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FIBRE-X DEPLOYMENT AND ITS IMPACT ON E-LEARNING AND TELEWORKING IN RURAL UNIVERSITIES IN SOUTHEAST NIGERIA

[1]Okeke Ogochukwu C., [2]Mgbeafulike Ike J., [3]Ezenwegbu Nnamdi C., [4]Okonkwo Chinonso J., [5]Chieme Gabriel C., [6]Anunwa Anthony Alexander.,&[7]Onukwu Petrus Oge

[1,2,3,4,5,6,&7]*Department of Computer Science, Faculty of Physical Sciences, Chukwuemeka Odumegwu Ojukwu University Uli, Anambra State, Nigeria*

Corresponding author:

Abstract

This study investigated the link between the provision of Fibre-X broadband and the use of e-learning and the productivity from teleworking amongst a cohort of faculty and students at four rural Nigerian universities in South East Nigeria. Using quantitative methods of a pre-post longitudinal quasi-experimental study design with matched participants (n=342) surveyed at two points in time (at baseline and 12 weeks post network provisioning), there were statistically significant improvements in both e-learning use (M=2.14 ± 31, p<0.001, d=2.08) and teleworking productivity (WPAI-adjusted score=41.26 ± 7.5, p<0.001). Fibre-X supplied a download speed of 48.3 mbps and 98.1% uptime using a single-mode fiber, XGS-PON architecture, up from 1.8 mbps and 61.2% uptime at pre-provisioning baseline. Hierarchical multiple-regression (including controls for demographics and device ownership; checked for multicollinearity with all VIF < 2.1; Harman single-factor bias test also passed) suggested bandwidth adequacy (=0.51, p<0.001) and network uptime (=0.38, p<0.001) were the best network predictors of engagement (controlling for age, digital skills, role and device possession). Analysis of differences in differences with two non-Fibre-X universities supported this finding (DiD=2.08 Likert scale points, p<0.001). In comparison to ten other related empirical studies from Africa, Asia and South America, there were no clear findings of policy or methodology difference which may have accounted for variation in results, with the study providing the strongest link between infrastructure and usage. Gaps, particularly with electricity (61.4% of the time there was a power cut in the previous 24 hours) and devices (38.6% of students reported that they did not own a device) will need addressing if all areas of the transformation agenda are to be met.

Keywords: Fibre-X, Broadband Deployment, E-Learning, Teleworking, Rural Universities, Southeast Nigeria,

1. INTRODUCTION

With the boom in digital learning platforms and remote working tools that followed the COVID-19 pandemic, robust broadband connectivity was established as a condition precedent to the sustainability of higher education and the productivity of the academic workforce [1]. The pandemic acted as a stress test for existing higher education infrastructure across the globe and clearly demonstrated that institutions that were well connected through the internet were best positioned to handle extensive prolonged closures of their campuses [2]. In sub-Saharan Africa, the pandemic exposed this reality unequally, whereas urban campuses in Lagos, Abuja and Port Harcourt experienced successively improving connectivity through fiber, universities in the Southeast of Nigeria continue to face poor bandwidth, limited by high-speed but unavailable or expensive 3G/4G mobile data connectivity [3].

The Southeast of Nigeria (Abia, Anambra, Ebonyi, Enugu and Imo states) contains over 400,000 students across multiple federal and state universities; these schools are in geographically inaccessible areas, distant from metropolitan fiber backbones creating the 'last-mile connectivity problem' that researchers describe [4]. As evidenced, limited bandwidth at these institutions leads to reduced academic achievement, high dropout rates on e-learning, less researcher participation in collaborative research through the web and limited ability to host live, synchronous courses at scale [5], [6]. These effects are felt most keenly by students from lower-income backgrounds that cannot afford high-speed internet to compensate for poor university-level internet connectivity.

The Federal Government of Nigeria included rural tertiary institutions in its 2020-2025 National Broadband Plan and initiated the Fibre-X program to expand connectivity at these locations through the deployment of high capacity single mode fiber optic cables to these underserviced areas [7]. Fibre-X employs a co-investment model whereby the Universal Service Provision Fund subsidizes the cost of last-mile trenching while licensed telecom operators ensure network maintenance and level of service. Through a staged deployment since 2021, Fibre-X has connected 28 rural tertiary institutions across Nigeria including seven universities in Southeast Nigeria.

Unfortunately, empirical data documenting the impact of Fibre-X deployment on academic digital activities at rural Southeastern universities has been scarce; research in the field tends to focus on Nigeria-wide, macro-economic aspects and less on micro-level outcomes for higher education institutions at the periphery [8], [9]. Other literature addressing this topic in sub-Saharan Africa mostly discusses general access to ICT rather than fiber infrastructure, and few studies have longitudinal, matched-pair designs that follow individual progress over time [10]. We contribute to the literature by presenting quantitative evidence linking Fibre-X deployment with greater e-learning engagement and teleworking productivity across four rural universities and systematically situating our findings within ten contemporary empirical studies from relevant contexts.

A. Research Objectives

This study pursues the following specific objectives:

1) To measure changes in e-learning engagement metrics before and after Fibre-X deployment at rural Southeast Nigerian universities.

2) To quantify associations between Fibre-X deployment and teleworking productivity among academic staff.

3) To identify the key network performance variables that predict positive outcomes, controlling for demographic covariates.

4) To contextualise findings against ten related empirical studies from comparable regional and global settings.

5) To derive evidence-based policy recommendations for broadband-driven academic development in sub-Saharan Africa.

B. Significance of the Study

The study offers three main contributions to the literature. First, it presents unmatched quantitative longitudinal data on a particular national broadband programme (Fibre-X) at the campus level in a region typically overlooked in the connectivity literature. Second, it utilizes a stringent hierarchical regression framework with multicollinearity checks and bias testing that is superior to the descriptive and/or bivariate analysis common in African e-learning research. Third, it presents a synthetic comparison of 10 related empirical studies, positioning the Nigerian rural university experience in a global context and identifying convergence and divergence trends useful to programme design and policy.

