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An Efficient Learning Management System for Low-Bandwidth Networks: A Framework for Inclusive and Sustainable Digital Education

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ABSTRACT

Well-functioning Learning Management Systems (LMS) are still not available to everyone around the world due to the fact that many online LMS platforms are designed for high-bandwidth users while learners in low-bandwidth and rural locations are not well served. In this study, the authors propose a lightweight, low-bandwidth and low-latency LMS, called Education Access System (EAS), specifically designed to expand the equitable digital education in the context of a 2G/3G network. The project was developed in four phases: requirement analysis and mapping of stakeholders; data analysis and design of a layered system architecture; implementation with react, node.js, mongodb and optimized APIs; and evaluation with manual/automated testing and user acceptance testing with students. Simulated use of low bandwidth (100–500 kbps) validated EAS, and showed practical use: 95.8% of the participants reported better learning outcomes even if they interacted in the forum to a lower degree (12.5%). The results indicate that optimization of LMS can contribute to closing the digital divide and promote SDG 4 through mobile and offline accessible learning. The study ends with recommendations for deployment in a mobile-first environment, offline synchronization, and further collaborative adaptations for the future, to maximize reach and impact.

Keywords— Digital Divide, EAS, Learning Management System (LMS), Low-Bandwidth Learning, Low-Latency Education, React-Node-MongoDB Stack, SDG 4.

1. INTRODUCTION

The rapid development and evolution of Information and Communication Technologies (ICT) has transformed education, allowing for the teaching and learning beyond the classroom, information sharing and collaboration [1]. Although Learning Management Systems (LMS), like Moodle, Blackboard or Google Classroom [2] facilitate systematic

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delivery and structured interaction, they are highly dependent on the availability of reliable broadband, supportive settings, and modern devices which are not always available in rural regions of developing countries [3][4]. In this kind of context, e-learning is not possible without having a proper assessment of readiness economically, as technological and policy constraints remain in the Least Developed Countries (LDCs) [6]. Hence there is a need for a realistic and user-centred planning process, which is built on assessment management, and it is broadly accepted that assessment management is one of the pillars of successful university-level e-learning [8]. The COVID-19 pandemic hastened the transition to online learning, and highlighted the limitations of LMS, leading to innovations and improvements in interface design, adaptive learning, chat-bots, proctoring, authentication, and network optimisation by the use of AI [9]. E-learning systems (ELS) are still exposed to security attacks, while cloud-based education is increasingly being used as a basis for cost-effective and flexible education; hybrid RSA/AES encryption is proposed to enhance data privacy while reducing latency and the computational load [10].

The Digital Divide (DD) — unequal access to ICTs — is a major barrier in higher education in developing countries, affecting pedagogy, engagement and achievement and can be tackled through interventions to affordability, infrastructure and digital-literacy for the adoption of LMS in an equitable way [4]. Interactive elements like discussion forums, auto-graded quizzes, assignments and online classes are found to be effective in boosting students' engagement and performance in a meaningful way, as revealed by the qualitative evaluation conducted at Al-Mujaddid Sabak Islamic Institute [11]. Based on the review of 34 studies (2013-2023) in the Arab Gulf Countries, 41 factors of adoption were found, which are majority associated with Perceived Ease of Use, Perceived Usefulness, Social Influence, and Facilitating Conditions as per the Technology Acceptance Model [12]. However, the conventional LMS platforms require significant bandwidth to support the interactivity, which necessitates support of next-generation, low-latency, customisable content services to reduce the gap and provide equal education [13]. AI and automation can also facilitate the convergence of personalized learning and diagnostics while reducing the need for extensive infrastructure, closing the digital divide in the fields of learning, healthcare, agriculture and economic development [14].

