A Blueprint for South African Public Schools ICT Infrastructure

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Abstract. In today's digital age, access to quality education is crucial for individual and societal growth. However, many South African public schools lack access to ICT infrastructure, resulting in significant implications for education quality. While efforts have been made by the Department of Basic Education and research communities, a systematic approach that considers the full technology spectrum for these schools is still missing. To contribute to this deficiency, this research paper introduces an innovative ICT infrastructure model in the form of a modular blueprint. The blueprint encompasses the complete technology spectrum, addressing existing operational schooling challenges and fostering a modern technology-based learning environment. The modular design enables incremental deployment, reducing ICT infrastructure underutilization and accommodating budget constraints. Additionally, each module's independence allows for seamless adaptation to evolving schooling challenges. Seven distinct modules are identified and described in this paper, providing a comprehensive framework for addressing ICT infrastructure deployment in South African public schools. To conduct this study, a comprehensive methodology involving research analysis, DBE publications, academic institutions, interviews, and examination of five public schools in the KwaDlangezwa community, KwaZulu-Natal, South Africa, was employed. Utilizing a design science approach, we developed modules as artifacts to be incorporated into the blueprint.

Keywords: ICT4D · ICT infrastructure · South Africa · Education · DBE · e-Learning

1 Introduction

The deficiency of ICT infrastructure significantly hinders the quality of education in South Africa [1]. However, progress in rolling out Information and Communication Technology (ICT) infrastructure and Internet connectivity to public schools has been sluggish [2]. In a draft white paper on e-Education from the Department of Basic Education (DBE) in 2004, former Education Minister Dr. Naledi Pandor highlighted the need

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to deploy ICT infrastructure tailored to Africa's requirements and future development capacity. To address this, the DBE and research communities have initiated projects to assess the effectiveness of specific devices for teaching and learning in South African public schools [2–4]. But these efforts do not yet consider the full technology spectrum that might be beneficial to all South African public schooling contexts such as administration, safety, for example. Guidelines have also been published by the DBE regarding the recommended ICT devices that should be present in both regular and special public schools [5, 6]. However, these guidelines do not address the overall connectivity of the devices or the Internet connection for each public school and the security of the ICT devices and learners.

The ICT for Rural Education Development (ICT4RED) project was part of the Technology for Rural Education Development (TECH4RED) research program initiated by the DBE in collaboration with the Eastern Cape Department of Education, and the Department of Rural Development and Land Reform. The objective of this project was to test and evaluate the suitability of tablets and supporting infrastructure for teaching and learning in 26 rural schools in the Eastern Cape Province. The supporting infrastructure included communication technologies such as Wi-Fi access points, switches, routers, and very-small aperture terminal (VSAT) satellites for each school. This ICT deployment followed a rigid and wholistic approach utilizing the "Earn As You Learn (EAYL) badge system," which ICT4RED developed to assess a public school's readiness to receive ICT infrastructure through assessments and micro-accreditation [2]. This system was developed in response to concerns about underutilization of ICT infrastructure, as also highlighted by [7], but doesn't consider the gradual deployment of the ICT infrastructure into these schools.

The EAYL badge system implemented by ICT4RED allowed the Department of Science and Technology (DST) to enhance their previous paper-based tool and develop the first version of a web-based decision support tool called eReady (www.eready.co.za). This tool enables the assessment of ICT readiness and maturity for schools across five perspectives or work streams, namely, ICT devices, Connectivity, Curriculum and Digital Content Development and Distribution, e-Administration, and Teacher Development and Support. These categories align with the Operation Phakisa ICT in Education presidential program, which aims to accelerate the deployment and integration of ICT infrastructure in public schools [8].

ICT4RED's project attempted to tackle the above workstreams, however from their analysis, ICT device such as tablets are not suitable for replacing a computer lab, due to their total cost of ownership. On the other hand, the project doesn't clearly outline the security measures that can be upheld using ICT. Motivated by the shortfalls of related works in accelerating ICT infrastructure deployments in public schools, focus on the application of ICT devices in the school in general and for connectivity. A similar initiative, Siyakhula Living Lab (SLL), launched in 2006 by Rhodes University and the University of Fort Hare, focused on ICT for Development (ICT4D) in 17 public schools within a rural community in the Eastern Cape Province (siyakhulall.org).

