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# Dynamic Directional Routing for the Physical Internet: A Sector-Based Approach with Dynamic Adjustment

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**Abstract:** *This paper introduces an innovative directional routing protocol tailored for the Physical Internet (PI), utilizing a sector-based approach that dynamically adjusts to optimize logistics across multiple transportation network tiers. By dividing the network into distinct sectors and implementing a hierarchical tier system, this method enhances the efficiency, reliability, and responsiveness of routing decisions by integrating real-time data on traffic density, container locations, and network disruptions.*

*Our methodology combines sector-based logic with dynamic routing tables and modular PI-container capabilities, which facilitates the consolidation of shipments and improves the adaptability of the logistics network. Through comprehensive simulations, we demonstrate how our approach significantly reduces total travel miles, increases truck fill rates, and avoids congested hubs, thereby minimizing idle time and enhancing overall operational efficiency.*

*The findings underscore the potential of sector-based dynamic routing in achieving a more sustainable and resilient logistics network, paving the way for future innovations in the Physical Internet. Future research will focus on integrating multimodal transport options, refining the dynamic adjustment mechanisms, and further optimizing the routing protocol to handle diverse and changing logistics demands efficiently.*

***Keywords:*** *Physical Internet, Hyperconnectivity, Mesh Network, Routing Protocols, Network Architecture, Multi-tier Network, Service Networks*

## 1. Introduction

The Physical Internet (PI) represents a groundbreaking shift in logistics, aiming to establish a globally interconnected network that boosts efficiency through the integration of digital, operational, and physical aspects, inspired by the evolution of the Digital Internet (DI) (Fahim et al., 2021; Montreuil, 2011). PI is characterized by its dynamism and reactivity, which allow it to adapt and respond quickly to changes and disruptions, a capability enhanced by the use of modular PI-containers that facilitate the consolidation of shipments (Pan et al., 2021). However, the complexity of managing the PI network necessitates the development of robust, consensual, and decentralized routing protocols to ensure the network's functionality, especially in the face of disruptions (Sallez et al., 2016). Research on PI routing protocols has been diverse, ranging from efforts to optimize vehicle routing problems with complex algorithms to the exploration of distributed and reactive routing protocols inspired by DI protocols, acknowledging the similarities and differences between the two networks (Sarraj et al., 2014). Despite these advancements, challenges persist in fully integrating vehicles and containers into the decision-making process, managing disturbances effectively, and optimizing the overall performance of this interconnected and dynamic system (Yang, Pan, and Ballot, 2017a, 2017b). Recent studies have proposed innovative solutions, such as auction-based protocols (Briand, Franklin, and

Lafkihi, 2022) and dynamic container routing, yet often overlook the collaborative principles of PI, the mechanisms for re-routing in case of disturbances, and the integration of local knowledge into routing decisions. This highlights an ongoing need for the development of routing protocols that are specifically tailored to the unique characteristics and challenges of the Physical Internet.

This paper introduces a directional routing protocol designed to navigate the PI's intricacies, leveraging sector-based divisions, hierarchical tiers, and the capabilities of smart containers. Smart packages within the PI have the ability to transmit data regarding their location, destination, and condition. This capability allows for a more responsive and adaptive routing mechanism, where packages can actively participate in the routing decisions that affect their journey through the network. This approach leverages the principles of dynamic routing and sector-based forwarding, ensuring that the Physical Internet can achieve its goals of efficiency, sustainability, and resilience in the face of changing demands and conditions in the global logistics landscape.

## 2. Methodology

Our methodology is structured to enhance routing efficiency in the Physical Internet by systematically addressing both the discovery of potential routing areas and the selection of nodes within those areas. The methodology is divided into two primary phases: Area Discovery and Node Selection.

- **Area Discovery Phase:** This phase is critical in establishing the geographic context for routing decisions. It utilizes two main approaches:
    - Cardinal Sector-Based: The network is divided into sectors determined by cardinal directions. This method simplifies the identification of potential hubs by grouping them into universally recognized directional sectors.
    - Density-Adjusted Dynamic Sector-Based: This more sophisticated approach adjusts sectors dynamically based on the density of traffic and container locations, allowing for a more responsive routing environment.

  Both approaches aim to define 'candidate hubs' (those within the potential routing path) and 'non-candidate hubs' (those outside the potential path)

- **Node Selection Phase**: Once the area has been defined and candidate hubs identified, this phase involves selecting the optimal routing nodes within the confined area based on a set of predefined protocols. These protocols are designed to evaluate factors such as network congestion, travel distance, operational costs, and environmental impact. The selection process is guided by dynamic programming techniques to ensure that decisions are both optimal and adaptable to changing network conditions.

