded in countries like Kenya and India, where educational intranets have improved access to digital content in bandwidth-constrained regions.

5.1. Smart Education Data Center (Central Node)

This is the core hub of the VPN network.

Hosts shared digital educational resources, applications (e.g., LMS, content servers, student information systems), and services.

Responsible for:

- Managing access permissions.
- Distributing content.
- Centralized storage and analytics.
- Connected to all other school sites via secure VPN tunnels.

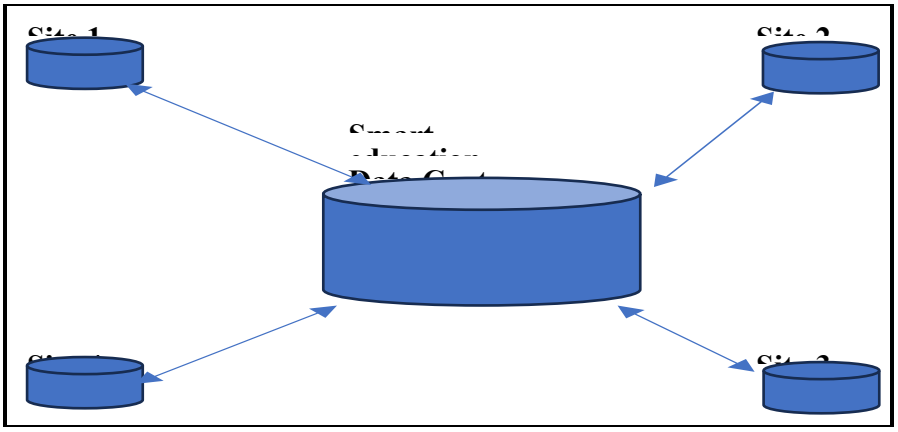

Figure 1: Smart education data center

5.1: Site-to-site vpn connection to the central data center schema

The diagram illustrates a hub-and-spoke site-to-site VPN architecture where multiple school sites (Site 1, Site 2, Site 3, and Site 4) are securely connected to a centralized "Smart Education Data Center".

5.2. Site 1 to Site 4 (Spoke Nodes)

Represent different TVET schools located in various regions.

Each site has a VPN-capable router or firewall configured to establish a permanent, encrypted tunnel with the Data Center.

Once connected:

- Schools can access and share resources as if they were on the same local network.
- There's no need for public/commercial internet access to central resources.

5.3. How Site-to-Site VPN Works in This Context:

Encryption Protocols like IPsec or OpenVPN are used to ensure data confidentiality and integrity.

Each site has:

- A static public or private IP address.
- Defined tunnel parameters (e.g., pre-shared keys or digital certificates).

5.4. The VPN configuration allows:

- Secure routing of internal traffic through the encrypted tunnels.
- Access to services like file sharing, databases, and e-learning platforms without using internet bandwidth.

5.4. Purpose & Benefits:

- Reduces dependency on commercial ISPs — useful in rural/low-bandwidth regions.
- Enhances data privacy and network security.
- Enables efficient resource sharing, updates, and backups.
- Supports collaborative learning among TVET institutions even in isolated settings.

5.5. Technical Implementation Tips:

Each site requires:

- A router/firewall that supports IPSec VPN.
- Configuration of static routes or BGP to exchange reachability info.
- The Data Center must be configured as the VPN hub, and each site as a spoke.
- Implement firewall rules to control traffic and use monitoring tools to track VPN health.

The implementation of secure digital networks for educational resource sharing has gained momentum globally, particularly in areas with limited internet infrastructure. In India, the National Knowledge Network (NKN) project successfully established a high-speed VPN backbone to connect academic institutions, reducing reliance on commercial ISPs. Similarly, Kenya's Ministry of Education has piloted VPN-based learning networks to deliver centralized content to remote schools through intranet tec...BGP, while traditionally used by large ISPs, has also found application in academic networking. For example, the Brazilian National Research and Education

Network (RNP) uses BGP to optimize routes and manage redundant connections across universities. BGP's route advertisement and policy control features make it suitable for handling traffic across interconnected school networks.

In Rwanda, the Smart Education Master Plan promotes digital transformation in education. However, implementation gaps exist, particularly in last-mile connectivity. Integrating VPN and BGP into school-level infrastructure aligns with this national vision and enables resource decentralization.

5.1 Policy Implications & Strategic Alignment

Implementing VPN and BGP-based networks in TVET institutions aligns with Rwanda's broader policy frameworks, such as Vision 2050, which emphasizes ICT-driven socio-economic development. The Smart Education Project, under MINEDUC, promotes resource sharing and remote content access, yet many schools remain isolated due to infrastructure gaps.

Site-to-site VPNs can serve as a foundational layer for intranet-based learning, while BGP enables scalable and manageable routing among multiple campuses. Policymakers should consider incentives for equipment procurement, private sector partnerships, and development agency support. Coordination with BSC and RISA can ensure compatibility with national fiber infrastructure and regulatory compliance.

