Physics-Informed Machine Learning for Routing

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Problem Statement:

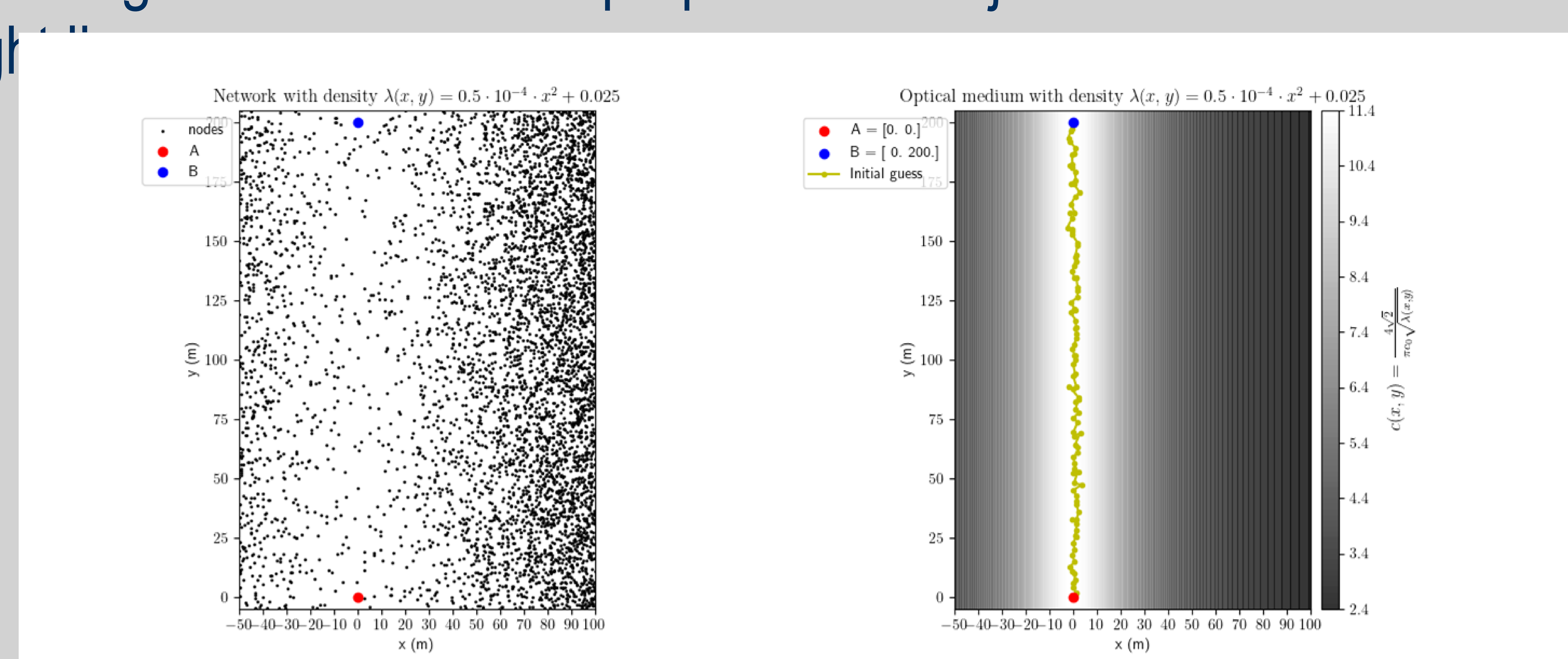
Given a wireless network whose nearby nodes are connected by wireless communication channels and a node *A* that aims to transmit information to a distant node *B*, find a path from *A* to *B* that optimizes the total cost arising from the nodes and the wireless communication channels that connect adjacent nodes.

Purpose:

While traditional consumer devices are only one hop away from a node with a wired communication channel to the Internet, there is growing interest in the problem of routing information on multi-hop wireless networks which are used in mesh networks, peer-to-peer relay networks, emergency management, and increasingly in other applications including warfighting & defense. The cost of a node is its network traffic density. Example costs for wireless communication channels include transmission area and the probability a signal is not received.