## 3. Area Discovery Phase

When a PI container has data to transmit, it initiates the process by identifying the area of communication that includes potential next-hop candidates. The goal of this phase is to establish an active region between the container location (origin node) and the destination node (which could be another hub within the Physical Internet), wherein all nodes within this defined area are deemed potential candidates for routing. Consequently, during this phase, communication between the container and the destination node generates a virtual pie-shaped region, as depicted in Figure 1.

### 3.1 Cardinal Sector-Based Routing (CSBR)

We divide the PI network into hierarchical tiers and sectors to simplify navigation and routing decisions. Each tier, ranging from unit zones to continents, is further subdivided into eight sectors based on cardinal directions (North, Northeast, East, Southeast, South, Southwest, West, Northwest). This structure facilitates both localized and global routing strategies.

#### 3.1.1 Defining Sectors and Tiers

The PI network is categorized into hierarchical tiers:

- Unit Zones (e.g., a city block)
- Local Cells (e.g., a city district)
- Areas (e.g., a metropolitan area)
- Regions (e.g., a state or province)
- Continents

Each tier is further subdivided into eight sectors, defined by their relative geographic orientation (N, NE, E, SE, S, SW, W, NW). Dividing each tier into eight sectors based on cardinal and intercardinal directions serves multiple purposes in the context of the Physical Internet:

1. Efficient Routing and Distribution: Goods can be directed through the most efficient routes within a sector, minimizing transportation times and costs, and reducing the environmental impact.
2. Scalability and Flexibility: As the demand for logistics services changes, the sectoral division allows for the flexible adjustment of storage and transportation capacities within and across different sectors.
3. Localized Operations: Each sector can focus on optimizing operations based on local demand, supply characteristics, and geographical constraints, enhancing the overall efficiency of the logistics network.
4. Disaster Recovery and Risk Management: The sectoral approach helps in isolating disruptions (e.g., natural disasters, strikes) to a specific sector, enabling more effective contingency planning and rapid response strategies to ensure continuity of operations.

For example, consider a shipment in a local cell, the sector-based approach determines the most efficient path by identifying the sector in which the destination lies relative to the origin, optimizing the routing process.

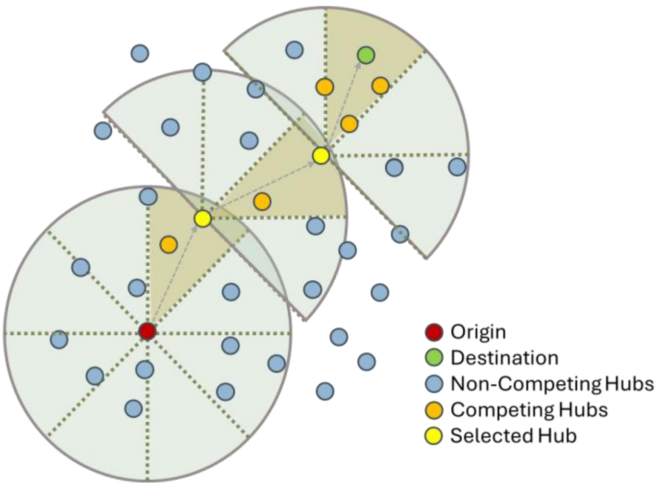


*Figure 1: Example of a container path using CSBR Protocol in a single tier setting*

### 3.2 Density-Adjusted Dynamic Sector Routing (DADSR)

This section introduces a refined approach to sector formation within the Physical Internet (PI) routing protocol, emphasizing dynamic adjustment based on the bearing from origin to destination and the density of the logistical network. This method, termed Density-Adjusted Dynamic Sector Routing (DADSR), enhances routing efficiency by tailoring sector boundaries to the specific geographic and logistical characteristics of each shipment path.

DADSR operates on the principle of creating sectors not solely based on fixed cardinal directions but by dynamically adjusting the sector's orientation and breadth based on the direct route from origin to destination and the density of available hubs within that trajectory. This approach ensures that each sector is optimized for both directness and logistical feasibility, addressing the key challenges of sparse network regions and ensuring robustness against network disruptions.

