Education Access System (EAS): A Low-Latency Learning System for Low-Bandwidth Education Access

Muhammad Inam ul Haq[1], Fazal Malik[2]*, Asiya Bibi[3], Muhammad Javed[4], Muhammad Shoaib[2]

[1]Department of Computer Science & Bioinformatics, Khushal Khan Khattak University, Karak, Khyber Pakhtunkhwa, Pakistan

[2]Shool of Computer Science, Iqra National University, Peshawar, Khyber Pakhtunkhwa, Pakistan

[3]School of Science and Technology, Middlesex University, London, United Kingdom

[4]Institute of Computer Science and Information Technology, University of Science and Technology Bannu, Khyber Pakhtunkhwa, Pakistan

*__Correspondence__: fazal.malik@inu.edu.pk

Citation | Haq. M. I. U, Malik. F, Bibi. A, Javed. M, Shoaib. M, "Education Access System (EAS): A Low-Latency Learning System for Low-Bandwidth Education Access", IJIST, Vol. 7, Issue. 4 pp 2976-2996, November 2025

Received | October 25, 2025 **Revised |** November 18, 2025 **Accepted |** November 24, 2025 **Published |** November 30, 2025

Online learning worldwide requires well-performing Learning Management Systems (LMS); however, most web-based application packages have no opportunities to execute their task in the low-bandwidth areas due to the infrastructure factor, the absence of digital literacy, and the barriers of institutions. It applies this digital divide to the countryside and the developing world and limits access to quality education. Existing LMS systems such as Moodle and Blackboard are designed to support high-bandwidth systems, and they are not applicable in locations where 2G/3G is the predominant network. This gap can be addressed by a low-bandwidth, lightweight, and low-latency LMS named Education Access System (EAS), which is developed, engineered, and tested in this research project. It also worked through four phases of methodology: requirement analysis and stakeholder mapping, data analysis and system architecture built upon a layered architecture, implementation of the application using React, node.js, MongoDB, and optimized APIs, and assessment of the project via manual/automated testing and User Acceptance Testing (UAT) with students. The findings show login and usable databases, 95.8% respondents had improved learning with the platform, but valid performance under the simulated conditions of a 2G/3G (100-500 kbps) was still simulated (low forum interaction 12.5%). EAS explains how LMS optimization solutions can be used to the advantage of equitable digital education, comprising SDG 4, and how the future will center on mobile deployment, offline adaptations, and long-term collaborative capabilities.

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

Introduction:

The rapid rise in information and communication technologies (ICT) has revolutionized the world of education, making it possible to engage in learning activities, share digital materials, and collaborate virtually [1]. Learning Management Systems (LMS), such as Moodle, Blackboard, and Google Classroom [2], have become essential tools in higher education, enabling the systematic delivery of course content and facilitating structured interaction between students, instructors, and peers. Nevertheless, the successful implementation of such platforms is highly dependent on reliable broadband internet connectivity, supportive learning environments, and access to modern computing devices. While these requirements are generally met in developed regions, learners in developing countries, particularly in rural areas, often remain deprived of the benefits of digital education due to persistent infrastructural limitations [3][4].

The expansion of e-learning in developing countries depends on the efficient and cost-effective delivery of educational content. However, this goal can only be achieved by carefully assessing the readiness to ensure successful implementation [5]. Technological and policy bottlenecks in the transfer of knowledge take place in low-bandwidth environments, particularly in Least Developed Countries (LDCs). A comprehensive assessment management is necessary to develop more realistic strategies that will solve these issues and bring lasting benefits to end users [6]. The assessment management can be considered as the basis of realistic planning, and arguably the first step to developing a naturalistic strategy aimed at this or that need of the end users [7]. It also plays a vital role in designing effective e-learning strategies within universities, with many studies recognizing it as a key pillar for successful technology-driven education [8].

The COVID-19 crisis boosted the world toward online education and demonstrated many limitations of the current Learning Management Systems (LMSs) to enable three types of effective learning. This prompted the efforts to expand AI-based improvements, such as smart interface/user experience design, adaptive learning, intelligent chatbots, proctoring, authentication, and network optimization to enhance convenient, dependable, and enjoyable online learning experiences [9].

Schools and colleges are increasingly adopting Information Technology (IT) to facilitate online learning through e-learning and mobile learning, while also utilizing services offered by cloud computing (CC) and internet networks to support cost-effective, versatile education. However, e-learning systems (ELS), being internet-based, are exposed to various security risks. Rivest-Shamir-Adleman (RSA) and Advanced Encryption Standard (AES) consideration under ELS named Integrated Encryption Methods (IEM) would additionally increase the privacy of data, minimise latency, minimise load on encryption in CC-based ELS [10].

The Digital Divide (DD), including unequal access to Information and Communication Technology (ICT), remains one of the major challenges facing developing countries in the context of higher education (HE). It hampers efforts to enhance pedagogy, student engagement, and academic performance. Addressing issues such as the affordability of ICT, inadequate infrastructure, and limited digital literacy is essential for the equitable adoption of Learning Management Systems (LMS) [4].

The Learning Management System (LMS) is tested using qualitative research carried out in Al-Mujaddid Sabak Islamic Institute. Interactive Designs such as discussion groups, auto-fill quizzes, online assignments, and online classes, are found to engage, encourage, and improve student performance. They report improvement of flexible, collaborative, and participatory learning in modern education settings with implementation [11].

Although Learning Management Systems (LMS) are implemented widely across universities in the Arab Gulf Countries (AGC), minimal studies have been done to explore

their use and the factors that govern their use. A summary of 34 reports (2013-2023) is matched with 41 critical factors, traditionally the majority of which are associated with Perceived Ease of Use, Perceived Usefulness, Social Influence, and Facilitating Conditions. The most used is the Technology Acceptance model with students as the main subjects [12].

With the disintegration of the digital education paradigm, appropriate interaction between learners in low-connectivity conditions continues to pose an urgent concern. Traditional LMSs are limited by their bandwidth to offer continuous interactive learning, therefore precluding participation and reducing the learning opportunities and outcomes. Research indicates that next-generation, low-latency, fully customizable content services with feedback mechanisms are essential for further reducing the digital divide and delivering equitable, high-quality education in underprivileged areas [13].

The potential of artificial intelligence (AI) and automation as transformative solutions for bridging the digital divide in developing countries is currently being analysed. The technologies encourage education, health services, the growth of agriculture, and economic prosperity. It makes personalized learning and diagnostics more effective than ever, enhances precision farming, and provides a gateway to the market, removing issues of infrastructure, skills gaps, cultural resistance, and policy handicapping [14].

Education has undergone a revolution due to the rapid elaboration of the Information and Communication Technologies (IC) category, and the Learning Management System (LMS) emerges as the necessary resource in the conveying of the materials, controlling the testing, and online collaboration, such as Moodle, Blackboard, and Google Classroom. The COVID-19 pandemic accelerated such a shift by raising a fairly clear awareness of how current platforms rely on high-bandwidth infrastructure. Though many developed states are rapidly becoming digitized, the rural and developing states continue to experience a digital divide due to infrastructural factors, poor levels of digital literacy, and institutional disincentives.

Educational Data Mining (EDM) is a key to improving e-learning platforms through analysis of learner interactions, curriculum optimization, evaluation technique advances, and adaptive tutoring systems. An overview of the literature reviewing 30 years since its beginnings notes that managers increasingly consider EDM as a tool to aid strategic decision making in higher education with a view to achieving platform efficiency and better educational outcomes [15].

The use of technology in the education sector in the form of learning management system (LMS) has increased flexibility, accessibility, and quality. In low-bandwidth areas, however, there is a lack of equitable access due to the lack of connectivity. Mobile Learning (M-Learning) and low-bandwidth applications, which rely on the mobility of portable learning tools such as smartphones and tablets, offer scalable, affordable, and easy-to-fit solutions in narrowing the educational disparity, enhancing inclusion, and socio-economic development at the international scale [16].

Another emerging educational application of Virtual Reality (VR) is the use of 360-degree videos to create immersive and interactive learning experiences. However, achieving high-definition (HD) quality can require bandwidths of up to 400 Megabits per second (Mbps, which poses a significant challenge in areas with limited internet connectivity. One way of doing this is an encode transformation filtering (ETF), where the viewports are predicted, more data is compressed more quickly, and a multicast is used to show only the necessary data that is sent with no loss in quality [17].

