

## Dynamic Freight Routing and Dispatch Protocols for the Physical Internet

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**Abstract:** *The Physical Internet (PI) promises to transform freight movement by enabling standardized modular containers to be dynamically routed and dispatched through interconnected hubs. A key challenge in such networks is determining the optimal dispatch timing that balances consolidation opportunities, service reliability, and efficient asset utilization. In this paper, we propose an integrated framework that simultaneously addresses three interrelated decisions at each hub: which containers to dispatch, where to send them next, and when to dispatch them. We compare combinations of two routing protocols, destinational routing (DER) and directional routing (DIR), and three dispatch protocols, Fixed Threshold Dispatch (FTD); Flow-Adaptive Dispatch (FAD); and Dynamic Adaptive Consolidation (DAC). Our simulation experiments, conducted using real-world network data, demonstrate that integrating DIR routing and DAC dispatch protocols significantly improves consolidation, reduces empty mileage, and maintains high on-time delivery performance.*

**Keywords:** *Physical Internet, Dynamic Directional Routing, Dispatch Deadline Protocols, Dwell Time Optimization, Maximum Latency, Freight Consolidation, Logistics Network Optimization, Adaptive Routing, Directional Freight Movement, Hyperconnected Logistics*

**Physical Internet (PI) Roadmap Fitness:**  PI Networks,  System of Logistics Networks.

**Targeted Delivery Mode-s:**  Paper,  In-Person presentation

### 1 Introduction

The Physical Internet envisions an open, globally interconnected logistics system in which standardized modular containers are routed through a network of multimodal hubs (Montreuil, 2011). Unlike current traditional logistics practices, where fixed dispatch schedules and static routing decisions often lead to underutilized truck capacity and suboptimal consolidation, the Physical Internet envisions dynamic operations. When dynamically operating hubs in such a system, three critical challenges must repeatedly be resolved concurrently at each hub considering all containers arriving or already at the hub: determining which containers to dispatch together (consolidation), selecting the optimal next hub (freight routing) for each container, and deciding when to dispatch (timing) each multi-container shipment.

Previously proposed methods for inter-hub freight routing each container from origin to destination essentially are based on finding and adopting a travel-time-based shortest path across the hub network, while those for containerized shipment dispatch decisions have relied on fixed schedules or simple volume thresholds. This is simple yet does not consider and leverage the interdependencies between these decisions. In this paper, we propose an integrated framework that combines dynamic freight routing with adaptive dispatch protocols. In

particular, our framework dynamically assigns the next hub for each container while also evaluating the current load, projected arrivals, and available slack time to determine the optimal dispatch moment for each shipment.

## 2 Literature Review

The Physical Internet (PI) has attracted significant attention as a means to revolutionize logistics operations through standardization, modularity, and decentralization (Montreuil et al., 2013). Early studies primarily focused on static routing approaches, employing traditional shortest-path algorithms. While effective under stable conditions, these methods fail to adapt to real-time network fluctuations such as congestion or dynamic demand patterns. To address this, more recent work has explored dynamic routing protocols, including directional routing methods that identify candidate next hubs based on their geographic bearing relative to the destination (Shaikh and Montreuil, 2024; Shaikh et al., 2025).

Separately, research on dispatch protocols has traditionally relied on fixed schedules or simple capacity-based triggers to initiate dispatch decisions (Venkatadri et al., 2016; Chargui et al., 2019). Shaikh and Montreuil (2023) introduced the Maximum Latency Time (MLT) concept to enable containers to wait strategically for improved consolidation along fixed predetermined paths. All these prior protocols did not account for the uncertainty and variability introduced by dynamic routing environments.

Our contribution advances the field by integrating dynamic routing with adaptive dispatch protocols within a decentralized framework. Specifically, we systematically analyze the interplay between routing and dispatch decisions by evaluating combinations of destinational and directional routing protocols with three levels of dispatch sophistication: fixed-threshold, flow-aware, and dynamically adaptive consolidation protocols. This integration enables more responsive and resilient hyperconnected logistics network capable of maintaining high performance under fluctuating demand and congestion conditions.

## 3 Methodology

In this section, we describe the theoretical foundation of our integrated framework. We begin by defining routing protocols, then detailing dispatch protocols, and finally explain how they are combined into our operational framework.

### 3.1 Freight Routing Protocols

We consider two freight routing protocols: Destinational Routing (DER) and Directional Routing (DIR).

