A protocol for node-to-node transshipment in the PI analogizing from Internet principles

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Abstract: *This paper introduces the PI-link protocol, a novel process inspired by the operational principles of the Internet, to address node-to-node transshipment within the Physical Internet (PI). Recognizing the critical need for efficient, standardized protocols to manage the complexities of logistic flows in the PI, we propose a simple, adaptable protocol designed to facilitate seamless collaboration among diverse logistics service providers. By drawing analogies to the TCP/IP model, our protocol emphasizes streamlined processes for dynamic and static information exchange, analogous to the Internet Protocol (IP) ensuring and supporting effective shipment processing, routing, and monitoring across interconnected logistic networks. The technical operations of the protocol are clearly demonstrated through pseudocode, providing a detailed blueprint for its implementation. This exploration aims to contribute to the ongoing development of the PI, by providing a first step towards a simple baseline protocol stack, as TCP/IP for the Internet.*

Keywords: *Physical Internet, Protocols, Protocol Stack, Nodes, Operationalization, Internet, Framework, TCP/IP.*

Physical Internet (PI) Roadmap Fitness*: ☐ PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories), ☐ Transportation Equipment, ☒ PI Networks, ☒ System of Logistics Networks, ☐ Vertical Supply Consolidation, ☐ Horizontal Supply Chain Alignment, ☐ Logistics/Commercial Data Platform, ☐ Access and Adoption, ☒ Governance.*

Targeted Delivery Mode-s*: ☒ Paper, ☐ Poster, ☐ Flash Video, ☒ In-Person presentation*

1 Introduction

The Physical Internet (PI) has gained considerable interest within the last few years and is meant to fundamentally change the transport sector to tackle its inefficiencies and environmental impacts. Even though implementation is urgently required, scalable and overarching concepts on the operationalization of the PI remain scarce. Managing several stakeholders in collaborative and seamlessly connected networks of networks requires efficient, effective and easy to run protocols similar in effect to protocols used for managing data exchange on the Internet (Dong & Franklin, 2021).[1] Establishing a network-of-networks requires, amongst others, a protocol that controls the connection between individual networks, i.e. the connection from node-to-node. Hence, as a first step towards a network-of-networks, we are developing the PI-link protocol.

[1] A protocol is defined as a system of rules that explain the correct conduct and procedures that should be followed in a formal situation.

This paper is centered around the central question of "How to operate the PI?". It is aiming to combine two areas of research into one. Particularly, the areas of logistics transportation management and information systems. Extensive research has shed light on the conceptual aspects of the PI (e.g. Dong & Franklin, 2021; Montreuil, 2011; Montreuil et al., 2018) and its assessments (e.g. Briand et al., 2022; Sarraj et al., 2014), revealing promising prospects. Introducing a protocol stack aligned with the OSI model, Montreuil et al. (2012) laid the groundwork for PI protocols, while Dong & Franklin (2021) highlighted the relevance of the DoD model. Technical attempts to design protocols for the PI were made by some authors addressing primarily the optimization of node internal structures such as consolidation or routing (Briand et al., 2022; Gontara et al., 2018; Sarraj, Ballot, Pan, Hakimi, et al., 2014; Shaikh et al., 2021). However, most protocols discussed in the context of the PI provide limited operational guidance for managing goods flows across a set of networks-of-networks. Here, the Internet serves as a valuable model that employs protocols that provide guidance for developing PI focused protocols based on physical rather than digital flows. The design principles of the Internet's protocols emphasize simplicity and openness as guiding factors that shape all system-level protocols and controls (Phillipson, 2021).

In keeping with the minimalist philosophy of the Internet, the protocols envisioned for the PI should also embody a straightforward design that specifies standard processes for managing and controlling flows across the PI. Following standardized processes fosters interoperability and represents an important element for the implementation of the PI (Münch et al., 2023). The Internet specifies these standard processes for various protocols via RFCs[2] (Requests for Comments) that are developed collaboratively and are continuously reworked and updated.