The key features of Density-Adjusted Dynamic Sector Routing (DADSR) are as follows:

- **Dynamic Sector Adjustment:** The base angle for sector creation is determined by the direct route from origin to destination. The sector then dynamically widens its angle to encompass a sufficient number of hubs, ensuring viable routing options.
- **Minimum Hub Inclusion Criterion**: A predefined minimum number of hubs within a sector ensures that each dynamically created sector has adequate routing infrastructure. If the initial sector does not meet this criterion, the sector's angle widens incrementally until the condition is satisfied.
- **Maximum Angle Constraint:** To prevent sectors from becoming impractically large, a maximum allowable angle or a maximum number of included hubs can be set. This ensures that while sectors adapt to include necessary infrastructure, they remain focused and efficient.
- **Network Density Awareness**: The approach inherently accounts for the varying density of the network across different regions, making it particularly suitable for large-scale, irregular networks like the Physical Internet.

#### 3.2.1 Mathematical Model for DADSR

The mathematical model for Density-Adjusted Dynamic Sector Routing (DADSR) integrates geometric calculations for bearing determination with algorithms for dynamic sector adjustment based on the logistical network's density. The model consists of several key components:

- **Bearing Calculation:** Calculating the bearing (θ) from the origin (O) to the destination (D) using the formula involving latitudes and longitudes of the origin and destination and the difference in longitude between the destination and origin.
- **Dynamic Sector Formation:** Formation upon determining the bearing, the sector's initial angular width ($\omega$) is set based on a predefined minimal criterion, which is then dynamically adjusted according to the density of the logistical network. The adjustment process follows:

  $$\omega = \omega_0 + \Delta\omega(n_{\min} - n)$$

  where:

  - $\omega_0$: initial angular width,
  - $\Delta\omega$: incremental angle adjustment per hub deficiency,
  - $n$: actual number of hubs within the initial sector,

  - $n_{\min}$: minimum required number of hubs to ensure adequate routing infrastructure.
- **Minimum Hub Inclusion Criterion and Maximum Angle Constraint:** Ensuring practicality for routing purposes by maintaining a minimum number of hubs within the sector and a predefined maximum angular width. The dynamic adjustment continues until either the sector includes at least the minimum required number of hubs ($n \geq n_{\min}$), or the sector reaches a predefined maximum angular width ($\omega_{\max}$), ensuring the sector remains practical for routing purposes:

$$\omega \leq \omega_{\max}$$

- **Network Density Awareness:** The density of the logistical network ($\rho$) influences both the initial angular width ($\omega_0$) and the incremental angle adjustment ($\Delta\omega$), with higher densities allowing for narrower initial sectors and smaller adjustments:

$$\Delta\omega = f(\rho),\ \omega_0 = g(\rho)$$

  where $f(\rho)$ and $g(\rho)$ are functions determining $\Delta\omega$ and $\omega_0$ based on the network density $\rho$, respectively.

The central angle, α, is predetermined for all nodes within the network, and R represents the distance from the container to the edge of the network area, as shown in Figure 2. Nodes neighboring the origin node are categorized as competing or non-competing, based on their position and direction relative to the origin node. Nodes that fall within the active region of the container, denoted as x∈A, are considered competing, whereas those outside this area, indicated as x∉A, are deemed non-competing. It's important to highlight that the direct path from the container to the destination node forms the center of this active region.

### 3.3 Multi-tier Hierarchical Network

In the context of a multi-tier setting within the Physical Internet, the area discovery phase takes on additional complexity due to the hierarchical structure of the network, which includes Unit Zones, Local Cells, Areas, Regions, and Continents.

Upon a container's entry into the system, three critical elements are predefined: its origin (O), destination (D), and the required service level (S). According to Shaikh et al. (2021), the container routing algorithm efficiently navigates containers across the Physical Internet using a structured tiered hub system, which includes local hubs (Tier 2), gateway hubs (Tier 3), and regional hubs (Tier 4). The algorithm strategically determines the necessity to elevate a container to a higher-tier hub based on its current location within specific zones, cells, areas, or regions. For instance, if a container's journey spans different regions, the system escalates its routing through local hubs, gateway hubs, to inter-regional hubs, before traversing to the target region. Subsequently, it systematically de-escalates through gateway and local hubs, reaching its designated destination.

Building on the logic presented by Shaikh et al. (2021), we suggest refining the area discovery process to exclusively encompass candidate hubs within the specific tier relevant to the required escalations. In a multi-tier network when a PI container is ready to be moved, it not only creates a virtual pie-shaped region but also must consider which tier of nodes should be activated for potential routing. The central angle, α, and the radius, R, still define the scope of the active region, but the selection of potential next-hop candidates is stratified by the relevant tier. For instance, if the origin and destination nodes span different regions, the area discovery will focus on activating the corresponding tier's nodes that align with the container's path from origin to destination as shown in Figure 3. This tier-specific focus ensures that only nodes capable of efficiently forwarding the container towards its destination are activated, streamlining the route selection process. By concentrating on relevant tiers, the network efficiently manages the movement of containers, reducing unnecessary interactions and enhancing overall logistical efficiency.