In the destinational approach, the network is modeled as a directed graph with hubs as nodes and travel times as edge weights. For container  $c$  at hub  $h$ , the shortest path from  $h$  to  $dest(c)$  is computed by minimizing the total delivery time:

$$\text{shortest\_path}_{(c)} = \arg \min_p \left\{ \sum_{(i,j) \in p} \text{travel\_time}(i,j) + \sum_{k \in p'} \text{dwell\_time}(k) \right\} \quad (1)$$

where  $p'$  represents the set of intermediate hubs in path  $p$ , and  $\text{dwell\_time}(k)$  is the estimated processing time at hub  $k$ .

This shortest path, computed at hub entry in the network is adopted through its journey across the network. Thus the next hub for  $c$  at any hub along its journey is then the next hub along this shortest path. This method is simple but does not adapt to real-time conditions.

Directional routing dynamically selects the next hub based on geographic alignment, service level constraints, and dynamic conditions. The process comprises several steps:

**Bearing Calculation:** For container  $c$  at hub  $h$  with destination  $d$ , we calculate the bearing from  $h$  to  $d$ .

**Directional Neighbor Filtering:** For each neighboring hub  $n$ , we compute the bearing  $b_{h,n}$  from  $h$  to  $n$ . A neighbor is considered aligned if

$$|b_{h,n} - b_{h,d}| \leq \theta \text{ or } |b_{h,n} - b_{h,d}| \geq 360 - \theta \quad (2)$$

where  $\theta$  is a threshold (e.g.,  $50^\circ$ ). The set of directional neighbors is:

$$DN(h, d) = \{n \in H: (h, n) \text{ is an edge, } |b_{h,n} - b_{h,d}| \leq \theta \text{ or } |b_{h,n} - b_{h,d}| \geq 360 - \theta\} \quad (3)$$

**Service Level Feasibility:** For each neighbor  $n \in DN(h, d)$ , we calculate the remaining time for container  $c$  as:

$$\text{remaining\_time}(c) = \text{due}(c) - t \quad (4)$$

Neighbor  $n$  is deemed service-feasible if:

$$\text{traveltime}_{(h,n)} + \text{traveltime}_{(n,d)} + (\text{handling\_time}(n) \times n_{est}(n, d)) \leq \text{remaining\_time}(c) \quad (5)$$

where  $n_{est}(n, d)$  represents the estimated number of hubs between  $n$  and the destination  $d$

**Next Hub Selection:** For each feasible neighbor  $n \in FN(c)$ , a tri-criteria score is computed that balances consolidation opportunities, travel efficiency, and network congestion:

$$\text{score}(c, n) = \alpha \times \text{cons\_factor}(h, n) - \beta \times \text{travel\_time}(h, n) - \gamma \times \text{congestion}(n) \quad (6)$$

where:

- $\alpha$ ,  $\beta$ , and  $\gamma$  are weighting parameters in the range  $[0, 1]$  with  $\alpha + \beta + \gamma = 1$
- $\text{cons\_factor}(h, n)$  quantifies the number of containers at  $h$  for which  $n$  is also feasible
- $\text{travel\_time}(h, n)$  is the transit time from hub  $h$  to neighbor  $n$
- $\text{congestion}(n)$  is the ratio of containers at or en route to  $n$  relative to its capacity

The next hub is chosen as:

$$\text{next\_hub}(c) = \arg \max_{n \in FN(c)} \text{score}(c, n) \quad (7)$$

If  $FN(c)$  is empty, a fallback strategy selects the neighbor closest to  $d$ .

In essence, directional routing computes the bearing from the current hub to the destination, filters neighbors based on directional alignment and then evaluates service feasibility. Finally, it selects the next hub using a scoring function that accounts for consolidation potential, travel time, and congestion.

### 3.2 Dispatch Protocols

Efficient dispatch decisions are critical to achieving enhanced consolidation and high on-time delivery performance within Physical Internet (PI) networks. In our framework, once a container's next hub is determined via the routing protocol, containers are grouped based on their common next hub. We evaluate three dispatch protocols that represent a progression in sophistication:

- **Fixed Threshold Dispatch Protocol (FTD)**
- **Flow-Aware Dispatch Protocol (FAD)**
- **Dynamic Adaptive Consolidation Dispatch Protocol (DAC)**

Each protocol builds upon the previous level by incorporating additional adaptive criteria that reflect real-time network conditions, service requirements, and consolidation opportunities.