While the protocols of the Internet have grown in complexity over time, the PI should aim to begin its journey with a simple protocol structure. This strategy allows the system to organically adapt its control processes in response to specific circumstances, mirroring the adaptive evolution of the Internet's protocols over the years. Hence, we make reference to the foundational TCP/IP protocols, constituting the fundamental protocol suite operating and controlling the Internet (Montreuil et al., 2012). We define the standards and showcase their functionality, enabling diverse actors in the PI to leverage them. Taking a cue from the Internet's TCP/IP model, we can consider a thought experiment in structuring PI-protocols that involve Sender-Receiver transfers (akin to TCP) and Node-Node transfers (comparable to IP) and therewith build a framework to operate the PI. This paper focuses on the inter-node (link) management of flows in the PI and defers discussion of the end-to-end management of flows (the TCP analog) for future research.

The overall objective of this research is to develop and test a protocol that addresses the collaborative transshipment of freight between two nodes involving different logistics services, executed by different LSPs. This objective is composed of three goals. First, we are aiming to develop a generalizable protocol artifact for inter-node flow management in the PI, analogous to the Internet Protocol (IP) that was developed by the Defense Advanced Research Projects Agency (DARPA) in 1973 (Clark, 1988). Second, we will demonstrate the protocols' feasibility and resilience by testing it in different situations and by introducing uncertainties in a simulation environment, using actual distribution center data (next steps). Being able to demonstrate that the protocol works shows practitioners that a collaborative network-of-networks like the PI is implementable. Third, similar to the development of the Internet where the TCP/IP protocols laid the groundwork and influenced the creation of more sophisticated protocols (Clark, 1988), our goal is to establish a simple and generalizable protocol structure

[2] » RFC Editor (rfc-editor.org)

that is intended to serve as a basis for the development of more sophisticated protocols that can address specific issues in various contexts.

In this paper, we discuss collaboration in logistics, the PI and Internet protocol models (Section 2), and then explain the framework and mechanics of our protocol with pseudocode examples (Section 3). We conclude with our findings and future research directions.

2 Literature review

2.1 Logistics collaboration

Collaboration in supply chains can be defined as "the ability to work across organizational boundaries to build and manage unique value-added processes" (Fawcett et al., 2008, p. 93). When the advantages of collaborative work surpass its drawbacks (Terjesen et al., 2012), companies might endeavor to merge complementary capabilities to generate value beyond what they could attain individually (Barratt, 2004; Daugherty et al., 2006). As a result, collaboration in supply chains is recognized as one of the most effective ways to improve freight transportation efficiency in the pursuit of sustainability (Goldsby et al., 2014).

Supply chains encompass various levels and hierarchies, but collaboration within this framework can be categorized into two forms: vertical and horizontal collaboration (Mason et al., 2007). Vertical collaboration focuses on the beneficial interaction between vertically integrated actors on different levels within a supply chain. This facet has been extensively explored in the literature, including studies by Barratt (2004), Power (2005) and Stadtler (2009). More recently, horizontal collaboration has gained traction which focuses on the interaction of companies that are operating on the same level of the supply chain, e.g., shippers, logistic service providers (LSPs), or customers (Mason et al., 2007; Pan et al., 2019).

In freight transportation, horizontal collaboration has grown both industrially and academically. Industrially, initiatives such as the European carrier association ASTRE have facilitated cooperation among independent carriers (Pan et al., 2019). Companies are seeking greater synergies to reduce inefficiencies, leading to extensive and efficient collaboration across supply chains in terms of lower delivery costs (Cruijssen et al., 2007), fewer carbon emissions (Karam et al., 2020), increased service levels (Chabot et al., 2018). Additionally, successful cases, such as the collaboration of four manufacturers in France (Mars, UB, Wrigley and Saupiquet), illustrate its effectiveness. Academically, horizontal collaboration is an evolving field that is witnessing the emergence of new concepts, methodologies and models that promote collaboration from the carrier level to the supply network level.