In recent years, the use of Educational Data Mining (EDM) has been on the rise and has proven to be a powerful tool for strategic data-informed decision making in higher education, offering the potential for analysing learner interaction and optimizing curricula; however, the adoption of this approach has been limited and presents significant challenges in areas with poor connectivity. The concept of Mobile Learning (M-Learning), based on low bandwidth and portable learning and teaching devices, provides a scalable and low-cost solution for closing this gap [16]. Virtual Reality (VR) and 360-degree videos provide immersive learning, but require bandwidths up to 400 Mbps; encoded transformation filtering (ETF) partial solution, by predicting viewports, compressing data, and multicasting only the content needed. Digital inequality has also been exacerbated in the country of Pakistan, as Covid-19 pandemic has created digital inequality in the country due to the lack of ICT infrastructure [18]. Together, data analytics, Student Information Systems (SIS) and LMS platforms enhance

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administrative efficiency and communication, with Smarter Education Environments (SEE) depending on seamless connectivity and personalization, and while 5G, AI-driven cloud and edge computing and blockchain are enabling, reliability, security, compatibility and resource constraints are open challenges [19]. The standard LMS architecture can not be used in 2G/3G (100–500kbps) environment of rural Pakistan for which the constraints of cost, low digital literacy and lack of trust in institutions limit access.

The purpose of this research is to design and develop the EAS (Education Access System) which is lightweight and low latency LMS for 2G/3G (100–500 kbps) rural and underserved area. Evaluated by manual testing, automated testing, and User Acceptance Testing (UAT) in simulated low bandwidth conditions, EAS maximizes the core LMS functionality (authentication, content delivery, quizzes, forum, tracking user progress) while minimizing data usage, and assesses functionality, usability and the role of EAS in equitable digital education to support SDG 4. Most of the existing LMS applications rely on high bandwidth, multimedia support and high end smartphones, while most of the rural and semi-urban population relies on cheap 2G/3G and low end smartphones, and then there is the lack of digital literacy among the students and teachers; EAS relies on lightweight, text-based interface, caching, lazy loading, micro-learning delivery, and adaptive streaming to ensure that it functions well under low bandwidth environments while contributing a replicable model of inclusive education toward SDG 4.

2. LITERATURE REVIEW

As mobile devices and demand for online education continue to grow, web apps need to continue to perform well on slow and cluttered connections. In the developing regions 2G/3G networks (100–500 kbps) are all around and cheap but traditional LMS platforms don't facilitate a consistent pedagogical experience.

2.1 LOW-BANDWIDTH LMS SOLUTIONS:

Internet access in Pakistan is only around 33% of the population and bandwidth is often limited a significant constraint on media-rich educational technology, especially in the rural areas, where there is low digital literacy [21][22]. Interfaces with less weight, content in text form, with lazy loading and caching, help in faster loading of web pages and reduce data consumption [23][24][25]; micro-learning, with the content presented in small and fast loading modules, helps in reducing the load time of web pages and increases the accessibility and engagement [26]. Open Educational Resources (OER) are sets of materials available free of charge for use in active learning most of which are available online and have no offline support [22].

2.2 MOBILE LEARNING:

Less platform preparedness among rural users makes a need for just-in-time training interfaces for solving digital illiteracy [27][28]. App design that uses a minimalist and localized approach is proven to enhance adoption rates among users with low levels of literacy, and with limited school budgets, there is a need to find cost-effective solutions to replace legacy systems [29].

2.3 POLICY INTERVENTIONS:

Progressive realisation, government funding and teacher training lower institutional resistance [30] and peer-led workshops and ongoing teacher training tackle concerns

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that stem from poor teacher preparation [31]. Progressive loading and data compression is key to supporting function in LMS even on low-end devices as Moodle Mobile does [33] and user friendly design and educator training are necessary to achieve a successful integration of LMS [32].

2.4 VIRTUAL REALITY (VR) IN EDUCATION:

Streaming video in low-band regions is especially difficult. Video quality can be dynamically adjusted to ensure continuity of playback with scalable video coding (SVC) and adaptive streaming protocols like DASH and progressive download (PD); H.264 compression will also help maximize performance on low bandwidth networks [37]. Video-based learning is still possible but, in order to implement low bandwidth LMS solutions in national education systems, policy makers need to allocate funding and organizational resources for this purpose as well [38].

