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From the Digital Internet to the Physical Internet: A Conceptual Framework With a Stylized Network Model

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Despite the increasing academic interest and financial support for the Physical Internet (PI), surprisingly little is known about its operationalization and implementation. In this paper, we suggest studying the PI on the basis of the Digital Internet (DI), which is a well-established entity. We propose a conceptual framework for the PI network using the DI as a starting point, and find that the PI network not only needs to solve the reachability problem, that is, how to route an item from A to B, but also must confront a more complicated optimality problem, that is, how to dynamically optimize a set of additional logistics-related metrics such as cost, emissions and time for a shipment. These last issues are less critical for the DI and handled using relatively simpler procedures. Based on our conceptual framework, we then propose a simple network model using graph theory to support the operationalization of the PI. The model covers the characteristics of the PI raised in the current literature and suggests future directions for further quantitative analyses.

Keywords: physical internet; digital internet; conceptual framework; model; operationalization

INTRODUCTION

There are a growing number of concerns about current logistics and transportation systems. From an economic perspective, transportation costs are steadily rising, which erodes the benefits of all other supply chain cost-saving efforts (Boston Consulting Group 2015). From a social perspective, the over-utilized road network brings substantial “stress” to our society regarding accidents, noise, air pollution, etc. (Maibach et al., 2007). From an environmental perspective, whereas all other industry sectors are steadily reducing greenhouse gas emissions, the transportation sector is, unfortunately, increasing these emissions (EUROSTAT 2015).

Clearly, the business-as-usual logistics industry is not sustainable and disruptive innovations are urgently needed. The Physical Internet (PI), originally described by Montreuil (2011), is regarded as such a paradigm-breaking concept to tackle the “logistics sustainability grand challenge”. Ballot et al. (2014) and Mervis (2014), have further elaborated the concept of the PI. They use the Digital Internet (DI), which is a well-established artifact and widely-accepted service technology, to illustrate its potential as a design metaphor for the PI. The classical analogy is, whereas the Digital Internet transfers digital data in packets smoothly among users, the Physical Internet moves physical objects seamlessly through an open and interconnected logistics network.

Despite its highlighted advantages, the PI has received serious criticisms. Recent research by Sternberg and Norrman (2017), among others, has challenged the PI by questioning a lack of developed business models that can illustrate how to move from the concept to its adoption. Their thoughts coincide with, for example, Cimon (2014) and Pan et al. (2017), that the implementation of the PI remains a challenge. Treiblmaier et al. (2016) point out that PI specific theories focusing on the advancement of the PI concept are also lacking. So far, the research on the PI has primarily focused on its conceptual development and the promised effect thereof. Knowledge on the operationalization of the PI remains limited.

Several studies have started to exploit PI operationalization, in topics such as protocol building (Montreuil et al., 2012), PI routing optimization (Sarraj et al. 2014), and modular container selection (Lin et al. 2014). The motivation of this paper is not to solve a specific PI problem. Instead, we investigate from a more fundamental perspective: What are the unique features of the PI, and how should these features be integrated into rigorous theories to support the PI’s implementation. By answering this question, we wish to obtain a more generalized understanding of the PI that can be used as a starting point for future PI research.

Motivated by this objective, our aim is to begin filling in this research gap by introducing a conceptual framework for modeling flows within the PI, as well as a highly stylized model based on analogies to the Digital Internet. We begin by investigating the conceptual origin of the PI, its analogical relationship to the DI, and establish our framework based on this analogy. There are two reasons for this initiative: (1) Since the DI is a metaphor for the PI, there must exist similarities between the two, from their namesake to models and implementations; and (2) the DI is a well-established artifact with well-known features and an extensive literature body on its operations. The history of the development of the DI, how it has come to be governed, the challenges it has faced in scaling, security, privacy and trust, its operation through a layered protocol approach, and many other aspects of its growth provide a starting point for considering similar issues with respect to the PI. However, since both the DI and the PI are extremely

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complex systems, it is beyond the scope of this paper to create a comprehensive "one-to-one" comparison between them or to solve all the PI "problems." Instead, the purpose of this paper is to support the PI theory building process and the practical implementation of the PI. Given this purpose, this paper aims to answer the following two research questions:

1. What are the primary similarities and differences between the DI and the PI?
2. What might be a simple, but useful model that supports research into, as well as, the implementation of the PI?