### 3.2.1 Fixed Threshold Dispatch Protocol (FTD)

FTD Protocol serves as the baseline approach. In FTD, containers at a hub are grouped based on their computed next hub, and a dispatch is initiated when either of the following triggers is activated:

- **Capacity Trigger:** The group of containers reaches the full capacity of the truck.
- **Time Trigger:** Any container in the group has been waiting longer than a threshold.

FTD relies solely on static thresholds that are invariant with respect to real-time flow patterns, service deadlines, or projected arrivals. Its simplicity establishes a reference point for assessing more adaptive approaches.

### 3.2.2 Flow-Aware Dispatch Protocol (FAD)

FAD Protocol extends FTD by incorporating service-based waiting times, which are derived from slack time calculations, and by taking into account containers that are already en route to the current hub. The key components of FAD are as follows:

#### 1. Slack Time Calculation

For a container  $c$  at hub  $h$ , the overall slack is computed as:

$$\text{slack}(c, h) = \max\{0, \text{due}(c) - t - \text{est\_tt}_{(h, \text{dest}(c))} - \text{handling\_time}(h) \times n_{\text{est}}\} \quad (8)$$

where  $t$  is the current time,  $\text{est\_tt}$  is the estimated travel time and  $n_{\text{est}}$  is the estimated number of hubs remaining.

#### 2. Equal Slack Distribution

The overall slack is allocated equally across the estimated remaining hubs:

$$\text{AsnDwellTime}_{c,h} = \frac{\text{slack}(c)}{\text{estimated\_remaining\_hubs}} \quad (9)$$

#### 3. Latest Departure Time (LDT)

Rather than applying a uniform fixed waiting time, FAD computes a container-specific Latest Departure Time at the current hub:

$$\text{LDT}(c, h) = \text{arrival\_time}(c) + \text{handling\_time}(h) + \text{AsnDwellTime}_{c,h} \quad (10)$$

#### 4. En-route Container Consideration

FAD monitors containers that are en route to the current hub. If additional containers, sharing the same computed next hub, are expected to arrive before the calculated LDT, dispatch is deferred to improve consolidation.

By adapting waiting times based on computed slack and near-term arrivals, FAD is more responsive than FTD, yet it does not consider network congestion or allow dynamic reallocation of slack beyond the current hub.

DAC Protocol further refines FAD by explicitly integrating the concept of Maximum Latency Time (MLT) to facilitate additional waiting time when consolidation opportunities justify a delay. In previous work (Shaikh et al., 2021), the concept of Maximum Latency Time (MLT) was introduced for scenarios with predetermined paths, where the number of remaining hubs was fixed. In our current framework, container paths are dynamically estimated, so the total available slack must be apportioned among the estimated remaining hubs. DAC allows a

container's Latest Departure Time at the current hub to be extended by "borrowing" slack allocated to subsequent hubs, provided that such delay does not compromise the overall delivery deadline or induce network bottlenecks defined as hubs operating above 90% capacity for extended periods, which can cause cascading delays throughout the network.

Let  $LDT_{c,n}$  denote the baseline Latest Departure Time for container  $c$  at the current hub  $n$  computed as in FAD, and let  $AsnDwellTime_{c,i}$  be the anticipated dwell time for container  $c$  at future hub  $i$  (with  $i = n + 1, \dots, n_{\text{remaining}}$ ). DAC defines Maximum Latency Time  $MLT_{c,n}$  as:

$$MLT_{c,n} = LDT_{c,n} + m \left( \sum_{i=n+1}^{n_{\text{remaining}}} AsnDwellTime_{c,i} \right),$$

where  $m$  (with  $0 \leq m \leq 1$ ) is a flexibility parameter that dictates the fraction of future dwell time that may be reallocated to the current hub.

DAC works according to the following operational mechanism:

### 1. Dynamic Decision-Making

DAC first calculates the available slack at the current hub as in FAD. Then it evaluates whether extending the waiting period-up to  $MLT_{c,n}$  will likely result in better consolidation. This decision is informed by the expected arrivals (through flow prediction) and real-time monitoring of en-route containers.

### 2. Bottleneck Prevention

To preclude congestion, DAC continuously monitors hub congestion defined by:

$$\text{congestion}(h) = \frac{\text{containers\_at\_}h + \text{containers\_en\_route\_to\_}h}{\text{capacity}(h)}.$$

If the congestion metric exceeds a predefined threshold, DAC curtails any additional waiting, thereby ensuring that extended dwell times do not translate into bottlenecks.

