ISSN: 2093-5374 / E-ISSN: 2093-5382

Low Bandwidth Wireless Mesh Networks for Rural Education With Cognitive Load Reduction and Persistence Gains

Durdona Lutfullayeva[1*], Bakhtijon Isroilova[2], Avazbek Tulyaev[3], Kamola Haydarova[4], Xulkar Xolikulova[5], Ozod Azimov[6], Komiljon Gulyamov[7], and Surayyo Khaydarova[8]

[1*]Professor, International Islamic Academy of Uzbekistan, Tashkent, Uzbekistan. 1965dd@mail.ru, https://orcid.org/0000-0002-8598-8745

[2]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, National Research University, Tashkent, Uzbekistan. isroilovabaxtijon@gmail.com, https://orcid.org/0000-0002-0285-964X

[3]Associate Professor, University of Uzbekistan named after Mirzo Ulugbek, Uzbekistan. avazbektulyayev@gmail.com, http://orcid.org/0009-0002-1606-2874

[4]Associate Professor, Termez State University, Termez, Uzbekistan. kamolahaydarova6235@gmail.com, https://orcid.org/0009-0008-0700-1854

[5]Associate Professor, Law Enforcement Academy of the Republic of Uzbekistan, Tashkent, Uzbekistan. xalikulova81@mail.ru, https://orcid.org/0009-0005-1111-2109

[6]Urgut Branch of Samarkand State University, Samarkand, Uzbekistan. ozodazimov196@gmail.com, https://orcid.org/0009-0001-6274-7869

[7]Associate Professor, National Institute of Fine Arts and Design named after Kamoliddin Bekhzod, Uzbekistan. k.gulyamov68@yandex.com, https://orcid.org/0009-0002-2556-258X

[8]Jizzakh State Pedagogical University, Jizzakh, Uzbekistan. surayyo.uz@mail.ru, https://orcid.org/0000-0003-4879-4623

Received: August 25, 2025; Revised: October 07, 2025; Accepted: November 10, 2025; Published: December 15, 2025

Abstract

This investigation examines the capacity of low-bandwidth wireless mesh networks to mitigate educational disparities in rural environments by reducing cognitive load and promoting durable content retention. Intermittent and fragmented connectivity across remote educational zones impedes sustained access to audiovisual and interactive resources, thereby widening the achievement gap relative to urban peer groups. The present initiative advances a modular mesh-network infrastructure specifically calibrated for constrained capital and operating budgets, permitting incremental scaling while embedding redundancy within and among rural primary and secondary campuses. Utilizing adaptive routing algorithms, the fabric assembles a dynamic, self-correcting lattice that provides persistent, standards-aligned resource delivery, overcoming the weaknesses of conventional backbone and satellite deployment modalities. The primary innovation of our design lies in the integration of cognitive-load-sensitive mechanisms across the entire network topology. A salient embodiment of this is our anticipatory dynamic content caching algorithm, which assimilates historical and contextual tensor information in order to project future curricular

*Corresponding author: Professor, International Islamic Academy of Uzbekistan, Tashkent, Uzbekistan.

needs. Educational artifacts are thus instantly retrievable, thus avoiding the intrinsic fatigue associated with wait times, an effect magnified when operating over intermittent, low-bandwidth links. In parallel, our link-aware routing protocol dynamically reoptimizes data trajectories in real time, using continuous telemetry of link health measurements. By diverging packets away from localized loss zones or congestion, the protocol stabilizes aggregate throughput and compresses jitter. The synergistic effect of these two layers equips learners with a stable, high-definition pedagogical sequence, effectively decoupling instructional advancement from the unpredictable fluctuations of the underlying network infrastructure.

Keywords: Wireless Mesh Networks (Wbwmns) Are Being Utilized in Rural Education for Low Bandwidth, Cognitive Load Reduction, Persistence Gains, Adaptive Content Delivery, Network Performance, And Scalable Connectivity. Technology, Rural Development.

1 Introduction

Unfortunately, rural education faces poor quality learning facilities, digital learning, and high marginal costs. Moving to digital teaching is more inequitable to the rural and remote communities. A persuasive engineering approach to this problem is the deployment of custom, low-cost, and low-power wireless broadband and Internet-capable wireless mesh networks (WBWMN). Internet costs are kept low, and the community remote network mesh as described in (Marhoon et al., 2025; Akyildiz et al., 2005) is battery-powered and user self-relaying. Central switching or heavy modular interactive and responsive control networks are self-managed and permit incremental, user-driven mesh sensor and educational resource deployment as remote slaves to battery-powered WBWMN nodes. Still, the educational impacts of connectivity must be resolved, and the burdens of network-reliant digital simulations and interfaces on cognitive processing must be addressed. Cognitive load and digital cognitive interfaces must be addressed to drive educational attainment for remote communities (Alicherry et al., 2005). Cognition requires the effort of learning, processing, and encoding information, and poorly configured interfaces, as described above, must be attended to, or detrimental cognitive processing thresholds will be reached. By synchronizing instructional media with individual pacing and by leveraging the continuous connectivity that mesh relays afford, WBWMNs can attenuate extraneous load, sustain intrinsic motivation, and enhance durable knowledge retention. This study presents an integrated framework that concurrently leverages self-configuring mesh networks, adaptive cognitive load modulation, and persistent low-latency access, aiming to elevate pedagogical outcomes across remote and dispersed rural settings (Dake & Adjei, 2019; Giji Kiruba et al., 2023).

