Temporal structure and multifractality of mobility networks during COVID-19: empirical analysis and mechanistic modeling

Keywords: complex systems, temporal networks, mobility dynamics, multifractality, COVID-19, network portrait divergence

Extended Abstract

Motivation. Human mobility is a key driver of epidemic spread and responds strongly to public health interventions. Understanding how mobility networks change their temporal structure and scaling properties under external constraints is important for modeling societal resilience during crises. Empirical studies have documented substantial cross-country differences in mobility dynamics during COVID-19 [1], but the mechanistic origin of these differences, in particular the emergence of multifractal scaling in temporal network dynamics, remains unexplained. We address this gap by combining an empirical analysis of inter-regional mobility networks with a generative model designed to reproduce and explain the observed patterns.

Approach and Methodology. In the empirical component, we analyze mobility data for Italy, the United Kingdom, Sweden, and Brazil over approximately two years of the pandemic using the Meta Data for Good initiative [2]. We construct temporal binary and weighted networks from 8-hour inter-regional mobility snapshots and quantify structural change using Network Portrait Divergence (NPD) [3] across three timescales: adjacent intervals (lag 1), daily (lag 3), and weekly (lag 21). We characterize the scaling properties of the resulting NPD time series using Multifractal Detrended Fluctuation Analysis (MFDFA) [4].

In the modeling component, we develop a generative framework for temporal mobility networks built around four mechanisms: (i) a globally acting AR(1) activity signal with daily and weekly periodic forcing; (ii) an inertial flow matrix evolving over a fixed spatial heterogeneity backbone encoding persistent mobility corridors; (iii) an activity-proportional edge inclusion threshold that produces a network whose density co-evolves with mobility intensity; and (iv) a Markovian lockdown process that intermittently suppresses global activity by a strictness factor $\lambda \in [0,1]$. We systematically explore the parameter space of lockdown frequency $p_{\text{lock}} \in [0,1]$ and strictness λ, running 60,000 simulations per unlock probability $p_{\text{unlock}} \in \{0.05, 0.10, 0.20\}$.

Results. Empirically, NPD time series exhibit a consistent timescale ordering $\text{NPD}(1) > \text{NPD}(3) > \text{NPD}(21)$, reflecting strong circadian and weekly regularities in network structure. Countries with strict public health interventions, Italy and the United Kingdom, display multifractal NPD profiles, while countries with milder measures, Brazil and Sweden, show predominantly monofractal behavior. This contrast suggests that policy-driven disruptions to mobility introduce hierarchical variability beyond the baseline temporal organization of the system.

In the generative model, regime-switching lockdown dynamics reproduce this contrast mechanistically. The multifractal width δH of simulated NPD series increases monotonically with lockdown intensity $p_{\text{lock}} \times \lambda$ across all temporal lags and all values of p_{unlock} (Fig. 1). When p_{unlock} is lower, corresponding to longer lockdown episodes, the amplification of multifractality at a given intensity level is markedly stronger. Short-lag and medium-lag NPD series are more sensitive to intervention strength than the weekly lag, reflecting the interplay between periodic forcing and intermittent suppression at different timescales.

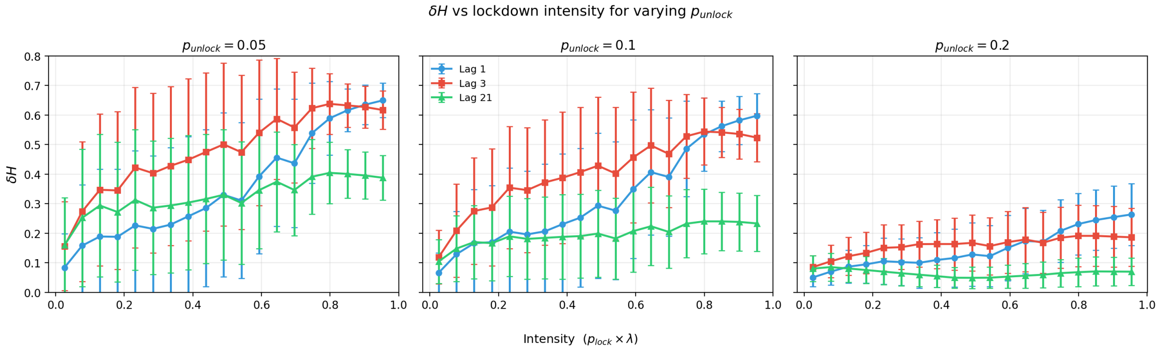

Figure 1: **Multifractal width δH as a function of lockdown intensity $p_{\text{lock}} \times \lambda$** for three unlock probabilities p_{unlock}. Points show mean δH per intensity bin across 60,000 simulation runs; error bars indicate standard deviation. Increasing lockdown frequency, strictness, or duration systematically amplifies multifractality across all temporal lags.

Conclusions and Outlook. Our results establish a mechanistic link between the frequency and severity of mobility restrictions and the emergence of multifractal scaling in temporal mobility network dynamics. The multifractality observed in empirical networks from countries with strict interventions is reproduced by a generative model in which Markovian regime switching intermittently suppresses mobility over a persistent spatial backbone. Ongoing work focuses on multi-country parameter inference and on quantifying how model parameters map onto the empirically observed NPD and MFDFA signatures across contrasting public health regimes.

References

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