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Routing and network-slicing-based protocols for the Physical Internet network

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Abstract: *The Physical Internet (PI) is a logistics network paradigm emphasizing operational, digital, and physical interconnectivity using encapsulation, interfaces, and protocols. However, the dynamic and shared nature of the network makes it complex to manage, and the lack of robust and effective routing protocols would prevent it from functioning efficiently. This paper proposes a dynamic and reactive routing protocol considering various contexts, such as disturbing events, route constraints, and PI actors' preferences and local knowledge of the system's state. Moreover, it proposes a network slicing-based protocol for more efficient resource allocation and management and to guide individual self-interested decisions toward a system-wide common goal.*

Keywords: *Logistics and supply networks; PI fundamentals and constituents; PI implementation; PI modeling and simulation; collaborative decision making.*

Physical Internet Roadmap ([Link](#)): PI Nodes, PI Networks, System of Logistics Networks.

Conference Topic(s): *Logistics and supply networks; PI fundamentals and constituents; PI impacts; PI implementation; PI modeling and simulation; collaborative decision making.*

Physical Internet Roadmap ([Link](#)): PI Nodes, PI Networks, System of Logistics Networks.

1 Introduction

The Physical Internet (PI) is a new logistics paradigm that emphasizes the interconnectedness of digital, operational, and physical networks through encapsulation, interfaces, and protocols (Ballot et al., 2014; Pan et al., 2021). Nevertheless, the PI network is highly complex due to its dynamic structure and intermediate centers that divide it into sub-networks, each operated by a single legal entity. Accordingly, the absence of consensual, robust, and effective routing protocols would prevent the entire network from functioning effectively.

Moreover, routing protocols in PI must be dynamic and flexible to accommodate the ever-changing logistics landscape (Brian et al., 2022). Such protocol must adapt to disruptions (e.g., shortage, emergency/canceled orders, unavailability) and route constraints (e.g., capacity, travel time, costs), and ensure that PI containers are effectively assigned to logistical service resources and delivered to customers (Brian et al., 2022; Sarraj et al., 2014; Yang et al. 2017).

Furthermore, in PI, involved actors (e.g., coordinators, shippers, carriers) must collaborate on route construction and disturbance management based on their contextual and local knowledge of the system's state (Sallez et al., 2016). Therefore, centralized decision-making is no longer applicable and should be replaced by distributed decision-making processes. In addition, this shared logistics services network challenges how logistics costs are allocated among involved

actors, requiring a radically different resource allocation and cost-sharing mechanism to incentivize individual self-interested decisions to align with the network's common goal.

To address these challenges, this paper proposes reactive routing and network slicing-based mechanisms designed to enhance the functionality and efficiency of the PI network. In summary, this paper intends to answer the following research questions:

- RQ1: what protocol to develop so that preference, contextual and local knowledge of the system's state of each actor in the PI network can be integrated into the decision-making process while considering disruption management?
For this purpose, a decentralized, dynamic, and reactive routing protocol is proposed (cf. Section 2).
- RQ2: what protocol to apply, that should interact with the routing protocol, to ensure a more efficient allocation of resources while facilitating cost-sharing?
For this end, a network slicing-based mechanism is proposed (cf. Section 3).

The protocols are evaluated using real orders data from two major retail chains in France, and the experiments provide insights into the performance of the PI network under different scenarios.

2 Routing protocol

This paper proposes a reactive and scalable routing protocol that copes with the ever-changing contexts while integrating containers and resources' local knowledge and preferences, and disturbances that may occur at each level in the decision-making process (see Figure 1). In this paper, we assume that:

- Container mirrors the customer's constraints and preferences. Hence, the container's decisions may rely on the customer priority, such as focusing on short delivery time and cost minimization. It is also allowed to communicate and exchange information and play an active role in decision-making.
- Transportation resource mirrors the carriers' constraints and preferences. They can have a variety of characteristics, such as heterogeneous capacities and departure points for drivers. Carriers are assumed to be service-level and cost-conscious, with preferred geographic zones for container delivery and other environmental and social criteria.
- Hub resource represents in-transit nodes at which containers are exchanged between transportation means, where containers can be handled, sorted, and stored. At the hub's level, containers with the same destination can also be consolidated. It also symbolizes the departure node for transportation means and can communicate and exchange information (e.g., states, disturbing events, containers, vehicles).
- Coordinator represents a coordinator platform that manages operations in the sub-networks. It can also detect, identify, and analyze disturbances and coordinate with other entities in the system to select a relevant decision given the actual context and the system's and each entity's preferences. Each chosen decision is evaluated using a set of key performance indicators (e.g., cost, lead time, service level).