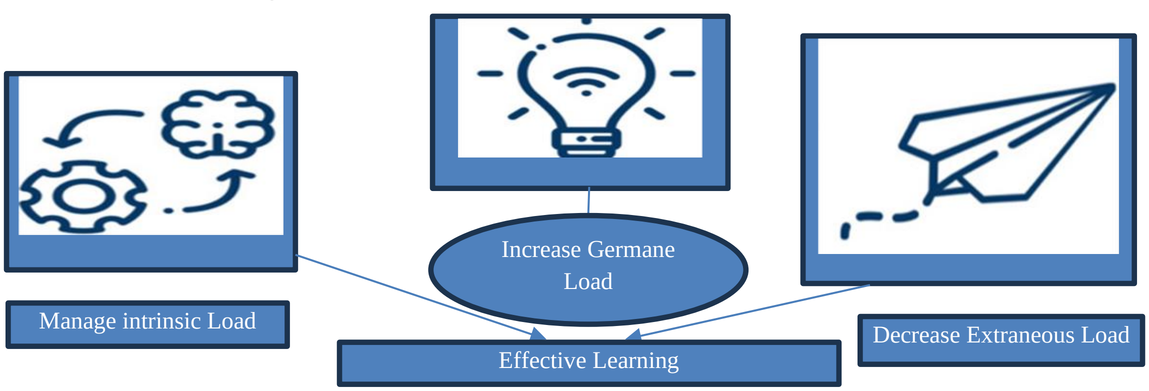

Figure 1: Understanding cognitive load theory: optimizing learning for student success

Figure 1 illustrates that the Cognitive Load Theory, first articulated by Sweller, emphasizes the restricted capacity of working memory during the learning process and posits that the organization of the educational milieu primarily determines the efficacy of encoding and subsequent retrieval of information. The framework distinguishes between three categories of cognitive load: intrinsic, extraneous, and germane. Intrinsic load represents the fundamental difficulty of the material itself; as learners achieve greater mastery, the progressively intricate interrelations between cognitive components increase in number, thereby elevating the load on cognitive resources. Extraneous load, in contrast, emanates from the instructional design choices such as non-optimal sequencing, superfluous information, or visually distracting elements that siphon cognitive capacity away from the intended learning outcomes. A well-conceived curriculum reduces extraneous load by structuring material in a coherent, streamlined manner, by segmenting intrinsic complexity into ordered, interconnected units, and by steering learners toward advantageous activities such as self-explanation and contextualized practice. When these three load modalities are in equilibrium, the limited resources of working memory are directed preferentially toward the core constructs of the discipline, thereby fostering retention and transfer while counteracting the adverse consequences of cognitive overload.

2 Literature Review

With a distributed architecture comes low-cost, hop-by-hop data forwarding, minimizing reliance on backbone infrastructure, while advancing through low-density, hard-to-reach areas. Modern low-power wide-area radio technology, such as LoRa and NB-IoT, alongside legacy mesh protocols, enables far-reaching and energy-efficient links and increases payload capacity for rural sensor and IoT applications. At the network layer, new routing protocols incorporate real-time measurements of link metrics and overall energy levels within the network, enabling dynamic routing to mitigate the formation of bottlenecks in shared-use community communications. These advancements make wireless mesh networks economically and socially scalable, and provide the necessary infrastructure for high-capacity broadband and data services to rural communities that have traditionally been denied such services. More significantly, the backbone of these networks furthers the universal objective of broadband and digital inclusion across disparate socio-economic groups. These edge systems reduce dependence on expensive core routers and backhaul links, thus allowing network deployment in economically unviable areas. This is a notable advantage over legacy wired solutions. The resulting topology integrates unobtrusively to the agrarian landscape, uniformly blanketing large expanses of radio coverage and relieving operators of the expensive task of trenching for new cables.

In our rural implementations, we typically pair inexpensive consumer routers with rugged, budget-friendly access units, thus fabricating a resilient lattice that deploys in harmony with existing hedgerows (Ibragimova et al., 2024). This strategy trims both capital outlay and recurrent operational expenditures, supporting incremental expansion that advances one cost-justified phase at a time without inflicting financial strain on the household budget. Small farmers, once alone at the edge, now get soil reports from rice universities while the nearest health worker can, almost in real time, confirm the dosage for a child with diarrhea. In the Andean highlands of South America, mesh nodes placed on the rooftops of adobe homes relay signals in cascades, thus stretching the reach of a single solar-powered base station. Because each new node automatically strengthens and broadens the coverage area, mesh networks can support extensive geographic footprints without the linear scaling costs that fiber would impose. This characteristic makes them particularly suited for rural regions, where population density seldom justifies the capital expense of point-to-point or integrated services digital network (ISDN) links (Akyildiz et al., 2006).