The role of Information and Communication Technology (ICT) is the most recent phenomenon being hailed to have revolutionized sectors of transport, health, business, and communication in both developed and developing countries. However, there is reported iniquitous Internet proliferation, and the Coronavirus Disease 2019 (COVID-19) pandemic

is being witnessed to exert more digital disparities in Pakistan because of the minimal ICT infrastructure and availability [18].

In education technology, Data Analytics is highlighting the seminal role in contrast to evaluated Student Information Systems (SIS) and Learning Management Systems (LMS). SIS managing student data is helping to perform administrative procedures, and LMS is helping to deliver information and collaborate with students. It has been reported that advancements in the Communication Technologies (CTs) have optimized instructional strategies and facilitated ongoing improvement in teaching and learning by providing seamless connectivity, real-time interactions, and personalized learning in Smarter Education Environments (SEE) [19]. This is demonstrated in the context of Fifth-Generation (5G) networks, AI-driven cloud computing, edge computing, and blockchain technologies; however, challenges such as network reliability, security vulnerabilities, compatibility issues, and limited resources continue to persist [20].

The physical characteristics of conventional LMS systems are not appropriate in areas with 2G/3G communications (100–500 kbps), e.g., rural Pakistan. Access to digital education is limited on an equal opportunity basis by technical requirements, which are media-intensive and have a high latency. The socio-institutional aggravating factors include fear of the teacher and financial constraints.

The main objectives of this research is to design and develop a lightweight and low-latency Learning management system, named Education Access System (EAS), that can perform in low-bandwidth (2G/3G, 100500 kbps) in low-bandwidth (rural and underserved) settings. It aims at maximizing the core LMS features in terms of authentication, content delivery, quizzes, and forums, and progress tracking in order to minimize data usage but maintain usability and reliability. To evaluate the system, it is tested by means of manual testing, automated testing, and User Acceptance Testing in simulated conditions of low bandwidth to assess its functionality, usability, and effect on learning, and evaluate its role in providing equitable digital education and SDG 4.

Demographically, the research is also driven by the educational background of the developing and lower-middle-income countries, especially the rural and semi-urban parts of Pakistan, where a large percentage of the population has no and/or intermittent access to high-speed internet services. Numerous students use cheap 2G and 3G mobile networks (100500 kbps) and low-end smartphones because of financial reasons. The low digital literacy of students and teachers also affects the use and access of the LMSs in these settings.

Technically, the current LMS systems are mostly designed with massive bandwidth, multimedia-intensive environments, and consistent connectivity. Low-bandwidth users, on the other hand, have high latency, frequent disconnections, and data overuse, particularly when streaming video and using interactive applications. The paper aims to overcome these limitations by paying attention to the lightweight system design, text-based interfaces, caching, lazy loading, micro learning content delivery, and adaptive video streaming mechanisms, which enable the functionality to be saved even in the case of sparse network conditions.

This work fills the gap by designing, developing, and assessing EAS, which is a lightweight LMS designed to operate in environments with low bandwidth conditions. It is built on low-latency architecture and directly integrates powerful data strategies, without sacrificing the critical elements of quizzes, forums, and content delivery. Based on an agile approach, it is developed as an MERN stack application and refined with manual, automated, and User Acceptance Tests (UAT). The study adds a reproducible model to inclusive education that can help in achieving the UN Sustainable Development Goal 4 (SDG 4).

The rest of this paper follows this format: Section 2 is a review of the literature on

the existing solutions and strategies in low-bandwidth learning. Section 3 describes the methodology, which includes requirement analysis, system design, implementation, and evaluation. Results and discussion of testing and UAT findings are presented in Section 4. Lastly, in Section 5, the principal results, limitations, and future research directions are observed.

Literature Review:

The growing reliance on mobile devices and the demand for online education have highlighted the need for web-based applications that function effectively on low-bandwidth networks. In countries like Pakistan, where 2G and 3G networks (100–500 kbps) prevail in rural areas due to their affordability and availability, conventional Learning Management Systems (LMS) often struggle to deliver consistent pedagogical experiences. The literature is organized under the following subthemes:

Low-bandwidth LMS solutions:

Approximately one-third of Pakistan's population lacks internet access, and even among those who are connected, bandwidth is often limited. This restricts access to multimedia-rich applications and poses a significant barrier to the adoption of educational technologies. Such a digital gap, combined with the lack of digital literacy, makes the use of LMS applications in rural areas highly problematic [21][22].

Studies also emphasize some of the measures that could be taken to enhance LMS performance in low-bandwidth settings. Text-based lightweight interfaces, lazy loading, and caching reduce page loading time, as well as data usage [23][24][25]. The greater availability and interaction level among the users is additionally stimulated by micro learning (delivery of content in a small and fast loading smaller module) [26]. It is also true that Open Educational Resources (OER) offer free materials that can be accessed during active lessons, although the online-only systems do not allow offline access [22].

Mobile Learning:

There is also research that rural users are generally underprepared on platforms, which means that interfaces with just-in-time training might be used to improve digital illiteracy levels [27][28]. Localized minimalism app design has been demonstrated to support higher uptake among low-literacy users. The limited budgets of many schools are the reason why many schools end up using outdated systems, which calls for cost-effective alternatives [29].

Policy Interventions:

Modeling has shown that with progressive realization, government subsidies, and educator education, resistance on an institutional level may be reduced [30]. Concerns developed by teachers (usually due to insufficient technical training) can be overcome with peer-driven workshops and continual technical training [31]. Among other factors, it is thus important to ensure that LMS integration is successful by incorporating user-friendly designs led by the training of the educators [32]. Moodle Mobile has demonstrated within these data centers that low-end devices can work through progressive loading and compression of data [33].

Virtual Reality (VR) in Education:

Video streaming is an especially troublesome problem in areas of limited bandwidth. Scalable Video Coding (SVC), adaptive streaming protocols, like DASH, and progressive downloading are designed to enable video content to dynamically adapt to network conditions to provide continuity of playback [34][35][36]. H.264 compression techniques also enable better performance in low-band networks [37]. With the right level of optimization, these solutions show that video-based learning is viable. Furthermore, it is essential to engage policymakers to integrate low-bandwidth LMS solutions into a country's education system, ensuring the provision of crucial funding and organizational support [38].

The convenience provided by the low-end devices, together with the universal design, will facilitate the ubiquitous deployment in resource-constrained environments.

The current learning management systems (LMSs) are mostly geared towards high-capability backgrounds without serving the students in low-access capacity areas. Other platforms, such as Moodle and Blackboard, rely heavily on multimedia content and stable internet connections, making them unsuitable for rural areas of Pakistan, where 2G and 3G networks are predominant.

The present work proposes one solution to this managed using EAS, a lightweight LMS that can be used in low-bandwidth setups. Cumulative to interventions developed in previous studies, such as text-based interfaces, caching, lazy loads, micro-learning, and adaptive video streaming, EAS provides functionality that persists under limited conditions. In addition to technical optimization, the platform emphasizes user-friendly interfaces, training, and institutional mechanisms, addressing important social and structural factors as well. By doing this, EAS helps meet the equitable digital education vision through a sustainable approach to under middle-income areas with low latency, thus supporting SDG 4: Quality Education directly.

Methodology:

The proposed methodology is based on four stages as presented in Figure 1. During the first phase, the system requirements are collected and analyzed, which comprises functional and non-functional requirements in addition to user interaction requirements. During the second stage, the system is developed based on the layered architecture, data representation, and process flow models. The third stage is devoted to architecture development and implementation: at this step, algorithms, databases, and APIs are combined into an operating system. In the last stage of functionality, they are evaluated by interface design, testing, and user acceptance analysis.

