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Interoperability, spectrum, and regulation in mobile money services: analysis and engineering-based recommendations for developing countries

Interoperabilidad, espectro y regulación en servicios de dinero móvil: análisis y recomendaciones desde la ingeniería para países en desarrollo

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Abstract: This article analyzes mobile money services as drivers of financial inclusion, taking the Colombian case as a reference. From an engineering perspective, it examines three critical factors: interoperability between platforms, radio spectrum management, and technical regulation. Using a documentary and comparative methodology—including international standards and technical data—it identifies low interoperability despite high mobile banking adoption, as well as a positive correlation between 4G coverage and the uptake of digital wallets. The study proposes an interoperable architecture based on open standards, along with cost estimates for dynamic spectrum in rural areas, offering a technical framework applicable to countries with financial ecosystems in transition.

Keywords: Mobile financial services, radio spectrum management, technology regulation, digital financial inclusion.

Resumen: Este artículo analiza los servicios de dinero móvil como promotores de la inclusión financiera, tomando el caso colombiano. Desde un enfoque ingenieril, estudia tres factores críticos: la interoperabilidad entre plataformas, la gestión del espectro radioeléctrico y la regulación técnica, mediante una metodología documental y comparativa, que incluye estándares internacionales y datos técnicos, identificando una baja interoperabilidad pese a la alta bancarización móvil, y una correlación positiva entre la cobertura 4G y la adopción de billeteras digitales. Se propone una arquitectura interoperable basada en estándares abiertos, con estimación de costos para el espectro dinámico en zonas rurales, ofreciendo un marco técnico aplicable a países con ecosistemas financieros en transición.

Palabras clave: Servicios financieros móviles, gestión del espectro radioeléctrico, regulación tecnológica, inclusión financiera digital.

1. INTRODUCTION

Mobile money services have emerged as key tools to foster financial inclusion in regions with limited banking access [1]. In Colombia, platforms such as Nequi, DaviPlata, and Movii have reached over 30 million users for payments, savings, and mobile transfers [2], [3], aligning with global trends of more than 2 billion registered accounts and GDP impacts of up to 1.7% in countries with high adoption rates [4]. However, the country faces three structural challenges: technical interoperability, efficient radio spectrum management [5], and regulatory frameworks that balance innovation, security, and equity [6], [7]. These issues, typically analyzed from economic or legal perspectives, demand an engineering approach to technical architecture, scalability, and sustainability.

1.1. Global context and common barriers

Despite the global growth of mobile money services, developing countries face common barriers that limit their potential, including: (i) fragmented payment ecosystems due to the lack of open technical standards and interoperability agreements among operators; (ii) uneven telecommunications infrastructure, with significant gaps in 4G/5G coverage in rural and low-density areas; (iii) radio spectrum allocation policies that prioritize tax revenue over universal connectivity, raising operational costs; and (iv) hybrid regulatory frameworks that, while promoting financial innovation, do not impose mandatory minimum technical requirements (such as security, availability, or traceability standards). Addressing these challenges from an exclusively economic or legal perspective has proven insufficient, creating a knowledge gap that this article seeks to fill from a systems and telecommunications engineering standpoint.

1.2. Relevance of the Colombian case

Colombia stands out in the global literature for presenting a paradox: high adoption of digital wallets coupled with low technical interoperability [2], as documented in the World Bank's global open finance guidelines [8], generating fragmented ecosystems where users maintain multiple balances, raising costs and limiting network economies. Also for its uneven geography, which imposes technical barriers to mobile coverage, exacerbating urban-rural gaps [3]. And for being a pioneer in regulations such as SEDPEs [6] and open banking [7], serving as a paradigm to examine the limits of institutional innovation without coherent infrastructure. Thus, it acts as a laboratory for lessons in inclusive, secure, and sustainable ecosystems, highlighting the risks of prioritizing commercial growth over systemic architecture.