3. METHODOLOGY

The proposed methodology is based on four stages as presented in Figure 1. In the first phase the requirements of the system are gathered and analyzed and this includes functional requirements, non-functional requirements, and user interactions requirements. In the second phase, the system is built using models of layered architecture, data representations and process flow. The third stage is dedicated to architecture development and implementation: the algorithms, databases and APIs are integrated into an operating system at this stage. In the final stage of functioning, they are judged based on the interface design, testing and user acceptance analysis. In below Figure1 the block diagram of the proposed work is shown:

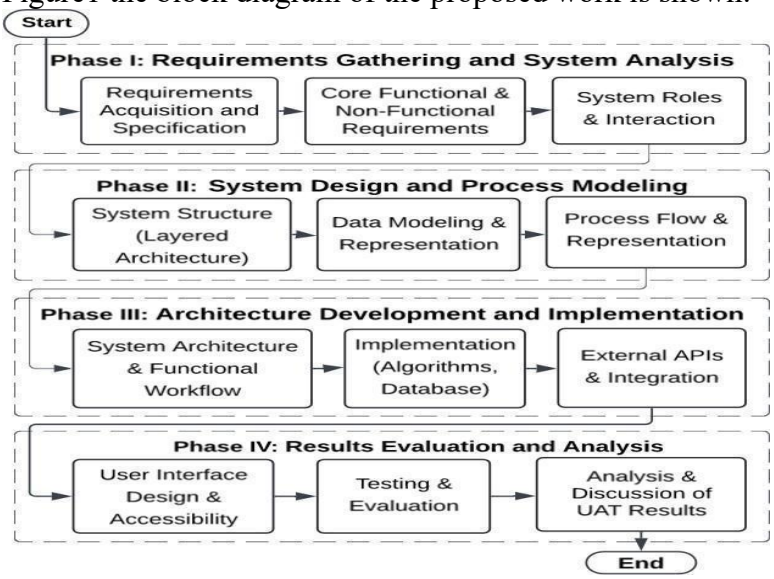

Figure 1. Block Diagram of the Proposed Work
Source: Authors' Compilation.

3.1 PHASE I:

For EAS, requirements gathering and system analysis were centred on the ability to capture clear, reconcilable functional and non-functional requirements from all stakeholders (students, teachers, administrators, content creators, institutions, monitors

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and parents/guardians) to ensure system goals meet real learning needs. Key features include user enrolment, authentication, personalised learning paths, course resources and assessments that can be downloaded, course creation and optimisation for teachers, assignment submission and marking, and live progress tracking and analytics for students and teachers. Non-functional requirements focus on low bandwidth operating, minimal data use, rapid load times, strong encryption and access controls, high levels of usability on low-end mobile devices, comprehensive error handling and cross browser/device compatibility, and scalable performance as users and courses increase. It models two kinds of users: Administrators and Students, with the interactions between them involving account management, publishing of courses, delivery of content as text, micro learning modules and video optimised for weak network, quizzes/exams, light forums, downloading of content, progress monitoring and reporting/ranking. These requirements work together to make EAS resilient and accessible and to enable learning in a constrained network environment.The use case diagram is shown in figure 2 and 3:

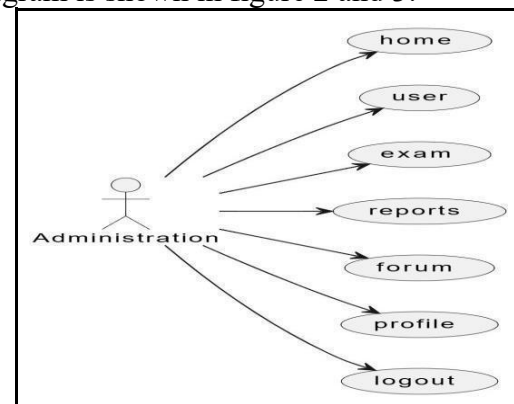

Figure 2. Administration Use Case Diagram

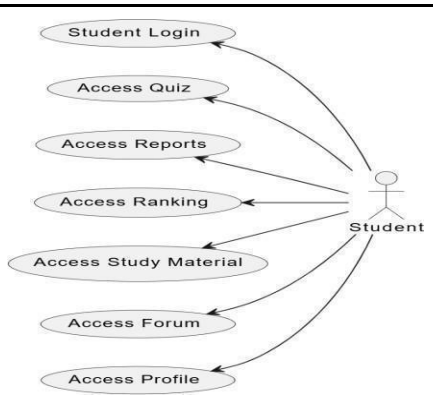

Figure 3. Student Use Case Diagram

Source: Authors' Compilation

3.2 PHASE II:

The system design and process modelling phase established EAS's formal and logical architecture based on the standard engineering artifacts for guiding development. EAS follows a layered architecture: Presentation, Application (business logic), Data, and Infrastructure, with Data Flow Diagrams (DFD) and Entity Relationship (ER) models that define the components interactions and the information flow. The Presentation layer is designed to be lightweight, provide efficient rendering, and adapt video to a user's available bandwidth to minimize data usage; the Application and Data layers handle authentication, content delivery, assessment logic and compact storage; the Infrastructure layer leverages cloud servers and CDNs to minimize latency and maximize availability to remote users. It supports 2G/3G (100-500 kbps) performance with minimum data exchange, including caching, lazy loading, compression of resources, optimizations for the server and adaptive H.264 streaming. The system is

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organized into data objects, such as materials (Books, Notes, Videos), which can be organized by class and subject; forums which are for collaborative learning; and assessment/reporting modules which are designed to track learner progress. These design decisions combine to form a scalable, low bandwidth LMS framework for a rural and resource constrained context.Figure 4 shows the ER diagram of the proposed database design.

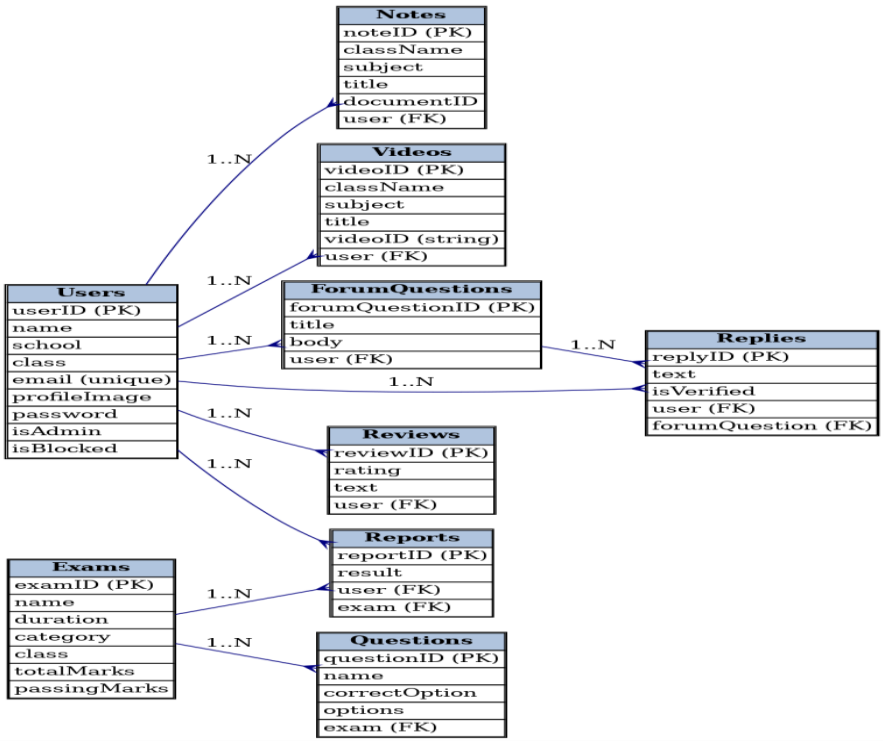

Figure 4. Entity–Relationship Diagram of EAS-LMS
Source: Authors' Compilation

3.3 PROCESS FLOW & SYSTEM REPRESENTATION:

The EAS-LMS process works well with limited bandwidth; users are able to register and securely log into the system. Upon successful login, the user is then assigned an appropriate role either as a student or administrator.Figure 5 outlines the step-by-step process of the proposed solution.