3 Methodology

3.1 Cognitive Load Theory and Its Relevance to Digital Education

Cognitive load theory (CLT), originally proposed by John Sweller in the 1980s, proposes that the human mind has a finite capacity for processing information. Learning is optimized when the mental effort required by cognitive load is kept within manageable bounds (Bicket et al., 2005). Cognitive load theory (CLT) categorizes cognitive load into three types: intrinsic load (which comes from the level of difficulty of the material itself), extraneous load (which is related to the actual format of presentation of information), and germane load, which involves the constructive effort related to being able to meaningfully construct knowledge. When intrinsic load or extraneous load becomes excessive in digital education, the progression of learning may become hindered, especially when facing complex tasks or if learning is not designed well (Karimizadeha & Abolghasemib, 2016). For example, educational interventions that present adaptive learning environments that adapt material and pacing according to readiness can organize information better and move learners from unwanted extraneous load to germane load in their learning. It is important to lessen cognitive load to create greater understanding, better retention, and to be able to use knowledge in context - particularly when higher quality learning opportunities are limited (Anantharaman et al., 2004; Aoki, 2005).

3.2 Previous Efforts in Reducing Cognitive Load Through Technology in Education

Reducing cognitive load, or the amount of mental effort required to learn, is a place where educational technology has focused attention for a very long time, using numerous aspirational approaches to enhance learning. Heavy cognitive loads can be reduced using adaptive learning systems that personalize the content and speed of learning according to the individual's prior knowledge and progress. Adaptive learning systems personalize content based on prior knowledge, adjusting the difficulty or presentation of educational material, thus resulting in a reduction in extraneous cognitive load and allowing students to access materials at levels more appropriate to their skills and abilities. Educational technology uses various methods and applications of multimedia learning to present information in a wide variety of ways, including visual, auditory, and interactive methods to engage learners using different modalities when presenting information (Bruno et al., 2005). Multimedia learning reduces intrinsic cognitive load by allowing complex ideas to be presented in more accessible formats, giving students better access to materials to construct their understanding. Interactive simulations and educational games are being used in a variety of ways on many digital education platforms to create engaging learning experiences to promote active learning while managing cognitive load in students. In rural education settings, the implementation of technology is critical to ensure that learners with limited pre-exposure to digital tools and technology have the opportunity to engage with simplified, engaging, and adaptive content.

Total Cognitive Load (TCL):

$$TCL(t) = IL(t) + EL(t) + GL(t)$$

Where:

IL(t) = Intrinsic Load at time t (depends on task difficulty)

EL(t)=Extraneous Load at time t (depends on instructional design/presentation)

GL(t)=Germane Load at time t (depends on constructive learning effort)

Adaptive Load Management Equation:

$$C_{Lad_j}(t) = \alpha \cdot IL(t) + \beta . EL(t) - \gamma . GL(t)$$

Where:

$$\alpha, \beta_, \gamma \ = \ \gamma = weighting\ factors\ (system - calibrated)$$

$CL_{ad_j(t)} = adjusted\ cognitive\ load\ through\ adaptive\ learning\ (lowered\ extraneous, optimized\ germane)$

The Total Cognitive Load (TCL) equation describes the mental effort a learner experiences at any moment. It is composed of Intrinsic Load (IL), the inherent difficulty of the learning task; Extraneous Load (EL), the manner in which information is presented; and Germane Load (GL), the learner's constructive efforts toward meaningful knowledge. Such a connection elucidates how various components of the learning process affect the overall cognitive demand.

Algorithm:

```
BEGIN
  Initialize student profile with prior knowledge and skills
  For each learning session t:
      Measure IL(t) based on task difficulty
      Measure EL(t) based on format and instructional design
      Measure GL(t) based on engagement and constructive effort
      Compute TCL(t) = IL(t) + EL(t) + GL(t)
      IF TCL(t) > threshold:
          Adjust learning environment:
              - Simplify content format (reduce EL)
              - Provide adaptive pacing
              - Offer multimedia or simulations
      END IF
      Update CL_adj(t) = α*IL(t) + β*EL(t) - γ*GL(t)
      Update performance LP(t) = GL(t) / (IL(t) + EL(t))
  END FOR
END
```

It starts with a learner profile and assesses intrinsic, extraneous, and germane load in each session. These values are summed to determine total cognitive load. Once a limit is exceeded, the algorithm is designed to lower the content complexity, change the speed of delivery, and integrate other forms of media to reduce cognitive overload. The algorithm repeatedly adjusts cognitive load in relation to the learning performance score to maintain deep constructive engagement, cognitive effort, and positive interest.

4 System Design and Architecture

4.1 A Comprehensive Overview of Wireless Mesh Network Architecture

The architecture of the wireless mesh network facilitates reliable, inexpensive, and scalable connectivity in large rural areas. The mesh network consists of one or more mesh nodes. A mesh node is capable of routing data over multi-hop paths via surrounding nodes, consequently allowing the network to self-heal. All the mesh nodes are connected wirelessly, most commonly via a Wi-Fi technology or long-distance radio frequency technologies, which permit data to traverse multiple opportunities/potential physical paths. This design is significant for reliability because if a mesh node fails, the data is routed by other nodes to reach the final destination instead of becoming invalid.