1.3. Theoretical Framework

The selection of three systems engineering frameworks (SSM, Leavitt's model, and TOGAF) makes it possible to approach the mobile money ecosystem as a complex sociotechnical system, where interoperability, spectrum, and regulation problems are neither exclusively technical nor purely organizational. SSM enables managing the multiplicity of stakeholder views (operators, regulators, users) and designing viable changes in contexts of high uncertainty and conflicting interests, something purely technical models fail to capture. Leavitt's model forces the analysis of interdependencies among technology, structure, tasks, and people, avoiding solutions that optimize only one variable (e.g., imposing APIs without redesigning processes). TOGAF is adopted as the architectural framework that translates strategic and regulatory requirements into a concrete technical roadmap (standards, data layers, applications, infrastructure), indispensable for proposing genuine interoperability and spectrum management. In the adopted methodology (qualitative, documentary, and comparative), these frameworks act as interpretive analysis tools rather than hypothesis-testing techniques, applied to empirical findings (Results) to explain detected gaps and to structure final recommendations (Discussion and Conclusions).

1.3.1. Soft Systems Methodology (SSM)

SSM [9] analyzes complex sociotechnical systems such as mobile money, mapping divergent stakeholder views (operators, banks, fintechs, regulators, users). It facilitates adaptive schemes for commercial-regulatory-social tensions. In Colombia, it maps perspectives on interoperability, designing viable paths beyond decrees.

1.3.2. Leavitt's Model

Leavitt's model [10] interconnects people, tasks, structure, and technology. In Colombia, it shows that interoperability implies redefining processes and aligning institutions; changes in APIs impact the entire system. Applied to the spectrum, it highlights that rural coverage depends on digital

literacy, business models, and available technology [11].

1.3.3. TOGAF (The Open Group Architecture Framework)

TOGAF [12] designs architectures that integrate business objectives and technology. Colombia lacks a national architecture for interoperability [13], cybersecurity, and scalability. A "Target Architecture" is proposed with domains for data, technology (spectrum, protocols), applications, and business, reducing redundancies and strengthening resilience.

1.3.4. Recent Literature on Digital Financial Inclusion

Studies such as Suri & Jack [1], [14] demonstrate the impact of M-PESA on poverty reduction in Kenya, enhanced by interoperability. In West Africa, technical pillars such as connectivity are key [15]. These reinforce systemic approaches for Colombia and similar countries [16].

Together, these three frameworks operate in a chained manner in the analysis: SSM to interpret stakeholder tensions explaining low effective interoperability (Result 1); Leavitt's model to diagnose how technological changes not accompanied by structural adjustments generate fragmentation (Results 1 and 2); TOGAF as a template to propose the interoperable architecture (Figure 2) and to evaluate the disconnect between spectrum policy and financial inclusion (Result 2). Thus, the triangulation is not merely declarative but explicitly executed in the Discussion and Recommendations sections.

1.4 Knowledge gap and research question

The literature on mobile money in developing economies privileges socioeconomic impact analyses [1] or financial regulation studies [17], with a gap in the systems-engineering approach that integrates three interdependent technical variables: interoperability architecture (protocols, messaging standards such as ISO 20022), spectrum planning as enabler of rural coverage, and translation of regulatory mandates into concrete technical requirements (latency, encryption, availability). This leads to partial diagnoses and recommendations that underestimate implementation bottlenecks.

Therefore, this study is guided by the following research question: What is the relationship among technical interoperability, radio spectrum management, and the current regulatory framework in shaping the mobile money ecosystem in a developing country such as Colombia, and what systems engineering recommendations can be derived to overcome the identified barriers? The main contribution is twofold: (a) a technical-quantitative diagnosis (coverage, latency, interoperability level) contrasted with successful benchmarks, and (b) a roadmap based on open standards (TOGAF, ISO 20022) and dynamic spectrum technologies, explicitly designed for contexts of uneven geography and limited resources.

2. MATERIALS AND METHODS

This work corresponds to a documentary analysis article with a comparative approach, integrating a systematic review of secondary sources with the construction of a comparison matrix between three countries (Colombia, Kenya, and Côte d'Ivoire) to identify gaps and formulate engineering recommendations. It is not limited to synthesizing literature; rather, it applies systems engineering frameworks (SSM, Leavitt, TOGAF) to interpret findings and propose a target architecture.

A qualitative, theoretical, and documentary approach is adopted, framed within applied exploratory and analytical research, aiming to identify and critically analyze the technical and regulatory factors that condition the sustainable, secure, and inclusive development of mobile money services in Colombia, emphasizing three structural axes: interoperability between platforms, radio spectrum management, and current regulatory frameworks. The non-experimental methodology is justified by the systemic and complex nature of the object of study, prioritizing a comprehensive interpretation of sociotechnical phenomena based on reliable secondary evidence [9], [10].

