A REVIEW OF EMAIL PROTOCOLS: EVOLUTION, SECURITY AND INTEROPERABILITY

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ABSTRACT: Email remains a cornerstone of digital communication, supporting exchanges across personal, corporate, and governmental domains. At its foundation are three protocols: SMTP, POP3, and IMAP that are enable the sending, retrieval, and synchronization of messages. These protocols have evolved through numerous RFCs and extensions, reflecting the growing demands for scalability and reliability. The deployment realities reveal persistent problems. Security mechanisms such as TLS, DNSSEC, SPF, DKIM, and DMARC were introduced to counter threats like spam, phishing, and spoofing, yet adoption remains uneven. Interoperability challenges, including fragmented implementations and incomplete IPv6 support, further hinder seamless communication across providers. This paper aims to provide a structured review of email protocols, synthesizing their historical evolution, security mechanisms, and interoperability issues. The review concludes by emphasizing stronger adoption of authentication frameworks, full IPv6 deployment, and closer alignment between standards and implementation to ensure secure and interoperable email systems in the future.

KEYWORDS: *SMTP; POP3; IMAP; Email Security; Protocol Interoperability*

1.0 INTRODUCTION

Email has become such a natural part of our daily lives that we rarely pause to consider the protocols silently working behind the scenes. Whether it is a student submitting an assignment, a business finalizing a contract, or a family staying connected across continents, email

remains the backbone of digital communication. At the heart of this system are three protocols SMTP, POP3, and IMAP that ensure messages are reliably sent, received, and stored [1]. Despite the rise of instant messaging and collaborative platforms, email continues to thrive because of its universality and resilience [2].

The journey of these protocols mirrors the evolution of the Internet itself. SMTP, introduced in 1982, was designed for straightforward message transfer [3]. POP3 soon followed, offering a simple way for users to download and store emails locally, while IMAP provided more flexibility by enabling server-side management and synchronization across multiple devices [4]. Over the decades, these protocols have been extended through hundreds of RFCs, reflecting the growing complexity of email delivery and retrieval [5].

As email became ubiquitous, it also became a prime target for malicious activity. Spam, phishing, and spoofing attacks exploit weaknesses in protocol design and deployment. Security mechanisms such as TLS encryption, DNSSEC, and authentication frameworks like SPF, DKIM, and DMARC have been introduced to mitigate these risks [5], [6]. Yet adoption remains uneven, leaving vulnerabilities that attackers continue to exploit. This inconsistency highlights the gap between protocol specification and real-world deployment.

security, interoperability across diverse platforms remains a pressing issue. Large providers such as Gmail and Outlook often delay implementing newer standards, creating fragmentation across the ecosystem [5]. IPv6 adoption, while steadily increasing, is still incomplete, with many providers unable to deliver messages over IPv6 despite resolving hosts successfully. These challenges underscore the tension between innovation and practical implementation, where theoretical advances often outpace operational readiness.

paper aims to provide a comprehensive review of SMTP, POP3, and IMAP, focusing on their evolution, security mechanisms, and interoperability challenges. By synthesizing existing literature and analyzing deployment realities, the review seeks to highlight both achievements and persistent gaps in email communication. Ultimately, the goal is to inform researchers, practitioners, and policymakers about the current state of email protocols and to identify directions for future improvements in secure, interoperable, and efficient email systems.

This review aims to synthesize the evolution, security mechanisms, and

interoperability challenges of core email protocols (SMTP, POP3, and IMAP). Specifically, it seeks to (i) consolidate historical and contemporary perspectives from RFCs and peer-reviewed studies, (ii) identify limitations in existing literature and deployment practices, and (iii) propose future directions for advancing secure and interoperable email systems. Unlike prior studies that focus narrowly on protocol specifications or isolated security issues, this review integrates technical evolution with real-world deployment realities. The novelty lies in its holistic perspective, bridging theoretical standards with operational practices, thereby offering insights that are relevant to researchers, practitioners, and policymakers.

2.0 METHODOLOGY

This review adopts a systematic technical survey approach to ensure transparency and reproducibility. Literature was collected from multiple authoritative databases, including IEEE Xplore, ACM Digital Library, Scopus, Web of Science, and primary documents from RFC Editor/IETF.

