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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.

INTRODUCTION

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

Global context and common barriers

Despite the global growth of mobile money services, developing countries face common barriers that limit their potential: (i) payment ecosystems fragmented by the lack of open technical standards and interoperability agreements between operators; (ii) uneven telecommunications infrastructure, with significant gaps in 4G/5G coverage in rural areas and areas of low population density; (iii) spectrum allocation policies that prioritize tax revenue over universal connectivity, raising operating costs; and (iv) hybrid regulatory frameworks that, although they promote 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 the perspective of systems and telecommunications engineering.

Relevance of the Colombian case

Colombia stands out in the global literature for a paradox: high adoption of digital wallets alongside low technical interoperability[2], as documented in the World Bank's global open finance guidelines[8]. This generates fragmented ecosystems in which users maintain multiple balances, raising costs and limiting network economies. It also stands out for its uneven geography, which imposes technical barriers in mobile coverage and exacerbates urban-rural gaps[3], and for being a pioneer in regulations such as SEDPEs[6]and open banking[7], serving as a paradigm for examining 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.

Theoretical Framework

The selection of the three systems engineering frameworks (SSM, the Leavitt model and TOGAF) makes it possible to address the mobile money ecosystem as a complex sociotechnical system, in which the problems of interoperability, spectrum and regulation are neither exclusively technical nor purely organizational. SSM makes it possible to manage the multiplicity of visions among actors (operators, regulators, users) and to design viable changes in contexts of high uncertainty and conflicting interests, which purely technical models do not capture.

The Leavitt model forces the analysis of interdependencies among technology, structure, tasks and people, avoiding solutions that optimize only one variable (for example, 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), something indispensable for proposing real interoperability and spectrum management. In the methodology adopted (qualitative, documentary and comparative), these frameworks act as interpretive analysis tools and not as hypothetical verification techniques, being applied to the empirical findings (Results) to explain the gaps detected and to structure the final recommendations (Discussion and Conclusions).

Soft Systems Methodology (SSM)

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

Leavitt model

The Leavitt model[10]interconnects people, tasks, structure and technology. In Colombia, it shows that interoperability entails redefining processes and aligning institutions; changes in APIs impact the entire system. Applied to spectrum, it highlights that rural coverage depends on digital literacy, business models and available technology[11].

TOGAF (The Open Group Architecture Framework)

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

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

Recent Literature on Digital Financial Inclusion

Taken together, these three frameworks operate in a chained manner in the analysis: SSM to interpret the tensions among actors that explain the low effective interoperability (Finding 1); the Leavitt model to diagnose how technological changes not accompanied by structural adjustments generate fragmentation (Findings 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 (Finding 2). In this way, triangulation is not merely declarative but is explicitly executed in the Discussion and Recommendations sections.

Knowledge gap and research question

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

Therefore, this study is guided by the following research question: What is the relationship between 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, level of interoperability) 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.

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 contrast matrix among three countries (Colombia, Kenia, and Costa de Marfil) to identify gaps and formulate engineering recommendations; it does not limit itself to synthesizing literature but applies systems engineering frameworks (SSM, Leavitt, TOGAF) to interpret the findings and propose a target architecture.

A qualitative, theoretical, and documentary approach is adopted, framed within applied research of an exploratory and analytical nature, with the aim of identifying and critically analyzing 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].

Search strategy and selection criteria

The documentary search was conducted in IEEE Xplore, Scopus, ScienceDirect, Google Scholar, GSMA, SFC, Banca de las Oportunidades, the World Bank, and ITU, covering the period 2014-2024(cut-off February 2025)[4],[5],[16],[2],[3],[6],[7],[8]. The 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/English languages; (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-Kenia-Costa de Marfil 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 the event of discrepancies. The evidence matrix is available upon request from the author.

Methodological Procedure

The analysis was carried out in three sequential phases:

Documentary Systematization: Classification of documents by axis (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 among Colombia, Kenia and Costa de Marfil, 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-Normative Interpretive Analysis: Application of systems engineering frameworks (SSM[9], Leavitt model[10], TOGAF[12]) to interpret findings, detect bottlenecks and formulate recommendations[11]. No simulations or primary data were used; rather, consolidated technical data and structural reasoning based on principles of systems architecture, process standardization and spectrum planning[13].