### 3. Flow Prediction

By incorporating real time estimation of future container arrival times, DAC assesses the potential gains from waiting. If enroute arrivals indicate significant consolidation benefits, DAC allows the container to remain until nearing  $MLT_{c,n}$ ; otherwise, dispatch occurs sooner.

DAC effectively permits containers to "borrow" time from future hubs by extending the Latest Departure Time under favorable consolidation circumstances. This dynamic adjustment is balanced by congestion monitoring and urgency measures, ensuring that the extended dwell time does not compromise overall service levels while enhancing consolidation opportunities. This extends the MLT concept from predetermined paths (Shaikh et al., 2021) to a fully dynamic routing context and incorporates new congestion-aware features, representing a significant contribution of our current work.

## 4 Performance Evaluation and Simulation Results

We evaluate our integrated framework through an extensive simulation study that compares both routing protocols (DER and DIR) across all three dispatch protocols (FTD, FAD, and DAC). Our simulation environment models a transportation network in the Southeastern United States, with ten origin hubs and two destination hubs. Each shipment has an associated service level (1, 2, or 3), translating into delivery deadlines of 24, 48, or 72 hours, respectively.

To ensure realistic freight flow patterns, container demands are gradually introduced into the system rather than simultaneously. The origin, destination, service level, and creation time for each container demand are randomly generated to reflect heterogeneous traffic patterns. Our simulator explicitly models both vehicle-level processes (routing, scheduling) and freight-level processes (loading, unloading, consolidation), distinguishing between truck operations and the handling of consolidated loads (sets of containers grouped together at hubs for transport on a single vehicle). Following digital freight matching principles, we assume trucks perform single hub-to-hub movements rather than multi-hub routing.

#### 4.1 Simulation Setup

Using destinational routing, each container demand follows the precomputed minimum travel-time path from origin to destination through the hub network, with hub-to-hub edges designed to respect driver hour limitations. Using directional routing, upon arrival at a hub, the system dynamically identifies candidate next hubs within  $\pm 50^\circ$  of the bearing toward the destination, selecting based on travel time, consolidation opportunities, and current congestion levels. Each truck has a capacity of 40 containers, and dispatch decisions are implemented using three distinct protocols FTD, FAD, and DAC that vary in sophistication as described previously.

We conducted simulations for five daily demand levels (500, 600, 1000, 2000, and 3000 shipments) across all six combinations of routing and dispatch protocols. All simulations were run on the same network with identical service level distributions and time windows, ensuring that observed differences can be attributed to the routing and dispatch protocols.

#### 4.2 Simulation Results and Analysis

Our simulation experiments yielded comprehensive data comparing the routing protocols and dispatch protocols across five demand levels. The next sections present the results, focusing on key performance metrics: on-time delivery, resource utilization, and consolidation efficiency.

Table 1: On-time Delivery Performance (%)

Demand Level	Shipments	Routing Protocol	FTD	FAD	DAC
Very Low	500	Destinational	100	100	100
		Directional	100	100	100
Low	600	Destinational	100	100	100
		Directional	100	100	100
Moderate	1000	Destinational	100	100	100
		Directional	100	100	100
High	2000	Destinational	99.8	100	100
		Directional	99.9	100	100
Very High	3000	Destinational	97.2	98.1	99.2
		Directional	98.1	98.6	99.9

##### 4.2.1 On-time Delivery Performance

Table 1 presents the on-time delivery performance across demand levels. At low to moderate demand levels, both routing protocols maintain perfect on-time delivery across all protocols. However, as demand increases to high and very high levels, performance begins to diverge. The service degradation becomes particularly evident with the FTD protocol, where destinational routing experiences a drop to 97.2% on-time delivery at very high demand, while directional routing maintains 98.1% performance.

Most notably, the combination of directional routing with the DAC protocol demonstrates remarkable resilience, maintaining 99.9% on-time delivery even at very high demand levels.

This suggests that the adaptive nature of directional routing, when combined with intelligent slack time management, creates a system that remains stable even under challenging conditions.

### 4.2.2 Resource Utilization

Resource efficiency was measured through trucks dispatched and total miles traveled illustrated in Figure 1. The truck utilization data reveals several important patterns. First, across both routing protocols, the progression from FTD to FAD to DAC results in substantial reductions in required vehicles. Second, directional routing consistently requires fewer trucks than destinational routing for the same protocol, with the difference becoming more pronounced at higher demand levels. For example, at very high demand, DIR+FTD requires 16.3% fewer trucks than DER+FTD.

