Modeling Group-level Behavioral Responses in the COVID-19 Pandemic: The role of coordinated social bubbles

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Extended Abstract

The dynamics of epidemics, such as COVID-19, revealed trajectories and policy outcomes that often differed significantly from predictions derived using basic compartmental models. These discrepancies have been attributed to multiple factors, notably behavioral responses [1, 2, 3], varying compliance rates [4, 5], and the influence of micro-level social structures [6, 7, 8, 9], along with the critical interactions between behavioral responses and structural or societal factors [10, 11, 12, 13, 14]. In recent years, particularly following the COVID-19 pandemic, the modeling of behavioral responses has received increased attention, leading to substantial advancements and transformations in epidemiological modeling approaches.

However, most behavioral models predominantly focus on individual-level responses [15]. While understanding individual behavior is crucial, these models often do not fully capture all types of behavioral adaptations occurring during pandemics. Specifically, coordinated or group-level responses can significantly shape epidemic dynamics beyond what individual responses alone might explain [16, 17]. Two examples illustrate this clearly: first, the early formation of social bubbles, which created structured interactions limiting virus spread; and second, the formation and evolution of local norms around risk mitigation, which dynamically influenced broader community behavior. Despite their importance, the formation and dynamics of these group-level behavioral responses have received relatively little scholarly attention, highlighting a significant gap in current epidemiological modeling research.

To bridge this gap, this paper focuses explicitly on how group-level behavioral responses impact the relative effectiveness of countries' pandemic containment measures. We conceptualize group behaviors as the dynamic formation and evolution of social bubbles, using a cooperative game-theoretic approach where agents cooperate by forming coalitions to reach better outcomes collectively.

Our model extends the framework proposed by Cao et al. [18] through three distinct stages (Figure 1): a pre-NPI stage characterized by pathogen spread across an unaltered network, a post-NPI stage involving modification of the network through removal of social links, and a relaxation stage during which agents form social bubbles, which reflects gradual recovery of social activities. Determining the exact relaxing timing is complicated and falls outside the scope of this paper. Therefore, we adopt a homogeneous compliance window for all target countries.

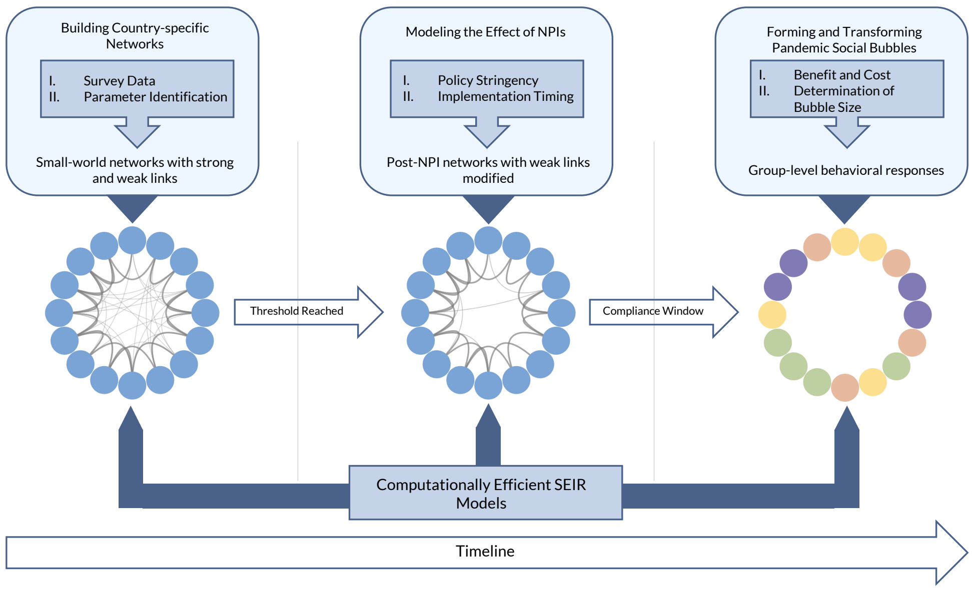

Figure 1: **Overview of the paper.** The structure of social interactions for each country in this work is abstracted as a scaled, contact-based small-world network with $10,000$ nodes. The representative network is then adjusted by disconnecting some of the weak links after cumulative confirmed cases reach a certain threshold. Next, given a policy compliance window (30 days), we use cooperative game theory which allows agents to form and transform social bubbles dynamically to incorporate group-level behavioral responses in the pandemic. We use a computationally efficient SEIR model to simulate the epidemiological dynamics.

The dynamics driving social bubble formation hinge upon perceived benefits from resource sharing, informational exchange, emotional support, infection risks within groups, and associated economic and health costs. While previous studies have explored related phenomena [19, 20], they predominantly employed exogenously defined behavioral rules rather than dynamically adaptive agent responses and have not extensively considered how group behavior varies across diverse populations. To address these difficulties, we develop a simple, compact agent-based model informed by cooperative game theory where agents endogenously form, grow, or dissolve social bubbles based on calculated social utilities, and collect model inputs that govern coalition forming from population surveys on physical contact records, economic forecasts, and mortality rate analysis.

We test the model on two sets of European countries with comparable socio-cultural characteristics yet sufficient variation in micro-level social interaction preferences. Our results indicate that our model accurately captures relative pandemic trajectories across target countries with a noticeable improvement from the micro-structure model [18] in both test sets and on longer timescale. In addition to simulating epidemic curves and comparing outcomes to empirical infection data, we monitor the evolution of social bubbles and correlate these patterns with contemporaneous changes in residential mobility where simulated social bubble evolution aligns well with observed mobility trends during the first wave of COVID-19 pandemic.

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