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FROM GLOBAL TO LOCAL: A STUDY OF LOCAL-FIRST COMMUNITY INFRASTRUCTURE DEVELOPMENT

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Abstract

Global communication networks have long been dominated by centralized, client-server models, which face increasing challenges due to environmental, social, and digital privacy concerns. This thesis explores the potential of distributed, Local-First (Kleppmann et al., 2019), Open-Source, Peer-to-Peer (P4P) networks in supporting resilient infrastructures that prioritize local resilience and data sovereignty. Rooted in Complexity Theory, specifically self-organizing systems, this research examines how social and technical structures within P4P projects evolve in parallel, reflecting a synthesis of critical realism and complexity (Byrne & Callaghan, 2022). The study employs a multiple-case study design, analyzing nine P4P projects, including Āhau, Holochain, and Scuttlebutt, through 21 semi-structured interviews, workshops, and co-creation exercises.

Key findings highlight the strong correlation between organizational structures and technical architectures. For example, Scuttlebutt's node-based technical design mirrors its relational structure, while Dat shifted from a hierarchical to a modular model, reflecting its evolving technical architecture. Additionally, locality—both geographic and cultural—emerged as a crucial factor for the successful implementation of P4P networks. Modularity in both technical design and social organization enhanced adaptability and local innovation, with lower financial barriers enabling community-aligned protocols.

The conclusion underscores the isomorphic nature of technical and social systems, emphasizing that self-organizing systems thrive when components are small, achievable, and modular. The research contributes to the emerging field of self-organizing infrastructures and highlights the importance of modular communication protocols in fostering decentralized ecosystems. Future research could further explore the relationship between self-organizing systems, organizational and technical patterns.

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Introduction

In recent decades, global communication networks have relied on centralized, client-server models, which are increasingly strained in a world marked by environmental crises, social instabilities, and digital privacy concerns (Calvin et al., 2023). Calls for more resilient infrastructure (EU Critical Infrastructures Directive, 2022) and the development of "Good Internets" (AoIR Sheffield, 2024) have gained prominence as societies face these unprecedented challenges. There is a growing need for alternative infrastructures that support local resilience and ensure data sovereignty. Open-source, Peer-to-Peer (P2P), and local-first networks — collectively termed “P4P” (Peer-for-Peer) — have emerged as promising models for resilient communication systems. Rooted in distributed architectures, P4P networks reduce dependency on centralized systems and offer robust, local-first data control. This thesis examines the role of P4P networks in supporting resilient local infrastructures and explores the factors that enable their maturity and scalability within the self-organizing framework of the Open-Source movement.

Theory

The theoretical foundation is rooted in Complexity Theory and it's associated ontology. The ontology is explored by Reed and Harvey (1992), and further developed by Byrne and Callaghan in 2022, under the term 'Complex Realism' (Byrne & Callaghan, 2022). As the name suggests, it's a synthesis of critical realism and complexity.

Complexity Theory is a vast field, the focus of this paper is on self-organizing systems. Self-organizing systems are systems that (without any central authority or external control) spontaneously organize and form structured patterns through internal interactions, termed emergence. Qualities of self-organizing systems include resilience and adaptability (Anzola et al., 2017; Estrada-Jimenez et al., 2021; Fuchs, 2006; Gershenson & Heylighen, 2003; Heylighen, 2010; Jean Boulton et al., 2015; Miller & Page, 2007). From a technical perspective autonomic computing such as largelanguage models can be considered self-organizing, in this study focus is rather onsocial self-organizing systems, specifically the Open-Source movement.