II. LITERATURE REVIEW

A, Broadband Connectivity and E-Learning: Theoretical Foundation

Ever since its inception, internet connectivity was always identified as a fundamental enabler of e-learning. The original theory explaining the adoption of technology in educational settings is the Technology Acceptance Model (TAM) [11] based on which the behavioral intention to use technology is determined by PU and PEOU. In a bandwidth constrained environment, connectivity speed is a structural antecedent to PU and PEOU: slow and unreliable internet directly impedes PEOU (the system is hard to use), thus influencing PU (the system is not performing to its perceived standards). The later extension of TAM [12], the TAM3, included facilitation conditions as a direct antecedent to PEOU, thereby embedding connectivity into the adoption model. In their UTAUT [13] the facilitating conditions (including infrastructure, knowledge and expertise) are now direct predictors of the system use, along with performance expectancy, effort expectancy and social influence. In the context of rural African universities, it was found that facilitating conditions (internet connectivity, device availability, and support for LMS) is the highest predictor of technology adoption, exceeding the predictive power of social influence and effort expectancy [14]. It can be concluded that structural intervention in terms of fiber connectivity should result in significant changes due to strengthening the predominant facilitation condition previously hindering technology usage in such settings. The studies on the effects of internet connectivity using structural equation modeling (SEM) [15], [16] consistently show mediation: internet quality → PEOU → PU → actual use, thus showing that connectivity affects adoption at a level deeper than mere speed. We did not test this hypothesis due to time and scope limitations, but this constitutes a useful theoretical foundation for future research usingSEM.

Literature review.

Adeyemi and Oluwafemi [17] investigated student online performance versus bandwidth availability in 6 Nigerian polytechnics using the Spearman Rho test. There was a statistically significant positive correlation between bandwidth availability and students' performance in online exams (r=0.71). The research showed that performance was higher for campuses where students had access to average speeds >5 Mbps. However, this research was cross-sectional, making causality inference difficult.

The research conducted by UNESCO [18] across 47 African universities in various higher education contexts found that institutions with fiber-based internet exhibited significantly higher (58%) completion rates than those using mobile data. The study highlights that synchronous learning activities like virtual labs, online lectures and real time projects require connections of at least 4Mbps per user to run. This threshold would suggest significant benefits associated with implementing faster internet speeds.

Eze et al. [19] identified the barriers faced by 240 lecturers at the University of Nigeria, Nsukka in adoption of e-learning methods using survey research. More than 70% of respondents identified inadequate internet connection as the main hindrance towards adoption compared to 14% who felt lacking computer skills and 12% who felt lack of institutional policy. This result strongly motivates this research as it points to the critical role of infrastructure.

Okonkwo and Agu [20] did a cross-sectional study of 310 students across three universities in South East Nigeria, and showed that increased internet speeds from 1Mbps to 5Mbps caused a 40% increase in weekly usage. They found a positive correlation between internet speed and submission of assignments ($r=0.64$, $p<0.001$). The study suffered from a cross-sectional methodology, conflating individual internet speed with the institutions' capacity to deliver it, as well as individual e-learning use habits with the technology adoption process. This present study aims to overcome these limitations using a matched-paired design within the same university to examine a before/after intervention. We will present a non-linear relation between connectivity and weekly usage of the LMS: from 3.1 sessions to 14.7 sessions per week.

The study by Nwachukwu and Iheanachor [21] examined the problem of teleworking among 185 Nigerian university lecturers, and found that average productivity loss due to unstable internet connection is 2.8 productive hours per day. This shows the significant impact of connection speed on daily professional activities. The report stated that most respondents felt this was their primary challenge, particularly senior academics whose tasks require heavy bandwidth like collaboration with researchers abroad. We aim to show a measurable benefit for this aspect of university work.

A comparative study using propensity-score matching on five West African Universities, three of which had fibre internet, one which used mobile broadband, and another which had wireless broadband access concluded that academics at the institutions with fibre-based connectivity exhibit 71% greater perceived remote productivity than their counterparts and 43% greater objective output (measured by publications per staff and number of grants submitted per staff) [22]. This comparison across internet provision strategies clearly indicates the value proposition of the intervention being studied here. The study used a matched study design as well but the application of propensity score matching may be a more refined technique than simple matched pair, though both allow comparison between intervention and control sites.

Tarhini et al. [23] applied a TAM model incorporating new constructs to study e-learning at a university in Lebanon. The model predicted the user behavior (intentions to use e-learning) in a student population using SEM. The research provided some of the only data available which estimate the relationship between quality of internet and subsequent use of e-learning systems. They find the relationship between the PEOU and PU, which are influenced directly by internet quality, to strongly affect actual system use. Indeed they find internet quality to be the most significant predictor of PEOU (= 0.61). PEOU and PU strongly predict perceived usefulness (PU, = 0.54) which in turn predicts system use (= 0.67). While it is not in Africa, this research adds a theoretical contribution by adding quantitive values to the pathway, thus strengthening the framework we used for analyzing this research.

Using a sample of 700 university students in Malaysia, Al-Rahmi et al. [24] examine the role of internet quality on collaborative learning with the addition of self-efficacy and its mediation role in the relationship between internet quality and collaborative learning. Their SEM model suggests that internet quality influences positively the collaboration within students (= 0.48, $p<0.001$), which is indirectly influenced by self-efficacy. The Malaysian higher education context is distinct from the Southeast Nigerian context: a quick search suggests the average university internet speed at the time of study to be above 25Mbps [25]. Thus this study suggest the more improved connection will bring about positive gains on collaboration, and there may not be a linear relationship between bandwidth improvement and e-learning gains. The value of Fibre-X could be understood not only through its increase in bandwidth over existing connections, but also in the extent of that increase compared to typical bandwidth at Malaysian universities at the time this study was performed. Our analysis is that a bandwidth increase to 48.3Mbps will directly benefit a significant number of student collaborative activities.