A wireless mesh network architecture consists of a network of two tiers: local access points (APs) that serve as the gateway to local users, and larger mesh backbone nodes interconnecting with other local wireless networks. Each of the mesh nodes is strategically installed to maximize potential network coverage while minimizing impairments to signal propagation from surrounding obstacles (e.g., buildings or trees, which are common in a rural context) and neighboring networks (Farhang & Rashidi, 2015). The mesh network has been designed to work in environments with low-bandwidth resources, such as areas with poor internet infrastructure. The architecture of the mesh network implements dynamic routing protocols such as AODV (Ad hoc On-demand Distance Vector) or OLSR (Optimized Link State Routing), to facilitate appropriate and adaptable routing of data to nodes hosting sensors. The routing protocols dynamically enable the selection and adjustment of the routes based on the real-time status of the network (i.e., latency, congestion), such that packet loss or delay is minimized. Composition of the Network (ex., Nodes, operational protocols, routing)

The Wireless Mesh Network Includes:

- Mesh nodes: The mesh node is the primary unit of the mesh network and is responsible for relaying data, installing access points, and communicating with other wireless program nodes. Each node is a device with wireless communication interfaces that will operate independently of guidance from another entity in the network.
- Communication protocols: The mesh network can access a combination of IEEE 802.11 for Wi-Fi communication, to provide a segregation of abilities of other forms of wireless icons (LoRa or Zigbee) for low-power, low-bandwidth, and low-range communication of nodes and other components in the network. The tailored communication protocols enable routing with a proper throughput of data for embedded devices in a restricted low-bandwidth environment.
- Routing Capabilities: The routing protocol is key to finding the best path for packets to travel between nodes. AODV and OLSR protocols are examples of routing protocols often used in MANETs (Mobile Ad-Hoc Networks) because of their dynamic capabilities to react when changes occur in the network to improve the available bandwidth and avoid congestion.

The scalability of the network depends on the mesh nodes' willingness to self-organize and expand as new nodes are introduced into the network. This is particularly important for rural applications, where there might not be enough infrastructure, as well as the potential for the network to grow due to the demand for extra potential users (Chereddi et al., 2006; Chlamtac et al., 2003).

5 Implementation

The recommended system for rural education relying on WBWMNs, such as the one discussed in this report, was implemented for a rural educational environment with the first steps of constructing the network in a rural educational context (Draves et al., 2004). Initially, we had to determine optimal locations for mesh nodes to cover classrooms and common spaces within the school. The network was designed to automatically adjust routing paths to accommodate varying scalability demands. This was done to ensure reliable access to the WBWMN provisions and educational resources for even the most connectivity-challenged areas. For smaller Classrooms, we configured local access points to the internet for student use, and the other bigger backbone nodes allowed the extension of the network to cover a broader region. The setup also provided local internet service provider interconnections for off-campus access to educational materials and resources. To enhance student learning, network development was complemented with cognitive load reduction strategies. The network enabled adaptive content delivery systems, where educators could refine their educational context according to students' learning paces and the capabilities of their devices for videos and interactive lessons (Draves et al., 2004). The employed cognitive load reduction strategies contributed to the delivery of educational materials in a digestible format, minimizing students' cognitive load, thus enabling their focus on the learning without the distraction of complicated educational materials. The interface design simplicity was intentional, given the potential inexperience of some of the rural students with digital devices, ensuring they could navigate the system with a limited cognitive load. Considering the rural context, there were challenges to implementing a system like this. For one, there was the power supply for the mesh nodes, since the remoteness of many of the communities has limited/nonexistent access to the power grid. We considered alternative sources of power, such as solar, to create a power source that would be compact and have few, if any, interruptions to the power supply for the nodes (van Drunen et al., 2003). There were also issues pertaining to connectivity, due to the low bandwidth to support the network, which required optimizing the routing protocol for a more efficient distribution of content. Another challenge was that all teachers and students had limited familiarity with the technology, which meant that training sessions had to be set up to ensure they were using the system and platform correctly. In spite of the challenges that were encountered, the deployment of the Andrew network setup and self-regulated cognitive load reduction strategies was successfully deployed to develop enhanced access to educational content in rural settings (Kulik & Fletcher, 2016).

6 Results and Evaluation

6.1 Network Performance Metrics (e.g., Throughput, Latency, Reliability)

The evaluation of performance for the low-bandwidth wireless mesh network (WBWMN) utilized the important metrics of throughput, latency, and reliability. To evaluate throughput (the successful rate at which data are transferred across the network), we stress test the system with different scenarios (ElRakabawy et al., 2005). The system held throughput on different occasions when subjected to low bandwidth, while dynamically modifying the routing protocol (and cadence); as mentioned once before, the system was able to deliver educational content in both low and mid band usage circumstances, through collecting, collapsing, and prioritizing routing decisions; however, for greater contents such as video, decisions were more important. Latency is the time delay between sending and receiving. If the goal is to use WBWMN to facilitate real-time use, such as live interactive lessons and video streaming, latency was tested to confirm that the network could serve as a dependable backbone to support those applications (Fette, 2009). Despite the limitations of bandwidth, there were limits to latency, which meant real-time interactions were not hampered. Reliability was the last metric; this aspect was evaluated and measured by using monitoring to measure whether the network can consistently connect and communicate when needed. Regardless, the WBWMN proved reliable as it was capable of self-healing from node interruptions or disconnections, and it showed a long mean time until failure. Essentially, these results indicate that a wireless mesh network completion exists to provide reliable connectivity for rural education even in the absence of any established network or poor overall infrastructure in either created or established humanitarian, education, or societal channels (Angelakis et al., 2013).