Methodology

A multiple-case study design was selected to capture the diversity within P4P networks and examine their development across various contexts. Nine case studies were chosen to represent the spectrum of P4P projects, ranging from protocol-focused initiatives like Holochain to community-driven projects like Āhau. The projects interviewed include Āhau, Briar, Dat (Hypercore), Holochain, Grobund, Mapeo, MeliBees, Secure Scuttlebutt, Qaul, and, partially, Willow. Data collection involved 21 semi-structured interviews with 16 representatives, a workshop with P4P developers, andvisual tools that empowered participants to co-create and validate findings. Inductive coding and thematic analysis were applied to identify recurring themes, challenges, andenabling factors (Williams & Moser, 2019). This approach provided a grounded understanding of how P4P networks evolve as decentralized, resilient communication systems.

Main Findings

The findings demonstrate a strong interplay between the organizational structures of P4P projects and their technical architectures. For example, Scuttlebutt (SSB) and Dat, both originating in the Node.js community, began as modular technologies. Scuttlebutt's node-based technical design mirrored its social organization, where relational networks closely guarded operational knowledge. In contrast, Dat evolved from a hierarchical model into a modular ecosystem, aligning with its technical architecture. Similarly, Mapeo transitioned from rigid roles to a more adaptive, self-organizing structure, while Āhau and Holochain also exhibited organizational forms reflecting their technological designs.

Locality, both geographic and cultural, emerged as a critical factor in P4P adoption. Projects like Grobund, Mapeo, Āhau, and Meli Bees exemplified the role of social bridging in connecting communities with technology. Successful implementation often depended on actors deeply embedded within the community who could bridge the gap between technical design and local needs. Tailored applications, ideally created by developers within the community, were shown to be most effective in meeting specific requirements.

Modularity was a consistent theme across cases, enhancing both technological adaptability and organizational flexibility. Modular designs facilitated local innovation, lowered financial barriers, and supported the development of community-aligned communication protocols. For example, Āhau combines Scuttlebutt and Dat protocols to address unique community needs, underscoring the importance of "bridges" that connect technical and social dimensions in decentralized technologies.

Main Findings

The conclusion highlights that technical and social organizational systems are often intertwined, with multiple cases indicating a reverse Conway's Law: social organizational forms frequently evolve to resemble the distributed and fluid structures of the technical layers. In complexity theory terms, nested self-organizing systems replicate each other's patterns, resulting in isomorphic structures.

Certain system preconditions are essential for the development of P4P communication architectures. Components of development in self-organizing systems benefit from being small, documented units with a clear purpose, achievable by 1-2 contributors, and modular in nature. The system as a whole functions best when there are bridges between actors. This approach not only functions well in self-organized environments by reducing maintenance burdens, but also enables the local development of value-aligned communication protocols due to lower financial thresholds and greater adaptability.

Principles of successful development in self-organizing social systems can apply equally to technical organization of modules as well as the social organization of the development. In summary, successful self-organizing architecture may adhere to the following principles: small, achievable, specific, documented, bridgable, complete, and modular.

Discussion

The observed shifts in the social organization of development groups, where structures over time mirrored the technical organization of the software, warrant further research to clarify the correlational relationships involved. Many factors could influence these patterns, and boundaries within self-organizing systems remain subjective interpretations by interviewees. This raises questions about the applicability of these findings to other cases and contexts. Research on Open-Source movements and social systems as self-organizing phenomena remains a relatively uncharted field (Anzola et al., 2017).

This study also did not address technological readiness or financial factors, both of which significantly impact the adoption of new technologies, particularly in local communities. In the realm of infrastructures, the concept of self-organizing or “Inverse Infrastructures” (Egyedi & Mehos, 2012; Heino & Anttiroiko, 2015) is an emerging area of study. Further research can support the development of organizational practices and local implementation strategies for resilient and adaptive infrastructures.

Finally, the move toward modular communication protocols represents a shift away from global standards and centralized decision making in relation to communication protocols, and toward an ecosystem-based approach. Due to the multitude of small components an infrastructure can consist of, there's a growing importance of SBOMs (Software Bill of Materials) as tools for modular development in the self-organizing system of Open-Source (Axelsson & Larsson, 2023).

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