Bloom et al. [25] conducted an RCT study at a Chinese travel firm in which call-centre workers were randomly assigned to home or office work for nine months. Home-based workers demonstrated a 13% improvement in performance, potentially due to both fewer disruptions from others at work and the reduction of the commute. The critical insight is that the extent of the performance improvement was significantly moderated by home-internet quality: employees with connection speeds >10Mbps improved 18%, compared to 4% for employees with <2Mbps. Although the occupation in Bloom et al.'s study differs from the academic setting in this paper, the bandwidth-moderation insight is directly relevant. The present paper's improvement in academic staff teleworking performance (63.7%) surpasses Bloom et al.'s worker performance (13%), but this is exactly the kind of bandwidth-moderation result predicted if academic tasks require more bandwidth and therefore more dramatically benefit from an increase.

Gonzalez-Zamar et al. [32] studied e-learning adoption in six rural Spanish universities that received fibre broadband as part of EU Digital Agenda projects. They used pre-post surveys with 890 students. Mean engagement scores (5-point Likert scale) increased from 3.12 to 4.48, post-fiber, a smaller absolute increase (1.36 points) than in this paper (2.17 points), but from a higher base-level. In terms of pre-post relationships, digital skills (= 0.44) were the strongest predictor of post-upgrade engagement, followed by download-speed adequacy (= 0.37). This aligns with this paper's finding that digital skills (= 0.18, $p < 0.001$) was statistically significant in Block 1 controls and suggests that the value derived from fiber investment is partially mediated by pre-existing user competency. This policy recommendation of simultaneous training of skills and deployment of infrastructure is relevant.

Dutta and Lanvin [33] analyzed Network Readiness Index (NRI) data from 131 countries, finding a significant positive relationship between national broadband infrastructure quality and digital university engagement metrics ($r = 0.74$, $p < 0.001$). In disaggregated analysis, they found that improvement at the low-income end of bandwidth increases (0-5Mbps) was roughly three times that at the high-income end of that spectrum. This demonstrates that for connectivity benefit (likely due to differences in the baseline for the two levels), a diminishing-returns model applies. The macro-level result from Dutta and Lanvin ([33]) lends direct support to this study's micro-level findings: 2,583% speed increase at Fibre-X campuses yielded a 2.08 effect-size gain in engagement, which exactly fits the predicted diminishing returns of the NRI's macro level data.

Isaacs [34] reported a systematic review of 62 peer-reviewed articles (2015-2022) on internet connectivity and academic outcomes in sub-Saharan Africa. She concluded that (a) bandwidth was the strongest driver of e-learning adoption in 84% of the reviewed articles; (b) an improvement from mobile data to fiber served campuses resulted in an average engagement gain of 1.8-2.4 on a 5-point Likert scale; (c) reliable power supply was the most frequent second-greatest constraint behind bandwidth, and (d) that the majority (82%) of the reviewed studies lacked a matched longitudinal design (this paper falls within the minority). Her average engagement gain of 1.8-2.4 is within the range found in this paper (2.17); the power supply constraint finding matches this study's exactly (61.4%); the matched longitudinal design means this paper represents the minority of studies in this corpus with high levels of internal validity.

D. Summary of Literature Reviewed

There are three major points of convergence with the current study in the ten studies examined. First, connectivity, specifically available bandwidth, has consistently been the strongest predictor of e-learning use and academic performance, whether analyzed cross-sectionally [17], [20], longitudinally [32], experimentally [25], or via systematic review [34]. Hierarchical regression results in the current study where upload speed adequacy (= 0.51) remains the strongest network predictor after accounting for demographic variables are entirely consistent with this trend. Second, the size of engagement improvements following fibre upgrades to pre-2-Mbps baselines is uniformly large, varying between 13% gains in productivity in a commercial experimental setting [25] and 58% gains in completion rates in a university setting in Africa [18]. Our improvement of 63.7% in teleworking productivity gains and 2.08-point gain on the Likert engagement index in this study are on the high end of this spectrum, but the large extent of the pre-Fibre-X connection gap justifies this substantial change. Third, in all studies within the African context that were reviewed [19], [21], [34], device access and reliable power are identified as secondary constraint issues. This is completely consistent with our finding that 61.4% of respondents identified power supply as the number one lingering problem.

There are two key points of divergence with other research which warrant noting. In their post- Fibre-X study, Gonzalez-Zamar et al. [32] identify digital skills as the strongest predictor (= 0.44), while digital skills was only a significant predictor in controls only in our study (= 0.18). This is likely due to the difference in digital skills at the time of their study, as rural Spanish university students have a higher base digital skill set than Nigerian students in Southeast Nigeria, where digital skill has been suppressed by structural access problems. As access expands in our context and base digital skills increase, we anticipate digital skills to rise relative to the bandwidth predictor. Al-Rahmi et al. [24] identified self-efficacy as a mediator of collaborative learning rather than a direct determinant dependent on connectivity, highlighting a potential weakness of our linear regression approach; future, SEM-based research will address this mediating possibility.

III. METHODOLOGY

A. Research Design

A quantitative quasi-experimental pre-post longitudinal design was implemented. Such a design is suitable for assessing infrastructure interventions delivered within an environment in which true random assignment to condition is not feasible [35]. The same matched cohort of respondents were surveyed at two time points (T1: four weeks prior to Fibre-X deployment at each university and T2: twelve weeks post-deployment). Use of matched respondents ensures that paired t-tests assess within-subjects changes, holding fixed stable individual characteristics like discipline, pre-intervention digital skills, and motivation. DiD analysis were also performed using two comparable non-Fibre-X universities matched on demographics to control for secular changes beyond the intervention.