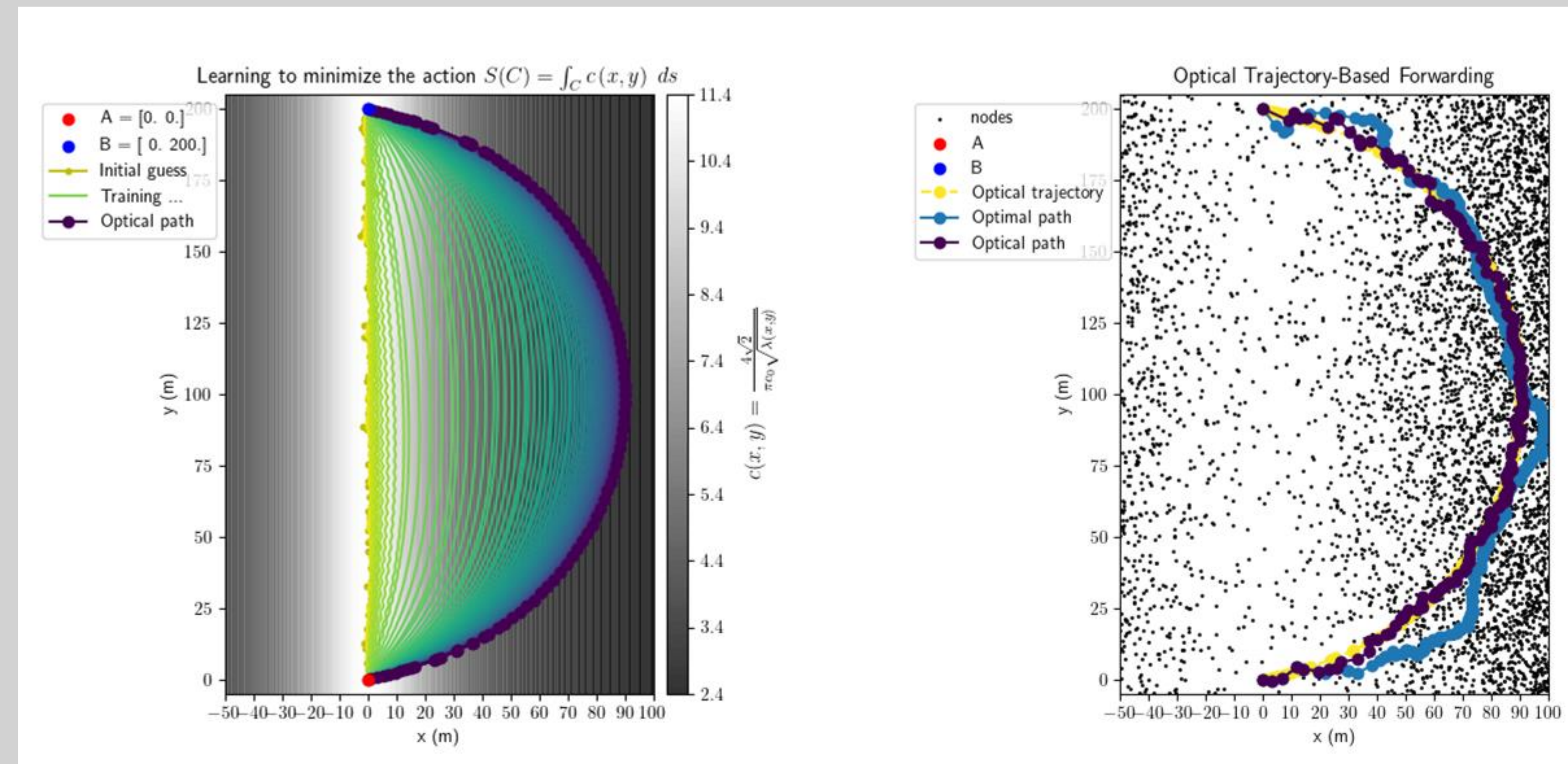
Approach:

An analogy is drawn between the propagation of information on the network and the propagation of light on an optical medium whose density at a point is characterized by the network traffic density of nearby nodes, so an asymptotically optimal network route is computed by forwarding information along a path which closely follows the trajectory taken by light (Catanuto et al, 2009). This trajectory is learned by a gradient descent algorithm which has been used to minimize action functionals in other areas of physics (Greydanus et al, 2023). The trajectory-based forwarding rules from (Catanuto et al, 2009) are reviewed and generalizations are proposed for trajectories which are not straigh



Discussion & Conclusion:

The cost function of an optical medium is constructed by analogy with the network traffic density. The initial trajectory *C* is the straight line from *A* to *B*. Each iteration computes the path integral of *C* and performs gradient descent to learn a better *C*.



The gradient descent algorithm successfully converges to a trajectory which empirically minimizes the path integral. The trajectory-based forwarding algorithm successfully finds a path in the network which closely follows the trajectory. This computed path closely approximates the optimal path computed by Dijkstra's algorithm. Resource usage by traditional graph algorithms like Dijkstra's scale with size, whereas our approach is effective for large wireless networks.

Path Forward:

The approach described for the unicast routing problem may generalize to multicast routing algorithms and distributed route discovery protocols, the latter of which replaces the analogy with geometric optics to the Feynman path integral formulation of quantum mechanics. This analogy suggests exploring many paths simultaneously and replacing the search for one long path with that for many short adjacent paths.

References:

Catanuto, R., Toumpis, S., & Morabito, G. (2009, July 28). On Asymptotically Optimal Routing in Large Wireless Networks and Geometrical Optics Analogy. Computer Networks, 53(11), 1939–1955

Greydanus, S. J., Strang, T. D., & Caruso, I. (2023, March 3). Nature's Cost Function: Simulating Physics by Minimizing the Action. ICLR 2023 Workshop on Physics for Machine Learning.

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