2.1. Search strategy and selection criteria

The documentary search was conducted in IEEE Xplore, Scopus, ScienceDirect, Google Scholar, GSMA, SFC, Banca de las Oportunidades, World Bank, and ITU, covering the period 2014–2024 (cutoff February 2025) [4], [5], [16], [2], [3], [6], [7], [8]. Keywords combined terms in Spanish/English: ("mobile money" OR "digital wallet") AND ("interoperability" OR "spectrum

pricing" OR "rural coverage") AND ("regulation" OR "technical standards").

Inclusion criteria were applied: (i) Spanish or English language; (ii) addressing at least two thematic axes (interoperability, spectrum, regulation); (iii) peer-reviewed or institutional sources (GSMA, BCEAO, etc.) [1], [15], [14]. Commercial documents without technical data, unsupported opinions, and duplicates were excluded.

For the Colombia-Kenya-Côte d'Ivoire comparative matrix (Table 1), five homogeneous technical indicators were defined (latency, interoperability, rural 4G coverage, % interoperable transactions, common technical framework). Data were extracted from [1], [4], [5], [16], [2], [3], [15], [14], [11] and validated by prioritizing GSMA/World Bank sources in case of discrepancies. The evidence matrix is available upon request from the author.

2.2 Methodological procedure

The analysis was developed in three sequential phases:

Documentary Systematization: Classification of documents by axes (interoperability, spectrum, regulation), extracting key categories such as standardization [13], spectral efficiency [5], operational resilience [11], technological governance, and network availability [9], [12].

International Comparative Analysis: Construction of a contrast matrix between Colombia, Kenya, and Côte d'Ivoire, with 5 technical indicators (latency, rural 4G coverage, interoperability, % interoperable transactions, common technical framework) to identify gaps, good practices, and opportunities [1], [15], [14].

Technical-Regulatory Interpretive Analysis: Application of systems engineering frameworks (SSM [9], Leavitt's model [10], TOGAF [12]) to interpret findings, detect bottlenecks, and formulate recommendations [11]. Neither simulations nor primary data were used; instead, consolidated technical data and structural reasoning based on systems architecture principles, process standardization, and spectrum planning were employed [13].

2.3 Justification of the engineering approach

This engineering approach addresses a gap in the financial inclusion literature, which privileges economic, legal, or sociological perspectives, underestimating the technical impact on feasibility, equity, and sustainability [17]. Variables such as network architecture, interoperability, spectrum allocation, and standards are analyzed using systems and telecommunications engineering tools, revealing problems in territorial equity, rural coverage, quality of service, and inclusion of emerging actors [5], [11].

2.4. Methodological limitations

Three main limitations are identified: absence of primary field data due to logistical and time constraints; reliance on secondary sources, susceptible to institutional biases; and impossibility of computational simulations or laboratory tests for interoperability or spectral efficiency scenarios. Nevertheless, the documentary approach is adequate for the objectives, thanks to the technical quality of the sources, their comparative validity, and the triangulation of regulatory, technical, and empirical information [9].

3. RESULTS

Result 1: Technical Fragmentation and Limited Interoperability.

Finding 1.1: Interoperability between mobile money platforms in Colombia is low; although Transfiya exists, less than 30% of transactions are interoperable (Table 1), forcing multiple wallet balances and raising costs [2], [3].

Finding 1.2: Closed or semi-open architectures predominate without a unified protocol, with non-standardized APIs and costly bilateral integrations, contradicting standards such as ISO 20022 [13]. In Côte d'Ivoire, interoperability improved access to educational payments by reducing frictions [16], [15]; in Colombia, this generates redundancies and low resilience, contrary to ITU-T principles [11].

Table 1 compares technical metrics with Kenya and Côte d'Ivoire, highlighting gaps in interoperability and rural coverage, aligned with CGAP/World Bank literature [1], [14].