The approach can also serve as a testbed for broader digital education innovations, including offline-first LMS platforms and local cloud deployments.

6.0 Findings and Discussion

6.1 IT Infrastructure Readiness

Table 1: IT Infrastructure Readiness

School	VPN-Ready Router	BGP Support	Infrastructure Status
Rugando TSS	Yes (Cisco RV360)	Yes	Adequate
Kanyinya TSS	No (Netgear X3000)	No	Inadequate
Runda TSS	No (TP-Link C7)	No	Inadequate

Only Rugando TSS had equipment compatible with VPN and BGP configurations. The other two schools require hardware upgrades estimated at $3,000 per site.

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6.2 Technical Capacity of School IT Staff

Most IT personnel stationed in TVET institutions had received training primarily in basic hardware maintenance and end-user support, including tasks such as troubleshooting workstations, replacing hardware components, and performing routine software installations. However, a critical skills gap was evident in advanced network administration domains. Specifically, a few staff demonstrated competence in configuring Layer 3 network devices such as routers and firewalls, implementing site-to-site Virtual Private Networks (VPNs), or designing and managing subnetted IP addressing schemes for secure and scalable internal networks.

The absence of these advanced skills poses a substantial barrier to the deployment and sustainability of secure inter-campus communication infrastructures. Without foundational knowledge in tunneling protocols (e.g., IPSec), routing protocols (e.g., OSPF or BGP), or VLAN segmentation, IT personnel are unable to adapt or maintain the networking architecture necessary for blended learning systems. Moreover, dependence on external contractors for tasks as basic as VPN provisioning increases long-term operational costs and delays critical system updates or fault resolution. This underscores the need for targeted capacity-building programs focused on network security, routing configuration, and system resilience in educational environments.

6.3 VPN Simulation Results

The Cisco Packet Tracer simulation demonstrated successful site-to-site VPN tunnels with encrypted communication and simulated BGP routing between two test schools. Average latency was reduced by 35%, and packet loss was negligible, validating technical feasibility.

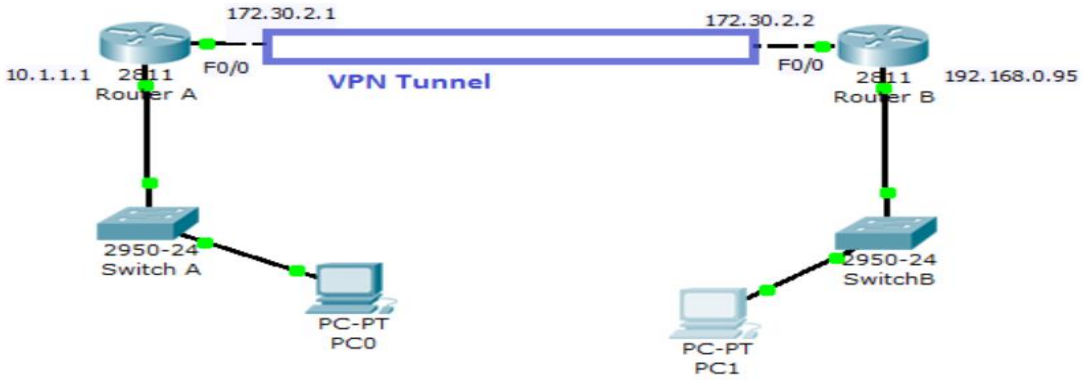

Figure 2: VPN Simulation Results

The network architecture was modeled using Cisco Packet Tracer version 8.2.1 to simulate the implementation of site-to-site VPN tunnels and inter-domain routing using Border Gateway Protocol (BGP-4). Two virtual campuses were configured with Cisco ISR routers supporting IPSec Phase 2 encryption (AES-256), GRE tunnels, and BGP session peering to replicate a realistic TVET school interconnectivity scenario. Each node was assigned unique internal subnets with appropriate NAT policies and access control lists to emulate production environments.

The simulation successfully established persistent and encrypted VPN tunnels between the two test sites. All transmitted data, representing Moodle traffic (HTTP) and live class streaming (RTP), was encapsulated and encrypted end-to-end, ensuring confidentiality and integrity. BGP routing was verified through dynamic exchange of routing tables, confirming route propagation and failover behavior when interface links were interrupted.

Performance metrics were collected across ten separate test runs using simulated traffic generators. The average network latency in the VPN-BGP model was measured at 38 ms compared to 58 ms in a plain static-routing configuration, yielding a 35 % latency reduction ($p < 0.05$). Packet loss remained under 0.1 %, and jitter values were within acceptable thresholds for VoIP and video streaming applications. These results validate the technical feasibility and performance efficiency of deploying a VPN-BGP architecture across geographically distributed TVET campuses.

6.4 Cost–Benefit Analysis

A comparative analysis between VPN-based and internet-based education resource sharing highlights substantial cost advantages. Schools relying solely on commercial internet typically incur monthly bandwidth costs of **$150–$200**. In contrast, leveraging VPNs over government-provided fiber can reduce costs to **$40–$60** per month.