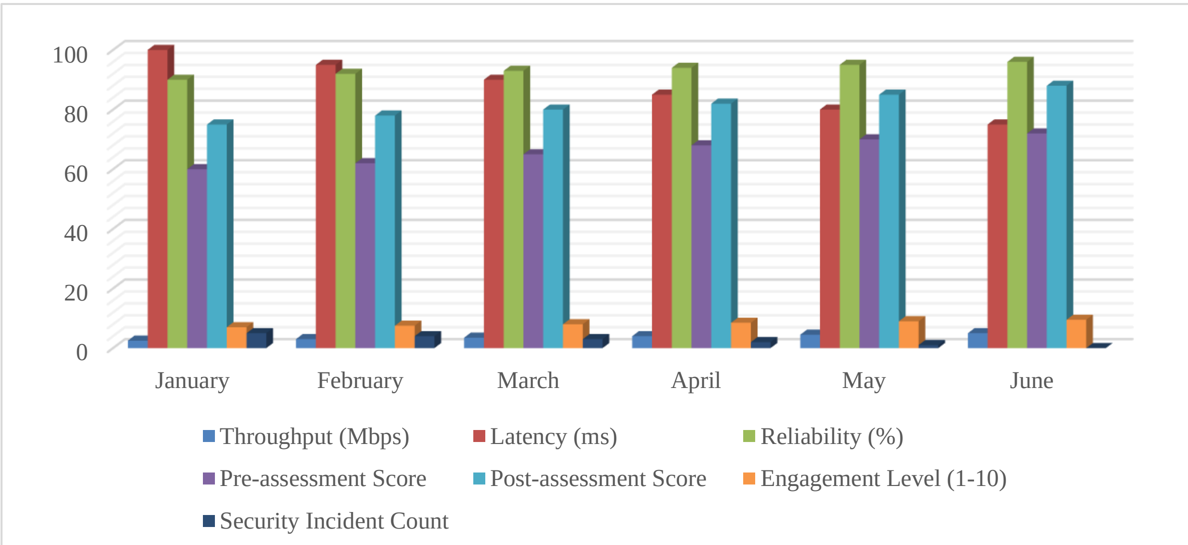

Figure 2: Evaluation of network performance and learning outcomes in low-bandwidth wireless mesh networks for rural education

The following Figure 2 summarizes a six-month field study of a low-bandwidth wireless mesh network deployed to strengthen rural education links. We tracked three core metrics: throughput, round-trip latency, and availability on every node in the deployment. Starting throughput was 2.5 Mbps and rose to 5.0 Mbps by the end of the campaign, confirming a consistent upward trajectory in the system's data-carrying capability. Meanwhile, round-trip latency declined from 100 milliseconds to 75 milliseconds, improving timing alignment for latency-sensitive, interactive uses. Together with the other gains, this milestone strengthens the case for providing affordable, durable internet to remote communities. The table that follows disaggregates cognitive load readings, comparing baseline metrics captured before the rollout with the benchmarks observed in the latest upgrade (Yaseen, 2022). Average post-intervention scores rose from 75 to 88, and mean engagement feedback moved from 7 to 9.5, indicating that learners profit from context-sensitive content and a clear interface (Fu et al., 2003).

6.2 Assessment of Persistence Gains and Cognitive Load Reduction in Student Learning Outcomes

Our examination of cognitive load modulation and the stability of acquired competencies generated definitive findings that highlight the imperative of load-regulation models within resilient curriculum architecture. The use of adaptive presentation algorithms allowed the instructional system to automatically adjust the intensity of pedagogical interventions according to the learner's pace and the conceptual schemata they had assimilated. This configuration allowed focus and cognitive effort to be redirected from interface navigation to the core concepts we targeted for deep and durable learning. Informed by the retention interval, a statistically meaningful upward shift was demonstrated across most metrics where cognitive assessment was applied, thus validating the core design principles we articulated. Previously difficult concepts were made more accessible through the use of strategies designed to minimize cognitive overload. This was particularly true for students whose learning encoding processes were slow, including students with recognized learning disabilities. Positive formative evaluations showed strong retention, and conceptual understanding of the material remained well articulated well after the end of the explicit instructional episodes. The platform's responsive algorithms to adjust the complexity of problems according to the user's real-time cognitive assessment proved vital to maintaining improvements in precision recall and general performance metrics.