Table 1: *Technical comparison of the mobile money ecosystem: Colombia, Kenya, and Côte d'Ivoire.*

Indicator	Colombia	Kenya	Côte d'Ivoire
Average transfer latency	~2–4 sec (ACH/QR)[1]	<1 sec (M-PESA)[2]	~2–3 sec[3]
Interoperability level	Partial (Transfiya)	High (M-PESA, Airtel)[4]	Medium
% Rural 4G coverage	~60 %[5]	>80 %[6]	~50 %[7]
% Interoperable transactions	<30 %[8]	>90 %[9]	60–70 %[10]
Common technical framework	No	Yes (regulator + GSMA)	Partial

Notes: [1]Estimated latency [2]; [2]Data from [1]; [3]Own estimate based on [15]; [4]Total interoperability [1]; [5]GSMA data [5]; [6]Ibid.; [7]Data from [15]; [8]Estimate [3]; [9]Data from [1]; [10]Estimate [15].
Sources: *[1], [16], [2], [3], [15], [14], [11].*

This comparison quantifies technical gaps, useful for public policies [11]. The chronology of regulatory/technological milestones, 2014–2024, based on GSMA and national regulations [4], [5], [16], [6], [7], shows advances such as SEDPE and Transfiya, but with delays in standardization.

Result 2: Gap in Spectrum Management and Impact on Rural Coverage

Finding 2.1: There is a disconnect between spectrum allocation and rural financial inclusion; auctions (e.g., 700 MHz, 2019) face high costs and taxes without incentives for expansion in low-density areas [5], [16]. This limits QoS, latency, and reliability for mobile transactions [17].

Figure 1 (map of 4G/5G coverage and regional wallet adoption, sources: GSMA, MinTIC, Banca de las Oportunidades [4], [5], [2], [3]) correlates incomplete coverage (south/east) with low adoption, demanding equitable policies. Parallels in regulatory challenges for sustainable wireless infrastructure [11] emphasize strategic alignment between telecommunications and finance.

Result 3: Correlation between 4G Coverage and Mobile Wallet Adoption

Finding 3.1: Evidence suggests an association between 4G coverage and departmental adoption of mobile wallets. The 2023 Financial Inclusion Report [2] indicates that the highest rates of low-account-balance deposits (associated with digital wallets) are concentrated in Bogotá and Antioquia. In contrast, GSMA [5] identifies that departments with low 4G coverage (e.g., Chocó) face greater affordability barriers and show lower penetration of digital services. This geographic association, consistent with findings reported in Kenya for M-PESA [1], [14], suggests that connectivity infrastructure is a critical enabler for digital financial inclusion.

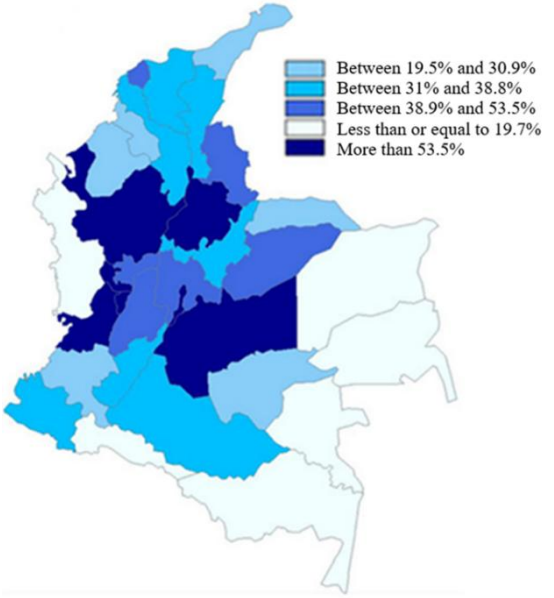

Fig. 1. *4G/5G coverage in Colombia and regional use of mobile wallets by department, Colombia (2023).*
Source: *[4], [5], [16], [3].*

Regulatory Framework: Advances with Technical Delays

Colombia was a pioneer with SEDPE (Law 1735/2014 [6]) and open banking (Circular 029/2014 [7]), diversifying non-bank actors. However, a standardized technical framework for interoperability is lacking, leaving implementation to operators and causing fragmentation [17]. Advances in APIs for open banking lack minimum security/scalability standards, a gap in distributed systems [13], [12]. Fiscal policy (digital taxes) acts as a barrier, reducing investments in interoperability/coverage [4], [5], [6]. Regulatory sandboxes with an engineering approach are essential for fintech innovations [17].