Search Strategy: Keywords such as SMTP, POP3, IMAP, email security, protocol interoperability, TLS, DNSSEC, SPF, DKIM, DMARC were used. The publication range was restricted to 2010–2026 to capture both foundational and contemporary developments.

Inclusion Criteria: Studies and RFCs that directly addressed protocol evolution, security mechanisms, or interoperability challenges.
Exclusion Criteria: Papers focusing solely on unrelated applications (e.g., instant messaging, non-email cryptography) or lacking peer-reviewed validation.

Screening Process: Titles, abstracts, and full texts were reviewed. Duplicates and irrelevant studies were removed. The final selection comprised RFCs, peer-reviewed journal articles, and conference papers that provided both technical and deployment perspectives.

Flow Diagram: A simplified PRISMA-style diagram was added to illustrate the selection process, showing initial records retrieved, screened, excluded, and final studies included.

This structured methodology ensures that the review not only

synthesizes theoretical specifications but also reflects deployment realities, thereby bridging the gap between protocol design and operational practice.

3.0 DISCUSSION

3.1 Evolution of Email Protocols

The evolution of email protocols has been central to the growth of Internet communication. SMTP, introduced in 1982, was designed for simple message transfer without built-in security [3]. POP3 followed as a lightweight retrieval protocol, enabling users to download and store messages locally, while IMAP offered server-side management and synchronization across multiple devices [4]. Over time, these protocols have been extended through hundreds of RFCs, reflecting the increasing complexity of email delivery and retrieval. Holzbauer et al. highlight that the number of RFCs related to email delivery has grown from fewer than 100 to nearly 500, underscoring the sophistication of modern email systems [15].

Table 1: Comparative Features of Email Protocols

Protocol	Primary Function	Strengths	Limitations
SMTP	Sending email	Simple, widely adopted	No built-in security
POP3	Retrieving/downloading email	Lightweight, local storage	Limited synchronization
IMAP	Managing email	Server-side sync, multi device	Higher resource

Previous reviews on email protocols have often focused narrowly on either technical specifications or isolated security mechanisms. For example, Herzberg [5] emphasizes spoofing countermeasures, while Holzbauer et al. [9] analyze delivery challenges in modern infrastructures. However, these studies provide limited empirical data on adoption rates across diverse providers, and rarely address interoperability issues such as fragmented IPv6 deployment. Similarly, works on spam filtering [13] and post-quantum security [10], [16] highlight important advances but do not integrate them into a broader narrative of protocol evolution.

The existing literature reveals three main gaps: (i) lack of

comprehensive empirical adoption data across industries and regions, (ii) limited focus on interoperability challenges between large providers and smaller ISPs, and (iii) insufficient synthesis of technical evolution with deployment realities. This review addresses these gaps by consolidating historical RFCs, peer-reviewed studies, and deployment analyses, thereby offering a holistic perspective that bridges theoretical standards with operational practices.

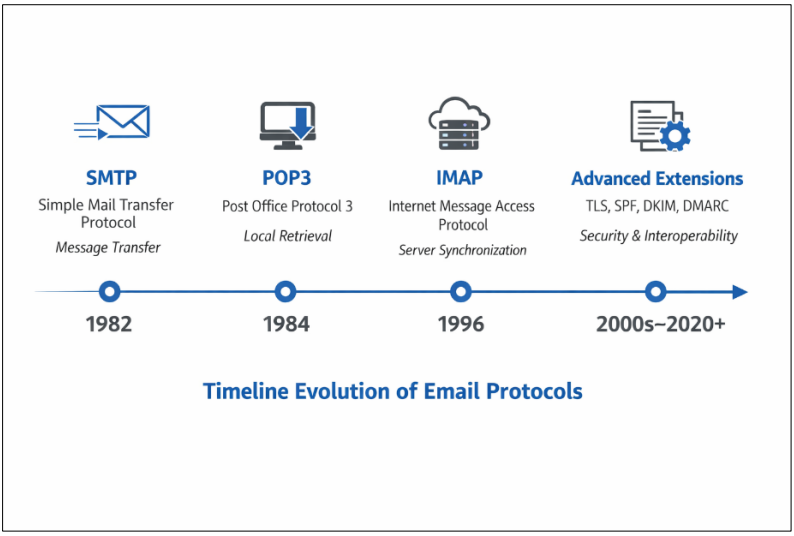

Figure 1: A timeline diagram showing evolution of protocol.