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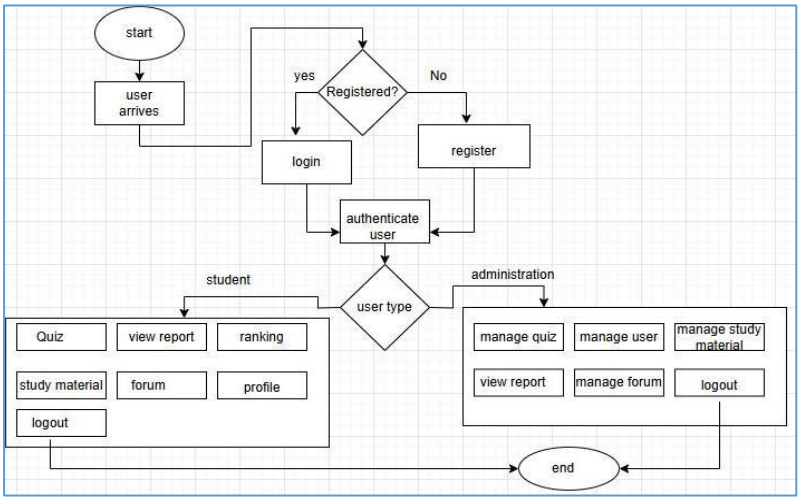

Figure 5. Process Flow Diagram of EAS-LMS

EAS-LMS implementation employs React on the front end, Node.js and Express on the back end, as well as MongoDB as a database to store the data quickly and efficiently. To optimize performance, caching and resource compression techniques are used.

3.4 THE DESIGN AND INTERECTION WITH THE SYSTEM:

The LMS designed for EAS Learning Platform uses a modular architecture in order to ensure high performance under conditions of low bandwidth. The LMS structures learning objects including books, notes, and videos in a flexible way which enables effective management of information and scalability. The LMS provides interaction among the user, exam, post, and learning material while providing modularity and separation of responsibility. CRUD operations are carried out using MongoDB that connects to the database securely.An overview of the system components is given in Figure 6.

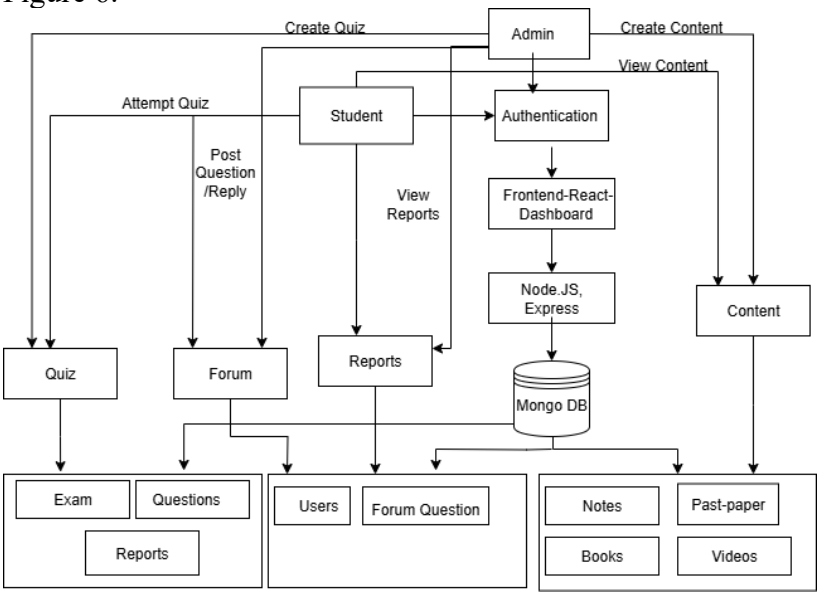

Figure 6. System Architecture and Functional Workflow of EAS-LMS

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The EAS Learning Management System (LMS) uses React on the frontend, Node.js and Express on the backend, as well as MongoDB for its flexible NoSQL databases. It uses caching and resource compression in order to cut down loading time, increase efficiency, and save on bandwidth in case of low connectivity. It utilizes a modular architecture which combines learning resources, interaction with users, and database operations. Multiple exams, posts, and learning resources can be accessed by the users via object relationships. CRUD operations in MongoDB ensure that the database is connected to the system securely. Additionally, MongoDB offers transaction management capabilities which include Connect, Commit, and Rollback.