On the carrier level, Pan et al. (2019) classified horizontal collaboration schemes into six categories, such as Carrier Alliance and Coalitions, Transport Marketplaces and, amongst the others, the Physical Internet (PI). In most collaborative scenarios, partner companies are required to share information about their transport orders and delivery vehicles with a central coordinator, such as a logistics service provider (Karam et al., 2021). This shared information is then used by the central coordinator to identify collaboration opportunities, formulate a joint delivery plan, or propose freight exchanges between partners.

However, the practical implementation of horizontal collaborative transportation networks is rarely observed. This is mainly due to the fact that the collaborating partners are often competitors, which raises concerns about establishing a trustworthy partnership (Basso et al., 2019). Providing the power over operations and customer information to a central coordinator would neither eliminate trust issues nor necessarily be compliant with competition law (Karam et al., 2021).

Nonetheless, there is the concept of the PI, which stands somewhat apart from the other horizontal collaboration schemes as identified by Pan et al. (2019). The PI circumvents the challenges linked with a central coordination entity by embracing Internet principles that employ distributed governance across a collaborative network-of-networks (Montreuil, 2011).

The Internet, which the PI concept originates from, provides a standardized approach for the distributed management of the transmission of data packages within the largest system ever created by mankind (Dong & Franklin, 2021). It connects billions of devices, networks and subnetworks transmitting data packets from source hosts to destination hosts, which is analogous to what the PI aims to accomplish. To enable such services, the Internet applies protocols, incorporating rules, guidelines and governance mechanisms that support the sharing of resources across networks. Internet -like protocols are also required for the operationalization of the PI.

2.2 Physical Internet protocols

We see the development and implementation of protocols addressing the management and organization of logistics flows in the PI as a central prerequisite for the implementation of the PI. The requirement for protocols comes from the different entities and actors involved in the PI. As the PI consists of a network-of-networks that incorporates nodes, lanes, carriers, shippers and shipments, the requirement for protocols addressing different purposes is fundamental (Montreuil, 2011). What is required are fast and reliable protocols like those employed in the Internet that are able to process large numbers of loads (Briand et al., 2022). Standard optimization techniques require either enormous computing power or significant calculation time to deal with the dynamic nature of the PI. Therefore, it is crucial to take one step back and look at the first Internet-analogous conceptualizations for a protocol stack.

Montreuil et al. (2012) proposed the first protocol stack taking into consideration the seven-layer OSI model. Other authors have used the five-layer Department of Defense (DoD) model as an example since it is the model upon which the Internet is built (Dong & Franklin, 2021). The DoD model is like the OSI model but consolidates three OSI layers into one.

First attempts to design technical protocols for the PI were made by Sarraj et al. (2014b) They laid the foundation for protocols by referring to Internet protocols and assessed PI performance based on a stylized case that validated the benefits of the PI. The transfer between Internet and PI protocols was conceptually further developed in Kaup et al. (2021) by a detailed comparison between these protocols relying heavily on the seven-layer OSI model.

In Sarraj et al. (2014a) they further proposed a structure for protocols, incorporating containerization, consolidation for efficient asset utilization and routing through the PI in combination with a clear assessment of the usability of the protocol. The results show a significant improvement in fill rates, reduction in $CO2$ emissions and lower costs. However, the approach lacks dynamism and scalability. The first scalable routing protocol is proposed by Gontara et al. (2018) taking advantage of the Border Gateway Protocol (BGP) used in the Internet for routing between neighboring networks, so called Autonomous Systems (ASs). They highlight the reliance on information exchange between ASs for their protocol that supports dynamism in the logistic network, especially when it comes to disruptions on lanes, e.g., congestion. Their protocol solves relevant problems in terms of container filling, flow routing and consolidation.

