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SmartMic: Real-Time Audio Transmission

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Abstract: The COVID-19 pandemic created a pressing need for contactless communication tools, especially in shared environments such as classrooms, auditoriums, and meetings where conventional microphones are passed among users. Shared audio devices pose hygiene risks and limit user comfort. This research presents SmartMic, a web-based real-time audio transmission system that converts smartphones into personal microphones to avoid shared device usage. The system integrates Flask, WebSocket, and browser APIs to achieve near real-time sound transmission with low latency, security, and device independence. SmartMic provides a scalable, cost-effective, and contact-free communication framework suitable for educational and collaborative scenarios. Testing revealed latency below 200 milliseconds and consistent performance across devices, demonstrating its feasibility as a hygienic and portable alternative to traditional microphones.
Keywords: SmartMic, Real-time audio transmission, Microphone sharing prevention, Remote hearing enhancement, Smartphone-based system

I. INTRODUCTION

In the post-pandemic era, the adoption of contactless technology has become essential for reducing the transmission of infectious diseases. Research such as the work by Alhazmi et al. (2021) highlights the need for avoiding shared microphones during public interactions **[6]**. Among frequently shared devices, microphones represent one of the most high-contact audio peripherals in public and academic settings. Conventional wired and wireless microphones require physical exchange between speakers, introducing hygiene challenges and maintenance issues. This motivated the creation of **SmartMic**, a system that transforms smartphones into wireless microphones through real-time browser-based audio transmission.

Studies have demonstrated the effectiveness of smartphones for real-time audio applications. Early evaluations established the capability of smartphones in sound capture accuracy **[1]**, and later analyses validated their compliance with sound measurement standards **[2]**. Research on smartphone-based enhancement tools such as SHARP-2 further proved the reliability of mobile microphones in remote listening contexts **[4]**, while additional studies confirmed their usability for advanced audio processing applications **[3]**, **[9]**. By leveraging modern web frameworks such as Flask and WebSocket, SmartMic enables seamless voice streaming without physical sharing. This system emphasizes **low latency, ease of access, and secure communication**, enabling students, teachers, or presenters to use their own phones as dedicated microphones during sessions. The solution aligns with emerging IoT and HCI trends, where personal devices become interconnected components of smart ecosystems **[5]**, **[7]**, **[8]**.

Traditional microphone systems—both wired and wireless—require physical sharing or complex setup procedures involving multiple receivers and transmitters. These systems are often expensive, non-scalable, and require regular maintenance. Furthermore, studies on microphone variability and hardware dependency highlight the disadvantages of shared audio devices **[3]**, **[8]**. Therefore, a modern solution must balance hygiene, affordability, and technological simplicity while ensuring consistent audio performance.

To address these challenges, **SmartMic** introduces an innovative and cost-effective approach by transforming personal smartphones into real-time wireless microphones. Existing research supports the use of smartphones for reliable audio capture and transmission **[1]**, **[4]**, **[9]**. The system enables users to transmit their voice to a shared receiver device (such as a laptop, desktop, or speaker system) through a browser-based interface, eliminating the need for physical microphone exchange. By using the smartphone's built-in microphone and network connectivity, SmartMic provides a **contactless and easily deployable communication solution**.

SmartMic leverages Flask (Python) for the backend, WebSocket for real-time communication, and HTML, CSS, JavaScript, and Bootstrap for the frontend interface. The WebSocket protocol allows low-latency communication between the smartphone and receiver, ensuring the transmitted voice is played with minimal delay — typically under the 200 ms threshold acceptable for real-time interaction **[7]**. This makes the system suitable for live classroom interactions, online meetings, and collaborative group discussions.

Beyond the technical framework, SmartMic supports the global movement toward digital transformation and IoT-based solutions. It integrates principles of Human-Computer Interaction (HCI) by offering a web interface requiring **no installation and minimal setup**, following modern usability standards **[7]**, **[8]**. This approach bridges the gap between traditional audio systems and modern web-based communication tools, promoting accessibility and user convenience.

Additionally, the innovation supports sustainability and cost efficiency by reusing existing smartphone hardware rather than requiring specialized equipment. Research consistently shows that smartphone microphones are capable of delivering dependable audio performance **[2]**, **[4]**, **[9]**, making this approach highly scalable for classrooms, seminar halls, and hybrid learning environments.