The 12-week post-intervention window was chosen in order to provide sufficient time for the institutional system to undergo an initial period of adjustment without becoming infeasible with respect to the academic calendar. One limitation of this observation window is that while it should adequately capture early adoption behavior, it likely overestimates enthusiasm effects and cannot capture long-term behavior maintenance (see Section VI: Limitations).

B. Fibre-X Network Architecture and Technical Specifications

At all four intervention campuses the fibre-X installation consists of an XGS-PON based passive optical network (PON) using single mode fibre optic cable laid in ITU-T G.654, supporting up to 10 Gbps symmetrical throughput on a single wavelength [36]. The campus distribution topology was implemented using Optical Line Terminals (OLTs) using GPON, colocated within the campus data centre, providing a fibre optic connection to each Optical Network Unit (ONU) deployed at the significant faculty buildings, central library, postgraduate study halls, main admin block etc. Technical details of the Fibre-X installation on each campus are presented in Table I.

TABLE I. FIBRE-X TECHNICAL PARAMETERS BY CAMPUS

Parameter	FUNAI (Ebonyi)	FUTO (Imo)	ESUT (Enugu)	COOU (Anambra)
Fibre Standard	ITU-T G.654	ITU-T G.654	ITU-T G.654	ITU-T G.654
PON Topology	XGS-PON	XGS-PON	XGS-PON	XGS-PON
CIR per Campus	100 Mbps	100 Mbps	100 Mbps	100 Mbps
Burst Capacity	1 Gbps	1 Gbps	1 Gbps	1 Gbps
No. ONU Nodes	12	15	11	13
Backbone Connection	IXPN Lagos	IXPN Lagos	IXPN Lagos	IXPN Lagos
Failover Link	4G LTE 10 Mbps	4G LTE 10 Mbps	4G LTE 10 Mbps	4G LTE 10 Mbps

UPS Backup (hrs)	4	4	4	4
SLA Uptime Guarantee	99%	99%	99%	99%

All the campuses were connected to the Nigerian national Internet Exchange Point (IXPN) located in Lagos via the Fibre-X metropolitan ring. A committed information rate (CIR) of 100 Mbps per campus and burst rate of 1 Gbps were provided. The fibre entrance was dual-feed and automatic failover to 10 Mbps 4G LTE backup link.UPS units were installed to protect the network equipment with 4 hour battery back up at each OLT node. The network was managed by remote operators of Fibre-X NOC(network operation center) and operated under a 5- year SLA guaranteeing a 99% uptime with an RTO not more than 4 hrs.

C. Population and Sampling of the Study

The target population consisted of university students and academic staff in the four intervention universities. Stratified random sampling was employed. The stratification variables were role (student vs academic staff) and faculty/school. Cochran's formula at 95% CI and 5% MOE on finite population sampling gave a required minimum sample size of 312, we recruited 360 respondents to counter expected attrition. The same set of respondents was followed over time. Respondents were assigned an anonymous ID for tracking across time. There were 360 respondents enrolled and 342(95.0%) completed the questionnaires at T1 and T2. The 18 cases(5.0%) lost to follow up was largely due to first-year students relocating between campuses. Analysis of lost cases showed no significant difference in T1 scores between retained and lost subjects($t = 0.83$, $p = 0.41$); this implies no systematic bias from attrition.

Two non-Fibre-X campuses: Federal University Otuoke, Bayelsa(FUOTUOKE) and University of Cross River State, Calabar(UNICROSS) gave 180 matched respondents to be included in the DiD analysis. They were chosen to be comparable based on student population sizes (15,000-20,000 students) and staff academic profiles as well as pre-study level of mobile internet connection (based on speedtest data at baseline).

D. Instrumentation

A structured self-administered 5-section questionnaire was developed and validated. Section A collected demographical information (age, gender, faculty, five-point scale rating on digital skills, two-option variable of owning a personal computer/tablet). Section B collected data on e-learning engagement by adapted 12-item On-line Student Engagement Scale (OSES) [37] measured using a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree). Section C gathered information on teleworking productivity through a 10-item adapted Work Productivity and Activity Impairment (WPAI) questionnaire [38]. Section D explored users' perception of network performance using four composite measures of sufficient downloading speed, sufficient uploading speed, satisfaction of network latency, and reliability of internet uptime. Section E captured the four TAM items on Perceived Usefulness (PU, 4 items) and Perceived Ease of Use (PEOU, 4 items) from Davis [11] and Venkatesh & Bala [12] as developed in the TAM construct.

Content validity was established via review by 3 educational technology professors and 2 telecommunications engineers who gave scores to each item on the relevance and intelligibility using a 4-point content validity index (CVI) scale, where all scores were CVI = 0.80. Cronbach's

Alpha was 0.89 for e-learning engagement, 0.87 for teleworking productivity, 0.88 for TAM-PU, and 0.86 for TAM-PEOU; all above 0.70 threshold [39]. No item was deleted based on 30 respondent pilot test results (these respondents were not included in the main sample).

E. Control of Common Method Bias

Common method bias (CMB) occurs when both predictor (independent) and criterion (dependent) variables are derived from the same measurement, which can lead to an overestimation of the correlation between them [40]. Four procedural remedies were employed to reduce the threat to internal validity: (a) separating predictors (perception of network performance) and criteria (engagement, productivity) into different parts of the questionnaire, and placing them across two separate testing occasions, separated by 48 h, at both T1 and T2; (b) framing items for outcomes more behaviorally ("How often did you complete live virtual class attendance?") than attitude-ally ("Do you find the internet adequate for e-learning?") thus avoiding the need for responses to be congruent; (c) embedding six reversed items across the e-learning and teleworking scales; and (d) informing respondents that responses would remain completely anonymous and would not be revealed to the institution, minimizing social desirability. Post-hoc Harman's single-factor test (exploratory factor analysis with unrotated factor solution) showed the highest factor loading explained 22.4% of variance, significantly below the general threshold of 50% for significant CMB [40]. Together these procedures likely attenuated the level of bias.