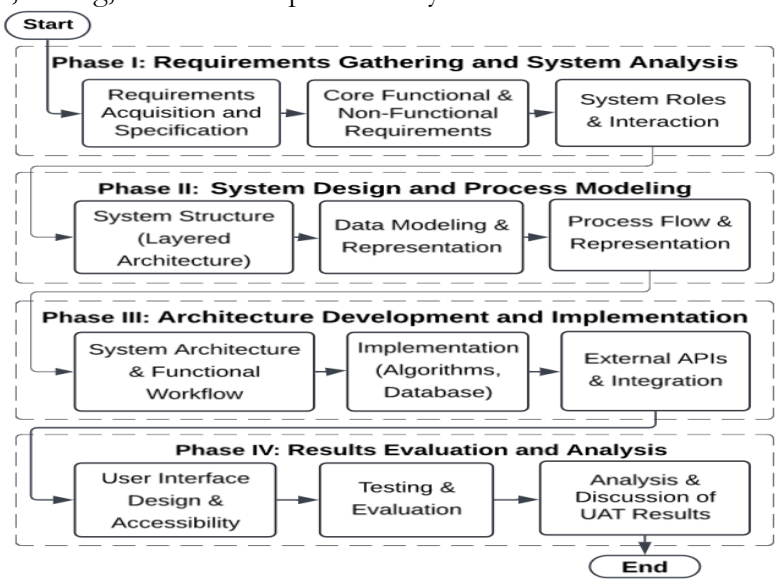

Figure 1. Block Diagram of the Proposed Work

Phase I: Requirements Gathering and System Analysis:

This phase is dedicated to identifying and specifying the functional and non-functional requirements of the EAS system. Needs analysis and specification are undertaken, client core system functionality is identified, and user roles and interactions are reconciled by use case analysis. Consistency between the demanded system objectives and the requirements of learners, instructors, and administrators is ensured.

Requirements Acquisition and Specification:

This section describes the requirements of the system, such as stakeholders, non-

functional and functional requirements of the system, and use cases. Visions: Essentially, these are students, teachers, administrators/system maintenance, content creators, the institutions, monitors, results, and occasionally parents/guardians who can follow up with student performance.

Core Functional Specifications:

The system has full learning capabilities, allowing users to enroll, log-in and receive customized learning. Where educators can create and run courses, optimize content, and trace student progress: Students can use, download course material and assessments, plus track their progress. The content management also includes creating, editing, and organizing the learning materials, as well as assessment features to aid the design, submission, and grading of assignments. Progress tracking offers in-depth analysis to both students and a tutor, so that academic performance is measured at any moment in time.

System Quality Requirements:

Besides the basic features, the system has some additional critical non-functional requirements which make it effective when in the low-bandwidth-setting. After enhancing performance, Tara minimizes data usage while maintaining fast loading times. Additionally, it ensures the security of user data and educational materials through encryption and controlled access.

The focus is on usability and the minimal and mobile-friendly interface serving low-end gadgets. It is minimally prone to crashes, has robust error-handling provisions, and has been demonstrated to work with numerous gadgets and browsers commonly employed in less developed nations. Additionally, scalability would mean that the system can support more users and courses and still perform well.

System Roles and Interaction Diagrams:

Figure 2 and Figure 3 provide examples of diagrams of the Administration and Student Use Case Diagram of the EAS-LMS, which suggest interactions between the system and the aims of the user. The portal has two categories, namely Administrators and Students. During the administration process, administrators control user accounts, create courses, update the system, publish optimized content, and monitor statistical data. Educational resources, including text materials, micro-learning modules, and video lectures, must function effectively on low-end devices and limited network connections. Students can complete quizzes, download notes, track their progress, and study while consuming minimal data.

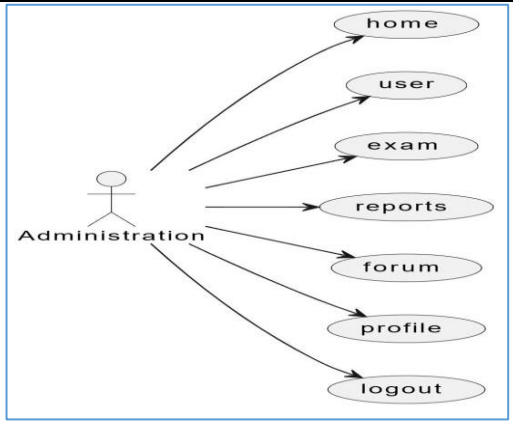

Figure 2. Administration Use Case Diagram

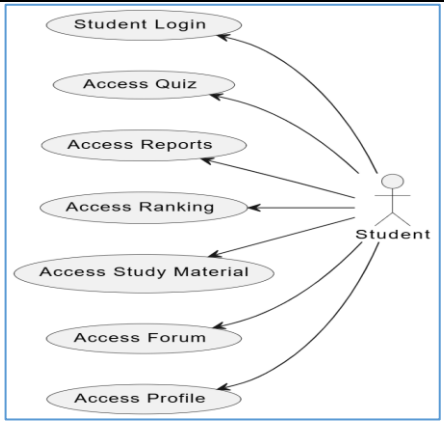

Figure 3. Student Use Case Diagram

Major application cases such as Register and Login to get access, Home to browse, along with Exam and Quiz to do exams, and Study Material to study. Lightweight forum and profile management make communication easier. Administrators also produce visuals on

Reports and Ranking, and the two roles terminate with certainty on Logout.

Phase II: System Design and Process Modeling:

Formal basis, logical basis, and structure of the system are determined during this phase. The system architecture is described as a layer-based approach to address concerns in three layers: presentation, business logic, and data layer. The data and data flow of the components are represented by data and process data flow diagrams (DFDs), and the interaction of the components is modeled by entity-relationship (ER) diagrams. These activities are combined to build a clear outline of how further development will occur.

System Structure:

The EAS Learning Management System (LMS) provided educational material like videos on a low bandwidth (100-500 kb), with rural users still able to access this anywhere in Pakistan, and thus provided them access to education. It employed a layered architecture comprising Presentation, Application, Data, and Infrastructure layers, with each layer designed to minimize data usage while maintaining scalability and performance.

This architecture specifies system data representation, process flow, and design models that help to deliver learning resources efficiently within constrained connectivity environments.

Layered Structure:

The system follows a layered structure to ensure accessibility in low-bandwidth environments.

Presentation Layer manages user interactions through a lightweight web-based interface optimized for low-end mobile devices. It minimizes bandwidth usage by employing text-based design, limited JavaScript, and lazy loading for non-essential resources. Video playback is optimized for low-speed networks, while features such as microlearning modules and simplified dashboards support students, educators, and administrators.

Application Layer contains the core logic, handling authentication, content delivery, user sessions, and role-based access control. Built on a lightweight framework, it processes requests from the interface while integrating analytics for usage tracking, ensuring low server load and minimal data overhead.

Data Layer responsible for persistent storage, this layer manages user profiles, course materials, and quiz records using a relational database like MongoDB. Optimized for basic queries and reporting, it supports efficient data retrieval in constrained environments.

Infrastructure Layer uses cloud servers in conjunction with Content Delivery Networks (CDNs) to cache content closer to end users, thereby minimizing latency. Collectively, the layered architecture ensures that EAS remains scalable, efficient, and reliably accessible across Pakistan.

Optimization Strategies for Low-Bandwidth Performance:

To ensure smooth operation under 2G/3G networks (100–500 kbps), EAS-LMS implements several architectural optimizations. Caching and lazy loading are employed to reduce data transfer and load times. Static assets and non-essential resources are cached via browser mechanisms and a Content Delivery Network (CDN), while lazy loading defers the rendering of images and content until needed, minimizing initial page load and bandwidth consumption.

Resource compression further enhances performance. Textual data, style sheets, and scripts are minified and compressed (e.g., GZIP) before transmission, while server-side optimizations streamline database queries and API responses to reduce payload sizes.

For video content, adaptive streaming protocols and efficient compression codecs (e.g., H.264) are used. This enables dynamic adjustment of video quality based on available bandwidth, preventing buffering and ensuring smooth playback even in low-speed networks.

Finally, the system follows a lightweight design principle. The frontend emphasizes a

minimalist, text-based interface, limiting graphical elements and relying on efficient CSS and minimal JavaScript. This approach delivers a functional, responsive UI while keeping data overhead low, ensuring usability in bandwidth-constrained environments.

Data Modeling and Representation:

The entity relationship schema of the system (Figure 4) brings to light the main objects in the platform: the users, the exams, the questions, the reports, the forum discussions, and the learning materials (books, notes, and videos). All these interconnected units collectively support academic activities, assessment, and the overall learning process.