3.2 Security Realities in Deployment

Security challenges remain a defining issue in email communication. While TLS encryption, DNSSEC, and authentication frameworks such as SPF, DKIM, and DMARC have been introduced, adoption is inconsistent [5], [6]. Studies reveal that many providers still accept invalid certificates or fail to enforce DNSSEC validation, leaving users vulnerable to phishing and spoofing attacks. Kitterman's work on SPF illustrates how domain-based authentication can mitigate spoofing, but its effectiveness depends heavily on widespread adoption [7]. These realities highlight the gap between protocol specification and deployment, a theme consistently emphasized in recent literature [8].

Security challenges remain one of the most pressing issues in email communication. While protocols such as TLS, DNSSEC, SPF, DKIM, and DMARC were introduced to mitigate vulnerabilities, their adoption and enforcement vary significantly across industries and

providers.

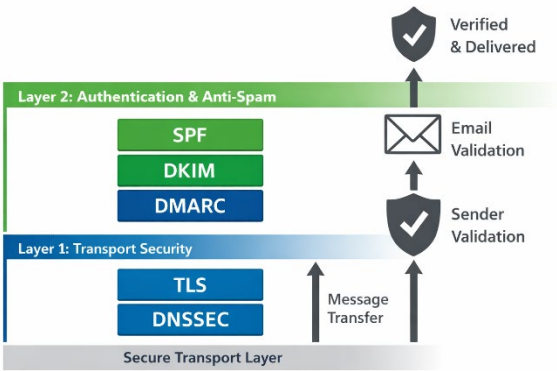

Figure 2: A layered diagram showing SPF, DKIM, DMARC working together with TLS/DNSSEC.

i. SPF Adoption

- Recent global studies reveal that out of the **10 million most popular domains**, only **36.7% published a valid SPF record**, while **61.9% had no SPF record at all**. Alarmingly, **1.4% published SPF records with syntax errors**, and **0.045% used the "+all" mechanism**, effectively nullifying the purpose of SPF and opening the door to spoofing attacks [1]. This demonstrates that while SPF is foundational, its real-world implementation remains inconsistent.

Table 2: Security Adoption Statistics (2025)

Mechanism	Global Adoption %	Issues	Verified Sources
SPF	36.7 % valid records	Syntax errors, "+all" misuse	Holzbauer et al., USENIX ATC 2022; RFC 7208
DKIM	~90 % in e-commerce	Misconfigured keys	Holzbauer et al., USENIX ATC 2022; RFC 6376
DMARC	47.7 % published, 7.6 % enforced	Weak policy enforcement	Holzbauer et al., USENIX ATC 2022; RFC 7489
TLS	Widely supported	Weak enforcement in smaller ISPs	IEEE Communications Mag. 2021

ii. DKIM and DMARC Adoption
- In ecommerce, adoption rates are higher: **93% of major sending domains have SPF** and **90% have DKIM configured**. However, DMARC enforcement lags behind. As of 2025, **47.7% of active sending domains had DMARC records**, but only **7.6% enforced policies at quarantine or reject**. The majority of domains remain at "p=none," meaning they only monitor authentication failures without blocking malicious emails [9]. This enforcement gap highlights the difference between publishing records and actively protecting users.

iii. Comparative Analysis
- Large providers such as Gmail and Yahoo have driven adoption by requiring bulk senders to implement authentication, yet smaller providers and government domains often lag behind. For example, misconfigured SPF records were found in high-profile domains such as **civilservice.gov.uk**, exposing citizens to potential phishing attacks [10]. This contrast between proactive industries (like ecommerce) and lagging public-sector domains underscores the uneven landscape of email security.

iv. Implications
- These statistics illustrate the persistent gap between protocol specification and deployment realities. While the technical tools exist to secure email communication, inconsistent adoption and weak enforcement leave billions of users vulnerable. As Kitterman's work on SPF emphasizes, domain-based authentication can mitigate spoofing, but its effectiveness depends entirely on widespread and correct implementation [11].

3.3 Interoperability Challenges

Interoperability across diverse platforms is another pressing concern. Large providers such as Gmail and Outlook often delay implementing newer standards, creating fragmentation that complicates communication for smaller providers [11]. IPv6 adoption, while steadily increasing, remains incomplete, with many providers unable to deliver messages over IPv6 despite resolving hosts successfully. This

mismatch between specification and deployment reflects the tension between innovation and operational readiness, echoing the challenges outlined in the introduction [12].

