ShareTrace: Proactive Contact Tracing with Asynchronous Message Passing

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Introduction: Types of Contact Tracing

- Digital contact tracing (DCT)
- Proximity tracing
- Decentralized DCT
  - Broadcast model
  - Message-oriented model

Introduction: Limitations of Other Approaches

- No DCT approach exists that incorporates both non-diagnostic information and indirect contacts to estimate infection risk.
- Accounting for indirect contact can substantially improve the efficacy of DCT [10].
- Cherini et al. [4] propose exchanging pseudonyms of indirect contacts, but restrict themselves to diagnostic testing.
- Gupta et al. [6] incorporate non-diagnostic information, but do not account for indirect contact.

Introduction: ShareTrace

- Accounts for both non-diagnostic information and indirect contact to estimate infection risk.
- Developed in collaboration with Dataswyft [2].
- Ayday, Yoo, and Halimi [1] designed ShareTrace to use proximity tracing for contact discovery.
    - In practice, this was infeasible, because Apple and Google's Exposure Notification API did not permit the user's ephemeral identifiers to be stored remotely in a Dataswyft Personal Data Store.

Proposed Design: Definitions

- Risk propagation
- Risk score
  - Symptom score
  - Exposure score

Synchronous Risk Propagation

$\textsc{Risk-Propagation}(S, C)$

$R_i^{(n-1)} \leftarrow$ top k of S_i

$r_i^{(n-1)} \leftarrow \max R_i^{(n-1)}$

$r_i^{(n)} \leftarrow \infty$

while $\|\mathbf{r}^{(n)} - \mathbf{r}^{(n-1)}\| > \epsilon$

  $\mu_{ij}^{(n)} \leftarrow R_i^{(n-1)} \setminus \{\, \lambda_{ji}^{(\ell)} \mid \ell \in [1 \mathinner{.\,.} n-1] \,\}$

  $\lambda_{ij}^{(n)} \leftarrow \max \{\, \alpha s_t \mid s_t \in \mu_{ij}^{(n)}, t < t_{ij} + \beta \,\}$

  $R_i^{(n)} \leftarrow$ top k of $\{\, \lambda_{ji}^{(n)} \mid f_{ij} \in N_i \,\}$

  $r_i^{(n)} \leftarrow \max R_i^{(n)}$

return $\mathbf{r}^{(n)}$

Experiment 1: Accuracy I

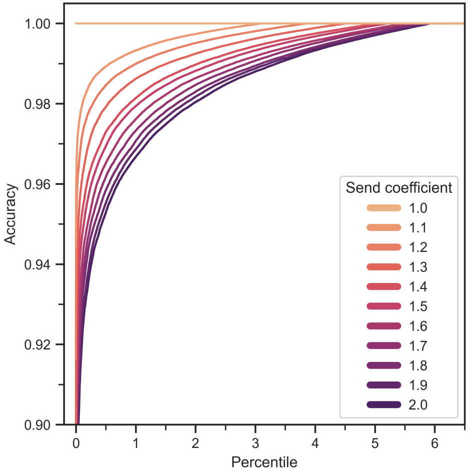


Figure: Cumulative accuracy distributions.

Experiment 1: Accuracy II

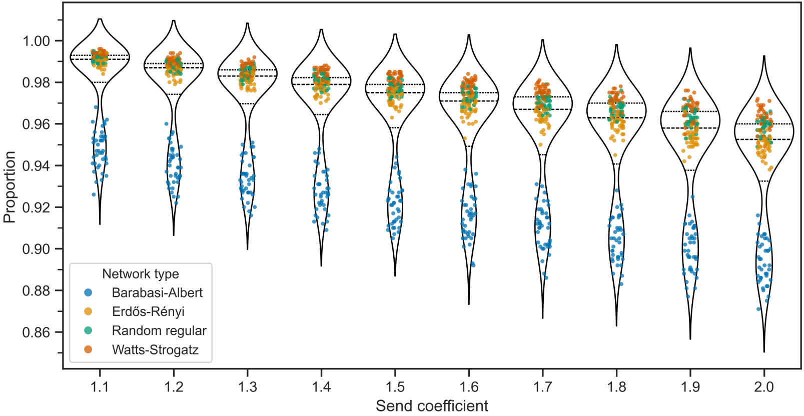
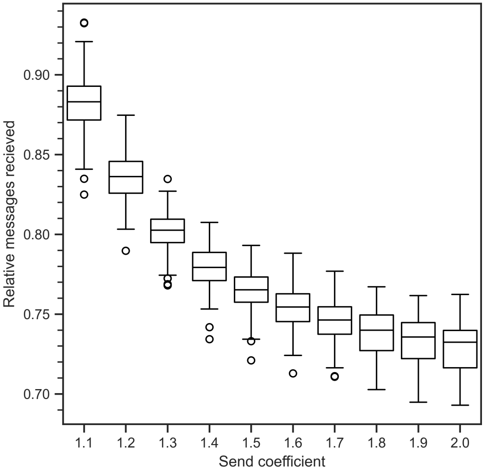


Figure: Send coefficient optimality distributions. The dashed line inside each violin marks the median. The upper and lower dotted lines inside each violin mark the upper and lower quartiles, respectively.

Experiment 1: Accuracy III

Experiment 1: Efficiency I



Experiment 1: Efficiency II

Figure: Message-passing efficiency. The send coefficient $\gamma = 1$ was used as a baseline for message-passing efficiency since it was found to be the maximum send coefficient that achieves perfect accuracy.