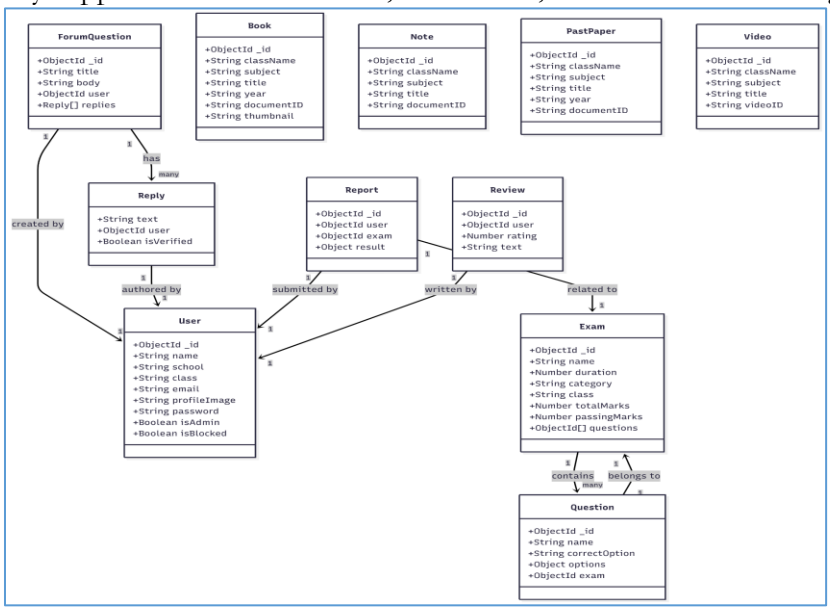

Figure 4. Entity–Relationship Diagram of EAS-LMS

The User side is the location where people, comprising students and administrators, gather. Each user is identified by his/her user ID, where he/she has his/her name, his/her class, his/her email, and their profile image, as well as permission(isAdmin, isblocked). The user is central, and he or she can take exams, post, reply, and generate reports. Forum interactions are organized around Forum Questions, Posts, and Replies. Topic Keepers (Forum Questions): Users are provided with a title and description for each topic and can create posts or comments. Posts (Broader Content): Users can generate posts or comments and include a verification flag (Post Message) for validation. Evaluation is done via the Exam entity, Question entity, and Report entity. Examination has metadata, including length, type, and marks, and is made up of several Questions holding text, options, and correct answers. The report captures findings and connects users to the tests and studies' performance.

Some of the learning material is shown under books, Notes, and Videos, and this is divided into Class, subject, and title. Reference X is the one you put your books in. Notes: Small snats of material you want to study. Videos: Multimedia learning in motion. Orderly review, cooperation, and access to resources are assured through these bodies.

Books, Notes and Videos are some of the learning materials that are organized and classified systematically in terms of classes, subjects, and titles.

The books are used as the main reference materials for organized study materials. Notes are brief study materials that are to be revised and read in a short time. Multimedia-based instructional materials are offered in the form of videos to facilitate dynamic and visual learning.

Process Flow & System Representation:

As shown in the process flow diagram (Figure 5), the user journey and their general workflow of the EAS-LMS were created specifically to function in low-bandwidth settings.

Once a user visited the site, the system first ensured that he or she was a registered user. None of the unregistered users were redirected to the registration or the login page. After the user was authenticated, the user was defined as either a student or an administrator, and each user was assigned particular permissions.

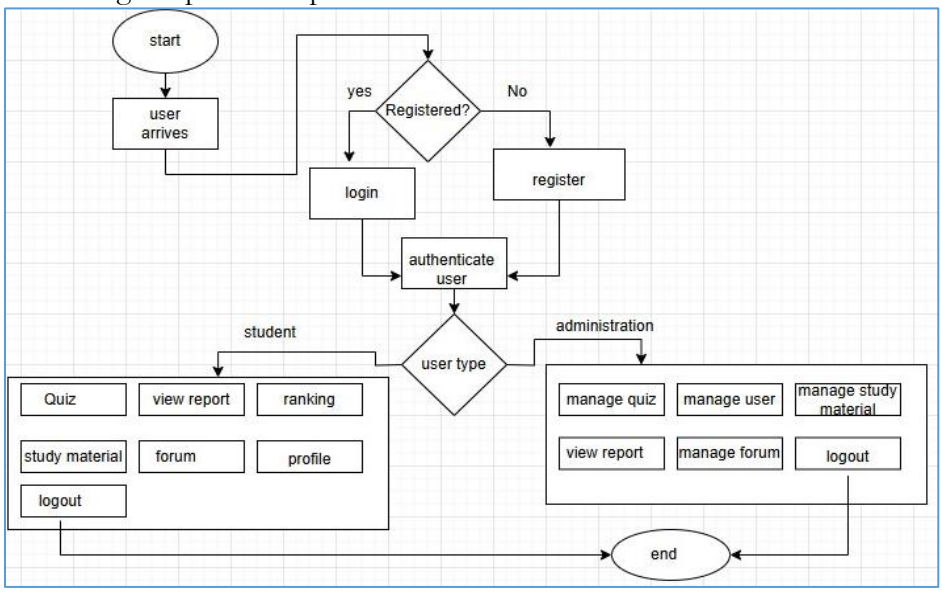

Figure 5. Process Flow Diagram of EAS-LMS

They include a variety of features that are vital to students, including timed quizzes that are automatically graded, access to textbook, watching or reading information (notes, videos), engaging in written discussion forums, editing their account profiles, and receiving performance analyses or rankings. In addition to those options, administrators can create and grade quizzes, create and manage user accounts and privileges, publish and refine learning material, and host periodic forums. The workflow has a termination (log out) feature that provides safety in the termination of a session.

The system was represented through a decision flow, where the user's path was determined based on their registration status and role classification. It was modelled on three key concepts: modularity, with a clear separation between student and administrator functionalities; low-bandwidth friendliness, achieved through text-only interactions to minimize data usage; and future-growth relevance, implemented via centralized authentication and role-based access control (RBAC).

Phase III: Architecture Development and Implementation:

The design specifications are converted into functional components in this phase. The general system structure and the mechanism are created, and, as the next part, the algorithms to identify the person, evaluate, and communicate the information to him are implemented. Client and server-side modules are created and implemented with MongoDB database management for the data operations. The APIs are also externalized to add functionalities to the system and provide twenty-first-century interoperability between the system and third parties.

System Architecture and Functional Workflow:

Figure 6 depicts that the workflow of the platform consists of three modules. The Quiz Module allows administrators to create tests using personalized settings, and students are given quizzes to complete, which are automatically graded to give immediate feedback on success. Performance reports regarding progress are available to both groups. The Forum Module has an interactive nature because it is framed around a textual discussion where the user can pose questions and can reply and receive replies. The Content Management Module

contains books, notes, past papers, and videos, and video streaming is optimized based on low-bandwidth requirements.

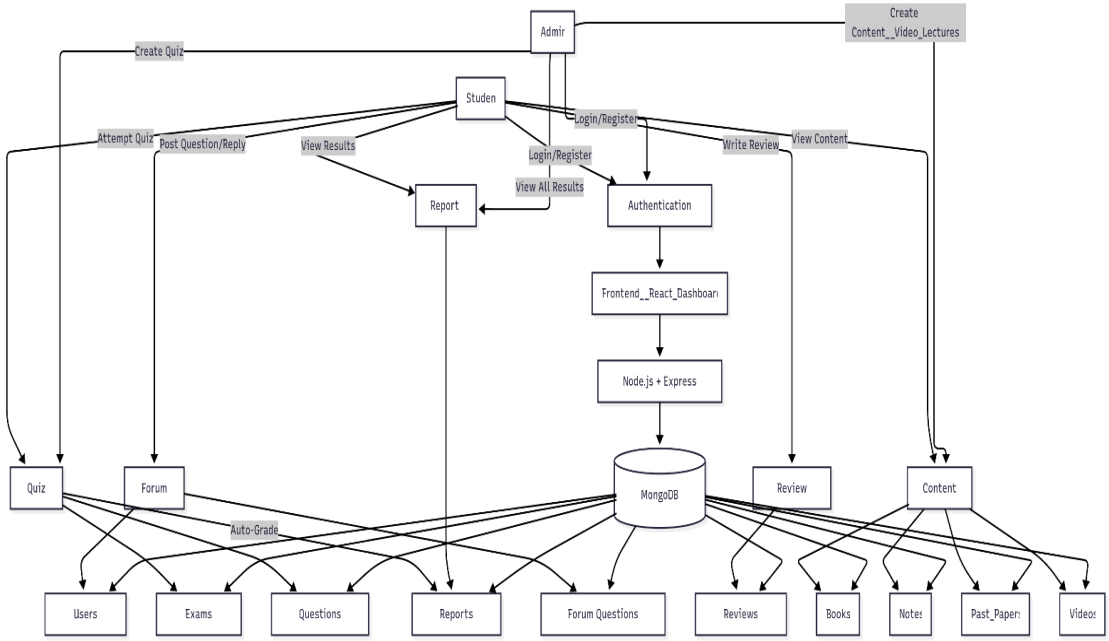

Figure 6. System Architecture and Functional Workflow of EAS-LMS

Technically, LMS is coded with the Assistance of the React-based frontend to enable the reactive user interface; that said, the backend is coded with the Assistance of Node.js and Express, which furnishes authentications, logic, and data flows. MongoDB is a flexible database that stores user information, quizzes, forum posts, and multimedia in the NoSQL format.