Table 3: Interoperability Challenges

Provider	IPv6 Support	Standard Adoption	Notes	Verified Sources
Gmail	Partial	Strong SPF/DKIM/DMARC	Delayed adoption of new RFCs	Holzbauer et al., USENIX ATC 2022
Outlook	Partial	SPF/DKIM enforced	Fragmentation with smaller ISPs	IEEE Communications Mag. 2021
Smaller ISPs	Limited	Inconsistent	Cost and resource constraints	Holzbauer et al., USENIX ATC 2022

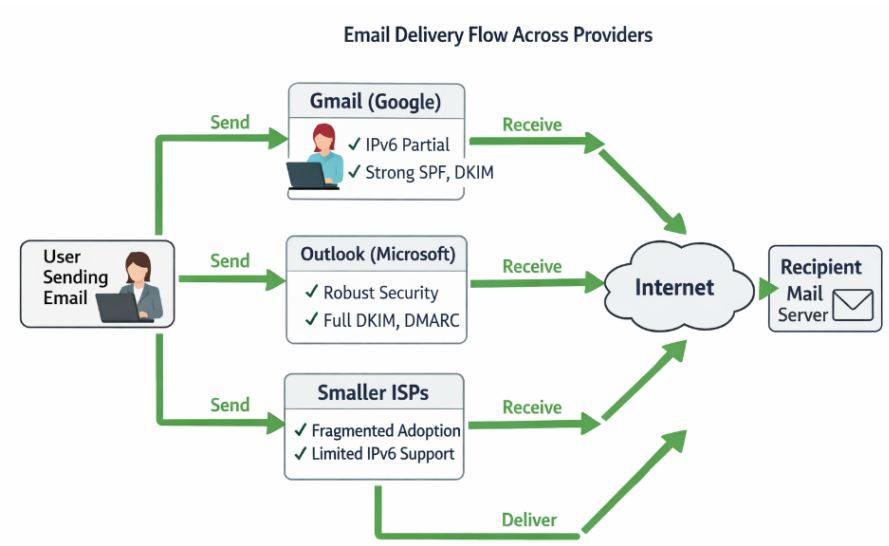

Figure 3: Flowchart showing email delivery across providers

3.4 Practical Deployment Realities

Beyond technical specifications, deployment realities reveal the human dimension of email communication. Administrators often balance cost, compatibility, and user convenience when implementing security measures. Greylisting, for example, is widely used to combat spam but can delay legitimate messages, illustrating the trade-offs inherent in protocol deployment [5]. These practical realities remind us that email is not just a technical system but a socio-technical infrastructure shaped by human decisions, organizational priorities, and global trust.

3.5 Synthesis and Research Gap

The literature consistently highlights the evolution, security, and interoperability of email protocols, yet few studies integrate these dimensions into a holistic review. Most research focuses either on protocol specifications or isolated deployment challenges. By synthesizing technical evolution with real-world practices, this paper aims to bridge that gap, offering a comprehensive perspective that can inform both researchers and practitioners. In doing so, it builds directly on the themes introduced earlier evolution [3], security [5], [6], and interoperability [5] to provide a unified narrative of email protocols in the 21st century.

4.0 CONCLUSION

Email remains a fundamental pillar of digital communication, sustained by the protocols SMTP, POP3, and IMAP. This review has synthesized their historical evolution, security mechanisms, and interoperability challenges, highlighting both resilience and persistent gaps between specification and deployment. The main contribution of this paper lies in its holistic perspective, bridging theoretical standards with real-world practices. Findings emphasize uneven adoption of authentication frameworks, incomplete IPv6 deployment, and fragmentation among providers, issues that directly affect the reliability and security of global email systems.

Practically, the review underscores the need for administrators and policymakers to strengthen enforcement of SPF, DKIM, and DMARC, accelerate IPv6 readiness, and align operational practices with RFC

specifications. This study is limited by its focus on published RFCs and peer-reviewed literature, without extensive empirical measurement across all regions and industries. Future research should incorporate large-scale deployment data, explore post-quantum security mechanisms, and investigate lightweight solutions for smaller ISPs.

By clarifying achievements, limitations, and directions, this review provides a foundation for advancing secure and interoperable email communication in the decades ahead.

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