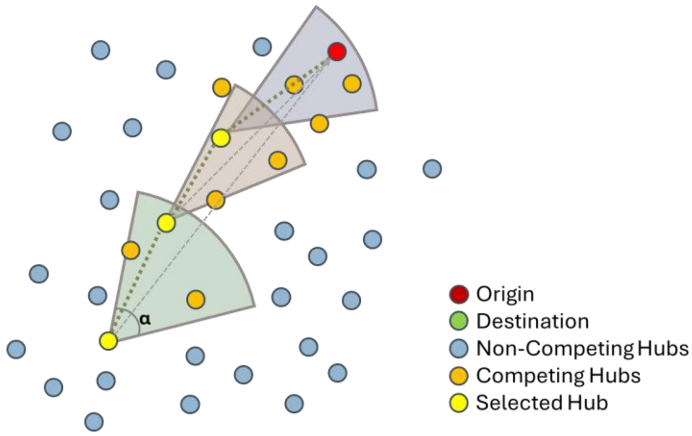


*Figure 2: Example of a container path using DADSR Protocol in a single tier setting*

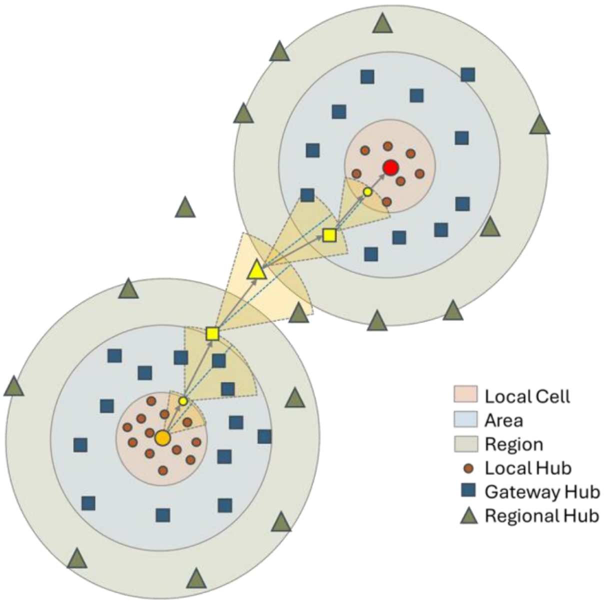


*Figure 3: Example of a container path using the DADSR protocol in a hierarchical multi-tier network*

## 4. Node Selection Phase

In this phase, nodes employ sophisticated dynamic routing tables that are continuously updated to reflect the real-time state of the network. These tables are integral to a decision-making framework that considers a wide array of metrics to guide the routing process. Each entry in a node's routing table captures critical information, including:

- Destination Sector: Identifies the target sector for the shipment.
- Estimated Transit Time: Predicts the time required to reach the next node.
- Waiting Time for Processing: Estimates waiting period for processing at the next node.
- Distance: Measures the physical distance to the next node.

- Cost: Estimates the monetary cost associated with routing through the next node.
- Environmental Impact: Assesses the carbon footprint of routing through the next node.

To address the diverse needs and priorities of PI users, the node selection phase has a flexible goal-weighting system. This system allows users or automated agents to assign varying degrees of importance to different routing goals, such as minimizing cost, reducing environmental impact, or optimizing for speed. The flexibility to prioritize goals can be achieved through the implementation of a weighted function.

## 5. Experimentation

The objective of this experimentation is to explore and demonstrate the efficacy of dynamic routing protocols, particularly focusing on directional routing and information sharing within the context of transportation networks. This research is structured to initially delineate an "area discovery" phase, followed by a "node selection" phase. While the area discovery process is designed to remain static, mirroring sector-based logic that does not vary with changes in node density, the study aims to delve into the implications of dynamic node selection in a single tier network. This is achieved through the application of directional routing, contrasting it with the traditional destinational (static) routing approach, which forms our baseline for comparison.

### 3.1 Model Assumptions

In the development of our PI network model, a series of foundational assumptions were made to streamline the complexity inherent in real-world transportation logistics, aiming to capture the essence of dynamic versus static routing protocols within a controlled simulation environment. Each truck is assigned to a parent node, adhering to the vision of the Physical Internet (PI) that emphasizes multi-segment transportation over traditional point-to-point deliveries.