Although the initial endeavors of SLL where to define a model for community internet access to allow for the access of e-Governance service in rural communities. They also deployed computing infrastructure to which the locals would use to access the Internet and the e-Government portal. The computing infrastructure deployed was based on the thin/thick client computing topology and the schools to which housed these computer labs where connect to the Internet via the model that SSL developed know as Broadband Island incorporating fewer VSAT satellites and using WiMAX to connect each school (Fig. 1). This model of connecting the schools to the Internet is more cost effective than deploying VSAT satellites in each school, done by ICT4RED. Having thin/clicks workstations in school is also more cost efficient in terms of total cost of owners in comparison to replacing desktop computer with tablets. Unfortunately, both initiatives focused primarily on ICT devices for computing and connectivity only.

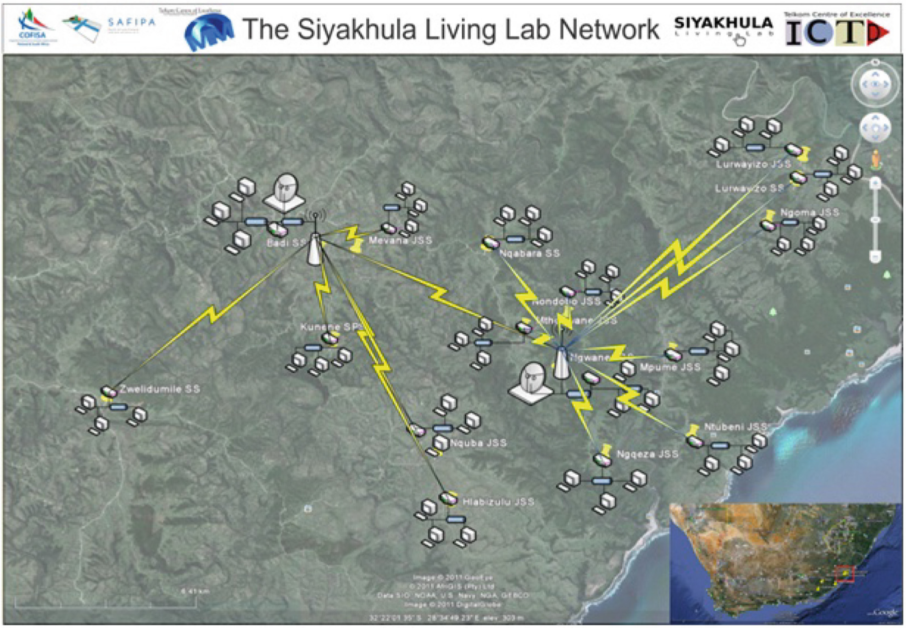

Fig. 1. SLL's Broadband Island

[7] suggests that the DBE should consider individual school contexts when deploying ICT resources to address existing operational challenges in education. This consideration not only reduces the underutilization of ICT infrastructure but also aligns better with budget constraints and avoids overwhelming changes in educational technologies, which may hinder effective ICT infrastructure service delivery planning.

While SLL and ICT4RED focused on ICTs for connectivity and computing, some research efforts have addressed other operational challenges in education, however there is no comprehensive document outlining the complete plan for deploying ICT infrastructure in South African public schools to address these challenges. Hence, a blueprint has been developed to provide an approach for deploying ICT infrastructure, enabling a modern technology-enabled learning environment in South African public schools.

The blueprint encompasses seven modules that can be utilized to address current operational challenges in schools through the implementation of ICT. This modular approach enables the incremental deployment of ICT infrastructure, reducing the overall annual expenditure while avoiding the underutilization of resources. By introducing and integrating ICT gradually into the educational system, the modular structure also simplifies maintenance and accommodates the adoption of new teaching practices and educational technologies. The following sections will elaborate on the motivation and background of this initiative before presenting the details of each module of the blueprint.