4. DISCUSSION

4.1. Findings derived from the evidence

The results show advances in the expansion of mobile money in Colombia, but technical and regulatory obstacles persist that limit its role in

financial inclusion. From an engineering perspective, these challenges arise from technical decisions affecting interoperability, spectral efficiency, and regulatory coherence.

Finding 1: Interoperability in Colombia is partial and bilateral, despite regulations such as Circular Externa 029 of 2014 [7], with less than 30% of interoperable transactions and a predominance of closed architectures [2], [3]. Finding 2: There is a disconnect between spectrum allocation policy and rural coverage, evidenced in auctions (e.g., 700 MHz) without expansion obligations in low-density areas [5], [16]. Finding 3: Documentary evidence shows a positive geographic association between 4G coverage and mobile wallet adoption [2], [3]. Finding 4: Colombia has regulatory advances (SEDPE, open banking) but lacks a standardized technical framework for interoperability, leaving implementation to operators and generating fragmentation [6], [7], [17].

4.2. Interpretations from the engineering frameworks (SSM, Leavitt, TOGAF)

Leavitt's Model: Findings 1.1 and 1.2 are explained because technology (non-standardized APIs) impacts structure (complex bilateral agreements), tasks (redundant integrations), and people (fragmented experience).

SSM: Reveals divergent stakeholder views. Operators see interoperability as a competitive threat, while regulators see it as a public mandate. Without a shared purpose, technical solutions are insufficient.

TOGAF: Findings 2.1 and 3.1 are explained because the business architecture (financial inclusion) does not align with the technology architecture (spectrum management). A target architecture with incentives for rural coverage is needed, treating connectivity as a strategic enabler.

4.3. In-depth international comparison

Côte d'Ivoire demonstrates that a common technical framework (driven by BCEAO) enables efficient school payments [16], [15]. Colombia has regulatory mandates focused on finance, leaving technical standards to entities, generating asymmetries and risks. From Kenya, we learn that total interoperability (M-PESA with Airtel) was possible because the regulator imposed it with deadlines and sanctions, while in Côte d'Ivoire, partial success was due to a uniform regional technical framework [1], [15], [14]. Regarding digital payment systems in emerging economies (Kenya, India, Brazil, Peru), it is confirmed that early and regulated interoperability is a key predictor of success in financial inclusion [18]. A cross-cutting lesson is that successful transformations depend on a shared technical-systemic vision among regulators, operators, and developers. Colombia has prioritized commercial growth over systemic architecture, resulting in fragmented ecosystems.

4.4. Recommendations and proposals of the study

Based on the findings and interpretations, the following engineering recommendations are formulated:

A distributed architecture is proposed with a centralized bus, standardized open APIs (ISO 20022 [13]), a unified security layer, and regulatory supervision (Figure 2), aligned with TOGAF [12], ITU-T D.50, and CPMI [17]. This responds to the findings with standardized APIs and governance, and incorporates lessons from SSM.

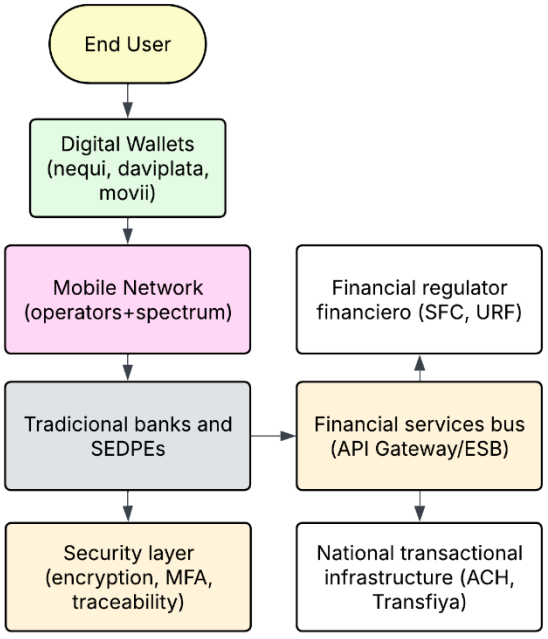

Fig. 2. *Propuesta de arquitectura interoperable para el ecosistema de dinero móvil colombiano.*
Fuentes: [16], [12], [13], [17], [11].