Justification of the Engineering Perspective

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

Methodological Limitations

Three main limitations are identified: absence of primary field data due to logistical and time constraints; dependence 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 normative, technical and empirical information[9].

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 balances in wallets and raising costs[2],[3].

Finding 1.2: Closed or semi-open architectures without a unified protocol predominate, with non-standardized APIs and costly bilateral integrations, contrary to standards such as ISO 20022[13]. In Costa de Marfil, 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 Kenia and Costa de Marfil, highlighting lags in interoperability and rural coverage, aligned with CGAP/World Bank literature[1],[14].

Table 1: Technical comparison of the mobile money ecosystem: Colombia, Kenia and Costa de Marfil

Indicator	Colombia	Kenia	Costa de Marfil
Average transfer latency	~2–4 s (ACH/QR)[1]	<1 s (M-PESA)[2]	~2–3 s[3]
Level of interoperability	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]Full interoperability [1]; [5]GSMA data [5]; [6]Ibid.; [7]Data from [15]; [8]Estimate [3]; [9]Data from [1]; [10]Estimate [15]. Source: [1], [2], [3], [11], [14], [15], [16].

This comparison quantifies technical gaps that are useful for public policy[11]. The chronology of regulatory and technological milestones, 2014–2024, based on GSMA and national regulations[4],[5],[16],[6],[7], shows advances such as SEDPE and Transfiya, but also lags 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 with no incentives for expansion in low-density areas[5],[16]. This limits QoS, latency, and reliability for mobile transactions[17].

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

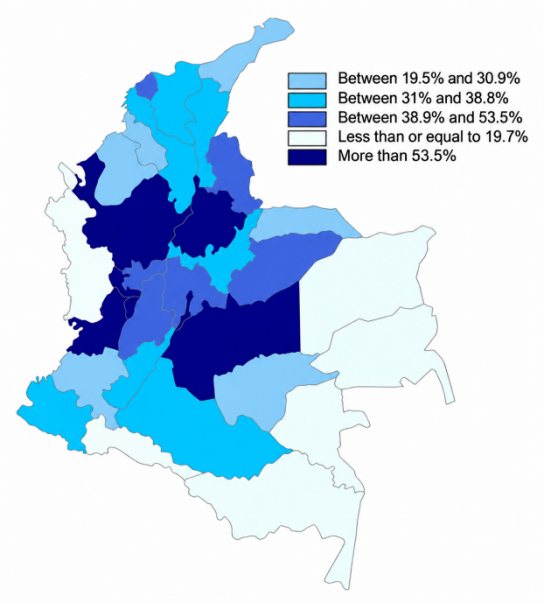

Fig. 1. *4G/5G coverage in Colombia and regional mobile wallet use by department, Colombia (2023). Source: [4], [5], [16], [3].*

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

Finding 3.1: The 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 holding low-value deposits (associated with digital wallets) are concentrated in Bogotá and Antioquia. Conversely, 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 Kenia for M-PESA[1],[14], suggests that connectivity infrastructure is a critical enabler for digital financial inclusion.

Regulatory Framework: Progress with Technical Lags

Colombia is 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, which leaves implementation to operators and causes fragmentation[17]. Advances in APIs for open banking lack minimum security and scalability standards, a gap in distributed systems[13],[12]. Fiscal policy (digital taxes) acts as a barrier, reducing investments in interoperability and coverage[4],[5],[6]. Regulatory sandboxes with an engineering perspective are essential for fintech innovations[17].

DISCUSSION

Findings derived from the evidence

The results show progress in the expansion of mobile money in Colombia, but technical and regulatory obstacles persist that limit its role in financial inclusion. From an engineering standpoint, these challenges arise from technical decisions that affect interoperability, spectral efficiency and regulatory coherence.

Finding 1: Interoperability in Colombia is partial and bilateral, despite regulations such as External Circular 029 of 2014[7], with less than 30% of transactions interoperable 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: The 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].

Interpretations from engineering frameworks (SSM, Leavitt, TOGAF)

Leavitt 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: It reveals divergent visions among actors. Operators view interoperability as a competitive threat and regulators as a

public mandate. Without a common purpose, technical solutions are insufficient.

