Algorithms and Applications of Dynamic Network Analysis using CANDY

Aashish Pandey
University of North Texas

Arindam Khanda
Missouri University of Science and Technology

S M Shovan
Missouri University of Science and Technology

Ali Y Khan
University of North Texas

Boyana Norris
University of Oregon

Sajal K. Das
Missouri University of Science and Technology

Sanjukta Bhowmick
University of North Texas

ACM Reference Format:
Aashish Pandey, Arindam Khanda, S M Shovan, Ali Y Khan, Boyana Norris, Sajal K. Das, and Sanjukta Bhowmick. 2018. Algorithms and Applications of Dynamic Network Analysis using CANDY. In *Proceedings of Make sure to enter the correct conference title from your rights confirmation email (Conference acronym 'XX).* ACM, New York, NY, USA, 3 pages. https://doi.org/XXXXXXX.XXXXXXX

1 Introduction

Graph modeling is a powerful tool for studying complex systems, enabling structural and functional insights through analysis of graph properties. In dynamic networks, where topology evolves over time, these properties must be updated continuously. In practice, most real-world networks are both large in scale and highly dynamic, making such updates computationally demanding and resource-intensive. To overcome these difficulties, we developed CANDY (Cyberinfrastructure for Accelerating Innovation in Network Dynamics), a high-performance platform tailored for scalable analysis of evolving large-scale networks. CANDY incorporates efficient update algorithms for a variety of graph properties, including single-source shortest paths (SSSP) [7], multi-objective shortest paths (MOSP) [6, 9], vertex coloring [2], strongly connected components [10], motifs, hypergraph motifs and PageRank. In addition to handling real data, it can generate synthetic dynamic networks (Figure 2) and provide an architecture-independent framework for building parallel update algorithms targeting distributed memory, shared memory, and GPU systems.

CANDY framework processes batches of edge changes, denoted ΔE, and leverages the earlier results to update graph properties without recalculating from scratch (Figure 1) to substantially reduce processing time and computational overhead. The update process first identifies the vertices or subgraphs affected by the changes through parallel processing of ΔE. Then, it incrementally updates the relevant properties using parallel threads to ensure both correctness and high performance. Previously, we presented CANDY (Cyberinfrastructure for Accelerating Innovation in Network Dynamics), a scalable platform for modeling, managing, and analyzing large dynamic networks. Here, we showcase a variety of real-world applications in domains such as transportation, biological systems, social networks, and public safety that can be modeled as dynamic networks and effectively analyzed using CANDY.

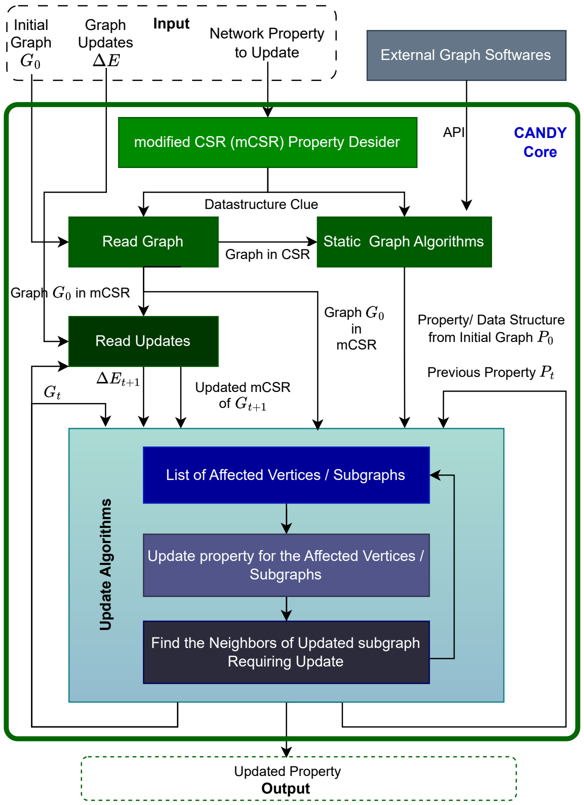

Figure 1: A generic framework to develop update algorithms

Conference acronym 'XX, Woodstock, NY

ACM ISBN 978-1-4503-XXXX-X/2018/06
https://doi.org/XXXXXXX.XXXXXXX

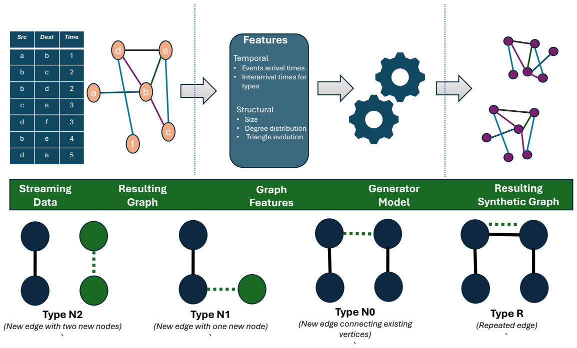

Figure 2: Overview of dynamic graph generator.