Currently, the transport within the model is unimodal, exclusively focusing on truck-based delivery to isolate and examine time-based performance indicators without the complexities of multimodal trade-offs. This simplification, albeit a deviation from the PI's vision for integrated multimodal logistics, allows for a concentrated analysis on the efficiency of routing protocols within a singular mode of transport.

A uniform container size is adopted to streamline the simulation framework, sidestepping the complexities of cargo consolidation and optimization. While this simplification may not fully align with the diverse container sizes in real-world logistics, it ensures a consistent baseline for evaluating truck fill rates and the effectiveness of routing protocols across various scenarios.

The handling of trucks at nodes follows a First-In-First-Out (FIFO) queuing mechanism, simplifying agent interactions and reflecting a potentially realistic operational strategy employed by some logistics companies. Moreover, the arrival of new orders is modeled to follow a Poisson process, leveraging the 'memoryless' property of exponential distributions to simulate independent arrival events, a common approach in logistical simulations.

### 3.2 Baseline Static Routing Protocol

The baseline protocol is a static routing protocol where the containers take the shortest path from the origin to the destination, and do not change their routing decision during the simulation. This model presupposes a constant network topology and edge weights. Consequently, the shortest routes across the network only require computation once. Every node implements Dijkstra’s algorithm to construct a routing table. Due to the consistent routing of containers with identical source and destination through the same neighboring nodes, the static routing protocol organizes the node's inventory based on the subsequent destination.

The protocol, hereby called *FixedRoute*, employs four primary strategies to effectively manage the dispatch of trucks. The initial strategy is centered on the reassignment of idle trucks back to their original nodes. In cases where these trucks belong to different nodes and are transporting cargo in the same direction, priority is given to loading that cargo first. Furthermore, an element of 'patience' is introduced where trucks are allowed to wait at their destination briefly to accumulate more cargo, thereby optimizing their load capacity for each trip. Prior to dispatch, the protocol emphasizes the complete filling of trucks, particularly focusing on expediting urgent shipments to reduce potential delays. Finally, it adopts an urgency-driven approach to determine the sequence in which shipments are dispatched, ensuring that time-critical cargo reaches its intended destination in a timely manner. By integrating these strategies, our foundational protocol establishes a robust framework for comparison with more dynamic routing approaches.

### 3.3 Dynamic Routing Protocols

In this section, we explore the development and application of dynamic routing protocols within the framework of a directional routing concept. In this protocol, we no longer presume the edge weights in the routing table to be constant though we use the baseline edge weights and then adjust them to create the dynamic routing tables with updated weights. We achieve this in two ways. . The first protocol, hereby called the InformRoute, retrieves relevant information about neighboring nodes. It uses this information to make a more informed routing decision. This protocol assesses the anticipated waiting times for trucks at nodes by examining the arrival of incoming trucks, which includes the scheduled arrival times of trucks. The assessment process involves estimating the arrival time of a truck if dispatched immediately, followed by a simulation of inbound docks determine the minimum waiting time. This simulation incorporates the estimated arrival time into the queue and predicts the service sequence, taking into account the capacity of available inbound docks. When the queue goes beyond the capacity of the docks, the protocol establishes a minimum estimate for delays by calculating how long the docks will be occupied, affecting trucks that arrive later. The calculation of these unavailability periods, along with the earliest possible service time for trucks arriving later, allows for the adjustment of route selection to mitigate potential delays. Should the calculated earliest service time exceed the estimated arrival time, the protocol adjusts the routing decision by increasing the "weight" value associated with that edge. Note that we still take the shortest path in this protocol, but this time with the adjusted edge weights. This protocol tests the value of information in the network.

The second protocol, hereby called the *FlexRoute*, allows suboptimal paths, in the direction of the destination, to be taken if more containers can be transported that way. In our experimentation, we calculate the slack time of the container using the service level of the container and the shortest path from the current node to the destination. If the slack time is positive, then we can deviate from the shortest path, and we can see which are the candidate nodes such that the deviation does not cause a delay in service. This can be adjusted as per need, as sometimes the containers may inherently have some flexibility in their delivery date. If that's the case, the slack can be adjusted for that. In our current study, we assume that the delivery date is not flexible.

## 6. Results and Discussion

Our simulations evaluated the FixedRoute, InformRoute, and FlexRoute protocols within a single-tier network in the Southeast USA. Utilizing data from the Freight Analysis Framework (FAF) , we assigned inter-arrival times to origins and destinations in proportion to their flow magnitudes. To assess performance under diverse traffic conditions, we manipulated the load coefficients (0.6, 1, 1.4), representing low, medium, and high flow scenarios, respectively. Additionally, the hub network for our simulations was constructed based on the methodology outlined by Kulkarni et al. (2021). ensuring a robust and realistic testing environment.