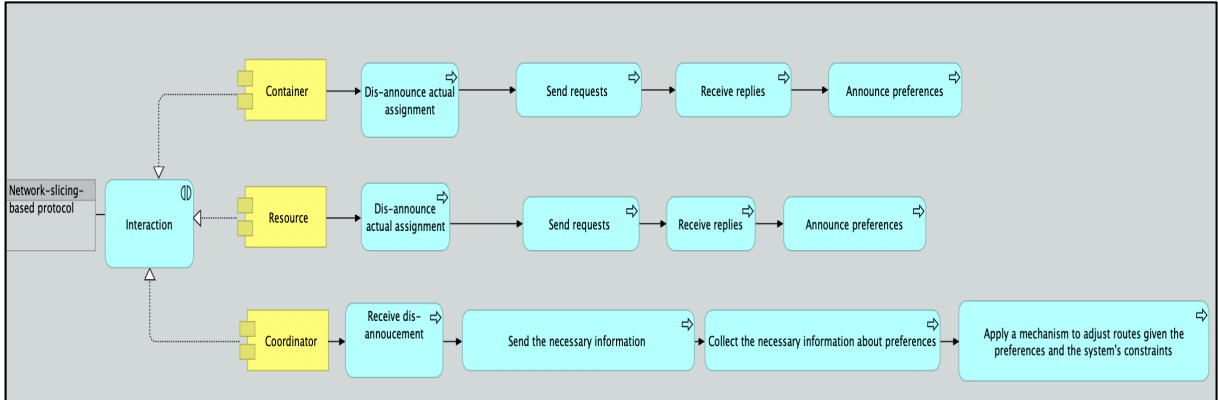


Figure 1: The proposed routing protocol.

The routing protocol is built upon the widely used Internet protocols, Route Request and Route Reply. As shown in Figure 1, the protocol proceeds as follows. When a container or resource's current routing assignment is disrupted due to external disturbances or prefers an alternative routing, it informs the coordinator in charge. The coordinator then sends all possible routing alternatives. Each container or resource uses a ranking mechanism (e.g., Technique for Order Preference by Similarity to Ideal Solution—TOPSIS) to assess the options based on its criteria, such as economic, social, and environmental criteria. Afterward, the containers or resources send requests to their neighbors (e.g., containers, hubs, transportation means) identified using a clustering mechanism (e.g., k-means algorithm), which apply a ranking mechanism to reply to the requests based on their criteria.

Once all the relevant information is gathered regarding the container and resource preferences and the system's constraints, the coordinator applies a mechanism to adjust the routing assignment. This mechanism can be implemented using several methods, including preference-based multi-objective evolutionary algorithms, Stackelberg game-based mechanisms, auction mechanisms, or negotiation protocols. The objective is to identify the most efficient routing solution that minimizes costs while considering the preferences of each container and resource.

Finally, the routing protocol interacts with a network slicing-based protocol for routing assignment (i.e., resource allocation) and cost-sharing facilitation. The network slicing-based protocol relies on the Fifth Generation (5G) mobile network slicing. It also employs assignment algorithms designed to offer good-quality solutions with simple computational capabilities that can be scaled to handle large-scale problems.

3 Network slicing-based protocol

This paper proposes a network slicing-based protocol among the involved actors based on their service efforts. For this end, we propose a mechanism built upon the 5G mobile network slicing mechanism (Habibi et al., 2017; Wijethilaka et al., 2021). Network slicing allows the creation of multiple virtual networks with a common physical infrastructure, each optimized for specific services or user groups (Kheddar et al., 2022). Indeed, due to its capability of splitting the physical network infrastructure into several isolated logical sub-networks, network slicing opens the network resources to vertical segments aiming at providing customized and more efficient end-to-end (E2E) services and allocating the network cost to the different deployed slices, which can then later be used to price the different E2E services (Habibi et al., 2017; Wijethilaka et al., 2021; Kheddar et al., 2022). Accordingly, in a PI slice-based network, each slice, with its own specific characteristics, will be considered a separate virtual network. This way, the physical infrastructure utilization and resource allocation will be much more cost-efficient.

Figure 2 presents the proposed network slicing-based protocol, which comprises three layers. The physical layer represents all the physical infrastructure and capabilities necessary for logistics services. It includes handling containers and the different resources –such as transportation means and hubs, and other nodes in the network, such as roads, railways, and ports. This layer also includes sensors and other devices that can collect data about the state of the physical infrastructure and the containers being transported, as well as all the hardware and software necessary to support communication within the PI network, including routers, switches, servers, and storage devices.