The most efficient combination is directional routing with DAC, which at very high demand requires only 480 trucks compared to 1198 for destinational routing with FTD—a 59.9% reduction. This dramatic improvement illustrates the compounding benefits of combining intelligent routing with adaptive dispatch timing. Interestingly, while both routing protocols show similar total miles at low demand levels (with directional routing occasionally requiring slightly more miles), directional routing demonstrates increasing advantage as demand rises. At very high demand, directional routing with DAC achieves a 7.9% reduction in total miles compared to destinational with DAC.

This pattern suggests that at lower demand levels, pure distance minimization through destinational routing performs well, but as network complexity increases with higher demand, directional routing's ability to distribute traffic and avoid congested areas becomes more valuable, resulting in overall distance savings despite not explicitly optimizing for minimum distance.

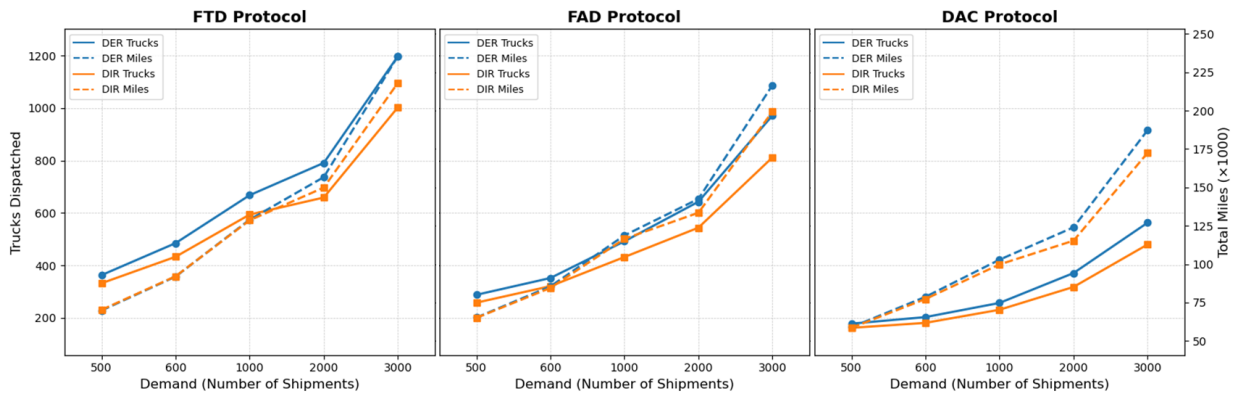


Figure 1: Comparison across three dispatch protocols showing how Destinational routing (blue circles) and Directional routing (orange squares) perform over five demand levels (500–3000 shipments). Solid lines plot Trucks Dispatched (left y-axis), while dashed lines plot Total Miles Traveled (x1000, right y-axis).

### 4.2.3 Consolidation Efficiency

The fill rate metric directly measures consolidation efficiency—the percentage of truck capacity utilized when dispatched. The fill rate data in Table 1 reveals several notable patterns. The DAC protocol dramatically outperforms both FTD and FAD across all demand levels and for both routing protocols. Directional routing consistently achieves higher fill rates than destinational routing for the same protocol, with an absolute improvement of 6-7 percentage points across most scenarios.

Table 2: Average Fill Rate (%) by Demand Level and Protocol

**Fill Rate Performance Across Protocols and Demand Levels**

Dispatch Protocol	Demand Level					Routing Protocol	
	Very Low	Low	Moderate	High	Very High		
DESTINATIONAL	FTD	29.5%	28.3%	30.0%	31.0%	30.5%	DESTINATIONAL
	FAD	39.5%	38.8%	40.5%	42.3%	40.7%	
DIRECTIONAL	DAC	65.0%	66.5%	69.0%	73.0%	74.3%	DIRECTIONAL
	FTD	35.8%	34.5%	36.4%	37.5%	37.0%	
DIRECTIONAL	FAD	46.2%	45.4%	47.0%	48.8%	47.2%	DIRECTIONAL
	DAC	71.4%	73.9%	75.7%	79.8%	81.0%	

The most striking observation is again the combined effect of DAC protocol with directional routing, which achieves fill rates of up to 81% at very high demand—an improvement of 50.5 percentage points over the traditional approach (DER+FTD). This represents a transformative improvement in vehicle utilization that would have significant economic and environmental benefits in practical implementation.