2 Motivation and Background

Goal 4 of the United Nations' Sustainable Development Goals focuses on quality education, aiming to "ensure inclusive and equitable education opportunities for all and promote lifelong learning" [9]. The second goal of African Union's aspiration 1 for a prosperous Africa based on inclusive growth and sustainable development, is "well educated citizens and skills revolutions underpinned by science, technology and innovation" [10]. The integration of ICT in teaching and learning is crucial for a country's development and the socioeconomic growth of individuals, leading to an increasing adoption of ICT in educational systems worldwide [11]. ICT in education refers to the utilization of information and communications technology to support, enhance, and optimize the delivery of information. The Department of Basic Education (DBE) captures school infrastructure information and publishes its findings annually through the National Education Infrastructure Management System (NEIMS) [12].

According to the NEIMS report from April 2021, approximately 59.20% (15 600 out of 23,276) of South African public schools do not have computer labs, around 20.35% have internet connectivity for teaching and learning, 92% do not have highspeed internet access, and a mere 2.55% have surveillance cameras, among other infrastructure-related information. Although there is ambiguity regarding the total number of public schools in South Africa (the annual report mentions 22,945 schools [2]), we have chosen to rely on the more detailed results reported by NEIMS. The DBE's e-Education white paper highlights three critical elements that will determine the future effectiveness of ICT as a tool for social and economic development. The first element is cost, emphasizing the need for cost-effective solutions to meet developmental demands and reach remote areas of the country. The second element is sustainability, recognizing that state-of-the-art technology must be sustainable to be worthwhile. Lastly, the efficient utilization of ICTs is crucial for maximizing their impact [1].

This paper is written particularly to allow administrators and decision makers, etc. to make choices based on technical and organizational factors concerning ICT infrastructure in South African public schools or developing countries alike.

3 The Blueprint Design

In contrast to a one-size-fits-all approach, our study focuses on investigating the ICT infrastructure in South African public schools in a modular manner, addressing specific operational challenges and proposing ICT-based solutions. This modular approach allows for independent evolution of each module and facilitates the incremental deployment of ICT infrastructure, considering annual budget constraints and existing implementations in certain schools. The blueprint comprises seven essential modules, each with variations that represent specific functionalities. Consequently, numerous combinations are possible, tailoring the fundamental modules to the unique needs of each school. Thus, different schools may sequence the deployment of the modules differently. The actual implementation of the modules will change overtime, because of the quick technology changes we are witnessing at the moment. However, the modules per se have much longer life due to the way they have been identified, reflecting on the needs of the schools.

The Computer Lab module proposes an efficient computing infrastructure, while the Classroom module encompasses the integration of ICT technologies into teaching and learning processes. The Administration module addresses administrative procedures and suggests improvements, while the Safety and Security module focuses on mitigating safety and security challenges. The Energy Conservation and Power Supply module outlines techniques to conserve energy in relation to the deployed ICT infrastructure. The Communication and Connectivity module describes the school's internal and external network connectivity for communication and internet access. Inherently, the Communication and Connectivity module also acts the module to which other modules are connected and disconnected. Lastly, the Cloud module presents a model for deploying a private community cloud in South African public schools.

To conduct this study, we utilized a methodology involving the analysis of research efforts, publications from the Department of Basic Education (DBE), academic institutions, as well as interviews and analysis of five public schools in the KwaDlangezwa community, KwaZulu-Natal, South Africa. Employing a design science approach, we developed modules as artifacts to be assembled in the blueprint.