Adoption of Dynamic Spectrum Access (DSA) and TV White Spaces is recommended to extend rural connectivity without compromising QoS [11], with an estimated cost of USD 100,000–300,000 per locality (base stations, spectrum management, solar

energy, backhaul), supported by the World Bank [15] and ITU [11]. This can be amortized through public-private consortia or shared licenses, with benefits for financial inclusion and local commerce. Modern regulation must include mandatory minimum requirements: uptime >99.5%, end-to-end encryption, multifactor authentication, disaster recovery, and periodic audits [17]. Regulatory sandboxes with an engineering approach are essential for validating fintech innovations [17].

Blockchain offers traceability and resilience, but in Colombia precautions are required due to limited connectivity; PoW should be avoided (due to latency and energy consumption); opt for permissioned networks such as Hyperledger Fabric or Corda, combined with digital signature and optimized storage for efficient scalability.
4.5 Strategic reflections, economic impact, and systemic synthesis

For Colombia, the following is recommended: adopt standards (ISO 20022, open APIs), design spectrum policies with a rural focus, implement technical sandboxes, foster infrastructure consortia, and define performance metrics in regulation [19]. Infrastructure duplication generates inefficiencies, higher fixed and operating costs, longer development times, and barriers to entry for emerging fintechs, reducing competitiveness, economies of scale, and inclusive growth. Finally, the identified problems are systemic failures: SSM explains social fragmentation; Leavitt's model reveals technical-human interconnections; TOGAF provides coherent redesign. The results validate this interpretation.

The fourth edition of the LATAM Fintech Regulation study [20] highlights that Colombia occupies an intermediate position in regulatory maturity compared to Brazil and Mexico, with advances in real-time payments and sandboxes, but with delays in mandatory technical standards.

4.6. Limitations of the study

This study adopts a qualitative-documentary approach, based on secondary sources (GSMA, government, multilaterals), offering a systemic vision but without primary data (surveys, interviews), which limits the capture of real perceptions and may entail institutional biases. The approach is relevant for conceptual objectives, is supported by standards (TOGAF [12], ISO 20022 [13]) and comparative cases, and reveals the technical-political divide, proposing an integrative systemic regulation.

5. CONCLUSIONS

This analysis shows that mobile money in Colombia, despite its mass adoption and commercial success, faces a fragmented technical and regulatory architecture that limits its inclusive potential. Interpreted through TOGAF [12], SSM [9], and Leavitt's Model [10], the findings reveal systemic bottlenecks: low standardized interoperability (Finding 1.1), disconnect between spectrum policy and rural coverage (Finding 2.1), and technical regulatory gaps (Regulatory Framework).

To move from quantitative to qualitative growth, the following strategic roadmap is proposed:

National interoperability architecture: Based on technical fragmentation (Findings 1.1, 1.2) and divergent views (SSM [9]), implement a financial services bus with ISO 20022 [13] and open APIs under TOGAF [12], supervised by the Financial Regulation Unit for multi-stakeholder governance.
Connectivity as critical infrastructure: Given the coverage-adoption association (Finding 3.1) and closed spectrum management (Finding 2.1), reform auctions with universal licenses, differentiated prices, and rural obligations; foster public-private partnerships for technologies such as TV White Spaces [11].

Technical regulation and adaptive governance: Faced with regulatory advances lacking technical rigor (Regulatory Framework), enact mandatory minimum requirements (uptime >99.5%, end-to-end encryption, multifactor authentication, business continuity); institutionalize a Regulatory Sandbox to validate solutions such as permissioned blockchain [21], [17].

Intersectoral coordination and fiscal sustainability: To overcome the technical-political dichotomy and excessive taxation [4], [5], [6], create a Permanent Technical Committee (MinTIC, Financial Superintendence, DIAN, Central Bank) to align digital, financial, and fiscal policies, incentivizing interoperability and resilience.

In summary, systems and telecommunications engineering provides the scaffolding for this transition, prioritizing interoperability, universal coverage, and security as design attributes.

Colombia can lead a robust, vibrant, and transformative mobile money model in Latin America by implementing this roadmap.

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