Experiment 1: Efficiency III

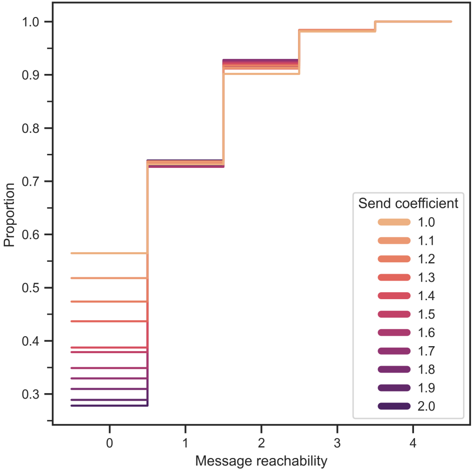
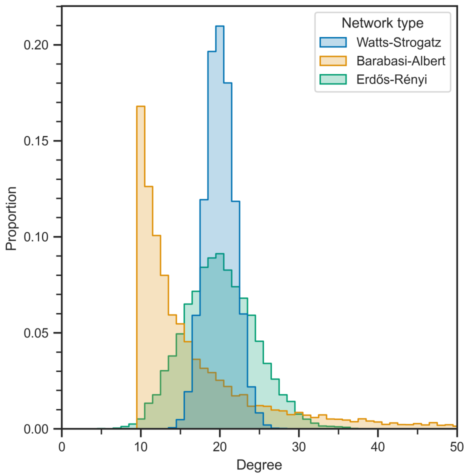


Figure: Message reachability cumulative distributions.

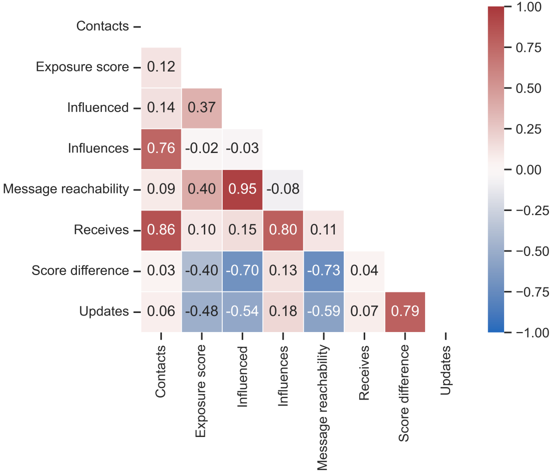
Experiment 1: Exploration I



Experiment 1: Exploration II

Figure: Contact network degree distributions. All vertices in random regular contact networks had a degree of 20, so the distribution was omitted to provide more visual space for the distributions of other contact networks.

Experiment 1: Exploration III



Experiment 1: Exploration IV

Figure: Correlation matrix of dataset attributes. Each cell is the Spearman rank partial correlation coefficient [15], controlling for the effect of the send coefficient. All coefficients are significant ($p < 0.01$), adjusting for multiple comparisons via the Holm–Bonferroni method [7].

Experiment 2: Benchmarking Hypothesis Testing

Experiment 3: Benchmarking I

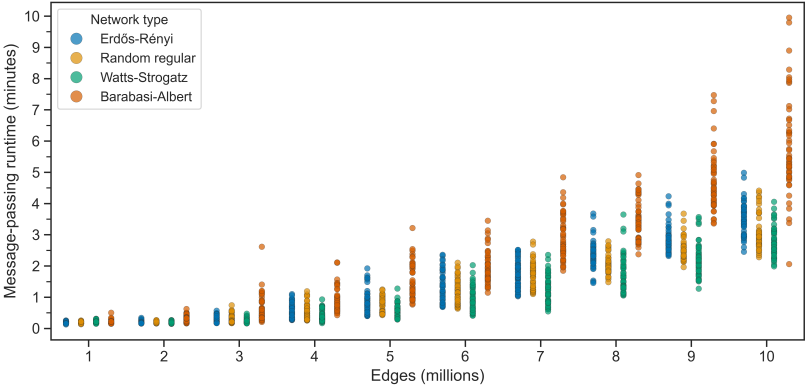


Figure: Message-passing runtimes.

Experiment 3: Benchmarking II

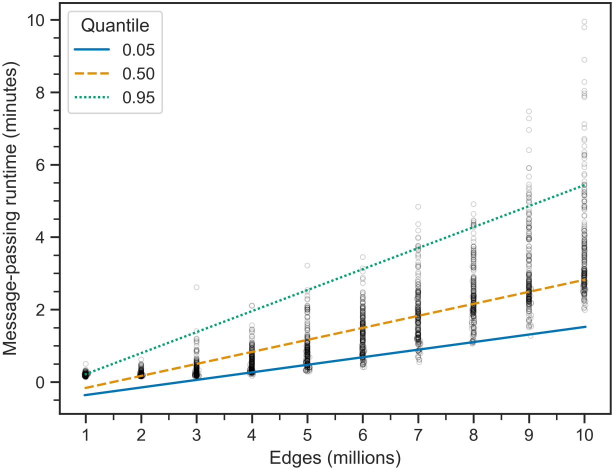


Figure: Message-passing runtimes with regression lines.

Conclusion: Future Work

- Incorporate differential privacy techniques that are designed for DCT applications that utilize risk scores [12].
- Formally define the security and privacy characteristics of ShareTrace, using the framework proposed by Kuhn, Beck, and Strufe [9] to characterize the latter.
- Conduct a simulation-based analysis of asynchronous risk propagation with COVI-AgentSim [5].
- Explore the utility and feasibility of integrating decentralized technologies [3, 8, 14, 17, 18] and self-soverign identity [11, 13] into the system design.

Prior Designs and Implementations

- "Thinking like a vertex" with Apache Giraph
- Factor subgraph actors
- Driver-monitor-worker framework
- Projected subgraph actors [16]
- Contact search

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