By examining these two questions, we conduct a comparison between the DI and the PI, and take the lessons learned from this comparison to propose a stylized model of the PI. Though the model is simple, it captures the distinct characteristics of the PI mentioned in Montreuil (2011) and employs approaches from classical transportation theories (such as shortest path and dynamic traffic assignment) to study the PI.

The rest of the paper is organized as follows. In Section 2, we review the related literature, and in Section 3, we report the structure of the Digital Internet. In Section 4, we discuss why flow optimization in the Physical Internet involves different complexities than those found in the Digital Internet. On the basis of this discussion, we propose a stylized network model of the Physical Internet and suggest a heuristic solution in Section 5. Finally, we discuss future research avenues in Section 6.

LITERATURE REVIEW

Our work is closely related to three streams of literature: the classical computer network literature of the Digital Internet, the emerging Physical Internet literature, and the classical transportation engineering literature.

The digital internet

The DI is arguably the largest system ever created by mankind, with billions of connected devices, including computers, phones, or any equipment with a sensor (Kurose and Ross 2016). The early concept of the DI dates back to Licklider and Clark (1962), who envisioned a group of globally interconnected computers for data transmission. Over the years, the DI has revolutionized worldwide data communications (Leiner et al. 2009). Specifically, a reliable data delivery is secured by the so-called Transmission Control Protocol/Internet Protocol (TCP/IP) originated by Cerf and Kahn (1974). New protocols, such as multi-protocol label switching (MPLS), are being used as intermediate routing protocols to facilitate traffic engineering services that are difficult or impossible to implement using TCP/IP (Farrel, 2020). These protocols allow DI traffic engineers to shape data and message flows to avoid congested paths and speed up traffic flow. Interested readers can obtain additional information on the foundation of the DI and digital networking in general through the studies by Petersen and Davie (2011), Comer (2014), Kurose and Ross (2016), etc.

In this paper, we use this stream of literature as the foundation for the analogies that inform the concept of the Physical Internet and establish a general foundation for its composition.

The physical internet

The PI is proposed as an analogy of the DI for managing the flow of physical objects, with the special purpose of increasing the efficiency and sustainability of logistics systems (Montreuil 2011). Despite being a relatively new concept (the first mention of the Physical Internet appeared in an article in the June 17, 2006 edition of The Economist (Markillie 2006)), it has attracted much attention from various stakeholders. The research on the PI spreads over various topics in logistics, such as container standardization (Lin et al. 2014); delivery schedule optimization (Yao 2017); vehicle routing optimization (Walha et al. 2016); city logistics (Mohamed et al. 2017); intermodal transportation (Sun et al. 2018); synchromodal transportation (Ambra et al. 2019); PI-enabled information systems (Chen et al. 2018); coordination of production, inventory, and transportation (Ji et al. 2019); and vendor-managed inventory management (Pan et al. 2015).

While the aforementioned articles have begun to examine many of the facets of what a PI might look like or the challenges that such a concept must address, notable criticisms of the idea remain. It is still not clear, for example, how the PI can be operationalized (Sternberg and Norrman 2017), and there is a lack of PI-specific theories that advance the knowledge of the current logistics literature (Treiblmaier et al. 2016).

A promising start to support the implementation and theory-building concerning the PI is to understand its distinct features when compared to digital networking structures and the DI. A number of researchers have followed this logic. Montreuil et al. (2012) propose a seven-layer Open Logistics Interconnection model inspired by the seven-layer ISO Open Systems Interconnection model. Sarraj et al. (2012) explore the analogies between a Digital Internet network and a logistics service network demonstrating the potential for efficiency improvements by following similar practices. More recently, Sarraj et al. (2014) propose novel transportation protocols for the PI and evaluate their static performance via simulation-based optimization.

Compared to the previous PI literature, we offer a more comprehensive comparison between the DI and the PI and highlight distinct features that need to be addressed in future PI studies. We then propose and illustrate how to integrate these features into a stylized PI model, which establishes a link to the classical transportation theories for future PI research. More specifically, our proposed model covers a wide variation of the PI problem, such as real-time, multi-objective, and network equilibrium, which makes it more realistic than those currently covered in the literature.