Dong & Franklin (2021) address the dynamism issue by considering the operationalization of Internet networks. They consider metrics such as cost, time, schedule, emissions and capacity that must be dynamically optimized for effective and efficient operationalization of the PI. To address these issues, standard optimization processes face scalability problems in a dynamic environment like the PI. Briand et al. (2022) propose a fast, reliable and resilient mechanism for routing and assignment of Full Truck Loads (FTL) that is scalable and based on an auctioning mechanism. Their approach is among the first that considers the competitive interaction of stakeholders in the PI. They show by simulation that their protocol leads to a significant reduction in cost as well as environmental impact in terms of reduction in empty milage. In addition to Briand et al. (2022), Lafkihi et al. (2019) consider an auction-based optimization protocol for a PI-like network. Their protocol takes incentive mechanisms and collaborative rules into account for the management of shipper-carrier relationships and routing across the network.

Apart from routing, other protocols are required for the PI. Shaikh et al. (2021) developed protocols for fast and efficient dynamic consolidation of PI containers at hubs under the assumption of on-demand transportation services being available. They propose the idea of using maximum latency to adjust waiting times at nodes and schedule flexibility based on upstream visibility. In the context of parcel logistics Orenstein & Raviv (2022) proposing the design and operation of a Hyperconnected Service Network for parcel delivery considering a routing mechanism and math heuristic for routing and scheduling at service points where vehicles are arriving and leaving according to fixed schedules.

Protocols focused on tasks such as auction logistics scheduling for perishables (Kong et al., 2016) and truck/container scheduling at road-rail hubs (Chargui et al., 2020) provide operational value, but don't fully align with the Physical Internet (PI) concept, which aims to optimize load flows between nodes. While most PI protocols differ significantly from digital ones, our approach, inspired by Internet studies, may evolve to address the physical-digital divide, as discussed by Dong & Franklin (2021)

2.3 Internet protocol suite

Since the PI takes its name and functionality from an analogy to the Internet, we focus on this analogy and the functionalities of the Internet to assist in organizing our thoughts concerning the development of protocols for the PI. It is, therefore, important to understand some key considerations of the Internet and its protocols before we take the Internet analogy into consideration for the PI protocols.

In the early 1970s, research on packet-switched networks aimed at sharing computer resources laid the groundwork for the Internet's protocols (e.g., Heart et al., 1970; R. Kahn & Crowther, 1972; R. E. Kahn, 1972; Roberts & Wessler, 1970). Unlike earlier efforts that focused on intra-network communication, Cerf & Kahn (1974) introduced a framework for sharing resources across networks, detailing an architecture that included hosts, packet switches, and their interconnections. They addressed the need for standard protocols, such as TCP/IP, to handle network variations, including packet sizes and error handling. Their work also emphasized the importance of "gateways" for connecting independent networks and facilitating process-to-process communication under varying network conditions.

TCP, as first described by (Cerf & Kahn, 1974), governs the division of data or messages into transmittable packets, oversees the transmission of these packets over the Internet, and guarantees the successful delivery of the transmitted data to its intended destination. In fact, TCP represents the start and the end of the transmission of the data packet. In the physical freight industry, TCP is analogous to a freight forwarder responsible for ensuring and regulating the reliable end-to-end delivery of goods. However, the Internet is constructed from interconnected networks, with routers serving as pivotal connection points between these networks (Clark, 1988). Within this framework, IP manages the transmission between routers and establishes rules for packet routing and addressing, enabling routers to direct packets from router to router seeking to reach their designated destination hosts. This is what freight/carrier companies are intended to do in the physical world.

The protocols utilized on the Internet serve as a robust starting point. Consequently, we consider the information systems literature with a focus on what was published on networking protocols as a relevant source to inform our research. Specifically, the early literature on the Internet Protocol (IP) is of great importance for our research, given that we are developing inter-node protocols in this project, similar in their requirements to the requirements that resulted in the IP.