2 Application of CANDY

2.1 Application in Bioinformatics

Finding network motifs (recurring subgraph patterns) has broad applications in comparing and aligning networks across domains such as biology, epidemiology, and social science. In bioinformatics, motifs are particularly useful for uncovering functional modules and regulatory mechanisms in biological systems; for example, motif-based analysis of regulatory element networks has been used to identify key transcription factors driving cancer progression [8]. ParaDyMS [1], developed using the CANDY framework, is a scalable parallel algorithm for efficient motif counting in dynamic networks. Tested on GPUs and shared-memory CPUs (Fig: 3) with real-world datasets, ParaDyMS demonstrates strong performance on dense and insertion-heavy graphs, outperforming state-of-the-art static methods by up to 90%.

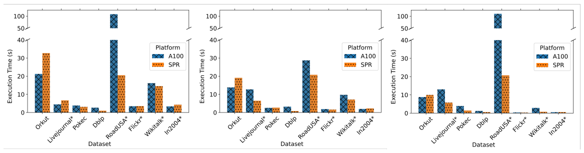

Figure 3: Runtime of ParaDyMS on an A100 GPU and Sapphire Rapids CPU with different ratios of insertions to deletions(0-100 (left), 50-50(middle) and 100-0(right)

2.2 Drone-based Delivery System

In a drone-based delivery system (Figure 4), energy consumption and flight time can depend on wind speed and direction. A tailwind can reduce both, while a headwind can have opposite effect. Under varying wind, finding the most time efficient route can be modeled as a single source shortest path (SSSP) problem in a dynamic network [3]. When multiple objectives, like optimizing both time and energy efficiency, are considered, the problem becomes a multi-objective shortest path (MOSP) in a dynamic network. CANDY offers an efficient update algorithm with a CUDA implementation for SSSP, as well as an effective method for solving MOSP.

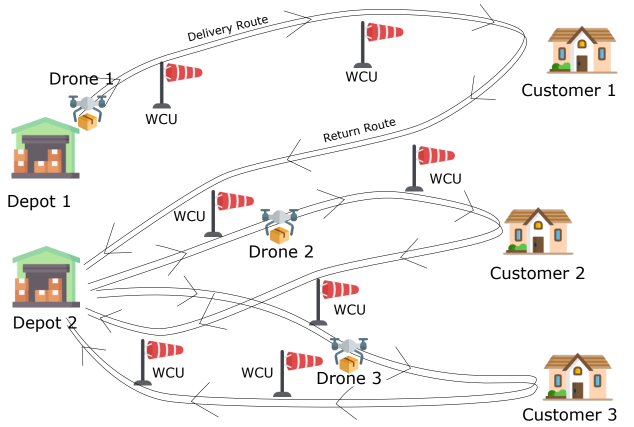

Figure 4: A drone-based delivery system. WCU: Wind Control Unit [3]

2.3 Inter-community Communication

Structural gap in a social network is the absence of direct connections between communities. Structural hole spanners (SHS) are nodes that bridge these gaps, enabling interaction and exchange between disconnected groups. By linking communities, they facilitate information flow, collaboration, and innovation. However, identifying SHS is NP-hard, and various heuristics address it. Some use vertex scoring based on the number of feed-forward loop motifs linked to a vertex [4, 5]. Since most social networks are large-scale and online, these motifs evolve over time, leading to the problem of detecting feed-forward loop motifs in large dynamic networks, a capability supported by CANDY [1].

2.4 Higher-order Interactions

Higher-order interactions in complex networks are modeled as hypergraphs, where recurring substructures called H-motifs reveal multi-entity interaction patterns beyond pairwise relationship. Identifying H-motifs is computationally challenging, especially in large dynamic systems. To address this, we develop a **D**ynamic **H**yper-**G**raph (DHG) data structure with an H-motif update algorithm that counts motifs of three connected hyperedges. DHG is optimized to support large-scale hyperedge insertions and deletions in GPU environments.

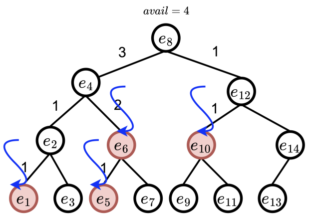

Figure 5: Multi-threaded deletion operation on DHG data structure.

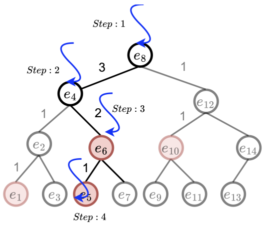

Figure 6: Multi-threaded insertion operation on DHG data structure.

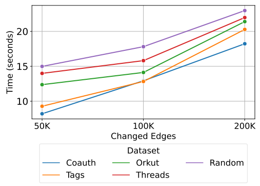

Figure 7: Execution time requirement as we vary the ΔE.

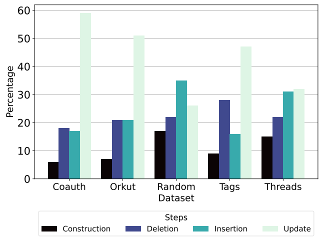

Figure 8: Time portion taken by different parts of the algorithm.