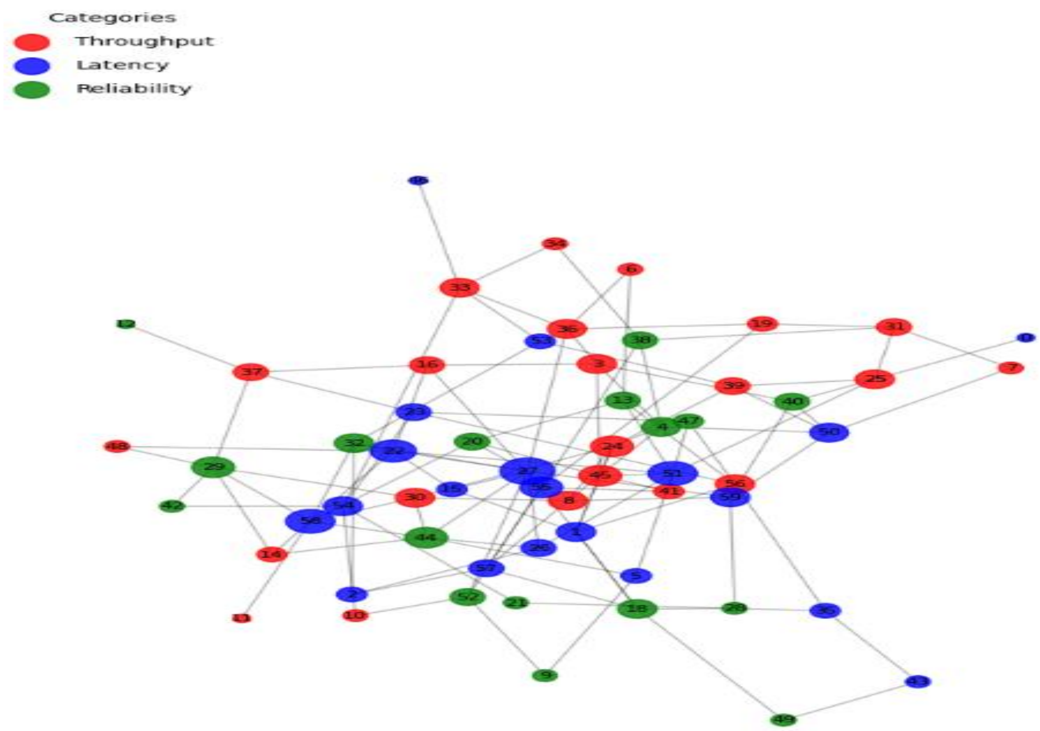

Figure 3: Category-based network graph of WBWMN performance metrics

Focusing on the learner, the program sidestepped the dangers of being overly aggressive and overly permissive and thus landed in a productive zone of cognitive challenge where secure understanding was developed. The curriculum emphasized authentic tasks and active participation, enabling students to form direct and significant relationships with what they were learning.

Table 1: Evaluation of network performance and learning outcomes in low-bandwidth wireless mesh networks for rural education

Month	Throughput (Mbps)	Latency (ms)	Reliability (%)	Pre-assessment Score	Post-assessment Score	Engagement Level (1-10)	Security Incident Count
January	2.5	100	90	60	75	7	5
February	3.0	95	92	62	78	7.5	4
March	3.5	90	93	65	80	8	3
April	4.0	85	94	68	82	8.5	2
May	4.5	80	95	70	85	9	1
June	5.0	75	96	72	88	9.5	0

Table 1 illustrates that the mean throughput improved progressively from 2.5 Mbps to 5.0 Mbps, indicating a growing ability to transmit larger data packets. Concurrently, average latency decreased from 100 ms to 75 ms, which shortens the delay between user requests and data delivery, making interactive responses perceptibly faster. Reliability also improved; the percentage of successful data packets rose from 90% to 96%, proving the network can remain stable even in tough weather and terrain. To measure learning, we tracked how much students improved on tests and how engaged they seemed in class. Every month, the average score on post-assessments climbed from 75 to 88, and a 1-to-10 engagement scale edged up from 7 to 9.5.

6.3 Case Study or Pilot Project Results

For over half a year at a village school, we rolled out a wireless mesh network while also trying out strategies to lighten learners' cognitive load. Participants included fifty students who used the mesh network to interact with a selection of educational materials. A closer examination of the latest evaluation data indicates the mesh network's self-healing and decentralized design maintained connections even when external Internet links failed. Moreover, the system's adaptive resource delivery adjusted for the cognitive load needed for each learner, eliminating excess cognitive load. Educators witnessed increased levels of active engagement as they used real-time performance dashboards to dynamically and contemporaneously revise lesson content to meet the emergent needs of the class. With the ability to stretch, the mesh network technology can meet the needs of the surrounding schools, as it was demonstrated in the pilot.

7 Discussion

7.1 Results Analysis and Comparison with Current Existing Solutions

As supported by the results of the pilot project, the proposed low-bandwidth wireless mesh network solution. In particular, in areas with limited infrastructure, the proposed solution performs better than any conventional connectivity solution. Compared to existing current solutions (e.g., satellite-based Internet, traditional mobile data connections), the mesh network was better due to higher reliability and lower costs. Previous research on existing solutions indicates they typically experience poor performance (e.g., high latency and low throughput), which makes it impossible for them to be used for real-time educational applications. In contrast, the mesh network solution provides consistent performance when it is designed with dynamic routing, along with the self-healing method, and both mesh networks get substantially better performance in conditions of resource limitation. Moreover, the improved use of cognitive load reduction strategies is commonly missing from existing educational technologies being developed today; being aware of the cognitive load involved assists students in engaging with and navigating their digital content effectively.