#### 4.2.4 Network Stability and Resilience

To better understand the mechanisms behind the observed performance differences, we analyzed the formation of bottlenecks—defined as hubs operating above 90% capacity for extended periods—across demand levels. Figure 3 shows the number of critical bottlenecks observed during simulation.

The bottleneck analysis reveals a critical insight: while destinational routing creates an increasing number of bottlenecks as demand grows (reaching 17 at very high demand), directional routing dramatically reduces bottleneck formation (only 2 at very high demand). This reduction in bottlenecks directly correlates with the improved on-time delivery performance observed earlier. The mechanism behind this improvement is directional routing's ability to distribute traffic more evenly across the network. By considering alternatives to the shortest path when making routing decisions, directional routing prevents the concentration of traffic that leads to bottlenecks in the destinational approach. This, in turn, reduces the cascading delays that bottlenecks introduce into the system.

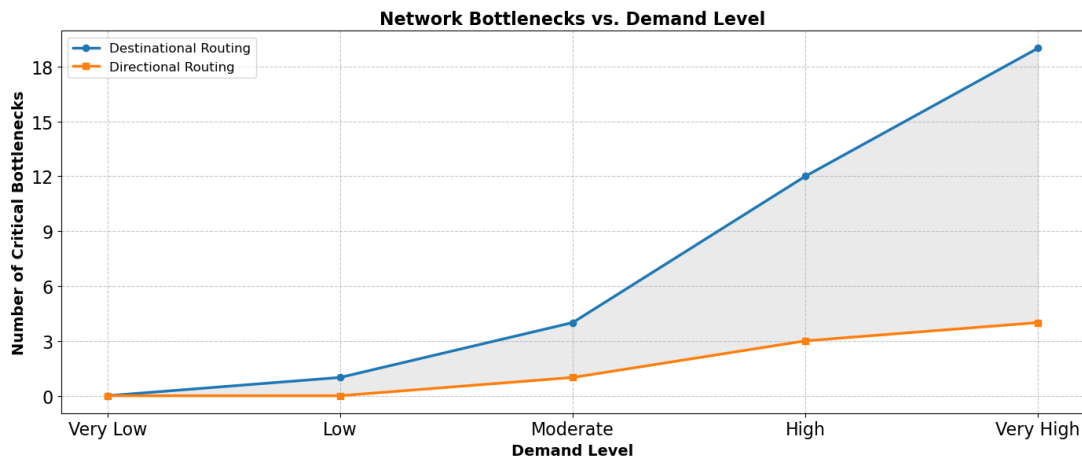


Figure 2: Number of Critical Bottlenecks (>90% Capacity) by Demand Level with DAC

The simulation results demonstrate that path diversity increases with directional routing and advanced dispatch protocols. While the destinational approach consistently routes shipments through predetermined minimum-time corridors, the directional approach explores alternate feasible routes as shown in Figures 4. This diversity becomes particularly valuable in high-demand scenarios where traditional corridors experience congestion.

Figure 4 illustrates this effect by visualizing sample shipment paths between common origin-destination pairs. With directional routing and DAC, shipments between the same origin-destination pairs often follow diverse paths, distributing flow more evenly across the network and avoiding congestion bottlenecks.

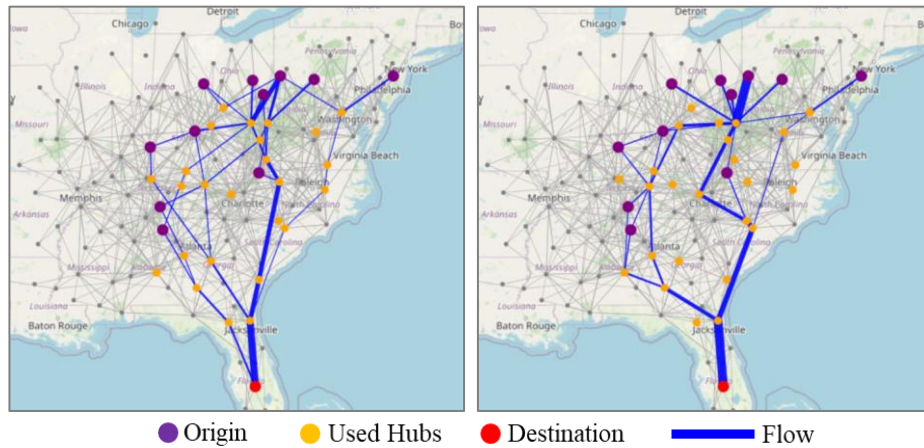


Figure 3: Path Selection and Consolidation Efficiency: Destinational Routing (Left) and Directional Routing (Right)