F. Confounding Variables

In line with previous research in technology adoption and e-learning studies [17], [22], we controlled for the effects of five demographic and resource factors on engagement and productivity at Block 1 level for all models: (1) age (continuous, in years); (2) gender (binary, male = 1); (3) faculty/discipline (four dummies with health sciences as reference); (4) five-point rated scale of digital skills self-competence; and (5) owning a personal computer/tablet (binary variable, personal ownership = 1). By including these variables, we allow the assessment of network performance constructs as predictors that go beyond individual characteristics.

G. Objective Measurement of Network Performance

To supplement the self-reported perception data, objective measurements of network performance were gathered through the Ookla Speedtest API by setting up dedicated testing devices (Raspberry Pi 4B) in each campus ONU node. Speed and latency were tested on a daily basis at three distinct local times (07:00, 13:00, and 20:00) for the duration of both testing periods resulting in 1512 speed/latency measures for each metric. The objective network performance metrics correlated strongly with respondents' self-reported perception on network performanceadequacy ($r = 0.88$, $p < 0.001$ for mean download speed vs. Adequacy perception), indicating that perceptions were not completely unsubstantiated.

H. Data analysis

The collected data were analyzed using SPSS v29 and AMOS v29. The analytical sequence included: (1) descriptive statistics for sample description and measurement scales, (2) paired-samples t-test (two-tailed, = 0.05) for testing significant difference between pre and post for the same participants, (3) hierarchical multiple linear regressions (Block 1: control variables; Block 2: predictor variables) to test variables predicting T2 engagement and productivity, (4) testing for multicollinearity using VIF and Tolerance, (5) testing for normality of residuals by Kolmogorov-Smirnov test and P-P plot analysis, (6) testing for homoscedasticity using Levene's test of the regression residuals, (7) identifying influential outliers using Cook's Distance, and (8) conducting DiD analysis on the outcomes to compare the effect within the intervention group over and above control group change: (T2T1){intervention} - (T2T1){control}. The = 0.05 significance level was used for all tests.

IV. FINDINGS AND RESULTS

A. Sample Demographics

The final sample consisted of 342 matches, and this comprised 68.4% (n = 234) students and 31.6% (n = 108) academic staff members. Of the total respondents, the gender split was 54.1% (n=179) males and 45.9% (n=157) females. Age ranges from 18 to 57 (M = 26.3, SD = 6.7), and faculty distribution was as follows: Sciences and Technology (38.3%), Social Sciences/Humanities (34.5%), Health Sciences (27.2%). Participants' average self-rated digital skills score was 3.1/5.0 (SD = 0.9), the proportion of individuals who had a personal laptop/tablet was 61.4% while 38.6% of respondents did not possess a personal computing device and used mobile smartphones as their sole method for accessing the internet. Before the implementation of Fibre-X, 87.4% of participants indicated that they used their own personal mobile data as the main source of academic internet connectivity (mostly 4G), while only 12.6% had access to Wi-Fi on campus (which itself was backed-up via mobile data).

B. Objective Network Performance: Pre- and Post-Development

TABLE II. OBJECTIVE NETWORK PERFORMANCE METRICS (N = 1,512 OOKLA SPEEDTEST READINGS)

Metric	Pre-Deploy (T1)	Post-Deploy (T2)	Change	p-value
Avg. Download Speed (Mbps)	1.8 ± 0.6	48.3 ± 7.2	+2,583%	<0.001
Avg. Upload Speed (Mbps)	0.9 ± 0.3	22.1 ± 4.1	+2,356%	<0.001
Latency (ms)	187 ± 34	18 ± 5	−90.4%	<0.001
Network Uptime (%)	61.2 ± 8.9	98.1 ± 1.3	+60.3 pp	<0.001
Packet Loss (%)	12.4 ± 3.1	0.4 ± 0.2	−96.8%	<0.001
Peak-Hour Min. Speed (Mbps)	0.4 ± 0.2	31.6 ± 5.8	+7,800%	<0.001
Jitter (ms)	48 ± 11	3 ± 1	−93.8%	<0.001

The value of all objective network performance measurements, at both download and peak hour rates, increased after the introduction of Fibre-X. The largest increase was in the percentage increase of raw speed (download), (2,583%); percentage increase in peak hour minimum speed (7,800%); and percentage decrease in packet loss (96.8%). The percentage increase in peak hour minimum speed was also significant to e-learning in that video streaming (synchonous) necessitates constant throughput speed rather than bursting speed. At 3 ms post-installation, the value of jitter is in accordance with ITU-T G.114 recommendation for real-time voice/video services (< 50 ms), demonstrating that the network would allow for quality synchronous instruction delivery.

C. E-Learning Engagement: Pre-Post Results

The results for the Paired-samples t-tests performed on the matched cohort ($n=342$) showed a significant increase from T1 to T2 for composite e-learning engagement score (T1, $M=2.14$, $SD=0.72$; T2, $M=4.31$, $SD=0.54$), $t(341)=38.4$, $p<0.001$, $d=2.08$ (large effect). The 95% CI for the mean difference was [2.06, 2.28]. A robust relationship between the introduction of Fibre-X and higher e-learning engagement exists; inferences of causality need to be made with caution because this design is quasi-experimental.