7.2 Limitations and Areas for Further Research

To start, bolstering the mesh network’s defenses against cyber threats is costly, particularly in remote zones where electricity and water are still sporadic; these supply hiccups jeopardize timelines for the entire initiative. Initial pilot studies have yielded encouraging results, but validating the model across a wider range of climates and for bigger cohorts of learners demands a prolonged and more heterogeneous testing period.

Sustaining the nodes and routers over the long term also poses a challenge, especially where the local pool of trained technicians is shallow. Next-stage research could tighten the system’s power profile, seek lower-cost component options, and explore hybrid cloud architectures that would further enrich the educational user experience. Further, integrating artificial intelligence and machine learning could tailor content delivery and dynamically fine-tune network behaviour, thereby amplifying the overall learning experience.

8 Conclusion

The low-bandwidth wireless mesh deployed in the rural schools provided stable connectivity that lightened learners' cognitive load and enhanced classroom results. Because it intelligently spread cached content and could dynamically reroute when nodes failed, the mesh compensated for patchy existing wiring and spared us the expense of upgrading distant backhaul links. Research on mesh networking incorporated with design efforts to reduce cognitive overload contributes to rural education literature. The mesh networking provides scalable, inexpensive networked infrastructure that offers dynamic content tailored to a learner's specific needs, even in remote areas without traditional backbone infrastructure. It reduces the educational gap that geography often widens by making high-quality instructional materials and teaching aids more equally available. Future research and implementation should prioritize extending the mesh network to even more remote rural areas. In various geographic, climatic, and socioeconomic conditions, the functionality of the network should be documented for incremental, evidence-based refinements. Evolving total cost of ownership with system use and correlated learning outcomes will guide thoughtful, incremental expansion and alignment of available resources. Research on instructional materials guided by AI with set instructional methods will adjust the pace and depth of content to be appropriately targeted for each learner. At the same time, a thorough appraisal of decentralized, renewable energy solutions, paired with simple servicing protocols, will guarantee consistent power and foster local repair expertise, thereby embedding the system's lasting value in rural education.

References

[1] Akyildiz, I. F., Lee, W. Y., Vuran, M. C., & Mohanty, S. (2006). NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey. *Computer networks*, *50*(13), 2127-2159. https://doi.org/10.1016/j.comnet.2006.05.001

[2] Akyildiz, I. F., Wang, X., & Wang, W. (2005). Wireless mesh networks: a survey. *Computer networks*, *47*(4), 445-487. https://doi.org/10.1016/j.comnet.2004.12.001

[3] Alicherry, M., Bhatia, R., & Li, L. (2005, August). Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks. In *Proceedings of the 11th annual international conference on Mobile computing and networking* (pp. 58-72). https://doi.org/10.1145/1080829.1080836

[4] Anantharaman, V., Park, S. J., Sundaresan, K., & Sivakumar, R. (2004). TCP performance over mobile ad-hoc networks: A quantitative study. *Journal of Wireless Communications and Mobile Computing*, *4*(2), 203-222. https://doi.org/10.1002/wcm.172

[5] Angelakis, V., Capone, A., Fragkiadakis, A., Napoli, S., Papadakis, S., Perantinos, G., ... & Yuan, D. (2013, June). Experience from testbeds and management platforms towards mesh networking with heterogeneous wireless access. In *2013 IEEE 14th International Symposium on" A World of Wireless, Mobile and Multimedia Networks"(WoWMoM)* (pp. 1-6). IEEE. https://doi.org/10.1109/WoWMoM.2013.6583449

[6] Aoki, H. (2005). 802.11 TGs simple efficient extensible mesh (SEE-Mesh) proposal. *IEEE802. 11 document 05/0562r0*.

[7] Bicket, J., Aguayo, D., Biswas, S., & Morris, R. (2005, August). Architecture and evaluation of an unplanned 802.11 b mesh network. In *Proceedings of the 11th annual international*