2.4 Internet protocol

The first official specification of the IP was made in 1981 by Jon Postel. In general, he specified the IP as crafted for application in interconnected systems of packet-switched computer communication networks (Postel, 1981). The IP facilitates the transmission of data blocks, known as datagrams, from sources to destinations. These sources and destinations are hosts identified by fixed-length addresses. Additionally, the IP accommodates the fragmentation and reassembly of lengthy datagrams when needed (similar to deconsolidation and reconsolidation in logistics networks), ensuring seamless transmission through "small packet" networks. Fragmentation is especially necessary when the bandwidth of a network is not sufficient for the size of the datagram (or the capacity of a transport mode is small compared to load size). It is important to mention that the IP is limited in its functions. It does not incorporate end-to-end data reliability mechanisms, sequencing, flow control or other mechanisms that are commonly found in host-to-host protocols like e.g., TCP. However, the IP relies on the services incorporated in its underlying networks by providing information for handling a message transmission and consuming information based on transit parameters. The IP sits between the layers of the host-to-host protocols, such as TCP and local network protocols. IP is called on by TCP and calls on local network protocols to carry the datagram to the next node. We refer interested readers to Postel (1981) for a detailed elaboration on the specifications and operation of the IP.

3 The PI-link protocol

3.1 Integration into the overall frame

The PI-link protocol is designed to facilitate the movement of shipments across a network of interconnected nodes. This involves transferring shipments from one node to another until the destination is reached. Therefore, the PI-link protocol specifies the operational node-to-node information-exchange for the link layer. This information exchange can be distinguished into two types of information. Static and dynamic information. Static information refer to shipment specifications that are set at the beginning of the journey and are passed from link to link without any changes. They serve as inputs for nodes to process, route and assign shipments in a productive way. In contrast, dynamic information refer to shipment state information and is encrypted into each link at the beginning of each link journey by the nodes. Shipment state information is collected along the link, handed over to the node at the end of the link and then purged for that link. Nodes push this state information to the control layer, where they are processed and monitored. Figure 1 illustrates this process visually. Based on this information the control layer can control the shipment and make decisions that inform the nodes about how to behave (route, assign or handle the shipment). However, the control layer and its respective protocol is subject to future research. This paper focuses on the link layer and its governing PI-link protocol and assumes inputs from the control layer are provided to the nodes in a "black-box" fashion.

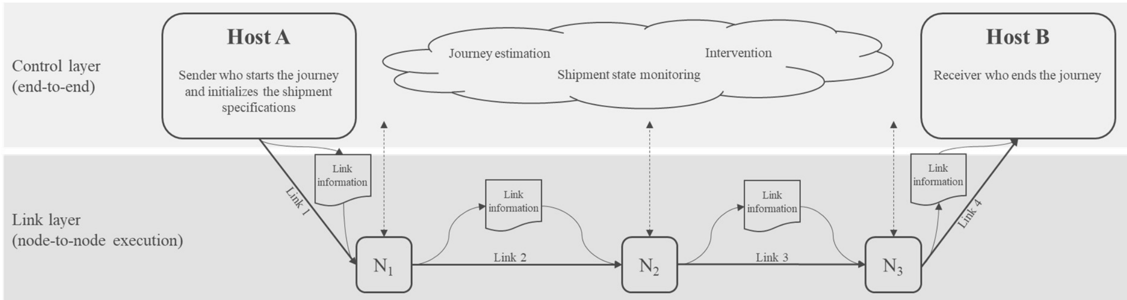

Figure 1: Shipment journey operations on two layers

3.2 Information management

As mentioned, the PI-link protocol specifies the sharing of two types of information: **Information about shipment specifications** and **information about the shipment state**.