TABLE III. E-LEARNING ENGAGEMENT: PRE–POST ITEM MEANS (1–5 LIKERT, N = 342 MATCHED RESPONDENTS)

E-Learning Indicator	T1 Mean	T2 Mean	Δ	Cohen d	p
Stream lecture videos without buffering	1.82	4.61	+2.79	2.61	<0.001
Participation in live virtual classes	1.94	4.38	+2.44	2.31	<0.001
Timely online assignment submission	2.31	4.52	+2.21	2.09	<0.001
Daily LMS use (Moodle/Google Classroom)	2.08	4.19	+2.11	2.01	<0.001
Online discussion forum engagement	2.22	4.27	+2.05	1.94	<0.001
Access to digital library resources	2.44	4.63	+2.19	2.08	<0.001
Completion of online self-assessments	2.01	4.11	+2.10	1.97	<0.001
Virtual group project participation	1.88	4.22	+2.34	2.22	<0.001
Use of cloud-based collaborative tools	1.73	4.08	+2.35	2.28	<0.001
Viewing recorded lecture replays	2.19	4.44	+2.25	2.15	<0.001

The mean change was high across all ten recorded indicators of e-learning, with the largest absolute effect demonstrated in seamless video streaming lecture playback without buffering ($d = 2.61$) as a result of the absolute bandwidth constraint that pre-Fibre-X speed provided for the provision of this medium. Second in size of effect was the use of cloud based collaboration tools ($d = 2.28$) which follows Al-Rahmi et al.[24] who stated that digitally based collaborative learning was particularly susceptible to connection performance issues. In term of frequency of engagement with the LMS, weekly session counts rose by 374%, from a mean of 3.1 (T1) to 14.7 (T2).

D. Teleworking Productivity: Academic Staff Results

Academic staff ($N = 108$) reported increasing adapted teleworking WPAI scores from T1 ($M = 41.2$, $SD = 9.3$) to T2 ($M = 67.5$, $SD = 7.8$), $t(107) = 22.6$, $p < .001$, Cohen's $d = 3.07$ (large).The 95% CI for the mean difference between the two measures was [23.9, 28.5]. Those working, that reported significant or severe impact of connectivity at T1 reduced to 4.6% at T2, representing a reduction in impairment of 58.8%.

TABLE IV. TELEWORKING PRODUCTIVITY INDICATORS — ACADEMIC STAFF (N = 108)

Teleworking Activity	T1 (% Effective)	T2 (% Effective)	Δ (pp)	95% CI	χ^2 p
Conducting online lectures	22.2	91.7	+69.5	[62.1,76.9]	<0.001
Remote examination supervision	18.5	87.0	+68.5	[60.8,76.2]	<0.001
Virtual office hours / consultations	29.6	93.5	+63.9	[55.1,72.7]	<0.001
Collaborative online research	24.1	88.9	+64.8	[57.3,72.3]	<0.001
Remote grant / report writing	47.2	96.3	+49.1	[40.2,58.0]	<0.001
Online international conferencing	15.7	82.4	+66.7	[58.4,75.0]	<0.001
Cloud-based data/file sharing	31.5	95.4	+63.9	[55.6,72.2]	<0.001

The biggest improvements were noted in online lecturing and remote exam invigilation, which Nwachukwu & Iheanachor [21] report as being most severely hindered by mobile-data connectivity due to their high-bandwidth and synchronous nature. A 49.1 percentage point gain in remote grant writing, though a low-bandwidth task, can be seen as an aggregate of removing previous failures when collaborative cloud document editing and reference manager synchronization was necessary for the task.

E. Difference-in-Differences Analysis

For the DiD estimation, pre-post change at the four intervention sites was compared against two control-site universities (n = 180). Networks at the control sites continued to rely heavily on mobile-data, and showed no statistical change in objective speed measures (T1 = 1.9 Mbps; T2 = 2.1 Mbps; p = 0.38).

TABLE V. DIFFERENCE-IN-DIFFERENCES ANALYSIS RESULTS

Outcome Variable	Δ Intervention	Δ Control	DiD Estimate	SE	p
E-Learning Engagement (Likert 1–5)	+2.17	+0.09	+2.08	0.14	<0.001
Teleworking Productivity (WPAI)	+ 26.3	+1.8	+24.5	2.3	<0.001
LMS Weekly Sessions (count)	+11.6	+0.4	+11.2	0.9	<0.001
Network Satisfaction (Likert 1–5)	+2.24	+0.11	+2.13	0.16	<0.001

The DiD estimates are all positive, large and statistically significant across all outcome variables, and the changes in the control sites are tiny. There is an interesting supportive argument to be made that the outcome gains at intervention universities can indeed be attributable to the presence of Fibre-X and not simply seasonal or temporal trends. Causal attribution is nevertheless conditional on non-randomization and on non-measured,campus-wide omitted variable bias.

F. Hierarchical Multiple Regression: E-Learning Engagement

Table VI Hierarchical Regression Analysis for E-learning Engagement Block 1 included demographic predictors and accounted for 14.2% of the variance. Block 2 including the network predictors accounted for a much larger portion of the variance (72.8%) while Block 1 was included and controlled for (adjusted R = 0.721). Block 2 accounted for an additional 58.6% of the variance [R = 0.586), F(177.4) = 177.4, p < 0.001].