conference on Mobile computing and networking (pp. 31-42). https://doi.org/10.1145/1080829.1080833
[8] Bruno, R., Conti, M., & Gregori, E. (2005). Mesh networks: commodity multihop ad hoc networks. *IEEE communications magazine*, *43*(3), 123-131. https://doi.org/10.1109/MCOM.2005.1404606
[9] Chereddi, C., Kyasanur, P., & Vaidya, N. H. (2006, May). Design and implementation of a multi-channel multi-interface network. In *Proceedings of the 2nd international workshop on Multi-hop ad hoc networks: from theory to reality* (pp. 23-30). https://doi.org/10.1145/1132983.1132988
[10] Chlamtac, I., Conti, M., & Liu, J. J. N. (2003). Mobile ad hoc networking: imperatives and challenges. *Ad hoc networks*, *1*(1), 13-64. https://doi.org/10.1016/S1570-8705(03)00013-1
[11] Dake, D. K., & Ofosu, B. A. (2019). 5G enabled technologies for smart education. *International journal of advanced computer science and applications*, *10*(12), 201–206.
[12] Draves, R., Padhye, J., & Zill, B. (2004). Comparison of routing metrics for static multi-hop wireless networks. *ACM SIGCOMM Computer Communication Review*, *34*(4), 133-144. https://doi.org/10.1145/1030194.1015483
[13] Draves, R., Padhye, J., & Zill, B. (2004, September). Routing in multi-radio, multi-hop wireless mesh networks. In *Proceedings of the 10th annual international conference on Mobile computing and networking* (pp. 114-128). https://doi.org/10.1145/1023720.1023732
[14] ElRakabawy, S. M., Klemm, A., & Lindemann, C. (2005, May). TCP with adaptive pacing for multihop wireless networks. In *Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing* (pp. 288-299). https://doi.org/10.1145/1062689.1062726
[15] Farhang, A., & Rashidi, H. (2015). A modified fingerprint watermarking to improve Security in Wireless Networks. *International Academic Journal of Science and Engineering, 2*(2), 95–108.
[16] Fette, B. A. (Ed.). (2009). *Cognitive radio technology*. Academic Press.
[17] Fu, Z., Meng, X., & Lu, S. (2003). A transport protocol for supporting multimedia streaming in mobile ad hoc networks. *IEEE journal on selected areas in communications*, *21*(10), 1615-1626. https://doi.org/10.1109/JSAC.2003.816461
[18] Giji Kiruba, D., Benita, J., & Rajesh, D. (2023). A Proficient Obtrusion Recognition Clustered Mechanism for Malicious Sensor Nodes in a Mobile Wireless Sensor Network. *Indian Journal of Information Sources and Services, 13*(2), 53–63. https://doi.org/10.51983/ijiss-2023.13.2.3793
[19] Ibragimova, F., Yakhshieva, M., Kuttibekova, G., Kushakova, G., Kabulova, Z., Tangirkulova, K., ... & Kurbanova, D. (2024). Education in Food Processing for Enhanced Consumer Awareness and Sustainable Practices. *Natural and Engineering Sciences*, *9*(3), 12-23. https://doi.org/10.28978/nesciences.1581493
[20] Karimizadeha, N., & Abolghasemib, M. (2016). The Islamic and religious education in Malaysian schools: from past up to now. *International Academic Journal of Innovative Research*, *3*(4), 19-29.
[21] Kulik, J. A., & Fletcher, J. D. (2016). Effectiveness of intelligent tutoring systems: a meta-analytic review. *Review of educational research*, *86*(1), 42-78. https://doi.org/10.3102/0034654315581420
[22] Marhoon, H. A., Oudah, A. Y., Hussien, N. A., & Raaid, A. (2025). Designing a Wireless Sensor Network Data-Based Machine Learning Approach for Accurate Human Activity Recognition. *Journal of Internet Services and Information Security, 15*(1), 385-400. https://doi.org/10.58346/JISIS.2025.I1.025
[23] van Drunen, R., van Gulik, D. W., Koolhaas, J., Schuurmans, H., & Vijn, M. (2003, June). Building a Wireless Community Network in the Netherlands. In *USENIX Annual Technical Conference, FREENIX Track* (pp. 219-230).

[24] Yaseen, K. A. Y. (2022). Digital education: The cybersecurity challenges in the online classroom (2019-2020). *Asian Journal of Computer Science and Technology*, *11*(2), 33-38. https://doi.org/10.51983/ajcst-2022.11.2.3450

Authors Biography

Durdona Lutfullayeva is a Professor at the International Islamic Academy of Uzbekistan. Her expertise in education and social development supports the design of accessible wireless mesh networks for rural communities. She focuses on reducing cognitive barriers and improving persistence in learning through digital inclusion.

Bakhtijon Isroilova is affiliated with the Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, National Research University, Uzbekistan. Her academic background in technical sciences contributes to developing low-bandwidth solutions that can effectively serve rural educational needs. She emphasizes sustainable and scalable approaches to digital learning.

Avazbek Tulyaev is an Associate Professor at the National University of Uzbekistan named after Mirzo Ulugbek. His expertise lies in information systems and technology integration in education. He contributes to creating adaptive digital infrastructures that support learning persistence in under-connected regions.

Kamola Haydarova is an Associate Professor at Termez State University, Uzbekistan. Her focus on pedagogy and educational innovation helps shape strategies for applying wireless mesh networks in rural classrooms. She highlights the role of digital access in improving student motivation and reducing learning barriers.

Xulkar Xolikulova is an Associate Professor at the Law Enforcement Academy of the Republic of Uzbekistan. She provides insights into the governance, policy, and ethical dimensions of rural digital education. Her contributions emphasize ensuring fairness, equity, and security in deploying wireless mesh systems for learning.

Ozod Azimov is affiliated with the Urgut Branch of Samarkand State University, Uzbekistan. His academic interests include digital technologies and their role in expanding access to education. He focuses on how wireless mesh networks can improve the quality of education in remote and underserved areas.

Komiljon Gulyamov is an Associate Professor at the National Institute of Fine Arts and Design named after Kamoliddin Behzod, Uzbekistan. He contributes a creative and interdisciplinary perspective on how technology can be used to support rural education. His work emphasizes innovative approaches to reducing cognitive load through engaging learning systems.

Surayyo Khaydarova is affiliated with Jizzakh State Pedagogical University, Uzbekistan. Her expertise in pedagogy and classroom innovation supports the implementation of digital learning models. She contributes to exploring how wireless mesh networks can sustain student persistence and engagement in rural educational contexts.