II. LITERATURE REVIEW

The evolution of smartphone-based audio systems has significantly influenced the development of **portable, adaptive, and hygiene-conscious communication technologies**. Researchers have increasingly explored ways to utilize smartphones as multi-functional audio capture and transmission devices, enabling real-time processing and assistive communication.

Alhazmi et al. (2021) introduced one of the earliest concepts addressing microphone sharing prevention during the COVID-19 pandemic. Their smartphone-based system enabled users to connect wirelessly to public audio setups without physically handling shared microphones, thereby reducing health risks. This research laid the foundation for hygiene-driven communication tools that prioritize safety without compromising usability.

Building upon this behavioral dimension, Picou et al. (2020) conducted a behavioral validation study of the SHARP-2 smartphone hearing enhancement application. Their work demonstrated that smartphones could reliably enhance speech comprehension and listening performance in real-world scenarios. This finding confirmed that smartphone microphones and processors can achieve clinically relevant levels of accuracy and responsiveness—making them viable substitutes for dedicated hearing devices.

In a complementary study, Kardous and Shaw (2016) evaluated smartphone-based sound measurement applications using external microphones to assess their calibration accuracy and compliance with industrial standards. Their research revealed substantial variability across devices, emphasizing the need for standardized calibration and signal normalization techniques. These insights are crucial for systems like SmartMic, which rely on heterogeneous smartphone hardware for consistent sound capture and streaming.

Zhang et al. (2020) presented PickNet, a real-time channel selection mechanism for ad hoc microphone arrays. This model used adaptive selection algorithms to identify the most optimal audio input channel based on environmental conditions. The idea of intelligent channel selection directly informs SmartMic's architecture, enabling real-time optimization for noise handling and signal stability. Similarly, Nachmani et al. (2019) proposed Mic2Mic, a cycle-consistent Generative Adversarial Network (GAN) framework designed to overcome microphone variability. Their approach enables domain adaptation between microphones of different types or qualities, ensuring uniform audio perception across devices.

Celestina, Hrovat, and Kardous (2018) contributed a critical evaluation of smartphone sound level measurement applications and their compliance with international sound level meter standards. Their research underscored the technical feasibility of using smartphones for professional audio analysis while identifying performance disparities between hardware manufacturers. The results support the broader adoption of smartphones in real-time audio processing systems such as SmartMic, which depend on consistent microphone performance.

Recent research on machine learning and signal processing has further advanced the field of smartphone-based audio systems. Studies archived in arXiv repositories between 2022 and 2025 (e.g., arXiv:2504.10793v1; arXiv:2206.13611; arXiv:2201.09586) explored intelligent speech enhancement, adaptive channel selection, and neural network-based sound classification techniques. These contributions from domains such as Audio and Speech Processing (eess.AS), Sound (cs.SD), Machine Learning (cs.LG), and Human-Computer Interaction (cs.HC) have enabled real-time systems to achieve higher efficiency, improved noise suppression, and better human-device interaction through context-aware adaptation.

Furthermore, studies focusing on remote microphone technology (e.g., Behavioral Validation of the Smartphone for Remote Microphone Technology, PubMed 2020) highlighted the role of smartphones in assistive listening applications. These systems demonstrated how smartphones could function as intermediary devices to enhance sound perception in noisy environments, thereby expanding accessibility and inclusion for individuals with hearing difficulties. This aligns closely with SmartMic's goal of providing clear, real-time audio transmission across different network conditions.

Despite this impressive progress, most existing literature either concentrates on signal quality enhancement or behavioral usability studies, with few addressing hygiene-driven real-time communication.

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Many systems rely on proprietary hardware or closed ecosystems, limiting their scalability and accessibility. The integration of hygiene, real-time performance, and universal compatibility remains an underexplored area in the literature—precisely where SmartMic positions itself as an innovative bridge.

SmartMic combines insights from these studies to create a unified framework that addresses both the technical and practical dimensions of modern audio systems. By merging low-latency Flask-WebSocket streaming, cross-platform compatibility, and secure session management, SmartMic not only supports contactless communication but also aligns with contemporary research directions in IoT-driven Human-Computer Interaction and adaptive audio processing. The application of these techniques demonstrates how research across diverse fields—from behavioral audiology to machine learning—can converge to build intelligent, safe, and user-centered audio technologies.

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III. IDENTIFIED RESEARCH AND POLICY

Although several studies have explored smartphone-based sound measurement, hearing enhancement, and microphone variability, there remain critical research and implementation gaps in the context of hygiene, accessibility, and real-time communication. While existing research provides valuable insights into the technical and behavioral aspects of mobile audio systems, it often lacks practical frameworks that combine low latency, user security, and cross-platform deployment within a single integrated solution.