As for the service layer, it represents user and business services (i.e., order management, handling, shipment), which are expected to be supported by the PI network. Each service is represented by a service instance and used based on its characteristics to create network slices in the network slicing layer.

Finally, on the virtual network slicing layer, physical infrastructure is sliced/partitioned into multiple virtual networks, called a slice, composed to support, and build up services (represented in the service layer) that are supposed to be delivered to the user. It involves the creation of virtual logistics network slices that correspond to different stakeholders in the network, such as shippers, carriers, and logistics providers. Each slice has common physical infrastructure, can have its own architecture and is responsible for delivering a specific service and application to a specific user. Examples of network slices can be a slice to manage orders, a slice serving for container handling/storing/shipping, and a slice dedicated to providing communication service between involved actors.

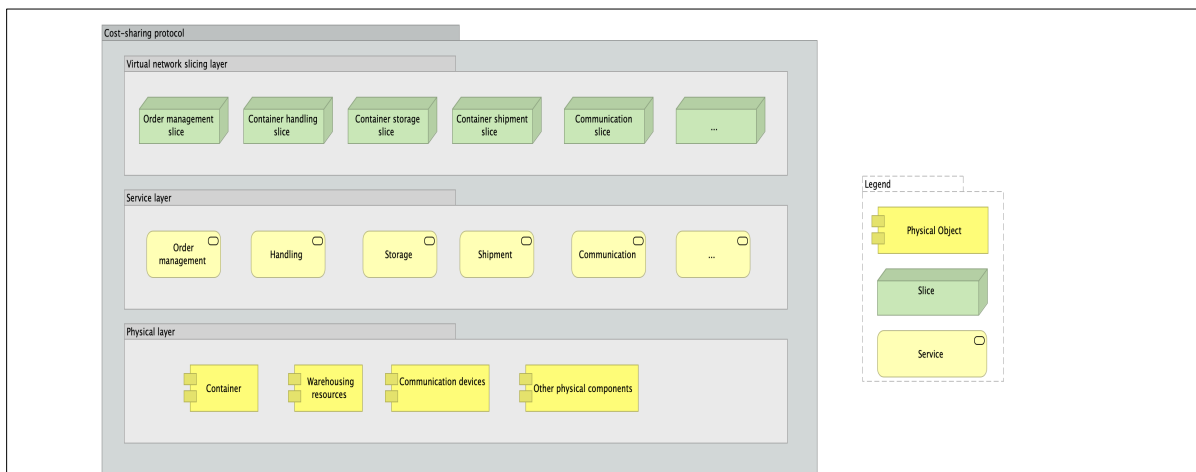


Figure 2: The proposed network slicing-based protocol.

In this protocol, a slice can be created using different mechanisms. In this paper, a slice is created by reserving physical resources (such as transportation means, hubs, and other infrastructures). The resources are allocated based on the service layer requirements. That is, the requirements of the logistics service provider, the availability of the resources in the network, and the objectives of the network coordinator. The slice is then created for a specific time and used during that period. For a sake of simplicity, this paper uses a multi-criteria decision-making mechanism, namely TOPSIS, and reactive assignment algorithms that select, for each slice and given the actual state of the network, the resources to be provided along with the appropriate logistic providers, the period for which the resources are to be provided, and the price to be paid to use them.

On the management level, under this protocol, each physical infrastructure and resource provider (PIRP), described in the physical layer, would be responsible for setting up and

managing the physical infrastructure and other hardware components required to support the virtual network slicing layer. The PIRP would also be responsible for allocating the resources required to support the virtual network slices, such as order management, storage, handling, and shipping. On the other hand, the virtual network operators (VNOs) would be responsible for managing the virtual logistics network slices and providing logistics services to their customers. Each VNO would have a specific set of resources allocated to it, which it could use to provide logistics services to its customers. The cost of these resources could be shared among the VNOs based on a pre-defined cost-sharing ratio.