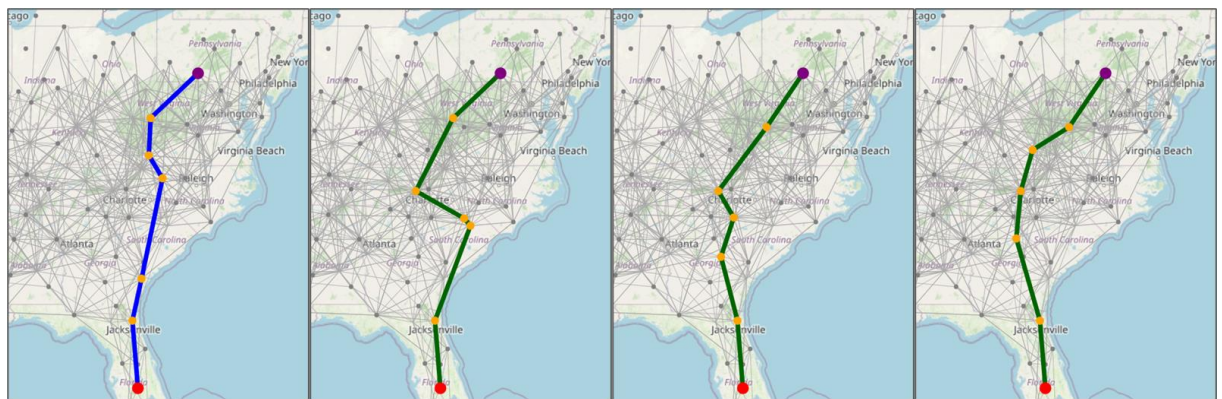


Figure 4: Visualizing Routing of Containers with the same Origin and Destination (Destinational: Blue, Directional: Green)

## 5. Conclusion

Our simulation experiments demonstrate that both routing and dispatch protocols selection significantly impact Physical Internet performance, with their effects becoming increasingly pronounced at higher demand levels. The most significant finding is the remarkable synergy achieved when combining directional routing with adaptive dispatch protocols. While each component individually improves performance, their integration creates multiplicative benefits through network load balancing, responsive consolidation, and reduced network oscillation.

The performance gap between the baseline DER + FTD protocols and the proposed DIR+DAC protocols widens as demand increases. At very high demand, the DAC protocol achieves a 59.9% reduction in trucks dispatched compared to FTD, while maintaining higher service levels. This demonstrates superior resilience under stress conditions, as directional routing

maintains 99.9% on-time delivery with the DAC protocol at the highest demand level, compared to 99.2% for destinational routing.

Beyond improving service levels, our proposed combination of DIR+DAC protocols offers substantial operational and environmental benefits. The dramatic improvement in fill rates—from 30.5% with the baseline DER+FTD protocols to 81.0% with our proposed DIR+DAC protocols represents a transformative change in asset utilization. The 26.8% reduction in total miles traveled, combined with higher fill rates, would significantly reduce carbon emissions, fuel consumption, and road congestion, aligning with growing sustainability imperatives in the logistics industry.

Implementing our proposed approach in real-world PI networks requires consideration of computational requirements, data integration needs, and parameter tuning. Directional routing requires more computational resources than destinational routing, particularly for real-time bearing calculations and scoring potential next hubs. The DAC protocol relies on accurate data about container locations, hub capacities, and predicted arrivals, highlighting the importance of standardized information exchange protocols across PI participants.

## 6 Future Research

Our findings strongly support the potential of the Physical Internet to transform logistics operations through standardization, modularity, and intelligent coordination. Our research indicates that the traditional focus on minimizing direct travel time may be suboptimal in hyperconnected PI networks, where consolidation opportunities and network-wide traffic distribution become increasingly important considerations.

Future research should explore the integration of time-dependent traffic data to enhance responsiveness to real-world dynamics, including rush hour congestion, weather disruptions, and infrastructure bottlenecks. Extending directional routing models to incorporate multi-objective optimization balancing transit time, consolidation, congestion avoidance, and environmental impact could further elevate network efficiency. Additionally, enhancing dispatch decisions through predictive analytics, leveraging not only en-route containers but also broader traffic forecasts, holds promise for improving the Dynamic Adaptive Consolidation Dispatch Protocol (DAC).