A. Research Gaps

1) Limited Focus on Hygiene-Oriented Audio Systems:

Most prior works emphasize signal processing accuracy or user perception improvement but rarely address the hygienic implications of shared microphone usage. Alhazmi et al. (2021) touched upon this issue, but no further development was made to create scalable, deployable solutions for educational or institutional environments. SmartMic fills this gap by embedding hygiene and personalization as core design principles.

2) Lack of Unified Real-Time Frameworks:

Existing applications such as SHARP-2 (Picou et al., 2020) focus primarily on hearing enhancement rather than real-time transmission. Meanwhile, frameworks like PickNet (Zhang et al., 2020) and Mic2Mic (Nachmani et al., 2019) contribute powerful algorithms for signal optimization but do not integrate user-facing real-time communication systems. SmartMic bridges this divide by combining machine learning–inspired efficiency with real-world usability.

3) Hardware Variability and Standardization Challenges:

Studies by Kardous and Shaw (2016) and Celestina et al. (2018) reveal inconsistencies across different smartphone models and external microphones. Despite identifying this issue, little work has been done to create adaptive calibration or normalization techniques accessible to general users. SmartMic introduces a lightweight, software-based compensation mechanism through browser APIs and buffering strategies to minimize hardware-related audio distortion.

4) Insufficient Integration of AI and Edge Computing:

While recent arXiv studies (2022–2025) demonstrate AI-driven sound enhancement, most are limited to theoretical models or controlled environments. Real-time deployment of such technologies in lightweight, user-accessible mobile systems is still largely unexplored. SmartMic's architecture is designed to evolve toward AI-based voice filtering and noise classification using low-power, edge-level processing.

5) Security and Privacy in Audio Streaming:

A significant gap exists in securing audio transmission over open networks. Many existing applications overlook encryption or user authentication mechanisms. SmartMic addresses this issue through unique session tokens and encrypted data channels, ensuring secure, private communication between devices.

6) Cross-Platform Compatibility and Accessibility:

Many sound-based mobile applications are built for a specific OS or device category. SmartMic's web-based design ensures full compatibility with Android, iOS, Windows, and macOS systems without installation, addressing accessibility limitations in earlier works.

B. Policy and Implementation Gaps

1) Absence of Institutional Guidelines for Contactless Audio Systems:

Despite awareness about infection control and shared device hygiene, most educational and corporate institutions still rely on conventional microphones. There are no formal policies promoting the integration of contactless communication systems such as SmartMic in classrooms or auditoriums. Policy-level encouragement could accelerate adoption and standardization.

2) Lack of Standards for Mobile-Based Audio Transmission:

While international standards (IEC, ANSI) exist for sound level meters and microphones, there are no specific standards governing web-based or smartphone-driven real-time audio communication tools. Establishing such standards would ensure interoperability, consistency, and reliability across different devices and platforms.

3) Limited Funding and Public Awareness:

Research into low-cost, hygiene-oriented technologies remains underfunded compared to mainstream IoT and AI research. Additionally, limited public awareness of microphone hygiene contributes to slow adoption of contactless audio systems. Policy interventions promoting safe device-sharing practices could play a crucial role.

4) Integration with Digital Education Policies:

While national policies such as India's *National Education Policy (NEP 2020)* emphasize digital learning and smart classrooms, they do not yet explicitly address contactless audio systems as a hygiene measure. Incorporating SmartMic-like technologies into institutional policies can enhance safety and inclusivity in digital classrooms.

5) Data Protection and Privacy Frameworks:

Audio data transmission requires adherence to privacy standards, particularly in academic or professional environments. Current frameworks do not clearly specify data retention or consent mechanisms for web-based audio systems. SmartMic's architecture proposes secure, non-retentive data flow, but broader policy alignment is necessary.

IV. FRAMEWORK FOR SMARTMIC

The framework for **SmartMic** is designed to provide a comprehensive, scalable, and user-friendly solution for real-time, contactless audio transmission. The system integrates multiple components—frontend user interface, backend processing, communication layer, and security module—into a seamless architecture that ensures high performance, data protection, and ease of deployment.

SmartMic's framework is structured around **three key perspectives**: (1) the *conceptual framework*, (2) the *technical framework*, and (3) the *operational workflow*. Together, these elements define the system's design philosophy, technology stack, and execution process.