Classical transportation theories

Although the context of our model is the PI, its mathematical structure is similar to that found in the literature on classical transportation problems, whose richness and rigor could be of great help in developing more rigorous theories concerning the

PI. Our model is especially close to models of the shortest path problem and the dynamic traffic assignment problem.

The shortest path problem studies how a single traveler finds a shortest route (in terms of cost, time, emissions, etc.) between two vertices (or nodes) of a transportation network. Over the years, this problem has developed various extensions. For example, the parameters are time-dependent, the cost terms are subject to capacity constraints, or the objective is multi-dimensional. Interested readers should refer to, for example, Ahuja et al. (1993), Pardalos et al. (2005), Zhu and Wilhelm (2007), Lozano and Medaglia (2013), Case y et al. (2014), Duque et al. (2015), Shi et al. (2017), and Madkour et al. (2017) for reviews and recent advances.

While each traveler independently manages his/her shortest path optimization, the joint actions of all travelers might unintentionally lead to congestion in the transportation network and eventually prevent the travelers from achieving their predesigned optimality. Dynamic traffic assignment models (e.g., Merchant and Nemhauser, 1978) find equilibria for such problems. These algorithms generally require an iterative framework including the calculation of shortest paths of the individuals and the adjustment of route choices toward an equilibrium. Extensive reviews of these models can be found in, for example, Hoogendoorn and Bovy (2001), Peeta and Ziliaskopoulos (2001), Rakha and Tawfik (2009), Szeto and Wong (2012), and Wang et al. (2018).

In this paper, we discuss how our PI model can be linked to the classical shortest path problem and the dynamic traffic assignment problem. To the best of our knowledge, we are among the first to discuss and encourage such connections.

THE DIGITAL INTERNET

Since we aim to consult the Digital Internet (DI) to guide the design and operationalization of the Physical Internet (PI), we are primarily interested in the following two questions concerning the DI: 1) How is the DI structured and 2) How is data transmitted in the DI. In this section, we first present a simple but representative network within the DI (called a computer network in the computer science literature) and then discuss data transmission by briefly explaining the relevant Internet protocols.

The internet networks

The DI is a complex engineering system that connects billions of devices all over the world and, theoretically, allows every device to communicate with all others. To this extent, it is hard to describe the whole DI. For simplicity, we show a basic outline using some critical structures of the DI in Figure 1. We believe this simplified picture is representative of the more complex structure of the DI, and sufficient for the descriptive purposes of this paper.

Internet users could be governmental, commercial, or private entities, all equipped with terminal devices such as computers or smart phones. The users insert flows into the DI in the form of digital data, which is sealed in data packets and transmitted via a network of communication links. Routers direct the data flows in the network, physical media such as copper and optical cables or air-based processes carry the data flows over the links, and modems/cable terminal systems allow data to be switched between different physical media. The Internet services are operated by various Internet Service Providers (ISPs), which ensure smooth flows of all kinds of digital information.

We use the term "router" as a general term to cover the functions of classic routers, switches and hubs. We recognize that there are significant differences in the functioning of these devices as independent entities. However, today's modern routers have become general purpose devices incorporating the functionality of all three of these technologies, thus our use of the term "router" in its more modern manifestation.

The internet protocols

The operationalization of the Digital Internet, or more specifically, the smooth data transmission in the DI, would not be possible without standards. Internet protocols have been introduced to standardize and organize its operationalization. A protocol defines the format of the packets of digital information exchanged between peers in the DI, how hosts should be addressed, as well as the actions taken in the transmission of the packets across the DI.

The protocols have evolved over time to be organized in a layered architecture (Clark 1988). A network layer is often a mixed implementation of hardware and software and focuses on a specific type of information transmission. When taken together, the collection of protocols at various layers becomes the "protocol stack." The classic Internet protocol stack consists of five layers: the physical, link, network, transport, and application layers (Postel 1981). It should be noted that the Internet follows what was originally known as the Department of Defense (DoD) Internet Protocol suite (Clark 1988). This protocol suite evolved independently from the International Organization for Standardization (ISO) Open Systems Interconnection (OSI) seven-layer model and, while similar in many ways to the OSI model, also differs considerably from that model (Ennis 1983). We refer the interested readers to Kurose and Ross (2016) for the historical background of the ISO model, although "in fact, the inventors of the original OSI model probably did not have the Internet in mind when creating it" (Kurose and Ross 2016, p.53). Since we want to compare the PI with the classical Digital Internet structure, we stick to the five-layer DoD model to describe the flow of messages in the Digital Internet. This approach differs from other authors who have generally employed the OSI seven layer model (e.g., Montreuil et al. 2012) to define a layered approach to the PI. The function of each of the layers in the DoD Internet protocol stack is briefly outlined in Table 1.