The cost-sharing ratio could be determined based on various factors, such as the level of investment required to set up the PI infrastructure, the number of resources used by each VNO, and the level of service provided to customers. The PIRP and VNOs should agree on the cost-sharing ratio before setting up the virtual logistics network slices. For this, mechanisms can be used individually or in combination, depending on the specific requirements and agreement between the PIRP and the VNOs. The choice of mechanism should aim to achieve a fair and transparent distribution of costs based on the agreed-upon factors and objectives. For instance, the cost-sharing ratio can be based on an equal distribution among the participating VNOs. This approach assumes that all VNOs will have an equal share of the costs, regardless of their individual resource usage or service levels. The cost-sharing ratio can also be determined proportionally based on specific criteria such as the percentage of resources utilized or the revenue generated by each VNO. This approach ensures that the cost allocation reflects the relative contributions of each VNO. Moreover, the cost-sharing ratio can be tied to the service levels provided by each VNO. VNOs offering higher service levels may be allocated a larger share of the costs, while those providing basic services may have a lower share. In addition, the cost-sharing ratio can be determined through negotiation between the PIRP and the VNOs. This allows for flexibility and considers various criteria and specific circumstances unique to the virtual logistics network deployment. Finally, developing cost models considering multiple factors such as investment costs, operational costs, and revenue projections can help determine the cost-sharing ratios. These models would provide a quantitative basis for the allocation of costs.

4 Experimental design

We evaluate the performance of the proposed protocols using the data provided by two major French retail chains, namely, Carrefour and Casino and their 106 largest suppliers (Sarraj et al., 2014; Yang et al., 2017). We simulate the designed protocol using AnyLogic. Multi-agent simulation is used since the protocols' implementation requires the integration and interaction of multiple actors, time-bounded processing of data, and a distributed modeling and assignment algorithms to be solved.

In summary, the distribution network consists of 303 plants, 57 warehouses (either operated by manufacturers or sub-contracted to 3PLs), and 58 distribution centers (operated by retailers or 3PLs) across France. For a sake of simplicity, we consider a 7-day simulation, 10 plants, 10 warehouses, 10 carriers (trains and trucks), 1000 orders of 5 different products to ship, and only storing and shipping services. In addition, we only model one flow: from plant to warehouses (WHs).

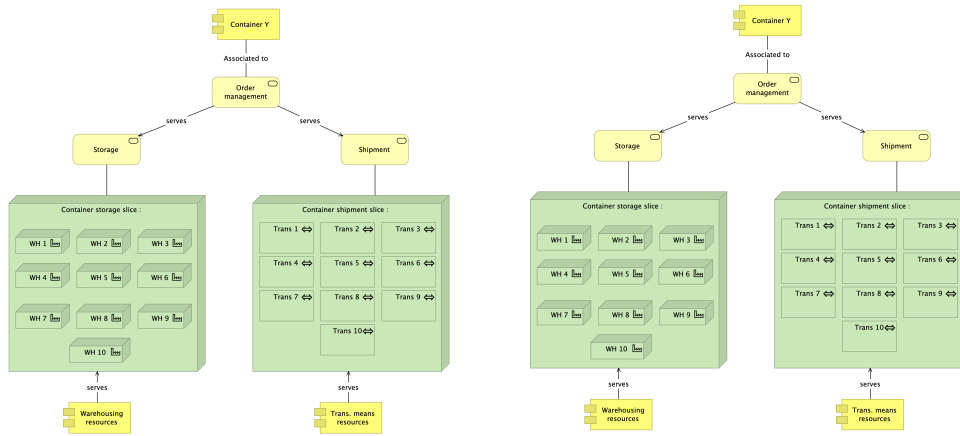


Figure 3: Examples of slices that can be created to handle orders being received.

Without loss of generality, to assess the performance of the protocols, two scenarios are examined:

- Protocols without network-slicing.
- Protocols with network-slicing.

For each scenario, the performance of the proposed protocols is evaluated considering a disturbance, namely, warehouse breakdown. Three key performance indicators are computed: increase in the total cost (i.e., transportation and storage), lead time, and CO₂ emissions, compared to the case with no disturbance. Further, we consider long rare, less frequent mi-long, and frequent short disturbance profiles.

Finally, each logistic provider makes service proposals generated using reactive assignment algorithms, along with the price computed based on costs. Then it becomes up to the coordinator to select the appropriate proposal based on cost, time, and CO₂ emissions criteria while considering the actors' preferences.

5 Experimental results

This section briefly presents the results of simulation. Figures 4, 5, and 6 report the increase in the total cost (i.e., transportation and storage), the lead time, and CO₂ emissions, respectively.

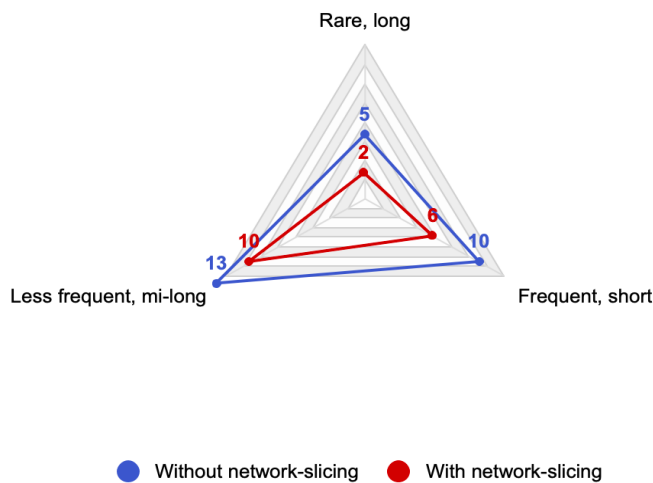


Figure 4: Increase in total costs in %, compared to the case without warehouse disturbance.