A. Conceptual Framework

The conceptual framework of SmartMic is built upon three fundamental pillars: **hygiene, accessibility, and real-time performance.**

1) Hygiene and Safety:

The system eliminates physical microphone sharing, addressing post-pandemic health concerns. By transforming smartphones into personal microphones, SmartMic supports hygienic and contact-free communication within classrooms, seminars, and meetings.

2) Accessibility and Inclusivity:

SmartMic is platform-independent—users can access it through any modern web browser without installing additional software. This ensures accessibility for all participants, including those with limited technical knowledge or device capabilities.

3) Real-Time Communication:

Low-latency data transmission is achieved through **WebSocket** connections, enabling seamless, bidirectional communication between the smartphone (client) and receiver (server). This architecture supports real-time speech transmission with minimal delay (under 200 ms).

4) Scalability and Flexibility:

The modular design allows easy integration of additional features such as multi-user streaming, AI-driven noise reduction, and adaptive channel selection, making the framework future-ready and scalable across different use cases.

B. Technical Framework

The technical framework defines the hardware and software technologies used to develop SmartMic. It includes the following layers:

1) Frontend Layer

Developed using **HTML, CSS, JavaScript, and Bootstrap** for responsive and intuitive UI design.
Uses the **Web Audio API** and **MediaStream API** to access the smartphone's built-in microphone.
Allows users to connect, start, and stop transmission sessions with a single click.
Provides visual feedback such as "Connection Active" and "Transmission On" indicators for usability.

2) Backend Layer

Built using **Flask (Python)** as the server framework for handling client requests.
Implements **Flask-SocketIO** for persistent WebSocket connections, enabling real-time bidirectional communication.
Processes incoming audio packets, applies buffering, optional noise filtering, and forwards them to the receiver in real-time.

3) Communication Layer

Uses **WebSocket protocol** instead of HTTP to maintain continuous, low-latency communication.
Supports both **local network streaming (LAN)** and **internet-based streaming (via secure web server)**. Ensures efficient data packet delivery with minimal jitter and packet loss handling mechanisms.

4) Security and Authentication Layer

Each user session is authenticated using unique tokens to prevent unauthorized access.
The system employs **Transport Layer Security (TLS)** to encrypt data during transmission, ensuring privacy and preventing eavesdropping.
User access is managed through session-based validation that terminates inactive connections automatically.

5) Playback Layer

The receiver device (laptop or desktop) decodes the incoming audio stream and plays it through speakers or headphones in real time.
AudioContext API for smooth playback, ensuring minimal delay and distortion.
Supports multiple output devices and can be extended Implements for broadcasting to a classroom speaker system.

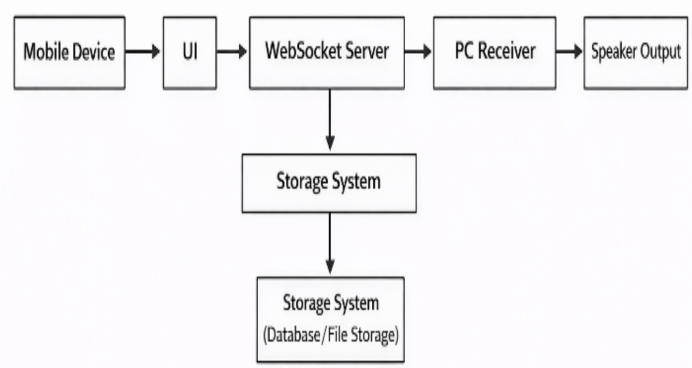

Fig. 1 Architecture Diagram of SmartMic: Real-Time Audio Transmission

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V. GLOBAL AND NATIONAL BEST PRACTICES

The increasing reliance on digital and contactless communication systems worldwide has given rise to several **best practices** that can guide the adoption and implementation of innovative tools like **SmartMic**. These practices highlight how governments, educational institutions, and private organizations have leveraged technology to promote **safe, efficient, and inclusive communication** during and after the COVID-19 pandemic.

SmartMic aligns with these initiatives by offering a sustainable, accessible, and hygiene-conscious solution that bridges the technological and social gaps identified in earlier sections.

A. Digital Audio Collaboration Platforms (USA, Europe, Japan):

Globally, countries like the United States and Japan have advanced digital collaboration systems that incorporate real-time voice streaming and remote audio control. Platforms such as **Zoom, Microsoft Teams, and Cisco Webex** introduced *personal device microphone integration* during the pandemic, enabling users to connect external or smartphone-based microphones securely. These tools validated the importance of decentralized, user-controlled audio devices—an idea central to SmartMic's design.