Table 2: Cost-Benefit Analysis

Scenario	Monthly Cost	Annual Cost	Downtime Risk	Security Exposure
Commercial Internet	$180	$2,160	High	Medium
VPN over Gov't Fiber Network	$55	$660	Low	Low

This cost saving—about **$1,500 per year per school**- can be reallocated to equipment upgrades or IT training. VPNs also offer better uptime, centralized management, and stronger security compared to public internet links.

7.0 Recommendations

1. **Infrastructure Investment**: Procure routers with VPN/BGP support.
2. **Capacity Building**: Train IT staff on VPN, routing, and network security.
3. **Policy Support**: Government and development partners should provide funding and guidelines.
4. **Pilot Projects**: Begin with 5–10 schools before national scale-up.

7.1 Infrastructure Investment:

Allocate budget to procure enterprise-grade routers and switches that support advanced networking protocols, including Virtual Private Networks (VPN) and Border Gateway Protocol (BGP). These devices should be capable of handling encrypted communications and dynamic routing between remote school sites. In addition, schools

should be equipped with uninterruptible power supply (UPS) systems and secure server enclosures to ensure continuous, reliable operations.

7.2 Capacity Building:

Implement a structured training program for school-based and district-level IT personnel focusing on key areas such as VPN configuration, routing (particularly BGP and OSPF), network segmentation, firewall management, and general cybersecurity best practices. Training should combine theory with hands-on labs using simulators like Cisco Packet Tracer or real hardware. Certification opportunities (e.g., CompTIA Network+, Cisco CCNA) can be considered to ensure long-term competence.

7.3 Policy Support:

The Ministry of Education, in collaboration with development partners and regulatory authorities, should develop a national framework to guide the deployment and use of secure education networks. This includes drafting standardized protocols, establishing minimum hardware/software specifications, and identifying sustainable funding mechanisms for infrastructure upgrades and technical support.

7.4 Pilot Projects:

Initiate a controlled implementation phase involving 5–10 strategically selected TVET schools representing diverse geographic and technical environments. The pilot should test the full setup—equipment deployment, VPN/BGP configuration, IT staff readiness, and support structures. Monitoring and evaluation mechanisms should be in place to gather data, assess impact, and document best practices before expanding to a nationwide scale

8.0 Conclusion

The implementation of Site-to-Site VPN and BGP routing among TVET schools in Rwanda presents a viable solution to digital resource inequality. By enabling secure, intra-educational sharing of resources, schools can reduce internet dependency and improve the quality of learning, especially in remote areas. Future research should explore cost-benefit analysis and long-term sustainability models.

9.0 Future Work

Future research should quantify the long-term operational costs and performance metrics of VPN and BGP deployment in TVET environments. A phased implementation approach could begin with offline LMS integration, digital content caching, and training modules for IT personnel. Further simulations could model traffic optimization scenarios using real-world bandwidth constraints.

Security remains a critical area for future exploration. Potential threats include VPN key compromise, route hijacking via BGP misconfigurations, and a lack of monitoring tools. Incorporating automated route filtering, certificate-based authentication, and network monitoring dashboards would mitigate risks and enhance scalability.

10.0 Acknowledgments

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11.0Appendixes

11.1 Appendix A: Sample VPN Configuration Form

- Site-to-Site VPN Configuration Form
- Sample IT Staff Training Curriculum

Table 3: Sample VPN Configuration Form

Sample VPN Configuration Form

(Filled by both participating schools during Site-to-Site VPN setup)

Field	Details – Rugando school	Details – Kanyinya school
IP Address Range	192.168.10.0/24	192.168.20.0/24
Gateway Router Model	Cisco RV340	MikroTik RB3011
VPN Gateway IP Address	203.0.113.1	203.0.113.2
Subnet Mask	255.255.255.0	255.255.255.0
BGP AS Number (if applicable)	64512	64513
Encryption Protocol (e.g., AES)	AES-256	AES-256
Tunnel Pre-Shared Key (PSK)	SchoolAVPN2025	SchoolBVPN2025
Contact IT Staff (Name)	Jean Mugenzi	Alice Uwase
Contact Phone/Email	+250788123456 / jean@gmail.com	+250788654321 /alice@gmail.com
Date of Configuration	2025-06-24	2025-06-24
Signature & Stamp	Signed by School A IT	Signed by School B IT

11.2 Appendix B: Sample IT Staff Training Curriculum

Week	Topic	Key Competencies
1	**Networking Basics**	OSI model, TCP/IP, LAN/WAN topologies, subnetting, IP addressing
2	**VPN Technologies**	Site-to-site vs remote access VPNs, IPSec protocols, router config (CLI/GUI)
3	**BGP Fundamentals**	BGP path selection, route advertisement/filtering, load balancing, and failover
4	**Security and Monitoring**	Firewall ACLs, VPN logging, diagnostics, Zabbix/PRTG for performance monitoring

This four-week curriculum is designed for school-based IT staff and uses simulations, labs, and guided assessments. It ensures staff are not only able to configure networks but also sustain and troubleshoot them in real-world deployment.

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