Our analysis demonstrated that all protocols consistently achieved on-time delivery, with each protocol successfully delivering the containers within the specified service times. In Figure 4, we present the average truck utilization for all three protocols across various load coefficients. At lower load coefficients, the FixedRoute and InformRoute protocols perform similarly, as the InformRoute's advantage—its ability to adapt at bottlenecks—only activates under conditions of higher congestion, which are absent at these lower coefficients. As the load increases, InformRoute shows slightly better performance compared to FixedRoute reflecting InformRoute's adaptive capabilities as the network experiences more frequent bottlenecks.

For the FlexRoute protocol, it consistently outperforms both FixedRoute and InformRoute across all load coefficients. This superior performance can be attributed to its ability to dynamically alter its routing paths based on the potential for load consolidation, which enhances truck utilization more effectively than the other protocols, especially under higher load conditions.

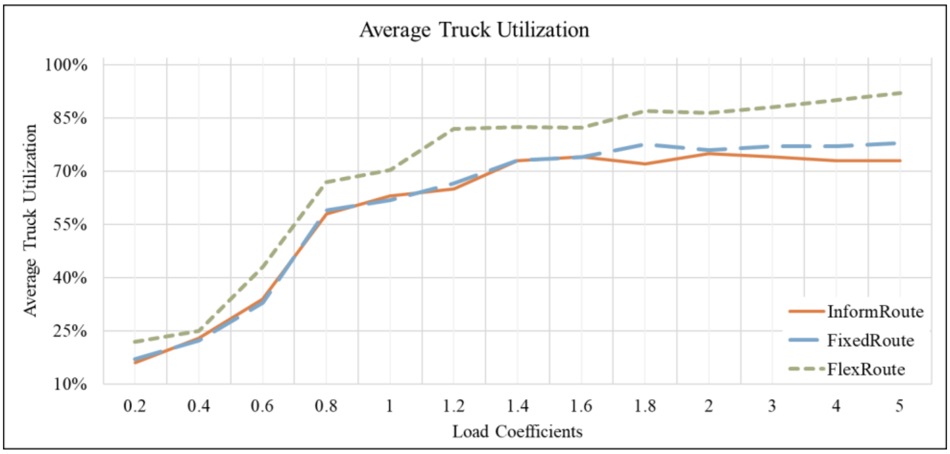


*Figure 4: Average Truck Utilization across different protocols with increasing load coefficients*

Figure 5 displays the traffic flow for FixedRoute, InformRoute and FlexRoute protocols under different load coefficients. This visualization highlights the distribution and volume of orders under each protocol, illustrating how FlexRoute adapts routing decisions based on increased order frequency.

Figure 6 offers a visual comparison of the routing paths selected by FixedRoute and FlexRoute for two distinct sets of origin-destination pairs. The first two maps on the left contrast the routes chosen under each protocol for one set of O-D pairs, showcasing the static versus dynamic nature of the routing decisions. The subsequent two maps on the right perform a similar analysis for another set of O-D pairs, providing further insights into how each protocol adapts to differing traffic conditions and routing challenges.

We observe that with the additional data utilized in the InformRoute, the total number of network edges engaged increased, indicating a more complex route selection process. Conversely, when allowing sub-optimal directional routing in FlexRoute, significant consolidation of routes was achieved. This adjustment suggests that FlexRoute is effective in optimizing the routing process by utilizing less direct paths that cumulatively reduce overall driving time and distance.