4 Modules of Blueprint

4.1 Computer Lab

Schooling Operation Challenges:
According to the DBE (2021), approximately 58% of public schools lack a computer lab. One operational challenge is the theft of computing infrastructure, while another is the maintenance of the infrastructure. Although ICT4RED experimented with the use of tablets in 26 schools, they are not an efficient substitute for a dedicated computer lab due to. In the KwaDlangezwa community, three secondary public schools adopted a common deployment method used in South African public schools, utilizing Microsoft Windows fat clients without a central server [5]. In contrast, SLL conducted tests and proposed the use of thin/thick clients and a central cluster of servers. Linux was chosen as the operating system, and the Linux Terminal Server Project (LTSP) was employed as the enabling software [3]. Thin clients are cost-effective, low resource, and low-power computers with a minimal operating system, while thick clients are similar computers with the ability to process applications locally. By relying on a central server for booting,

the risk of theft is reduced, and maintenance becomes more streamlined since application installation and configuration occur solely at the central servers.

Proposed ICT Solution:
Our proposed ICT solution includes the use of Zero clients, which do not require a minimal operating system and are nonfunctional without a central server (Fig. 2). However, it is important to note that both thin clients and zero clients have limitations when it comes to supporting complex peripheral devices such as projectors, interactive pen technologies (IPTs), or assistive technologies. These limitations need to be assessed on a case-by-case basis [12].

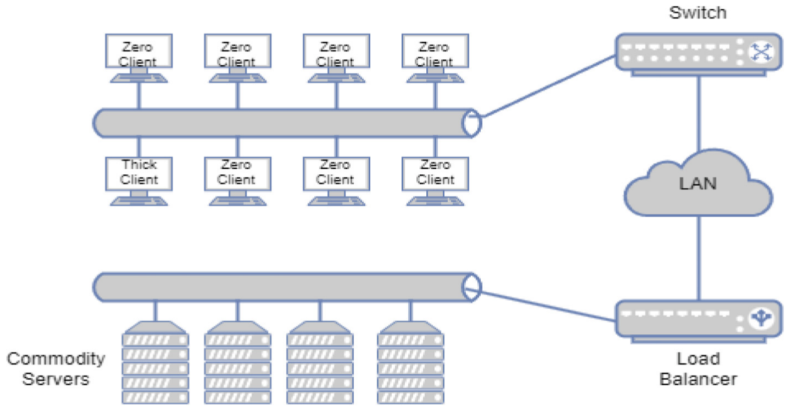

Fig. 2. Computer Lab

Therefore, it may be necessary to utilize thick or hybrid clients for teachers or learners with special needs. The cluster of servers serving the zero/thick clients can be based on Linux. These cluster servers can also be utilized for web caching, local web hosting, and hosting the school's Learning Management System (LMS) [13]. To efficiently distribute the zero-client sessions among the servers, a load balancer is then required.

In terms of transitioning from a fat client computer lab to a thick client computer lab, the school can gradually make the switch as the disks on the computers fail. Subsequently, they can consider transitioning to thin clients when user requirements and expectations exceed the capabilities of the existing hardware. Changing the operating system to Linux can be accomplished using a flash drive.

4.2 Classroom

Schooling Operational Challenges:
The primary and secondary schools in KwaDlangezwa have distinct schooling operations, with teachers visiting learners and learners attending various venues. To enable a more cost effective and enhanced schooling experience for all learners, a classroom is defined as a discipline-specific learning facility. As such, each classroom will be

equipped with 3D-printed artifacts to create an environment conducive to learning a particular subject [14]. The deployment of ICT devices and applications per classroom aims to minimize duplication of efforts, as each classroom will have its own personalized ICT setup while learners share the facilities. ICT devices should be tailored to the specific subjects taught in each classroom, optimizing budget allocation. For instance, subjects like digital art or music composition may require more computing resources compared to language classes and mathematics.

The use of interactive whiteboards (IWBs) in classrooms of developed countries has been extensively studied, highlighting the benefits of this technology for teaching and learning. However, a study conducted by SLL on the use of IWBs in classrooms for selected classrooms of schools in the Easern cape province, revealed certain drawbacks. As an alternative, image processing technology, such as eBeam, was suggested due to its similarity to IWBs but at a lower cost and with greater portability [15]. The eBeam technology involves a receiver placed on the edge of a flat surface, typically a whiteboard, and a radio-wave emitting pen. While the potential applications that can be used in each subject/classroom are extensive, we will outline the main applications that can facilitate teaching and learning in the following section.