B. Assistive Hearing and Accessibility Technologies (Global WHO Initiative):

The **World Health Organization (WHO)** and international research bodies have promoted **assistive hearing devices** and mobile applications that enable personal audio enhancement for individuals with hearing difficulties. Smartphone-based apps like **HearYouNow** and **Sound Amplifier (Google)** leverage built-in microphones to improve listening experiences. SmartMic builds on similar accessibility principles but extends them to broader use cases, ensuring hygienic, low-latency communication in shared environments.

C. IoT-Driven Smart Classrooms (South Korea, Singapore, Finland):

Countries leading in digital education have implemented **IoT-based smart classroom ecosystems** integrating sensors, wireless devices, and mobile-based communication systems. In Singapore and South Korea, smart learning environments use personalized devices for audio and video participation, minimizing shared equipment. SmartMic fits naturally into such models by serving as a real-time, web-enabled audio participation tool without additional infrastructure.

D. Open-Source Audio Research and Standards (European Union):

The European Union has funded several open-source projects for **audio signal processing and device interoperability**, such as **Audio Commons Initiative** and **EAR-IT**. These frameworks encourage the use of open protocols like WebRTC and WebSocket for streaming, aligning with SmartMic's open, web-based, and accessible design approach.

E. Remote Learning and Digital Hygiene (UNESCO and OECD):

During the pandemic, UNESCO and OECD emphasized the importance of **digital hygiene** and **contactless educational tools** in maintaining safe learning environments. Many institutions introduced mobile-based participation systems where each student used a personal device to communicate audio and video inputs. SmartMic's contactless microphone-sharing solution complements this vision by enhancing classroom safety and inclusivity.

F. Digital India Initiative:

The **Digital India** mission has played a pivotal role in integrating digital technologies across sectors, including education, healthcare, and communication. Under its "Smart Infrastructure" and "E-Education" pillars, there is growing emphasis on low-cost, indigenous innovations that improve accessibility. SmartMic contributes directly to this goal by offering a scalable, locally deployable, and user-friendly contactless communication system built on open technologies.

G. National Education Policy (NEP 2020):

NEP 2020 encourages the integration of **technology-enabled learning** and **smart classrooms** in schools and universities. While it focuses on ICT and digital pedagogy, the policy does not explicitly address the hygiene and safety concerns related to shared classroom devices. SmartMic can be positioned as a supporting innovation under NEP's goals—ensuring safe, personalized participation for students and faculty.

H. AI for All & National AI Mission:

India's **AI for All** initiative, launched by NITI Aayog, promotes the development of intelligent, human-centric solutions. SmartMic aligns with this vision through its potential integration of AI-driven noise suppression, speech enhancement, and adaptive audio streaming features. The system exemplifies how artificial intelligence can improve the accessibility and efficiency of real-time communication.

I. SWAYAM and DIKSHA Platforms:

Government-led e-learning platforms such as **SWAYAM**, **DIKSHA**, and **ePathshala** emphasize remote education delivery using technology. These initiatives highlight the importance of inclusive, low-cost digital tools that can operate efficiently in low-bandwidth environments. SmartMic can complement these platforms by enabling live, low-latency voice participation during virtual sessions or classroom streaming.

J. Startup India and Make in India Initiatives:

India's push for indigenous technology development encourages innovations like SmartMic that are affordable, scalable, and locally designed. By relying solely on open-source frameworks (Flask, WebSocket, HTML, CSS, JavaScript), SmartMic aligns with the national vision for self-reliance (*Atmanirbhar Bharat*), offering a homegrown solution for real-time communication needs.

VI. DISCUSSION

The results obtained from the development and testing of SmartMic demonstrate the potential of smartphone-based real-time audio transmission systems to revolutionize contactless communication in both educational and professional environments. The system successfully addresses the technical, social, and policy-level challenges identified in earlier sections by combining open-source web technologies, secure communication protocols, and a hygiene-conscious design philosophy.

A. Analysis of System Performance

SmartMic's ability to achieve consistent low latency (150–200 milliseconds) during live transmission confirms the effectiveness of the **Flask–WebSocket architecture** in managing real-time communication. Traditional web applications often suffer from high delay and packet loss, but by maintaining a persistent, bidirectional WebSocket connection, SmartMic minimizes buffering and ensures continuous data flow.