4 IMPLEMENTATION AND ARCHITECTURE

A modular client–server structure has been implemented with the MERN stack, while JSON has been used to ensure smooth data exchange. The portal was broken down into individual functional modules, such as authentication, examination, forums, study materials, and reporting allowing for ease of scalability and maintainability. Stateless JSON Web Tokens (JWTs) were used to implement authentication, as they are created when users log in and validated by a middleware on the protected routes, ensuring that users cannot access the protected routes without first logging in. The application's core algorithms were created for exam management and forum moderation, and structured JSON responses were implemented throughout the app, while all errors were treated in a consistent manner. On the client, a light and responsive UI was created using React, and API calls were grouped by domain and handled via Redux for state management. The server- side of the application was handled by Express.js, which was used to structure routes and controllers, validate the requests, execute business logic and provide normalized responses. Key schemas like users, materials, exams, forums, and reports were saved by MongoDB (via Mongoose). JWTs, AES and RSA encryption, Bcrypt for password hashing, Nodemailer for OTP delivery, and Multer with Google Cloud Storage for file uploads were all used to increase security. The interface structure has been simplified and optimized for mobile devices to minimize bandwidth consumption and to be user friendly in low bandwidth situations, including simplified registration, navigation of quizzes and simplified display of results. Testing involved automated testing, manual testing and User Acceptance Testing (UAT) to incorporate feedback from users of the system.

4.1 USER INTERFACES FOR PROGRESS, RESOURCES AND INTERACTION:

In bandwidth-limited environments, the EAS-LMS enables light learning interfaces which enable the monitoring and social interaction between students. The EAS-LMS reporting interface offers a detailed analysis of quizzes in tabular format as shown below:

Table 1. Student Quiz Performance Reports in EAS-LMS

Exam Name	Date	Total Marks	Passing Marks	Obtained Marks	Verdict
chap1 Science	17-05-	30	20	2	Fail

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	2025 06:11:17				
chap1 Science	17-05-2025 05:04:08	30	20	4	Fail
chap1 Math	16-05-2025 03:11:53	10	6	0	Fail
SST Quiz	16-05-2025 12:16:25	10	6	0	Fail
SST Quiz	15-05-2025 09:43:01	10	6	3	Fail