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

In-depth international comparison

Costa de Marfil demonstrates that a common technical framework (driven by BCEAO) makes it possible to promote efficient school payments[16],[15]. Colombia has regulatory mandates focused on financial aspects and leaving technical standards to the entities, generating asymmetries and risks. From Kenia it is learned that full interoperability (M-PESA with Airtel) was possible because the regulator imposed it with deadlines and sanctions, whereas in Costa de Marfil the partial success was due to a uniform regional technical framework[1],[15],[14]. Regarding digital payment systems in emerging economies (Kenia, 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.

Recommendations and proposals of the study

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

We propose a distributed architecture 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 on standardized APIs and governance and incorporates lessons from SSM.

It is recommended to adopt Dynamic Spectrum Access (DSA) and TV White Spaces to extend rural connectivity without compromising QoS[11], with an estimated cost of USD100.000–300.000 per locality (base stations, spectrum management, solar power, backhaul), supported by the World Bank[15]and ITU[11]. This can be amortized through public-private consortia or shared licenses, with benefits in financial inclusion and local commerce.

Modern regulation must include mandatory minimum requirements: uptime >99.5%, end-to-end encryption, multi-factor authentication, disaster recovery and periodic audits[17]. Regulatory sandboxes with an engineering perspective are essential for validating fintech innovations[17].

Blockchain offers traceability and resilience, but in Colombia it requires precautions because of limited connectivity; PoW should be avoided (due to latency and energy consumption), opting instead for permissioned networks such as Hyperledger Fabric or Corda, combined with digital signature and optimized storage for efficient scalability.

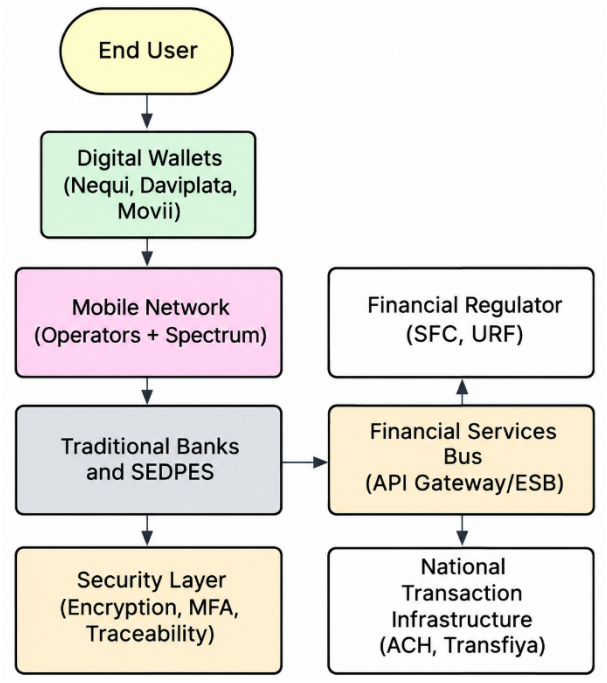

Fig. 2. *Proposed interoperable architecture for the Colombian mobile money ecosystem. Source: [16], [12], [13], [17], [11].*

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 technical regulation[19]. Infrastructure duplication generates inefficiencies, higher fixed and operating costs, longer development times, and entry barriers for emerging fintechs, reducing competitiveness, economies of scale, and inclusive growth. Finally, the problems identified are systemic failures: SSM explains social fragmentation; the Leavitt model reveals the technical-human interconnections; TOGAF provides the coherent redesign. The results validate this interpretation.

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

Study limitations

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

CONCLUSIONS

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

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

National interoperability architecture: Based on technical fragmentation (Findings 1.1, 1.2) and divergent visions (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-actor governance.

Connectivity as critical infrastructure: Given the coverage-adoption correlation (Finding 3.1) and closed spectrum management (Finding 2.1), reformulate auctions with universal licenses, differentiated pricing, and rural obligations; foster public-private partnerships for technologies such as TV White Spaces[11].

Technical regulation and adaptive governance: In view of regulatory advances without technical rigor (Regulatory Framework), enact mandatory minimum requirements (uptime >99.5%, end-to-end encryption, multi-factor 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 Superintendency, DIAN, Banco de la República) 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 in Latin America with a robust, vibrant and transformative mobile money model by implementing this roadmap.

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