EAS-LMS can effectively address the challenges of resource-constrained learning environments in educational institutions by incorporating caching and resource compression, reducing load times, enhancing performance, and optimizing bandwidth usage.

System Design and Database Interaction:

EAS Learning Management System (LMS) has a modular design that combines study materials, user relationships, and database interaction to facilitate high performance in low-bandwidth systems. The idea that material is a logical superclass of the resources is because, dynamically, to render the different kinds of resources, material includes books, notes, videos, and polymorphism. It connects it to the class of users who can upload and run the content on the basis of real-life educational administration. The relationships in the class chart are given attention to behaviors and encapsulation rather than mere storage of data.

A single User object can be linked to multiple Exam, Post, or Material objects to ensure modular touchpoints, scalability, and clear responsibility allocation among other system components.

EAS-LMS uses MongoDB at a database level to work with create, read, update, and delete (CRUD) operations. The interaction classes are planned to be run under a resource-constrained environment by reducing bandwidth requirement and data privacy is assured. Attributes Core attributes are the Client, which provides and sustains a constant connection to MongoDB Atlas, and the Database, which is the reference to collections, users, courses, and content. For instance, the big ones are: "Connect, Disconnect, and GetCollection and the following transaction control methods, such as: BeginTransaction, Commit Transaction, and Rollback, which track actions taken through a sequence of actions taken. These elements would provide a usable, extensible system architecture.

Implementation:

EAS Learning Management System (LMS) is ushered as a learning system in contemporary learning where subject matter is examined, discussed in forums, and delivered. It is based on a solid technology foundation comprising React (the frontend application), Node.js and Express (background service), and MongoDB as the non-relational database engine. It is the kind of architecture that establishes the roles of a client and a server explicitly and with regularized protocols of communicational manual forms and models of data representation. The modular architecture offers scalability, maintainability, and flexibility that allow future upgrades. Authentication and authorization are controlled using JSON Web Tokens (JWTs) that deliver a stateless, secure user management architectural framework that enables security provision to education content and a secure ambiance wherein authentication can interact with users freely during authenticated user sessions.

Core Algorithms:

The system is based on a number of algorithms underpinning its functionality. The authentication algorithm produces and authenticates JWT tokens, which ensure secure access with token creation at login, local storage on the client, and validation of secured routes by middleware. The exam management algorithm controls the production of exams, recovery, alteration, and analytics of exam data, analytically validating and transforming exam data. Equally, the management algorithm of the forums regulates posting, replies, and the structuring of a thread with correct user perspective and content authentication. The use of a uniform error-handling pattern guarantees uniform request-response cycles and transmits sensible messages and formatted payloads back to consumers.

Client-Side Management:

The front-end uses React to provide a free-flowing and minimalistic interface to basic functionalities. The client-side processes are controlled by a centralized API communication strategy composed with the help of Axios, with setup parameters to automatically attach authentication tokens in the request header. The API functions are organized into modules (e.g., exams.js, forum.js, reports.js, studymaterial.js and reviews.js) to maintain some level of organization and reuse. All requests undergo a standardized process of replying to authenticated requests, responding, and controlling failure by using a try-catch block. Redux is a globally managed state that maintains the different elements in sync, enabling a standard and user-friendly interface and offering secure communication with a back-end service.

Server-Side Management:

It uses the express.js-based backend to create modular API endpoints and controllers by domain, such as exam management, forums, users, analytics, and study materials. Middleware functions are quite necessary, particularly when performing JWT authentication that authenticates tokens before transmitting them via encrypted paths. Server operations have a coherent flow: authentication control, input control, business logic, interaction with the database, and normalized response formatting. Strong checks against errors, achieved by using blue boxes, provide stability, security, and uniformity in all server tasks.

Database Structure and Management:

The database management system utilizes MongoDB, with Mongoose as Object Document Mapper (ODM) to create a definition of the schema, validate the data, and manage the relationships. This allows flexibility in storing a wide array of educational content, coupled with enforcing integrity where needed. Express routes support CRUD operations used to perform such activities as searching study materials, filtering exam results, or aggregating forum conversations.

The document-based model not only supports high performance and flexibility but also facilitates the storage, retrieval, and analytical processing of user activities related to learning outcomes.

Security Architecture for Constrained Environments:

The security design of EAS prioritizes protocols that are robust yet efficient for low-bandwidth and cloud-hosted deployments. JSON Web Tokens (JWT) are employed for authentication because they are stateless, eliminating the need for continuous server-side session storage and reducing database lookup overhead with each request—a critical efficiency for minimizing latency and server load in scalable cloud environments. For data encryption, a hybrid approach is utilized. Advanced Encryption Standard (AES) is used for symmetric encryption of stored data and transmitted content due to its high speed and lower computational footprint compared to asymmetric algorithms, conserving client-side resources and bandwidth. RSA (Rivest–Shamir–Adleman) is applied for asymmetric encryption during key exchange and initial secure handshakes (e.g., for TLS). This combination ensures that while strong public-key cryptography establishes secure channels, the bulk of data protection relies on the more bandwidth- and compute-efficient AES, ensuring security does not become a performance bottleneck in 2G/3G network conditions.

External APIs:

To improve the functionality and performance, EAS extends the functionality of this product by incorporating some external APIs and libraries. Axios implements HTTP communication; JWT and Bcrypt authenticate and store passwords. Nodemailer allows sending email counts and OTP validation, Multer just responds to file upload and storing of study materials and profile images on Google Cloud storage. Unique identifiers are assigned to uploaded files, and APIs are used to monitor response times, helping prevent system failures through tools like UUID. MongoDB, in combination with Express, manages database operations and data modeling.

All these integrations are intended to provide secure authentication, powerful content management, efficient communication, and efficient storage. This combined deployment makes EAS an economical and scalable LMS that can deliver quality online education even when the bandwidth is limited.

Technical Implementation Specifications:

The EAS platform is a full-stack web application built on the MERN (MongoDB, Express.js, React, Node.js) stack, selected for its scalability, efficiency, and compatibility with JSON-driven APIs. This foundation ensures low-latency performance and minimal data overhead in low-bandwidth environments.

System Architecture & Stack:

EAS follows a client-server layered architecture. The frontend, developed in React.js, delivers a lightweight single-page application (SPA) with lazy loading, minimal JavaScript, and text-optimized design for fast rendering on low-end devices. The backend, using Node.js and Express.js, handles business logic including authentication, role-based access control, API routing, and session management, leveraging a non-blocking I/O model for efficient concurrency. MongoDB serves as the database, storing user profiles, course materials, quizzes, and forum data, while cloud deployment with CDN ensures fast content delivery globally.

Database Schema & Modeling:

Data is managed via Mongoose ODM. Key schemas include: User: name, email, hashed password, role, class, profile metadata. Course/Material: title, subject, class, file URL, upload date. Exam & Question: exam metadata and embedded questions with automatic grading support. Forum: structured questions and posts for lightweight discussions. Report: links user performance to exams with Pass/Fail verdicts.

Core Algorithms & API:

Authentication uses JWTs, generating tokens on login and validating them via middleware. Exam management handles creation, presentation, auto-grading, and result

calculation. RESTful API endpoints include /api/auth/*, /api/exams/*, /api/materials/*, /api/forum/*, and /api/reports/*. Unified middleware manages errors and ensures consistent JSON responses under unstable network conditions.