All the hardware and software components of the DI work under the contracts designed by these protocols. Whereas protocols in each layer focus on specific tasks, the operation of protocols across all five layers provides an operational solution to the *reachability problem*: how to transmit data from A to B. This function is, after all, what the Internet was created for. Considering the billions of users and vast amount of data transmitted over the Internet, solving the reachability problem is a tremendous accomplishment in and of itself. Note that the reachability problem, as defined here, is addressed in the Internet through a subset

Figure 1: A simple schematic of part of the Digital Internet.

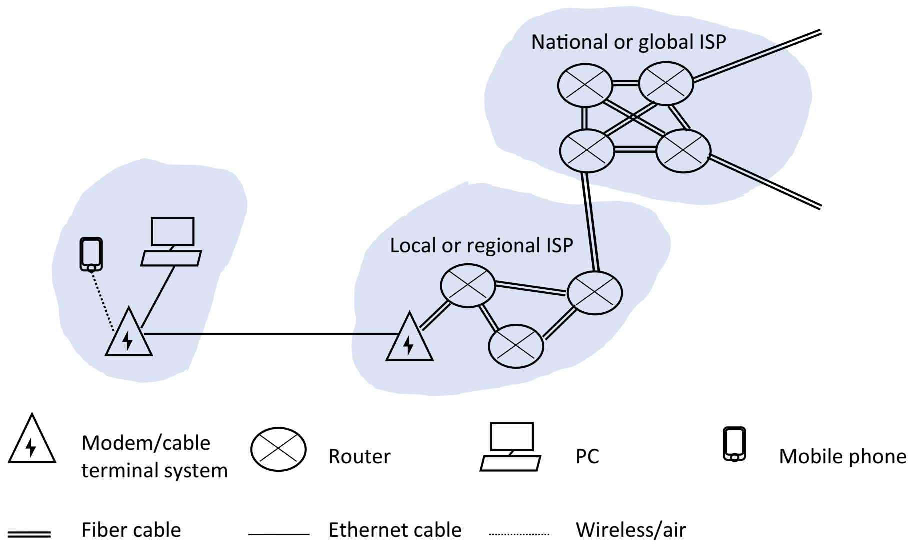


Table 1: How data flow is operationalized in a five-layer Internet protocol model

Layer	Operation
Application Layer	Communicates applications/services between separate Internet users. An example is an email application that sends an email from one computer to another.
Transport Layer	Establishes the connection between Internet users to send data and keeps track of the sending process.
Network Layer	Manages the routing of a data packet as it traverses the Internet from the sender to the receiver. The DI uses a connectionless model allowing the network itself to route a message from origination address to destination address using a "best effort" approach to the transmission of the packets.
Link Layer	Governs the data transmission within a single connection, for example, the fiber connection.
Physical Layer	Ensures that the 0/1 digital data are transmitted over the physical media of the connection (e.g., the fiber connection mentioned before).

of the DoD protocol stack, the Transmission Control Protocol/Internet Protocol, which is today more generally known as TCP/IP (Clark 1988).

FROM THE DIGITAL INTERNET TO THE PHYSICAL INTERNET

The Physical Internet is regarded as a conceptual analog of the Digital Internet. We first discuss the similarities and then the differences between the two concepts, with a special focus on the logistics-relevant metrics embedded in the PI.