Research should also investigate network design implications, multimodal integration strategies, and collaborative decision-making frameworks among multiple stakeholders. Real-world pilot studies will be essential to validate simulation findings, assess computational scalability, and identify practical barriers to adoption. Finally, developing structured approaches for the incremental transition from traditional logistics operations to fully realized Physical Internet networks remains a critical area for future exploration.

## References

- Ballot, E., Gobet, O., & Montreuil, B. (2012). Physical internet enabled open hub network design for distributed networked operations. In *Service Orientation in Holonic and Multi-Agent Manufacturing Control* (pp. 279–292). Springer.
- Chargui, T., Bekrar, A., Reghioui, M., & Trentesaux, D. (2019). Multi-objective sustainable truck scheduling in a rail–road Physical Internet cross-docking hub considering energy consumption. *International Journal of Production Research*, 57(23), 7412–7431.
- Crainic, T. G., & Montreuil, B. (2016). Physical Internet enabled hyperconnected city logistics. *Transportation Research Procedia*, 12, 383–398.
- Darvish, M., Larrain, H., & Coelho, L. C. (2016). A dynamic multi-plant lot-sizing and distribution problem. *International Journal of Production Research*, 54(22), 6707–6717.
- Fazili, M., Venkatadri, U., Cyrus, P., & Tajbakhsh, M. (2017). Physical Internet, conventional and hybrid logistic systems: A routing optimisation-based comparison using the Eastern Canada road network case study. *International Journal of Production Research*, 55(9), 2703–2730.
- Montreuil, B. (2011). Toward a Physical Internet: meeting the global logistics sustainability grand challenge. *Logistics Research*, 3(2–3), 71–87.
- Montreuil, B., Meller, R. D., & Ballot, E. (2013). Physical internet foundations. In *Service Orientation in Holonic and Multi-Agent Manufacturing and Robotics* (pp. 151–166). Springer.
- Pan, S., Ballot, E., Huang, G. Q., & Montreuil, B. (2017). Physical Internet and interconnected logistics services: research and applications. *International Journal of Production Research*, 55(9), 2603–2609.
- Qiao, B., Pan, S., & Ballot, E. (2018). Revenue optimization for less-than-truckload carriers in the Physical Internet: dynamic pricing and request selection. *Computers & Industrial Engineering*, 126, 727–736.
- Sarraj, R., Ballot, E., Pan, S., Hakimi, D., & Montreuil, B. (2014). Interconnected logistic networks and protocols: simulation-based efficiency assessment. *International Journal of Production Research*, 52(11), 3185–3208.
- Shaikh, S. J., & Montreuil, B. (2023). Conceptual framework for hyperconnected transport and delivery logistics infrastructure. In *9th International Physical Internet Conference*.
- Shaikh, S., & Montreuil, B. (2024). Dynamic directional routing for the Physical Internet: A sector-based approach with dynamic adjustment. In *10th International Physical Internet Conference*.
- Shaikh, S., Muthukrishnan, P., Lai, Y., & Montreuil, B. (2025). Dynamic directional routing in a Physical Internet network. In *Proceedings of the IISE Annual Conference & Expo*.
- Sternberg, H., & Norrman, A. (2017). The Physical Internet—review, analysis and future research agenda. *International Journal of Physical Distribution & Logistics Management*, 47(8), 736–762.
- Venkatadri, U., Krishna, K. S., & Ülkü, M. A. (2016). On Physical Internet logistics: modeling the impact of consolidation on transportation and inventory costs. *IEEE Transactions on Automation Science and Engineering*, 14(4), 1571–1584.
- Yang, Y., Pan, S., & Ballot, E. (2017). Innovative vendor-managed inventory strategy exploiting interconnected logistics services in the Physical Internet. *International Journal of Production Research*, 55(9), 2685–2702.
- Zhong, R. Y., Xu, C., Chen, C., & Huang, G. Q. (2017). Big data analytics for Physical Internet-based intelligent manufacturing shop floors. *International Journal of Production Research*, 55(9), 2610–2621.
- Shaikh, S. J., Montreuil, B., Hodjat-Shamami, M., & Gupta, A. (2021). Introducing Services and Protocols for Inter-Hub Transportation in the Physical Internet. *arXiv preprint arXiv:2111.07520*.