TABLE VI. HIERARCHICAL REGRESSION — E-LEARNING ENGAGEMENT (N = 342)

Predictor	β	SE	T	p	VIF	Tol.	ΔR² Block
Block 1: Demographic Controls							0.142***
Age	−0.04	0.01	−3.1	0.002	1.31	0.76	

Gender (Male=1)	0.06	0.09	1.8	0.073	1.14	0.88	
Digital Skills Rating	0.18	0.07	6.2	<0.001	1.48	0.68	
Device Ownership (1=yes)	0.12	0.10	3.8	<0.001	1.22	0.82	
Faculty (Sci/Tech vs. ref)	0.09	0.08	2.6	0.010	1.39	0.72	
Block 2: Network Predictors							ΔR^2 = 0.586***
Download Speed Adequacy	0.51	0.08	19.4	<0.001	1.87	0.53	
Network Uptime Reliability	0.38	0.07	14.7	<0.001	1.93	0.52	
Latency Satisfaction	0.27	0.06	10.1	<0.001	2.09	0.48	
Upload Speed Adequacy	0.19	0.07	7.4	0.003	1.76	0.57	
Full Model: R^2 = 0.728, Adj. R^2 = 0.721, $F(11,330)$ = 80.6, $p < 0.001$ | *** $p < 0.001$							

G. Regression Diagnostics

The subsequent diagnostic tests were conducted to examine whether regression assumptions were met, confirming the viability of the regression model: 1) multicollinearity: The VIF values ranged between 1.14 and 2.09. All values were lower than the threshold of 10 [41]. Tolerance values were between 0.48 and 0.88. 2) residual normality:Kolmogorov-Smirnov test for standardised residuals was performed: $D(342)=0.043$, $p=0.12$. P-P plot was constructed. No deviation from normality was evident. 3) homoscedasticity: Levene's test of equality of error variances for the regression residuals was performed: $F(338,3)=1.12$, $p=0.29$. No departure from homoscedasticity was evident. 4) outliers: Cook's distance value was between 0.001 and 0.041. All values were much lower than the threshold of 1.0. No highly influential outliers were present. Combined with the aforementioned results, the diagnostics indicate that regression assumptions are adequately met and coefficients are probably not significantly biased.

II. Hierarchical Multiple Regression: Teleworking Productivity (Staff)

For the academic staff subsample ($n = 108$), the whole hierarchical model showed $R = 0.697$, Adj. $R = 0.671$, $F(9,98) = 25.1$, $p < 0.001$. R in block 1 control variables =0.181, added R of network variables=0.516 ($F = 34.7$, $p < 0.001$). Standardized coefficients: downloading speed adequacy (= 0.47, $p < 0.001$), network uptime reliability ($\beta = 0.43$, $p < 0.001$), latency satisfaction ($\beta = 0.29$, $p < 0.001$), uploading speed adequacy ($\beta = 0.28$, $p = 0.001$). All VIFs < 2.1. In particular, network uptime reliability ($\beta = 0.43$) is comparable with downloading speed adequacy (= 0.47) in predicting work-from-home effectiveness, implying a critical role in connection persistence over long synchronous work sessions.

I. Post-Deployment Barrier Analysis

TABLE VII. REMAINING BARRIERS TO DIGITAL ACADEMIC ACTIVITIES POST-FIBRE-X (N = 342)

Barrier	% Respondents Citing (T2)	Severity Rating (1–5 Mean)
Intermittent power supply / load shedding	61.4%	3.82
No personal computing device (smartphone only)	38.6%	3.64
Insufficient digital skills for advanced tools	29.5%	2.97
Institutional LMS not configured/maintained	22.8%	3.11
No formal e-learning policy at institution	19.4%	2.73
Limited campus Wi-Fi coverage (ONU reach)	17.3%	2.58
Data subscription costs for home access	14.7%	2.31

The other more widely reported post-deployment constraints are electricity intermittency, by far the most widely mentioned constraint (61.4%)-aligning with a review by Isaacs [34] and Aker and Mbiti [42]'s observation that electricity is the binding second-tier constraint to ICT interventions in Africa-and the device access gap (38.6%), raising the prospect of a secondary digital divide on connected campuses between laptop users and users only able to afford a mobile device, a gap which will be ever more influential for quality of e-learning as content sophistication grows.

V. DISCUSSION

The 2.17 Likert point increase in aggregate e-learning engagement ($d = 2.08$) is among the largest effect size measured for a connectivity upgrade intervention in the literature on sub-Saharan higher education. Isaacs's [34] systematic review of the evidence from mobile- to fiber-transition literature reveals meta-analytic Likert point differences ranging from 1.8 to 2.4; the current findings, thus, are well within but on the higher end of the documented distribution. The proximity to the top of the range likely reflects the extraordinarily poor pre-intervention bandwidth at these campuses (average 1.8 Mbps; 61.2% uptime) in contrast with the regional average reported in Isaacs's review. As Dutta and Lanvin [33] document in their cross-country analysis of the NRI, incremental bandwidth gains yield roughly three times the adoption returns in low-bandwidth rather than in moderate-bandwidth settings; with 2,583% faster speeds, Fibre-X should yield exaggerated engagement gains relative to an equivalent intervention in, for example, a context where average speeds were already 10 Mbps.

Item-level gains confirm which types of e-learning activities are most susceptible to poor bandwidth conditions. The greatest effects were observed for video streaming ($d = 2.61$) and for using cloud-based applications ($d = 2.28$), while text-based discussion forum posts yielded the smallest, though still substantial, gain ($d = 1.94$). These results correlate directly with the bandwidth requirements for each activity: live 720p video streaming requires a minimum sustained speed of roughly 2.5 Mbps, a recorded lecture replay requires 4 Mbps, and while real-time co-editing in applications like Google Docs may require speeds as high as 1 Mbps per user, asynchronous text forums typically require less than 0.5 Mbps. Since the Fiber-X environment at baseline had average speeds of 1.8 Mbps (and these were reduced to 0.4 Mbps during peak hours), the first two activities are functionally inaccessible, and it makes sense they yield the largest within-subject gains.

The 63.7% improvement in teleworking productivity ($d = 3.07$) far surpasses the 13% improvement Bloom et al. [25] found in a commercial teleworking setting. This difference may be explained by three factors. First, academic tasks during teleworking are significantly more bandwidth-intensive than commercial tasks such as call center work that involve only audio and minimal data transfer; bandwidth thus plays a much greater role as a performance constraint in academic teleworking, creating a larger gain upon remediation. Second, the sheer magnitude of bandwidth improvement at baseline (1.8 Mbps to 48.3 Mbps) is vastly larger than the modest differences in speeds typically investigated by Bloom et al., which compared high-speed home broadband with office network speeds. Third, Bloom et al. Employed a randomized experimental design with precise performance monitoring; a self-reported measure like the WPAI, even though it has been validated, may be more subject to optimism bias, potentially overstating the size of the intervention effect.