Proposed ICT Solution:
IPTs (Interactive Pen Technologies) are portable and can be shared across the school, reducing the overall budget spent on ICT devices for teaching purposes. Therefore, we propose deploying several IPTs that can be shared based on subject demand. Instead of providing VR headsets for each student, purchasing Smart LED projectors is a more cost-effective option. When used with 3D plastic glasses, these projectors can display 3D graphics and support applications like spatial augmented reality (AR) [16]. Additionally, smart projectors can be interfaced with smartphones and support learning outside the classroom.

While web browsers, augmented reality (AR), LMS, 3D printing, artificial intelligence (AI), and word-processing applications are essential for most classrooms [17], accessing them can be done through various devices. LMS is a software application for the administration, tracking, reporting, automation, and delivery of educational courses, etc., [13]. Zero client desktops, smartphones/tablets, or low-cost laptops such as Intel's Classmate PC and Chromebook can be used to access the above-mentioned applications. However, it is important to consider the potential targeting of learners and higher maintenance overhead associated with smartphones/tablets, even though they may be more efficient for applications like AR. The LMS, being web-enabled, should be accessible within the school even without internet connectivity to facilitate the sharing of eLearning resources, as proposed in the computer lab module.

4.3 Administration

Schooling Operational Challenges:
The Personal Administrative Measures (PAM) government gazette outlines the duties and responsibilities of staff members in public schools, including teaching, extracurricular activities, administration, communication, and academic performance [2]. Therefore, the deployment of ICT infrastructure in South African schools should aim to facilitate

these tasks and responsibilities. According to the NEIM's report of 2021, only 30% of public schools in South Africa utilize Internet connectivity for administrative purposes, 93.53% do not have intercom systems, 45.91% have landlines, and 94.55% have access to cellular networks.

The South African School Administration Management System (SA-SAMS), maintained by the DBE, is a school administration and management system that assists educators in streamlining their administrative, management, and governance tasks. It collects teacher and student information, which is then analyzed using an online dashboard called Data Driven Districts (DDD) to visualize overall school performance and other key metrics [18]. However, the system currently relies on manual data entry and lacks support for an Application Programming Interface (API) to facilitate data integration with other applications. This limitation hinders data accuracy and restricts the potential for technological solutions involving the software. A subset of the collected data includes learner registration, results, and progress, as well as attendance records of learners, educators, and non-educators.

A LMS enables students to take assessments and courses, simplifies grading and result collection, and tracks student access and response times during tests or quizzes, aiding in identifying challenging sections [19]. Integrating the LMS with SA-SAMS is crucial for enhancing efficiency and accuracy for the data uploaded into SA-SAMS. In public schools, laptops have already been deployed for teachers to facilitate lesson preparation, mark capturing, teaching, and administrative duties. For a LMS, we recommend using Moodle [20].

Proposed ICT Solution:
To automate class/school attendance registration, we suggest using cost-effective QR codes instead of RFID tags. Teachers/secretaries can scan the QR codes using their smartphones to record attendance, which can then be manually uploaded to SA-SAMS. Alternatively, the data can be automatically uploaded to SA-SAMS' Microsoft Access database (which is used by the current implementation of SA-SAMS) using Java DataBase Connectivity (JDBC) technology, which is free. Considering the limited presence of intercom systems in public schools, we propose deploying Voice-over-IP (VoIP) phones in offices and classrooms, leveraging the existing IP network for easier and more affordable installation. For productivity and document processing, we recommend utilizing the user-friendly and language-supportive LibreOffice, a free and open-source office suite.