Similarities between the DI and the PI

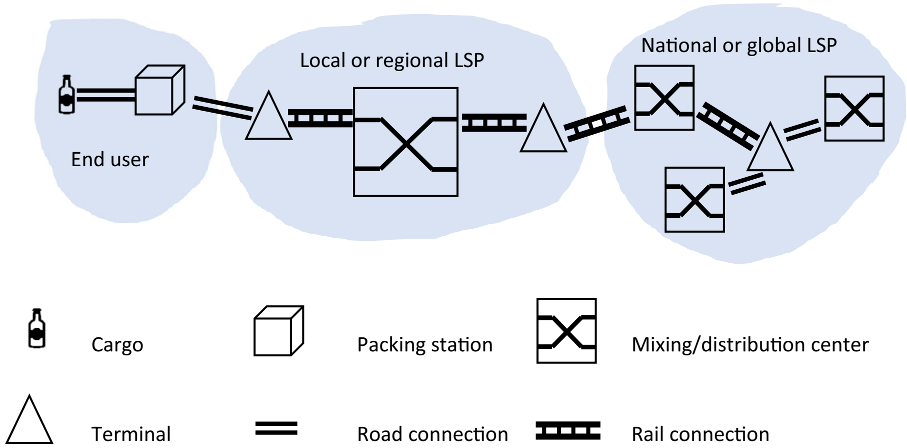
Inspired by the Digital Internet network in Figure 1, we present part of the Physical Internet network in Figure 2.

PI users could be both commercial and private shippers. They insert flows into the PI in the form of various physical objects such as groceries and consumer goods, which are packed into standardized packages in packing stations and then transported in a network of physical corridors. Mixing/distribution centers direct the package flows in the network, transportation modes such as road or rail carry the package flows, and intermodal terminals allow cargo to switch between different transportation modes. The PI services are operated by various Logistics Service Providers (LSPs), which secure smooth deliveries of all kinds of physical objects.

By comparing Figure 2 with Figure 1, additional similarities between the DI and the PI can be summarized (Table 2). Many of the distinct attributes of the PI, such as collaboration between different parties in the PI, can be traced to their counterparts in the DI. Note that this analysis only shows general comparisons between the DI and the PI. Its objective is to provide a better understanding of the two concepts going beyond their namesakes. More advanced and/or exceptional cases are always possible. For example, not all physical objects can be packed into standardized boxes. Some cargo will require special handling in packing, storing, etc. Typical of this example would be bulk cargo such as crude oil or grains, large-sized machinery parts, hazardous goods, and so on.

In its definition, the PI offers seamless interconnections of logistics services (Montreuil et al. 2013). In the light of this commitment, the PI is, despite all its other benefits, firstly an interconnected logistics system composed of a network of logistics networks. It should be able to deliver any physical item from any origin A to any destination B. As a result, the reachability

Figure 2: A simple schematic of part of the Physical Internet.



problem should be the first problem to confront. This problem is conceptually similar to the reachability problem addressed by the DI. In the process of delivering a physical object, there are numerous protocol-like international agreements that standardize the flows and ensure the smooth deliveries of cargos across the world (e.g., Incoterms, customs agreements, international modal legislation, international postal agreements). Prior work in the area of PI shipments by Montreuil et al. (2012) uses a seven-layer physical transportation protocol stack to model how freight might flow over the PI. Their model breaks the task of shipping an item over the PI into seven interconnected layers of smaller tasks facilitating the efficient and standardized movement of freight. This detailed breakdown of tasks, while organized slightly differently from our five-layer comparison, is structurally similar to the comparison provided in Table 2. Hofman et al. (2017) examine differences between the PI layers proposed by Montreuil et al. (2012) and the layers of the DI giving additional insights into the similarities (and differences) between PI and DI activities as outlined in Table 2.

The design of the DI and its protocols provide users with a "connection-free" service: They can simply use the DI without a need to understand how their data will be routed from its origination point to its destination. A similar "connection-free" service can be implemented in the PI: A PI user should be able to trust the PI and its services to ship their goods to any destination without knowing (or caring) about the route that the goods take. An LSP controlling several key nodes in the network can route the shipment via any convenient route so long as it arrives as per agreement between the shipper and LSP. For example, when a box is sent from Beijing to Brussels, the detailed route, Beijing–-Tianjin–Rotterdam–Brussels, can remain anonymous and the exact route taken is left up to the operational considerations of the LSP and their quality of service agreements with the shipper.

Differences between the DI and the PI

Although the PI is regarded as an analog of the DI, they are two completely different things. The basic unit transported by the DI is digital data, electronic 0s and 1s. In other words, a flow in the DI can be exclusively represented by a sequence of standardized high or low voltage values, light pulses, or carrier wave amplitudes and frequencies. The binary nature of signals used to encode information in digital packets establishes the basis of the DI and all relevant applications and protocols are designed based on this fundamental fact.