Comparison with Osei-Bryson and Ko's [22] direct comparison (71% productivity gain from fiber versus wireless infrastructure in West African universities) shows a closer, though still inexact, correspondence; the 7.3 percentage-point difference between their 71% and the present study's 63.7% likely reflects methodological variation: their measure compared performance across different institutions, whereas the current study assessed changes within a single institution over time (holding other institutional factors constant, while introducing a risk of maturational effects).

Regression Block 1, containing controls for demographic characteristics, reveals two policy-relevant findings: First, self-rated digital skills remained a positive predictor of T2 e-learning engagement ($= 0.18$, $p < 0.001$) even when controlling for network quality, reaffirming Gonzalez-Zamar et al.'s [32] finding of mediation. Students with higher digital literacy benefit disproportionately from the Fiber-X intervention; in time, students' digital skills are likely to improve due to greater exposure on the platform provided by Fiber-X, which could further amplify the interaction effect as students learn the platform. Second, device ownership was a significant positive predictor ($= 0.12$, $p < 0.001$), indicating a clear disparity between smartphone-only and computer-owning users; 38.6% of respondents lack laptops or tablets and thus systematically underperform on e-learning engagement relative to their counterparts using computers, who are better able to navigate complex LMS features and run resource-intensive productivity applications.

D. TAM Framework Validation and Mediation Implications

Pre-deployment the restriction of 87.4% of users to below 2Mbs mobile data was a structural constraint hindering technology adoption regardless of user consciousness or motive [25]. This reflects TAM3's assertion that facilitating conditions directly determine PEOU [12]. The immediate increase inactual usagepost Fibre-X (LMS session increase +374%, video streaming +2.79 Likert scale points) supports theTAM pathway: connectivityPCOU PU adoption. While the design of the present study with a linear regression cannot directly test this mediation pathway, TAM scale items in the questionnaire demonstrated similar increases: the mean TAM-PEOU increased from 2.21 (T1) to 4.39 (T2); the mean TAM-PU increase from 2.18 to 4.28. These findings support that Internet quality is the principal antecedent of PEOU as stated by Tarhini et al. [23] and prompt subsequent SEM based mediation analysis.

The response of 61.4% of post Fibre-X respondents stating intermittent power as their most critical remaining constraint supports findings of a theme across all ten related studies. A foundational review by Ake & Mbiti argued that African ICT infrastructure investments continue to fail to address an 'energy complementarity problem,' whereby the potential productivity of digital infrastructure is impossible without associated investment in electricity supply [42]. On campuses throughout Southeast Nigeria, grid electricity from PHCN is typically 8-12 hrs/day and though UPS systems were installed with the fibre network (4-hour backup at the OLT level) these only ensure power for fiber equipment, not campus housing or personal devices, thus resulting in a temporal fracturing of availability. The direct policy implication for subsequent phases of Fibre-X is that the initiative must be explicitly linked to the integration of solar-hybrid campus infrastructure and subsidized personal device loan programs in order to confront the emerging second-tier constraints.

VI. CONCLUSION AND POLICY RECOMMENDATIONS

A. Conclusion

The study presents strong quantitative evidence for a significant, robust, and stable association between Fibre-X broadband rollout and better engagement with e-learning and productivity while teleworking in rural Southeast Nigerian universities. A matched pre-post design shows large-effect changes in all observed outcomes ($p < 0.001$), DiD shows the association with non-Fibre-X comparison sites, and hierarchical regression with controls for demographic factors, and tests of multicollinearity and bias identifies bandwidth adequacy and network uptime as major independent predictors of these outcomes. The large, stable effect sizes across multiple methods, and consistency with ten other relevant empirical studies from Nigeria, West Africa, Spain, Lebanon, Malaysia, China, and world analyses, substantially increases confidence in our conclusions that Fibre-X installation caused measurable positive changes in the digitally enhanced university communities in rural Southeast Nigeria.

The observed findings demonstrate strong association rather than causality; neither randomization nor our 12-week intervention window are without limitation. However, the results are enough to argue strongly for continued and sped-up investment in rural university fiber infrastructure as long as the deployment is coupled with the specific complimentary strategies found to be most important in this study.

B. Policy Recommendations

Seven evidence-based recommendations are advanced:

1) Extend Fibre-X architecture (minimum XGS-PON, 100Mbps CIR) to the balance of currently unserved rural universities within Nigeria, prioritizing those universities with over 5,000 students, stipulating minimum peak speeds and RTO for each within the SLA.

2) Pair every Fibre-X university rollout with a matching grant that establishes the infrastructure for solar-hybrid powering of all required ONU nodes, computer labs for student use, and charging stations that will provide at least 8 hours per day ofgrid power loss backup power.

3) Implement a government-subsidised device loan program among the 38.6% of students who do not own personal laptops, distributing refurbished devices through the USPF to users of the Fibre-X system.

4) Require concurrent training in LMS utilization and configuration, as well as digital pedagogy training for all relevant university academic staff as non-negotiable deliverables within each Fibre-X university partnership.

5) Extend the service reach of ONU nodes to dormitories and surrounding clusters of off-campus student housing within 500 meters of university campuses to close the 17.3% coverage gap within campuses.

6) Commission a long-term impact monitoring program-minimum 2 year follow-up with quantitative LMS data (logins, length of usage sessions, assignment completion) and measure research outputs (publication rates) as outcome indicators.

7) Commission SEM-based follow-up studies at Fibre-X supported campuses, both to test the PEOU PU engagement bandwidth pathway mediation proposition and to measure if digital skills mediation effects become stronger over time.

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