4.4 Safety and Security

Schooling Operational Challenges:
In South Africa, communities can be prone to violence, including gang wars and turf wars, which sometimes spill over onto school grounds, endangering the lives of students and teachers. According to the latest NEIMS report, only 3% of public schools have camera surveillance, 5% have alarm systems, 9% have access control measures, and 80% have wire fencing. However, the presence of holes in the fence allows learners to escape from school and invites unauthorized individuals to enter and engage in violent or illegal activities, such as drug dealing.

Additionally, ICT mature nations face challenges such as cyberbullying, cyber-attacks, identity theft, and access to inappropriate internet resources like the dark web or pornography. To address these issues, the ICT guidelines for schools by the DBE recommend segregating administrative computers into a separate virtual network (VLAN) and virtual private network (VPN) from learners and guests. This segregation restricts their access to certain network and internet resources. This best practice should also be considered when public schools adopt IoT devices, which is an inevitable trend.

Proposed ICT Solution:
We propose a cost-effective school monitoring system utilizing Power over Ethernet (PoE) IP cameras and computer vision technology. These cameras offer higher resolution and require fewer units to cover a designated area compared to traditional CCTV systems [21]. To prevent tampering, fixed cameras are recommended.

All camera feeds are streamed to a central network video recorder (NVR), which records the footage for storage. Through machine learning-based computer vision, video analytics can be applied for object detection, tracking, and automatic human action recognition (HAR). This enables the system to identify the presence of ICT devices and monitor crowd behaviour, alerting the school to any potential risks, violence, or missing equipment [22]. Information security policies are essential to regulate and protect sensitive data within educational settings. For this we recommend a Data Loss Prevention (DLP) software maintaining data confidentiality, integrity, and availability, and enforce security policies. It detects and prevents data exfiltration and leakage, mitigating social engineering threats.

We also recommend that that public schools install a patch management system to automate the installation of patches and upgrades throughout the organization, minimizing vulnerabilities and potential data breaches. Essential security controls include firewalls, Intrusion Detection and Prevention Systems (IPS), a remote access server (VPN), honeypots, and monitoring software to ensure network security.

4.5 Energy Conservation and Power Supply

Schooling Operational Challenges:
According to the NEIMS 2021 report, public schools in South Africa have limited access to alternative power sources. Only 2% have generators and 6% use solar energy, while the majority (95%) rely on grid connections. However, 14% of schools face unstable electricity supply. To address this, schools can benefit from using multiple power sources and switching based on grid availability [11].

A study conducted in the Stellenbosch area compared energy usage in schools [23]. It revealed that lighting accounts for a significant portion of energy consumption, especially in underprivileged schools. Upgrading lighting systems to LED lamps can reduce electricity consumption by 26%. Implementing sub-meters for outsourced facilities and installing solar outdoor lighting can further contribute to energy savings [24].

Efficiency strategies in computer labs, such as adjusting brightness, disabling screensavers, and enabling power management features, can lead to substantial energy savings. A study in a Canadian university found these measures saved significant energy over a six-month period [25].

Projects like ICT4RED have explored alternative power supply systems such as biogas and hydrogen fuel cells. Overall, improving energy efficiency in schools through various measures can help mitigate the challenges posed by limited and unstable electricity supply.

Proposed ICT Solution:
The proposed computer lab models for South African public schools utilize a zero/thick client-server topology with diskless workstations. Thin clients offer over 50% higher energy efficiency compared to fat clients, but server hardware plays a role in determining overall efficiency. Putting thin clients to sleep when not in use can further enhance energy savings. Incorporating energy efficiency strategies mentioned in [25] onto the server serving thin clients is also recommended. Implementing climate control measures in school buildings can reduce energy consumption by computers and technology, especially in hot environments [24].

The ICT infrastructure blueprint for South African public schools includes PoE (Power over Ethernet) devices, which allow for flexible power source alternation and minimize network downtime, Fig. 3. Examples of PoE devices include IP cameras, PoE LED lighting, VoIP phones, and Wi-Fi access points. All four current PoE standards support these devices, with PoE type 4 being the latest and providing a power output ranging from 71.30 W to 100 W. The maximum cable length supported by PoE technologies is 100 m, requiring PoE extenders for devices located beyond this distance. PoE LED lighting, a network-controlled device, can be centrally managed and monitored for energy usage through IT network management software, enabling lighting automation.