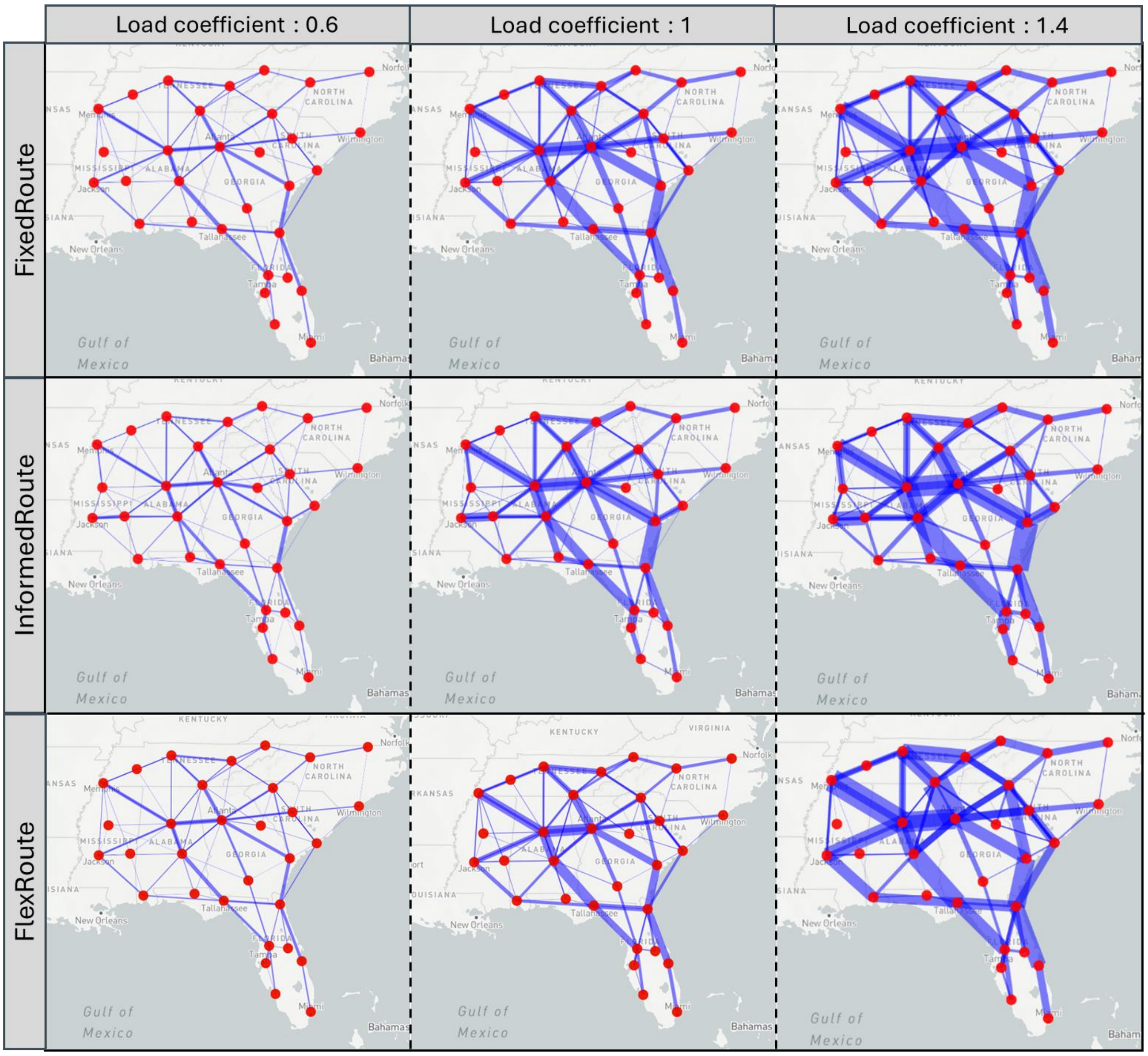


*Figure 5: Comparative visualization of traffic flows under FixedRoute, InformRoute and FlexRoute protocols across varying load coefficients depicting the adaptation in routing strategies in response to changing densities*

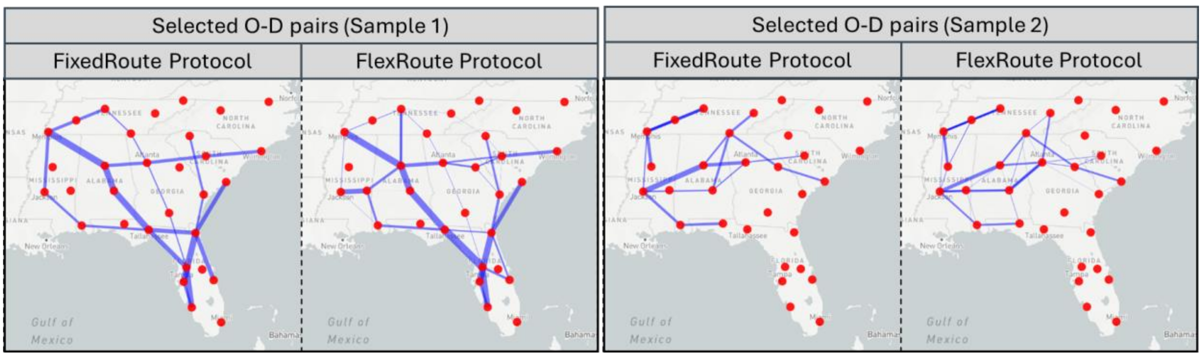


*Figure 6: Route comparisons for two distinct sets of origin-destination pairs under FixedRoute and FlexRoute*

We analyzed the driving distances for each protocol, as shown in Figure 7. This bar graph compares the driving time and distances between FixedRoute and FlexRoute across various load coefficients. Notably, FlexRoute achieves approximately a 6% reduction in driving time and distance at lower load coefficients, with even greater reductions at higher load coefficients. However, as the load coefficients increase beyond 1.4, the FixedRoute protocol consolidates more effectively than before, leading to a lesser reduction in driving distance.