External Libraries & Tools:

Axios handles HTTP requests, Bcrypt.js secures passwords, Nodemailer sends OTPs, and Multer with Google Cloud Storage manages file uploads with UUID-based identifiers. Performance testing under simulated low-bandwidth conditions (2G/3G) validated system responsiveness.

Results and Discussion:

Phase IV: Results Evaluation and Analysis:

The final step involves testing, validating, and evaluating the system's performance. To enhance usability, attention is given to user interface design and overall accessibility. Both manual and automated methods are employed to assess the system's reliability and accuracy. The final stage involves analyzing the results through User Acceptance Testing (UAT), during which end-users provide feedback on usability and overall effectiveness. Based on this feedback, improvements are implemented to ensure that the project objectives are fully achieved.

User Interface Design and Accessibility:

The EAS Learning Management System (LMS) features a minimalist, highly usable interface to help rural students in low-bandwidth regions (100-500 kbps) in Pakistan. Constructed on React, Node.js, Express.js, and MongoDB, the platform is integrated with the necessary features in user authentication, exam management, forums and study materials, video lectures, reporting, ranking, management profile, and content search. The interface is designed with low-end devices in mind, using a standardized deep blue and white theme throughout all the modules so that the interface remains easy to use, quick to load, and consumes minimal data.

The registration process starts with a clean sign-up form that gives the essential information and details required, such as name, school, class, email, and password, with a bold register button and navigation link displayed on the top part for existing users. After registration, the OTP verification screen provided a secure authentication screen and only one input field with a simple submit button, and the lightweight design ensured the connection was fast even under a low bandwidth environment. Once verified, the sign-in interface returned feedback immediately by displaying a confirming notification before displaying the login form again to allow further access. There were navigation links that directed users to switch intermittently between registrations and login.

After registration, the OTP verification screen provided a secure authentication interface with only one input field and a simple submit button, and the lightweight design ensured the connection was fast even in low-bandwidth environments. Once verified, the sign-in interface returned feedback immediately by displaying a confirmation notification before showing the login form again to allow further access. There were navigation links that directed users to switch intermittently between registration and login.

Student Quiz Experience and Interface Design:

EAS-LMS is a simplified and low-bandwidth interface through which students can easily access quizzes and complete their questions. The customized Quiz Dashboard equation with the user has a deep blue title containing the name and position of the user, a good message, and a search pack that allows the user to view the page with ease. Cards containing the basic information about unlocking the quiz, like the subject, the class, total marks, passing marks, and time, are shown on a dashboard with a button to start the exam. A bar provides fast access to the key functions, such as Quiz, Reports, Ranking, Study Material, forum, Profile, and Logout, thus providing a simple user aids with limited

information consumption.

Students are shown a clear screen with Exam Instructions before beginning a quiz to explain time constraints, automatic submission, page navigation, and avoiding page refresh. Action buttons to start or exit the quiz add more clarity and less confusion. When doing the quiz, the questions are presented as multiple choices in distinct boxes that have a countdown timer and a Next button to ensure ease of continuity.

On completion, the Result screen gives feedback in real time on the performance statistics: marks total and obtained, wrong marks, and an indication of clear pass fail outcome. There are action buttons on the Retake Exam/ Review Answers to facilitate learning. Its clean and minimalistic design allows it to load quickly and interact directly, which makes quizzes useful and convenient even when working in a low-bandwidth environment.

User Progress, Resources, and Interaction Interfaces:

The learning interfaces provided within the EAS-LMS supplement the tracking of progress and social engagement, optimized to operate in low-bandwidth settings. The reports interface will give specific information concerning performance in quizzes and will put results in a table with subject, total marks, passing marks, obtained marks, and verdict, as shown in Table 1.

Students are able to pick strengths and weaknesses fast (e.g., comparing between quizzes) and improve on them. On the same note, the Ranking interface shows a list of student positions in a straightforward tabular format and indicates rank, name, class, and marks. This functionality builds healthy competition and is easy to carry, lightweight, and loads quickly.

Table 1. Student Quiz Performance Reports in EAS-LMS

Exam Name	Date	Total Marks	Passing Marks	Obtained Marks	Verdict
chap1 Science	17-05-2025 06:11:17	30	20	2	Fail
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

The Study Material interface helps navigate education sources and provides subjects and classes where it is possible to see or download materials. Video lectures are designed in the grid format with a few thumbnails and Watch Now buttons, which enable the students to deal with the content without using a lot of data. The Profile interface also explicitly displays your or his/her user information, including name, email address, class, school, and position, and provides features that allow you to edit your or his/her user information, as well as change the passwords to allow you to manage your profile uniquely.

Lastly, the Forum interface also promotes some kind of cooperation, displaying discussion threads in terms of topic, author, date, and reply. Students will be able to observe a conversation or ask a new question, which leads to an interactive learning process. With all these interfaces, it will be made usable and easy to start, besides making it just for people

who have less bandwidth connections; rural people will experience the entire LMS world.

Testing and Evaluation:

In this section, this paper will discuss the testing and evaluation procedures to verify the robustness, functionality, and usability of the EAS Learning Management System (LMS). To find possible bugs and performance problems, to validate the core functionality, and to test user experience, both automated and manual testing are applied.

Manual Testing:

Manual testing was conducted through the verification of the system by directly operating the features of the system. Tests to compare the actual result with the expected result were done on user registration and log-in, quiz development, forum entries, and upload of the study material to the site. The outcome proved the creation of accounts successfully, their authentication, management of exams, discussions on forums, and management of content. System testing involved further testing of the LMS as a complete system, as per functionality, performance, reliability, and security, with all system components operating in a unified manner. Unit testing also looked at all the individual modules, including login, quizzes, study materials, and search functions, and ensured that each unit was functioning as expected. It was functionally tested on the user authentication process, exam management process, and content management process, with a high pass rate to the subject matter, and a high rate of implementation. Integration testing confirmed the cooperative behavior between the frontend, backend, APIs, and the database and ensured that various system components worked together appropriately.

As end users, 50 undergraduate students and 10 administrative users (instructors/LMS administrators), a pilot study was conducted on the Education Access System (EAS). The subjects were chosen in order to represent users with limited bandwidth and resource-restricted settings, which are in line with the study objectives. Students tested the fundamental learning capabilities, and administrators tested such system management capabilities as content upload and user management. The size of this sample is in line with other previous LMS usability and educational technology research, in which 25-45 people are believed to be enough to conduct pilot-scale research. Specific information has now been included in the methodology section.

Automated Testing:

Automated testing was conducted via special tools in order to model conditions in the network, audit the frontend, and ensure that the system is reliable when subjected to a limited network connection. Lighthouse, Clumsy, and simulated network throttling tools were used to confirm that the LMS could maintain functionality and be responsive without a lot of human involvement.

Analysis and Discussion of UAT Results:

Analysis of UAT Results:

User Acceptance Testing (UAT) findings, as explained in Table 2 offers valuable data that can inform the audience of the performance, usability, and educational efficiency of the EAS-LMS. The optimal results of the login functionality and the accuracy of the results of the quiz (100% accuracy, F1 score 100) demonstrate that the essential authentication and evaluation tools within the system are as reliable as possible. These findings bring to light the fact that students have been able to use the platform and pass the tests without any technical problems at all, which will be incredibly important in low-bandwidth settings when connectivity limitations can be an issue.

Table 2. User Acceptance Testing (UAT) Performance Metrics for Core LMS Functionalities

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

The result of quiz functionality (91.7-95.8%), learning impact (91.7-95.8%), and recommendation likelihood (91.7-95.8%) indicates that the LMS is actively involved in the educational process, interacts with students, and projects the images to the users as shown in Figure 7. This proves that, as well as this platform works correctly, it also positively impacts the learning experiences of students and proves to be education-wise valuable, which speaks of its classroom usage.