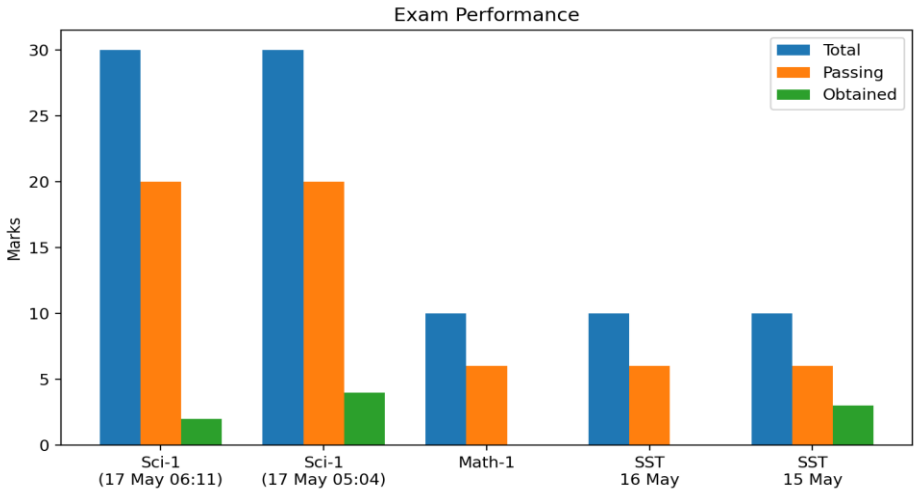

Figure 7. Exam Performance Matrics

EAS-LMS has a nice Study Material interface in which students can access and download study material organized by topic and class. Video lectures are delivered on a light-weight grid, while streaming it optimises data usage. The Profile interface is the interface where users can view and edit their personal information and settings. The forum interface includes discussion forums to enable collaborative activities like creating discussion topics, posting questions and answering them.

4.2 TESTING AND EVALUATION:

This section of the paper will give a discussion to the Testing and Evaluation of the EAS Learning Management System (LMS) for ensuring the robustness, functionality and usability. Automated testing and manual testing are used to identify any bugs or performance issues, validate the core functionality and test the user experience.

4.3 MANUAL TESTING:

The EAS-LMS underwent various tests, including manual testing, unit testing, integration testing, and system testing, to validate the performance, reliability, and

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security of the LMS. All the basic features of the LMS such as user registration, user authentication, quiz management, forum and managing study materials etc. were all tested and found to be satisfactory. The integration testing did guarantee that there was smooth communication between the front end, back end, API, and database. The assessment of learning and LMS management functionalities were pilot tested with 50 undergraduate students and 10 administrators.

4.4 AUTOMATED TESTING:

Special tools were used to conduct automated testing to simulate network conditions, audit the front end and make sure the system is reliable on limited network connectivity. The LMS was tested for responsiveness and functionality with the use of the Lighthouse, Clumsy and simulated network throttling tools with minimal human intervention.

4.5 THE ANALYSIS AND DISCUSSION OF RESULTS OF THE UAT ARE REQUIRED:

From the UAT tests, it was evident that EAS-LMS is a reliable, user-friendly and effective system for education. Both authentication and quiz evaluation were successful at 100% accuracy and 100 F1 score, guaranteeing reliable operations as shown in table 2. From the above, it is clear that the system can be accessed and assessments done even when the bandwidth is limited.

Table 2. User

Question	Accuracy (%)	Precision	Recall (%)	F1 Score
Log in without issues	100.0	1.0	100.0	1.000
The quiz module worked	95.8	1.0	95.8	0.979
Quiz result immediate	87.5	1.0	87.5	0.933
Quiz result accurate	100.0	1.0	100.0	1.000
Posted in the forum	12.5	1.0	12.5	0.222
Forum helpful	91.7	1.0	91.7	0.957
Helped learning	91.7	1.0	91.7	0.957
Recommend app	95.8	1.0	95.8	0.979

Acceptance Testing (UAT) Performance Metrics for Core LMS

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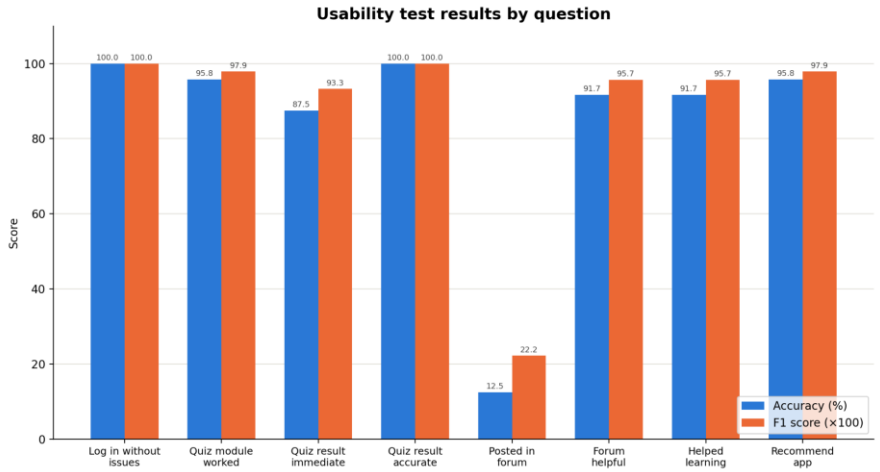

Figure 8. Usability Test Matrics

Results obtained from the implementation revealed that the LMS was efficient in providing quizzes, facilitating learning, and improving the engagement of students. The feedback received from the students was positive and indicated that the system was educational to the learners.Below figure 8 indicates LMS performance & Forum participation.