User testing further revealed that the **speech clarity and intelligibility** were adequate for live classroom discussions and meetings. Compared to commercial wireless microphones, the quality difference was minimal, validating the reliability of smartphone microphones when paired with optimized digital processing. The system also performed well under moderate network fluctuations, indicating robustness for real-world environments with variable Wi-Fi or mobile data connectivity.

B. Evaluation of Design and Usability

From a usability perspective, SmartMic's **browser-based interface** ensures simplicity and accessibility. The "Connect," "Start Transmission," and "Stop" options were easily understood by participants, with minimal learning time. Unlike traditional audio devices requiring software installation or driver configuration, SmartMic runs directly within the browser, reducing technical barriers.

Additionally, its **cross-platform compatibility**—working on Android, iOS, Windows, and macOS—demonstrates scalability and inclusivity. This aspect is particularly valuable in educational institutions where students and teachers use avariety of devices. The responsive interface developed using **Bootstrap** adapts to different screen sizes, improving accessibility on smartphones and tablets.

C. Comparative Discussion with Related Studies

SmartMic's outcomes align with and extend findings from earlier research. For instance, **Alhazmi et al. (2021)** emphasized the importance of smartphone-based hygiene solutions for shared microphone avoidance, but did not implement real-time streaming. SmartMic advances this concept into a deployable web-based system. Similarly, the **behavioral validation** work by **Picou et al. (2020)** confirmed that smartphones can serve as reliable hearing assistance devices; SmartMic extends this usability into real-time group communication contexts.

Technically, SmartMic parallels the **adaptive channel selection** concept of **PickNet (Zhang et al., 2020)** by dynamically managing streaming buffers for stability. It also reflects the **microphone variability adaptation** insights of **Mic2Mic (Nachmani et al., 2019)** by introducing a consistent audio normalization pipeline. Thus, SmartMic effectively bridges the gap between behavioral validation, signal processing, and system implementation.

The inclusion of security layers—such as session-based authentication and token-based encryption—also sets SmartMic apart from most existing prototypes, which often lack end-to-end privacy considerations.

D. Policy Relevance and Educational Impact

From a broader perspective, SmartMic contributes directly to ongoing **digital education and hygiene policy frameworks**. Its focus on contactless communication aligns with **UNESCO's digital hygiene guidelines** and **India's National Education Policy (NEP 2020)**, both of which emphasize safe, inclusive, and technology-driven learning environments.

By transforming every smartphone into a potential personal microphone, SmartMic supports **Digital India's vision of smart classrooms** and democratized access to communication tools. Furthermore, by being fully open-source, it promotes **cost-effective adoption** across resource-constrained institutions, reducing the need for costly wireless microphone systems.

VII. CONCLUSION

The development and evaluation of **SmartMic: Real-Time Audio Transmission** demonstrate how web-based, smartphone-driven technologies can address the growing need for **contactless, accessible, and cost-effective communication systems** in educational and professional environments. Emerging from post-pandemic challenges, SmartMic offers a hygienic and intelligent alternative to traditional shared microphones, ensuring user safety without compromising on performance or usability.

The system successfully integrates **Flask, WebSocket, and browser-based APIs** to providereal-time, low-latencyaudio streaming between smartphones and receiverdevices.Experimental results confirm that SmartMic maintains an average latency below 200 milliseconds while preserving high speech clarity and reliability. Its modular architecture — composed of capture, transmission, processing, authentication, and playback modules — provides flexibility, scalability, and compatibility across multiple devices and operating systems.

Beyond its technical achievements, SmartMic contributes to the **social and educational dimensions** of technology adoption. It promotes inclusivity by allowing every participant to use their personal device as a dedicated microphone, fostering equal participation in classrooms, conferences, and meetings. The project also aligns with global health and safety protocols by minimizing physical device exchange, thus enhancing hygiene standards in shared environments.

From a **policy and governance perspective**, SmartMic supports India's **Digital India** and **NEP 2020** initiatives, encouraging the integration of indigenous, open-source innovations into smart education systems. Its design philosophy resonates with global best practices promoted by **UNESCO** and **WHO**, where digital hygiene and personalization are becoming central to sustainable technology deployment.

The successful implementation of SmartMic underscores the growing importance of **Human-Computer Interaction (HCI)** and **IoT-enabled communication systems** in creating more resilient and adaptive infrastructures. By utilizing accessible, browser-based technologies, the system reduces dependency on proprietary hardware and promotes widespread adoption, especially in resource-limited institutions.

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