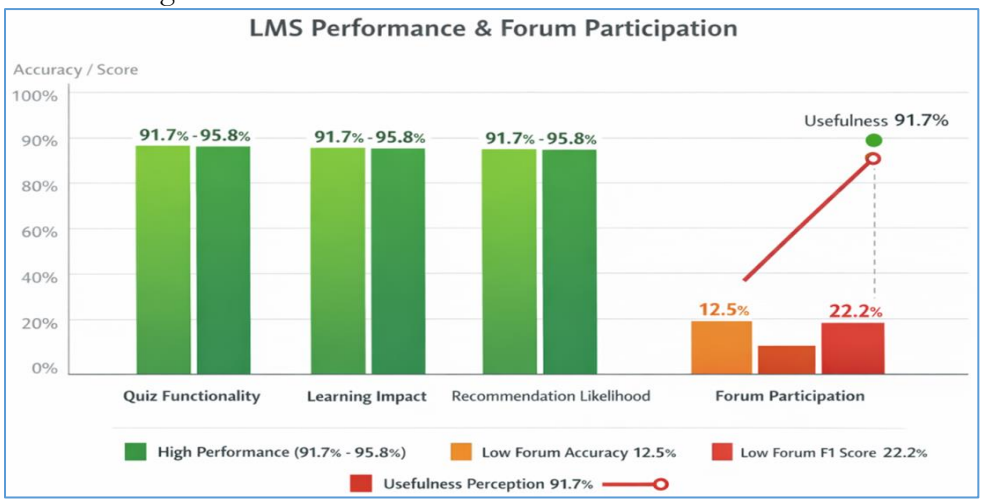

Figure 7. LMS performance metrics versus low collaborative engagement in low-bandwidth conditions

On the other hand, the low level of participation in forum posting (12.5% accuracy and F1 score of 0.222) suggests that participation in collaborative features was very low. Although users only found the forum to be beneficial (91.7% F1 score), the majority of the students did not engage in the Q&A activity, which could be related to a lack of familiarity with the feature, a lack of motivation, or inadequate instructions, as shown in Figure 7. This indicates an improvement opportunity, like improved onboarding, promptness, encouragement to interact with the forums, or other forms of incentive to optimize collaborative learning.

Comprehensively, the UAT outcomes indicate solid performance and significant learning impact of the LMS, as well as pinpoint particular elements, including the level of forum participation, where specific improvements might further enhance engagement with the system and learner adoption. The results can both affirm the performance effectiveness of the system and also direct its further development in new guises towards greater and wider application.

Discussion and Comparison with Existing Studies:

The EAS-LMS findings are consistent with and build upon current studies of the issue of low-bandwidth learning. The effectiveness in quiz functionality (95.8%) and the reported learning impact (91.7%) are supported by the results that well-optimized, mobile-centric LMS platforms can produce positive learning outcomes of more than 90% even in the context of limited connectivity, such as in studies of gamified mobile LMS [2] and mobile learning in remote locations [16].

Nevertheless, there is a significant difference in teamwork. Though forums are usually employed and appreciated in conventional LMS research studies [11][12], there was very little active engagement (12.5%) in the EAS against high perceived usefulness (91.7%). It implies that, within resource-constrained and low-bandwidth settings (which are frequently coupled with reduced digital familiarity), the impediments to collaborative features adoption are more socio-pedagogical than technical. This finding underscores the complex nature of the digital divide, where access and functionality do not automatically translate into all forms of digital participation [4][28].

Technically, the fact that the system was able to perform stably under simulated 2G/3G conditions justifies well-known optimization techniques, like lazy loading, lightweight interfaces, and adaptive streaming [23][24][34] which are shown to be effective in a completely integrated, real-world system. Therefore, EAS is both an affirmation of the current technical advice and a case study that demonstrates the subtle behavioral issues concerning the realization of holistic digital inclusion to quality education (SDG 4).

Conclusion and Future Work:

The research was conducted after it was realized that a majority of the Learning Management Systems (LMS) currently in use possess weaknesses that result in failure to sustain low-bandwidth engineered environments, where the majority of the conventional systems would not have been able to provide identical chances in digital learning. All of this was done to design and test EAS, an optimized LMS that could operate under limited connectivity conditions but had to remain accessible, usable, and scalable. The experimental results prove that EAS is useful in supporting the basic functions of the LMS, such as quizzes, forums, access to the study material, and video streaming, and does not exceed 2G/3G performance. Pre-testing of less than one-second latency was confirmed in simulated low-bandwidth conditions, and User Acceptance Testing indicated a high level of satisfaction, 95.8 percent of students rated the quiz-based module effective, and 91.7 percent of students said their learning results were improved. These results indicate EAS is useful and sustainable as a data-cost-reduction device to bridge the digital divide, particularly in underserved regions, and provide an indicator that quality education can be delivered efficiently and inclusively in digital formats to address the needs of SDG 4 of the United Nations on quality education. Practical studies with only 24 students and the limited capacity of multimedia support forced to lightweight video streaming are also limiting the study. Further development must also take into account larger and more varied populations, along with more test runs, adaptive learning analytics, and be able to work offline-first when connectivity is unavailable in all regions. Multimedia delivery can also be further optimized to increase system versatility. Finally, EAS provides evidence that democratic digital learning, including in a hotspot-limited environment, is possible, and provides an example of such a framework that is resource-efficient, user-centered, and replicable, thus helping to mitigate educational inequality and establish a baseline on which inclusive digital education innovation can be enhanced in the future.

References:

[1] W. N. Jean Baptiste Mushimiyimana, "ICT Integration in Rwandan Education: A Scoping Review of Opportunities and Challenges," *African J. Empir. Res.*, vol. 6, no. 1, 2025, [Online]. Available: https://ajernet.net/ojs/index.php/ajernet/article/view/956

[2] H. A. E.-S. & D. M. E. Hosnia M. M. Ahmed, "Effect of Gamified, Mobile, Cloud-Based Learning Management System (GMCLMS) on student engagement and achievement," *Int. J. Educ. Technol. High. Educ.*, vol. 22, no. 49, 20251, doi: https://doi.org/10.1186/s41239-025-00541-1.

[3] A. A. A. Taha Abuali, "Challenges and Opportunities in Implementing E-Learning in

Developing Countries," *Open Eur. J. Soc. Sci. Educ.*, vol. 1, no. 1, 20251, [Online]. Available: https://easdjournals.com/index.php/oejsse/article/view/2

[4] Y. Assefa, M. M. Gebremeskel, B. T. Moges, S. A. Tilwani, and Y. A. Azmera, "Rethinking the digital divide and associated educational in(equity) in higher education in the context of developing countries: the social justice perspective," *Int. J. Inf. Learn. Technol.*, vol. 42, no. 1, pp. 15–32, Jan. 2025, doi: 10.1108/IJILT-03-2024-0058.

[5] D. Gh.a., montazer b., "Evaluating E-Learning Readiness In The Iranian Universities," vol. 4, no. 3, pp. 181–190, Jan. 2010, Accessed: Dec. 24, 2025. [Online]. Available: https://sid.ir/paper/155498/en

[6] "E-Readiness Assessment Model for Low Bandwidth Environment | Download Scientific Diagram." Accessed: Dec. 24, 2025. [Online]. Available: https://www.researchgate.net/figure/E-Readiness-Assessment-Model-for-Low-Bandwidth-Environment_fig1_280935086

[7] "New technologies for teaching and learning: challenges for higher learning institutions in developing countries. IN: Mukherjee, D. (ed) Information and Communication Technology: Changing Education." Accessed: Dec. 24, 2025. [Online]. Available: https://www.researchgate.net/publication/225188696_New_technologies_for_teaching_and_learning_challenges_for_higher_learning_institutions_in_developing_countries_IN_Mukherjee_D_ed_Information_and_Communication_Technology_Changing_Education

[8] R. Boateng *et al.*, "Advancing E-Commerce Beyond Readiness in a Developing Country: Experiences of Ghanaian Firms," *https://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/978-1-4666-3622-4.ch001*, pp. 1–17, Jan. 1AD, doi: 10.4018/978-1-4666-3622-4.CH001.

[9] M. B. K. Sameer Qazi, "AI-Driven Learning Management Systems: Modern Developments, Challenges and Future Trends during the Age of ChatGPT," *Comput. Mater. Contin.*, vol. 80, no. 2, pp. 3289–3314, 2024, doi: https://doi.org/10.32604/cmc.2024.048893.