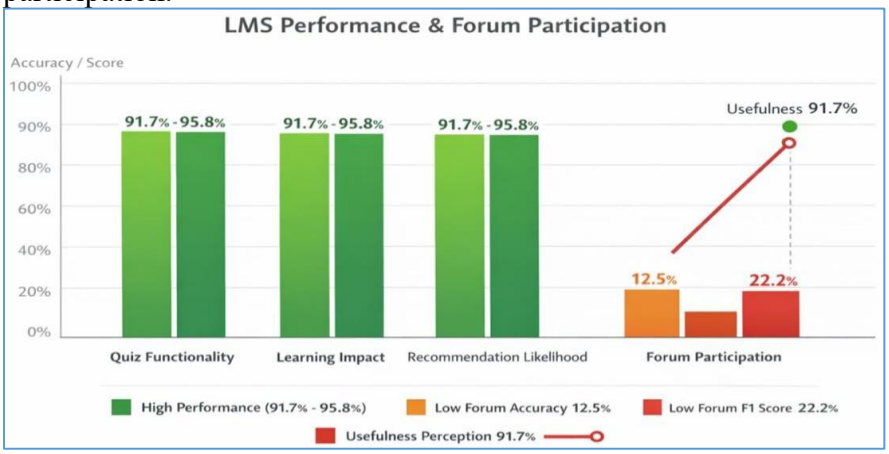

Figure 8. LMS Metrics vs. Low Collaboration in Low-Bandwidth Settings

The UAT results revealed that the overall performance of LMS was good but the participation of the students in the discussions of the forum was very low. The forum was seen by users as a helpful tool but not very many of the users used it due to unfamiliarity, low motivation or lack of guidance. The results indicate that there is a need for better onboarding, prompts, and collaboration incentives to support collaboration learning. Overall, the LMS was found to have a positive effect on learning, and forum engagement was identified as an area that needs to be improved and expanded to have a greater impact on future learning.

4.6 DISCUSSION AND COMPARISON WITH EXISTING STUDIES:

EAS-LMS findings are in agreement with previous research where optimized and low bandwidth LMSs have proved capable of providing high quality learning experience

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even under poor internet connection. The system exhibited efficient performance under simulated 2G/3G network through the implementation of methods like lazy loading, minimalistic interfaces and adaptive streaming. However, in contrast to previous research on LMSs, the low utilization of forums was observed although participants were aware of its importance. Thus, it may be suggested that obstacles to collaborative learning depend on the level of participants' digital competence and engagement rather than technological issues. EAS-LMS proves both the technical possibility and effectiveness of a low bandwidth learning system.

5 CONCLUSIONS AND FUTURE WORK:

The research focused on the problem with available Learning Management Systems and their incompatibility with low-bandwidth environments. Therefore, EAS-LMS was developed in order to be an LMS suitable for learning in environments with insufficient internet connection. Experiments proved that EAS was capable of implementing quizzes, forums, study material, and videos in a performant manner on 2G/3G networks. The results also revealed that EAS had low response time and high levels of users' satisfaction, as 95.8% of students rated the quiz module as effective and 91.7% of them had increased learning effectiveness. It means that EAS may be used not only to decrease data expenses but also to narrow the digital gap between rich and poor countries and communities. In addition, the research shows how the United Nations Sustainable Development Goal #4 may be reached by using EAS-LMS because it promotes inclusive education. Nevertheless, it should be noted that the research is characterized by two limitations related to the size of a test group and multimedia capacity of EAS. Therefore, it is necessary to conduct experiments with more participants and develop adaptive learning analytics, offline support, and better multimedia optimizations.

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