Shipment-specifications are generally static on a single link, they remain the same over time. However, they can be changed by nodes when starting out on to a new link, but then stay static until at least the next node. Static information includes (a) Addresses (origin -destination, prior node, subsequent node), (b) Shipment specification (order number, number of packages/items, dimensions and weights of packages, ability to break shipment up, belonging to larger shipment, time window of promised delivery), (c) Journey initiator (freight forwarder, shipper, PI), (d) Service requirement (careful handling for fragile goods, cooling for perishable goods) and (e) Priority (indicates that the shipment is to be handled in an expedited manner). Priority can be increased by nodes as it becomes clear that a shipment may run into a delay. Additionally, the (f) Service provider (carrier and transport mode used) must be specified for the link. The service provider is an outcome of the routing and load allocation procedure undertaken by the nodes. What comes along with this are the (g) Estimated "cost" for a link that must be encrypted into the link (costs are not limited to monetary costs but also to time elapsed on the link or emissions emitted)[3]. These costs are a planned target the link aims to achieve.

In contrast, shipment states are rather dynamic, they change along the journey of the shipment over a link. Shipment states are primarily focusing on the (h) Cumulative "costs" occurring on the link between two nodes (e.g., actual distance traveled, actual time traveled, etc.). These costs are collected so that comparisons of actual versus planned costs can be made. Nodes (using internal protocols) evaluate for inbound shipments the cumulative costs that occurred on the last link against the targeted costs specified at the start of the link journey. Deviations between current and target values will be conveyed by the node to the control layer which takes action based upon this information. This concept is inspired by the "Time to Live" trigger specified by the IP (Postel, 1981).

It might be questioned whether payment-related information is within the scope of the protocol. However, we argue that resolving payments for a shipment and associated services throughout the journey is a task for a comprehensive protocol that governs the end-to-end journey (the control layer), not just the node-to-node transfer and falls therewith out of the scope of this protocol. However, the PI-link protocol accumulates costs incurred along each link and communicates them to the higher-level protocol that performs total shipment cost calculation.

[3] The concept of cumulating costs per "hop" has also been suggested for predetermining a price for a connection on the Internet(Stiller & Reichl, 2001).

3.3 Model of operation

It is important to mention that the PI-link-protocol process is an information-sharing process. The protocol uses the services of its link origin-destination nodes but does not specify how they should use or process the information it carries (e.g., the node's internal systems are responsible for routing the shipment to a specific $d \in D$ based on certain decision parameters or algorithmic results). Nevertheless, it is responsible for exchanging and providing the relevant information based on which node-internal mechanisms can, for example, determine the optimal route. In line with Postel's (1981) description of the operations of the Internet Protocol, the PI-link protocol implements two basic functions: shipment data sharing and shipment state monitoring on a specific link. In addition to that, the nodes (in our model the T) implement mechanisms that process the information provided by the PI-link protocol and respond in a stochastic fashion. It is important to mention that these functions are not part of the PI-link protocol but are the responsibility of the node's internal management system. Table 1 provides an overview on the notations used in the following sections to describe the protocol.

Table 1: Notation of parameters used

Node parameter		**Load parameter**		**Link parameters**	
Upstream Node	$u \in U$	Load	$a \in A$	Link	$l \in L$
Downstream Node	$d \in D$	Request	$r_a \in R$		
Transfer Node	T	Load specification	$spec_a$		
		A cumul. cost ul	cc_a^l		
		A target. cost ul	$cc\_tar_a^l$		

To model the PI-link protocol we consider a section of a logistic network where several Upstream Nodes $u \in U$ generate loads $a \in A$ that are sent on a set of Links $l \in L$ connecting each u to an intermediate Transfer Node T and further downstream T to Downstream Nodes $d \in D$. The PI-link protocol will be implemented for each $l \in L$. Protocol supporting functions are implemented in the T. In a whole PI-network the PI-link protocol would be implemented for each link in the network. However, for explanatory simplification, we confine our discussion to the transmission of a shipment from an upstream node to a single intermediary transfer node and onwards from the transfer node to a downstream node. Figure 2 illustrates the operational interaction scheme specified by the protocol between nodes.