We also recommend the use of solar energy as an alternate power source for South African public school ICT infrastructure.

Fig. 3. Example of PoE devices

4.6 Communication and Connectivity

Schooling Operational Challenges:
In South Africa, 96% of public schools have access to a cellular network. However, during power outages, the cellular network service can be slow or unavailable, particularly in deep rural areas. To address this, ICT4RED deployed VSAT satellite dishes in each

school, aligning with the plans of SA Connect for government facilities. This differs from SLL's approach, where VSAT Internet connection is not deployed in each school, offering a more cost-effective solution. Internet access in public schools is capped, and once the cap is reached, it becomes the school's responsibility to provide their own Internet access. SLL uses a model called the Broadband Island, connecting schools to the Internet using multiple technologies. However, this model focuses on the WAN connection, not the internal LAN connecting the ICT infrastructure [4].

Proposed ICT Solution:
We propose an ICT infrastructure deployment using the hierarchical LAN model topology, consisting of three layers [26]. The access layer includes ICT devices and connected switches, while the distribution layer comprises switches connecting the access layer to the core layer (Fig. 4). The core layer connects the school to the Internet, potentially utilizing the Broadband Island model depicted in Fig. 1. Wi-Fi technology is now more accessible and widespread, making it a suitable wireless option for replicating the Broadband Island instead of using WiMAX, as suggested by [3, 4], as it also better facilitates backup routes.

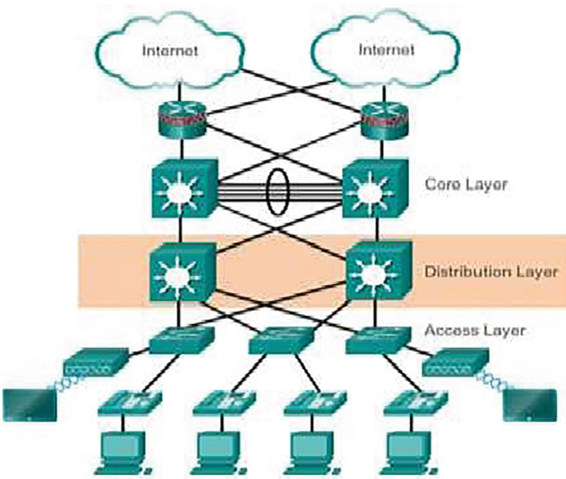

Fig. 4. Hierarchical LAN model

Additionally, we recommend adopting SDN (Software Defined Networking), a novel architecture that reduces data costs by abstracting network functions and requiring fewer network appliances and on-site IT staff [27]. Implementing the ICT infrastructure within SDN would enable the provision of a network abstraction to allow the independent deployment, maintenance, and scalability of the modules [29].

4.7 Cloud

Schooling Operational Challenges:
Cloud computing is a convenient model that provides on-demand network access to

a shared pool of configurable computing resources. It enables intensive computation, multiple applications, and mass storage to be hosted remotely in a data center, accessible by low-powered devices through an Internet connection and a browser [28]. There are four deployment models for cloud computing: public, private, community, and hybrid cloud.

Proposed ICT solution:
We propose a community cloud as a private cloud deployment shared by multiple schools in a community, connected through SLL's Broadband Island. One school within the Broadband Island can host the local cloud infrastructure, providing secure and cost-effective access to private cloud resources for all schools. Cost-effective in a sense that schools need not have an Internet connection. The size of the data center depends on the number and size of schools in the community. The data center can be realized using various technologies, and we recommend OpenStack as the cloud management platform with Linux servers.

5 Conclusion

The goal of this project was to provide a means to accelerate ICT infrastructure deployment in South African public schools. For this goal to be accomplished, it was necessary to understand the schooling operational challenges and how ICT infrastructure in South African public schools can be used to tackle these challenges.

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