[10] N. K. Sanobar Shadmanova, "Ensuring the Security of an Internet-based E-learning System through the Use of Integrated Encryption Methods," *J. Internet Serv. Inf. Secur.*, 2024, [Online]. Available: https://jisis.org/wp-content/uploads/2024/12/2024.I4.024.pdf

[11] "Optimizing Interactive Learning Management System (LMS) in Improving Students' English Language Skills | Zabags International Journal of Education." Accessed: Dec. 24, 2025. [Online]. Available: https://e.journal.zabagsqupublish.com/zijed/index.php/zijed/article/view/21

[12] T. T. Sulaiman, "A systematic review on factors influencing learning management system usage in Arab gulf countries," *Educ. Inf. Technol. 2023 292*, vol. 29, no. 2, pp. 2503–2521, Jun. 2023, doi: 10.1007/S10639-023-11936-W.

[13] S. Dhepe, P. Gebise, D. Lothe, and S. Pawar, "A Real-Time Monitoring System for User Attentivity on e-learning platforms," *Proc. - 2025 5th Int. Conf. Expert Clouds Appl. ICOECA 2025*, pp. 843–851, 2025, doi: 10.1109/ICOECA66273.2025.00149.

[14] A. D. Samuel-Okon and O. Abejide, "Bridging the Digital Divide: Exploring the Role of Artificial Intelligence and Automation in Enhancing Connectivity in Developing Nations," *SSRN Electron. J.*, May 2024, doi: 10.2139/SSRN.4839447.

[15] M. W. R. Anaile Rabelo, "Educational data mining and learning analytics: a review of educational management in e-learning," *Inf. Discov. Deliv.*, vol. 52, no. 2, pp. 149–163., 2024, doi: https://doi.org/10.1108/IDD-10-2022-0099.

[16] A. R. Liza Husnita, "The Role of Mobile Technology in Improving Accessibility and Quality of Learning," *al-fikrah J. Manaj. Pendidik.*, vol. 11, no. 2, p. 259, 20231, doi: 10.31958/jaf.v11i2.10548.

[17] K. A. Kadir, N. H. A. Wahab, M. S. Sunar, and S. Z. Harun, "Enhancing Virtual Reality Education with Low-Bandwidth 360-Degree Video," *2024 20th IEEE Int. Colloq. Signal Process. Its Appl. CSPA 2024 - Conf. Proc.*, pp. 260–263, 2024, doi: 10.1109/CSPA60979.2024.10525516.

[18] G. M. Sadia Jamil, "The COVID-19 Pandemic and E-Learning: The Digital Divide and Educational Crises in Pakistan's Universities," *Am. Behav. Sci.*, vol. 68, no. 9, p. 00027642231156779, 2023, doi: 10.1177/00027642231156779.

[19] N. D. D. Carlos David Barranco González, "Optimizing Education with Data Analytics: A Feature Comparison of LMS and SIS," *Preprints*, 2024, [Online]. Available: https://www.preprints.org/manuscript/202405.0459

[20] H. L. Jianfa Guo, "Optimization and Management of Communication Technology in Smart Education Environments," *J. Educ. Humanit. Soc. Res.*, vol. 2, no. 2, 2025, [Online]. Available: https://www.gbspress.com/index.php/JEHSR/article/view/221

[21] M. F. Sedef Sezgin, "Exploring the Digital Divide in Open Education: A Comparative Analysis of Undergraduate Students," *Int. Rev. Res. Open Distrib. Learn.*, vol. 25, no. 1, 2024, [Online]. Available: https://www.irrodl.org/index.php/irrodl/article/view/7236

[22] A. Huma, "The Digital Divide: A case of Distance Education in Pakistan," *Int. J. Distance Educ. E-Learning*, vol. 9, no. 2, pp. 57–68, Jun. 2024, doi: 10.36261/IJDEEL.V9I2.3347.

[23] H. S. Abayomi Agbeyangi, "Advances and Challenges in Low-Resource-Environment Software Systems: A Survey," *Informatics*, vol. 11, no. 4, p. 90, 2024, doi: https://doi.org/10.3390/informatics11040090.

[24] A. Turcotte, S. Gokhale, and F. Tip, "Increasing the Responsiveness of Web Applications by Introducing Lazy Loading," *Proc. - 2023 38th IEEE/ACM Int. Conf. Autom. Softw. Eng. ASE 2023*, pp. 459–470, 2023, doi: 10.1109/ASE56229.2023.00192.

[25] M. F. Dedi Kuswandi, "Implementation of personalized approach in video editing learning to improve digital competency of 21st century learners," *Cahaya Pendidik.*, vol. 11, no. 1, 2025, [Online]. Available: https://www.journal.unrika.ac.id/index.php/journalcahayapendidikan/article/view/7482

[26] W. P. da C. Elaine Santana Silva, "Contribution of Microlearning in Basic Education: A Systematic Review," *Educ. Sci*, vol. 15, no. 3, p. 302, 2025, doi: https://doi.org/10.3390/educsci15030302.

[27] N. Adel, "The impact of digital literacy and technology adoption on financial inclusion in Africa, Asia, and Latin America," *Heliyon*, vol. 10, no. 24, 2024, [Online]. Available: https://www.cell.com/heliyon/fulltext/S2405-8440(24)16982-4?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2405844024169824%3Fshowall%3Dtrue

[28] I. O. A. Viktoriia V. Sydorenko, "Improvement of higher education: how to bridge the digital divide during the transformation?," *J. Educ. Learn.*, vol. 18, no. 3, 2024, [Online]. Available: https://edulearn.intelektual.org/index.php/EduLearn/article/view/21078

[29] B. A. V. Kathiravan Ravichandran, "Moving towards a Blended Tomorrow: The Evolution of EdTech in Education," *Libr. Prog. Int.*, vol. 44, no. 3, 2024, doi: https://doi.org/10.48165/bapas.2024.44.2.1.

[30] K. M. Siyabonga Mhlongo, "Challenges, opportunities, and prospects of adopting and using smart digital technologies in learning environments: An iterative review," *Heliyon*, vol. 9, no. 6, p. e16348, 2023, [Online]. Available: https://www.cell.com/heliyon/fulltext/S2405-8440(23)03555-7?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2405844023035557%3Fshowall%3Dtrue

[31] S. Z. Raja Bahar Khan Soomro, "Assessing Teacher Training Quality and Student Learning Outcomes in North Sindh Secondary Schools: A Case Study," *Res. Sq.*, vol. 4, 2025, [Online]. Available: https://www.researchsquare.com/article/rs-6487278/v1

[32] J. S. & R. H. Usama Kalim, Asha Kanwar, "Barriers to AI adoption for women in higher education: a systematic review of the Asian context," *Smart Learn. Environ.*, vol. 12, no. 38, 2025, doi: https://doi.org/10.1186/s40561-025-00390-5.

[33] A. G. De Siqueira, "Toward New Ecologies of Cyberphysical Representational Forms, Scales, and Interaction Modalities," *TEI 2019 - Proc. 13th Int. Conf. Tangible, Embed. Embodied Interact.*, 2019, [Online]. Available: https://dl.acm.org/doi/10.1145/3294109.3302960

[34] H. Schwarz, D. Marpe, and T. Wiegand, "Overview of the scalable video coding extension of the H.264/AVC standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 17, no. 9, pp. 1103–1120, Sep. 2007, doi: 10.1109/TCSVT.2007.905532.

[35] I. Sodagar, "The MPEG-dash standard for multimedia streaming over the internet," *IEEE Multimed.*, vol. 18, no. 4, pp. 62–67, Oct. 2011, doi: 10.1109/MMUL.2011.71.

[36] G. J. Conklin, G. S. Greenbaum, K. O. Lillevold, A. F. Lippman, and Y. A. Reznik, "Video coding for streaming media delivery on the internet," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 11, no. 3, pp. 269–281, Mar. 2001, doi: 10.1109/76.911155.

[37] Thyagharajan K K, Vadivelan Ramachandran, "Performance Analysis of Media Transmission through Low Bandwidth Networks," *Natl. Conf. Signal Process. Intell. Syst. Netw.*, 2003, [Online]. Available: https://www.researchgate.net/publication/280383861_Performance_Analysis_of_Media_Transmission_through_Low_Bandwidth_Networks

[38] A. F. Lim, K. B. Ooi, G. W. H. Tan, T. H. Cham, M. A. A. Alryalat, and Y. K. Dwivedi, "Adapt or die: a competitive digital supply chain quality management strategy," *J. Enterp. Inf. Manag.*, vol. 37, no. 2, pp. 698–720, Apr. 2024, doi: 10.1108/JEIM-09-2022-0345.