2.5 Dynamic Evacuation Route in Wildfire

Wildfires create evacuation challenges due to unpredictable spread and congestion. We propose a dynamic, risk-aware framework that models evacuation (Figure 9) as a time-varying weighted graph. Road segments are assigned dynamic weights reflecting distance, fire risk, and congestion delay. Integrated with UAV-based monitoring, the proposed framework solves a multi-objective shortest evacuation path problem to minimize distance, fire exposure, and traffic delays, achieving up to 42× speedup on real-world networks.

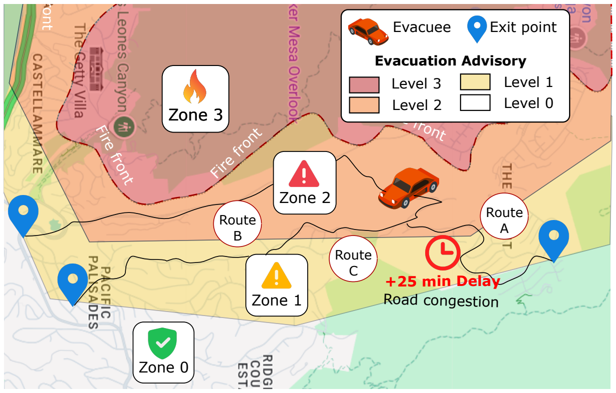

Figure 9: System model of a wildfire evacuation scenario.

Acknowledgments

References

[1] Ali Khan, Nigel Tan, Jack Marquez, Michela Taufer, and Sanjukta Bhowmick. 2025. ParaDyMS: Parallel Dynamic Motif Counting at Scale . In *2025 IEEE 25th International Symposium on Cluster, Cloud and Internet Computing (CCGrid)*. IEEE Computer Society, Los Alamitos, CA, USA, 1–10. https://doi.org/10.1109/CCGRID64434.2025.00046

[2] Arindam Khanda, Sanjukta Bhowmick, Xin Liang, and Sajal K Das. 2022. Parallel vertex color update on large dynamic networks. In *2022 IEEE 29th International Conference on High Performance Computing, Data, and Analytics (HiPC)*. IEEE, 115–124.

[3] Arindam Khanda, Federico Corò, Francesco Betti Sorbelli, Cristina M. Pinotti, and Sajal K. Das. 2021. Efficient Route Selection for Drone-based Delivery Under Time-varying Dynamics. In *2021 IEEE 18th International Conference on Mobile Ad Hoc and Smart Systems (MASS)*. 437–445. https://doi.org/10.1109/MASS52906.2021.00061 https://doi.org/10.1109/MASS52906.2021.00061.

[4] Arindam Khanda, Satyaki Roy, Prithwiraj Roy, and Sajal K. Das. 2024. Structural Hole Spanners Detection in Directed Social Networks: A Feed Forward Loop Motif Approach. In *IEEE Global Communications Conference (GLOBECOM)*. IEEE. https://doi.org/10.1109/GLOBECOM52923.2024.10901271.

[5] Arindam Khanda, Satyaki Roy, Prithwiraj Roy, and Sajal K Das. 2025. A Parallel Algorithm for Finding Robust Spanners in Large Social Networks. *arXiv preprint arXiv:2508.01485* (2025).

[6] Arindam Khanda, SM Shovan, and Sajal K Das. 2023. A Parallel Algorithm for Updating a Multi-objective Shortest Path in Large Dynamic Networks. In *Proceedings of the SC'23 Workshops of The International Conference on High Performance Computing, Network, Storage, and Analysis*. 739–746.

[7] Arindam Khanda, Sriram Srinivasan, Sanjukta Bhowmick, Boyana Norris, and Sajal K Das. 2021. A Parallel Algorithm Template for Updating Single-Source Shortest Paths in Large-Scale Dynamic Networks. *IEEE Transactions on Parallel and Distributed Systems* (2021).

[8] Daniel J Mullen, Zexun Wu, Ethan Nelson-Moore, Huan Cao, Lauren Han, Ite A Offringa, and Suhn K Rhie. 2025. Tracing regulatory element networks using epigenetic traits to identify key transcription factors: TENET R/Bioconductor package. *Bioinformatics* 41, 8 (08 2025), btaf435. https://doi.org/10.1093/bioinformatics/btaf435 arXiv:https://academic.oup.com/bioinformatics/article-pdf/41/8/btaf435/63920097/btaf435.pdf

[9] S. M. Shovan, Arindam Khanda, and Sajal K. Das. 2025. Parallel Multi Objective Shortest Path Update Algorithm in Large Dynamic Networks. *IEEE Transactions on Parallel and Distributed Systems* 36, 5 (2025), 932–944. https://doi.org/10.1109/TPDS.2025.3536357

[10] S Srinivasan, Arindam Khanda, A Pandey, SK Das, Sanjukta Bhowmick, and Boyana Norris. 2023. A Distributed Algorithm for Identifying Strongly Connected Components on Incremental Graphs. In *2023 IEEE 35th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. IEEE, 109–118.