In general, the process specified by the PI-link protocol can be subdivided into three separate processes, namely (1) outbound dispatch, (2) link monitoring (3) inbound receipt.

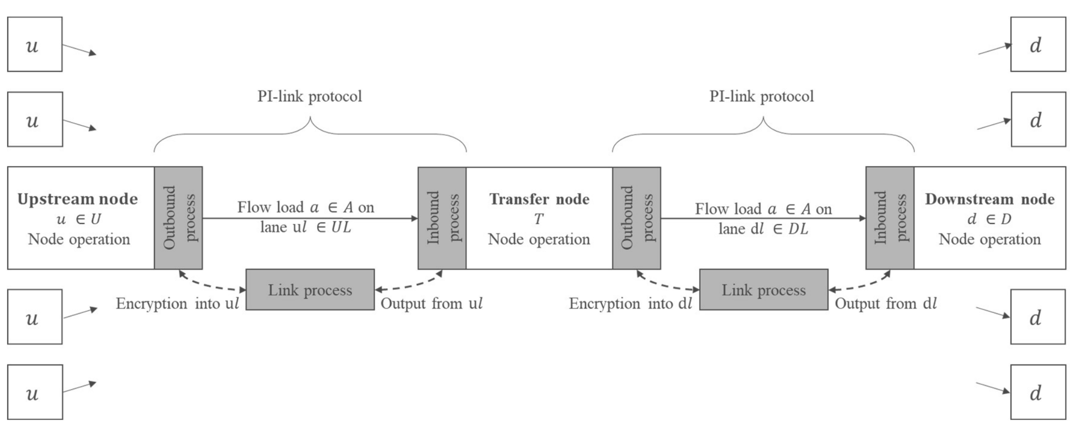

Figure 2: Schematic interaction model of the protocol

In our model, we assume the loads $a \in A$ to be generated at the upstream nodes $u \in U$ and to be assigned by an assignment mechanism (e.g., an auction as proposed by Briand et al. (2022)) to a link l. The prerequisite for an assignment of a load is that it is not in a ratention status. Retention can be initiated if a load faces an issue, such as excessive costs at a previous link or damage, that requires a decision from the responsible journey initiator. A successful assignment is indicated by an upstream request for assignment $r_a \in R$. Process 1 illustrates the outbound dispatch process after a succesfull assignment.

Upon receiving an assignment request $r_a \in R = 1$, including the load specifications $spec_a$, target cost $cc\_tar_a^l$ and the dedicated link $l \in L$ from a node $u \in U$, the protocol proceeds to encrypt the shipment specifications and the target cost in the link $l \in L$. In this context, the specification serves as a repository/carrier of shipment information (as discussed earlier). These details typically include factors like load weight, dimensions, or cooling requirements. The encryption establishes the link by providing the relevant information and conditions to the carrier operating on the link prior to dispatch. This is important for the carrier to plan operations accordingly. Thus, the encryption process prepares the journey of the load to the next node that is started when the node releases the load as an outbound shipment. Process 1 technically demonstrates this process.

Process 1: Outbound dispatch

Input: Receive $r_a \in R = 1$ including $spec_a$, $cc\_tar_a^l$ and $l \in L$ from $u \in U$
for $r_a \in R = 1$ **do**
encrypt $spec_a$ into l // journey static shipment specification encryption
encrypt $cc\_tar_a^l$ into l // link static cost target encryption
Output: Encrypted link l // link established
end for

Once a load $a \in A$ is dispatched and begins its journey on a link $l \in L$, the protocol actively tracks the load's progress. As a result, the costs cc_a^{ul} associated with the link are calculated and updated. This means that the collective cost factor cc_a^l, which incorporates a variety of cost such as money, time, and emissions, grows steadily as the load progresses on the link. Emission costs, for example, are determined using specific calculation methods that take into account the distance traveled and the mode of transportation used. This procedure is defined by process 2.