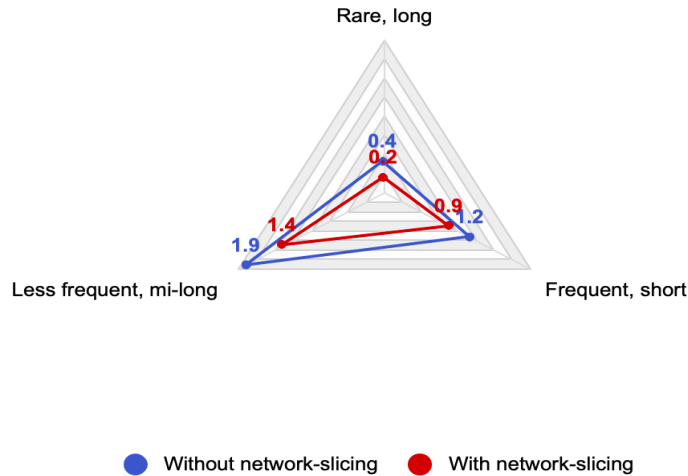


Figure 5: Increase in total lead time in hours, compared to the case without warehouse disturbance.

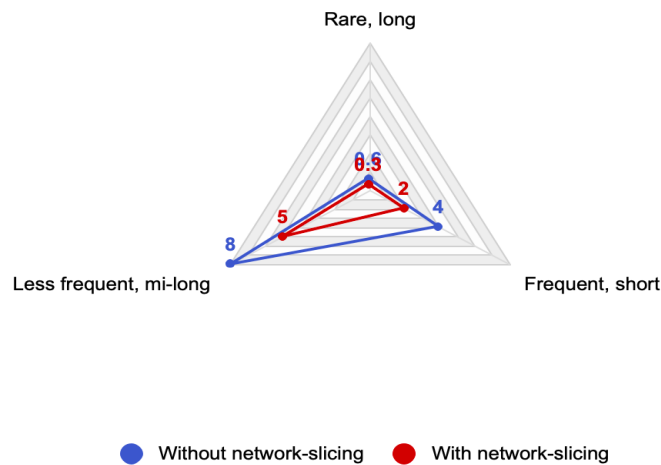


Figure 5: Increase in CO2 emissions in %, compared to the case without warehouse disturbance.

As expected, the total costs increase when the breakdown occurs, leading to a loss of capacity. Indeed, when warehouses experience breakdowns, redirecting shipments to other locations may become necessary. Moving “disturbed” containers from the original warehouse to the new location can involve additional storage and shipment costs. The same logic holds for lead time. Nevertheless, we see that this increase is relatively small as the proposed protocols allow for alleviating the impact of the disturbance, thus navigating through uncertainty while preserving good functioning and maximizing the “worst-case” performance of the system. This is made possible thanks to the interaction between the routing and slicing-network protocol, allowing for a more efficient allocation of resources, load consolidation, and improved coordination.

6 Conclusion

This paper investigates routing and network slicing-based protocols in the PI network. Results show that the proposed protocols are efficient and robust as they allow for more efficient allocation of resources, improved coordination, and better disturbance management.

Overall, our findings suggest that the PI network has the potential to revolutionize logistics management and operations, making them more efficient, robust, cost-effective, and adaptable to changes and disturbances. However, there is still much work to be done in this area, and

further research is needed to explore the potential benefits and limitations of routing protocol and logistics network slicing-based mechanisms in more depth. One area for improvement of our study is that it focuses primarily on the benefits of logistics network slicing without exploring its potential drawbacks or limitations. Future research should investigate the trade-offs in implementing logistics network slicing while considering decentralized protocol and managing disruptions. Finally, more research is needed to explore the potential applications of logistics network slicing in different contexts and industries. While our study focuses on a specific and small-sized logistics network, the benefits and limitations of network slicing will likely vary depending on the specific characteristics of the network and the nature of the logistics services involved. Further research is needed to explore our findings' generalizability and identify the contexts in which logistics network slicing is most effective.

Acknowledgement

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