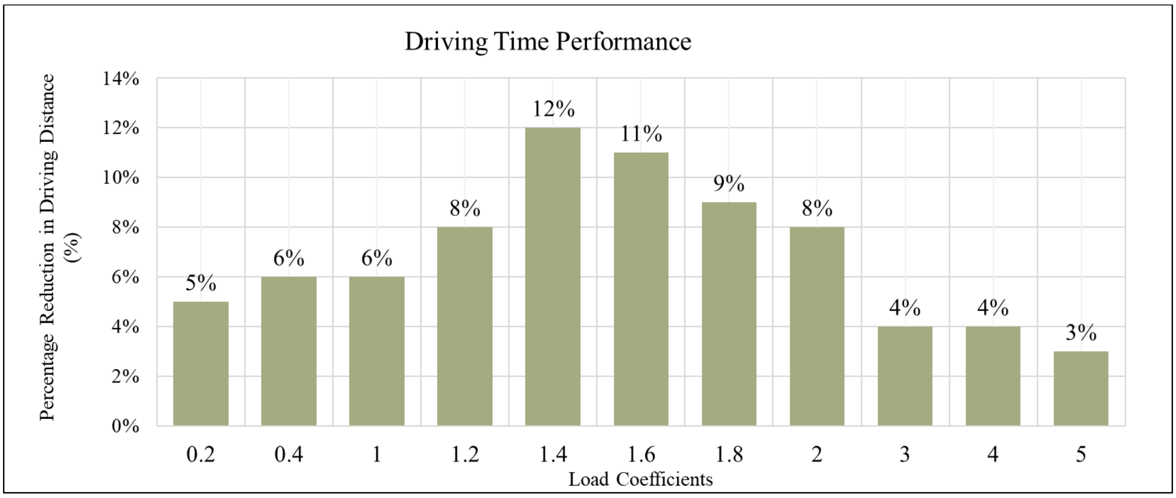


*Figure 7: Comparative analysis of driving distances in FixedRoute versus FlexRoute protocols*

## 7. Conclusion and Further Research

This study introduced a dynamic, sector-based directional routing protocol specifically tailored for the Physical Internet. By dividing the network into manageable sectors and dynamically adjusting routing decisions based on data from smart containers, we have laid the groundwork for a logistics system that balances efficiency, sustainability, resilience, and cost-effectiveness. Our results indicate that the proposed directional routing methodology enhances the ability to handle dynamic network conditions and disruptions effectively, thereby increasing the reliability and robustness of the Physical Internet. The flexibility of the model to adapt sector boundaries dynamically based on traffic density and shipment directions proves particularly beneficial in optimizing routing strategies and improving overall network performance.

In the future, the research will focus on several critical areas to enhance the capabilities and efficiency of the proposed routing protocol:

- Multimodality Integration: Future iterations of our model will include a more comprehensive integration of multimodal transport options. This will involve adapting our routing strategies to account for the unique characteristics and requirements of different modes of transportation, such as rail, air, and maritime, in addition to the existing road-based routes.
- Advanced DADSR Optimization: We plan to delve deeper into the parameters of Density-Adjusted Dynamic Sector Routing, optimizing its mathematical model and adjustment mechanisms. This will involve refining the criteria for sector adjustment, improving the accuracy of hub inclusion criteria, and fine-tuning the network density awareness functions. Advanced optimization techniques and machine learning algorithms will be utilized to dynamically adjust these parameters in real-time based on ongoing network performance data.

- Robust Testing and Validation: Comprehensive testing and validation of the enhanced model will be conducted across diverse scenarios and network conditions. This includes simulation-based testing as well as real-world pilot studies to evaluate the performance of the routing protocol under various logistical challenges and traffic densities.
- Parameter Sensitivity Analysis: A detailed sensitivity analysis will be carried out to understand the impact of different parameter settings on the performance of the routing protocol. This will help in identifying the most critical factors influencing routing decisions and network efficiency.

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