Process 2: Link monitoring

Input: Encrypted link l
for $a \in A$ on $l \in L$ **do**
accumulate cc_a^l // accumulation of cost along the link
end for

As a load $a \in A$ arrives at at a destination node, e.g., node T, the inbound process (process 3) starts its action. This is a process for handling and analyzing load-related data carried and collected by the link.

Initially, the node receives a load, denoted as a, from a set A, which comes from an upstream link ($l \in L$). For each load a, the protocol specifies the decryption of several pieces of information: the load specification $spec_a$, the target cost $cc\_tar_a^l$, and the actual cumulative cost cc_a^l. These encrypted parameters represent the detailed shipment information, the cost goals set for the load and the specific link, and the actual costs incurred on that link, respectively. Upon receiving these parameters, the node T performs a critical comparison between the actual cumulative cost cc_a^l and the target cost $cc\_tar_a^l$.

If the actual cost exceeds the target, indicating a discrepancy or inefficiency in handling the load, the node notifies the control layer about the discrepancy. When the total cost incurred exceeds the target cost the node communicates the actual cumulative costs cc_a^l to the control layer for additional actions or analysis. Conversely, if the actual costs cc_a^l do not exceed the target, the actual cumulative costs are simply communicated to the control layer without the need for special attention.

Process 3: Inbound receipt

Input: Receive $a \in A$ from $l \in L$
for $a \in A$ on $l \in L$ **do**
    decrypt $spec_a$ from $l \in L$ // handover of load specification to node
    decrypt $cc\_tar_a^l$ from $l \in L$ // handover of target cost to node
    decrypt cc_a^l from $l \in L$ // handover of actual cumulative cost to node
    Input: Receive encrypted parameters $spec_a$, $cc\_tar_a^l$ and cc_a^l
    if $cc_a^{ul} > cc\_tar_a^l$ **then**   // target-performance comparison
        retain a // retention of problematic load
        Output: Inform control layer on $cc\_tar_a^l$ exceedance
            Broadcast cc_a^l to control layer
    else
        Output: Broadcast cc_a^l to control layer
    end if
    purge cc_a^l
end for

After handling the comparison and necessary communication with the control layer, the PI-link information for the shipment is purged and the PI-link protocol for that shipment on the link is terminated. This cycle repeats for each load a within A received from the links l, ensuring each load is evaluated and managed according to its performance relative to cost targets.

4 Conclusion

In conclusion, this paper has laid the foundational framework for the PI-link protocol, drawing parallels with the Internet's operational principles to enhance the PI node-to-node transshipment processes. Our research delineates a comprehensive structure for managing and controlling logistic flows, emphasizing the significance of streamlined, standardized protocols akin to those that have revolutionized digital communication.

Our findings underscore the critical role of simplicity, interoperability, and standardized processes in facilitating seamless collaboration across diverse logistics service providers (LSPs). By analogizing from the Internet's TCP/IP model, we have outlined a protocol framework that not only facilitates efficient and resilient transshipment between nodes but also sets the stage for future advancements in end-to-end logistics management. The IP equivalent PI-link protocol emphasizes the importance of managing dynamic and static information exchange between nodes, ensuring that shipments are processed, routed, and monitored effectively across the network.

Future research directions are pivotal, with a particular focus on simulation and testing of the proposed protocol in varied and uncertain environments. These steps are essential to validate the protocol's adaptability, efficiency, and resilience, demonstrating its practical applicability and effectiveness in real-world logistics scenarios. Such empirical testing, using real world data, will not only affirm the protocol's theoretical underpinnings but also provide invaluable insights into its operational impact, fostering a more collaborative, sustainable, and efficient logistics network in line with the overarching goals of the Physical Internet.

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