In the world of the PI, however, the basic flow consists of various physical objects that may be quite different from each other. There is no such thing as a standardized 0/1 unit that is the fundamental building block of these physical objects. Even if different physical objects can be packed into the same standardized boxes, and these boxes are treated equally in the PI by the LSPs, the boxes are valued differently from the eyes of the PI users because of their contents. Users probably do not care if they receive the same box in each shipment, but they do care if what is in the box is different from what they expect.

The Internet also employs the concept of packet retransmission, which allows packets that have been lost or discarded due to congestion at a router to be retransmitted after a period of time. Retransmission of physical goods is a costly undertaking and something that no user of the PI would appreciate seeing happen. Transporting physical objects instead of transmitting digital signals, therefore, requires additional effort in physical distribution. Important logistics metrics, therefore, in physical distribution need to be confronted. These metrics can be sorted into five major categories: cost, time, schedule, emissions, and capacity.

Cost

Whereas sending an email incurs trivial variable cost linked to electricity consumption (infrastructure costs are generally included in the bandwidth and connection fees charged by ISPs and carriers), distributing a physical object incurs substantial variable costs linked to transportation modes, packing and unpacking, loading and unloading in distribution centers, etc. These shipment costs are linked to the flow of each single object in the PI and are oftentimes the most critical factor for PI users. Note, the cost here not only means the monetary fee paid for logistics services, but also the externalities such as accidents, noise, pollution, and congestion (because of its increasing importance, emissions are listed as a separate metric below), which can be internalized (e.g., Maibach, Schreyer, Sutter, van Essen, et al. 2007).

Table 2: The similarities between the Physical Internet and the Digital Internet

	Physical internet	Digital internet
User	Private and commercial shippers	Private and commercial Internet users
Flow	Physical objects	Digital data
Unit of the flow	Standardized packages, for example, standard containers, the MODULUSCHCA Box (European Commission 2016)	Data packets
Routing of the flow	Ports, cross dock facilities, distribution centers, multi-modal transfer centers, etc.	Routers and switches
Carrier of the flow	Transportation modes, for example, roads, rail, sea, air, inland waterway, pipeline	Physical medias, for example, coaxial, fiber, air (wireless)
Protocols	Standardized sending/receiving processes	Five-layer Internet protocol model
Service providers	Logistics service providers	Internet service providers
Collaboration between operators	Transshipment and revenue sharing between different LSPs, groupage services, pallet networks	Roaming and revenue sharing between different ISPs
Collaboration between users	Shared transportation services, shared warehousing, etc.	Peer-to-peer networking, intranets, etc.
Collaboration between a user and an operator	3PL services	Dedicated access lines (e.g., T1 links)
Ownership of basic infrastructure	Partly government-owned (highways, bridges, etc.)	Primarily privately owned (by the ISPs), but some government ownership, for example, national telephone carriers, etc.

Time

Since digital signals are traveling almost at the speed of the light, their lags in the DI are, in most scenarios, negligible. The flowing speed and arrival time of physical objects in the PI, which is subject to transportation modes, availability of labor, handling time in the transshipment nodes, etc., are critical to PI users. Transit times are not negligible and vary significantly by network routing decisions.

Schedule

The transmission of digital information is almost instantaneous. Should problems arise in the transmission process, the speed at which rerouted signals or retransmitted packets travel make delays negligible (note that there are exceptions for certain information flows requiring continuous streaming or assured delivery). These facts mean that for most users of the DI the scheduling of information deliveries is not generally a concern. However, the schedule of flow in the PI is a dynamic and potentially problematic process subject to the real-time status of the network. For example, if congestion arises or a vehicle breaks down, new routings may need to be implemented that lead to delayed deliveries. Such delays are of concern to shippers, customers, and service providers as they may generate penalties and lost business and other additional costs.

Emissions

Although the running of electronic devices in the DI requires significant energy, the marginal energy consumption of sending an email is almost negligible. The emissions from the DI can be regarded as a “fixed cost” term that is linked to the rigid infrastructures, but not to the size of the data transmitted. In the PI, however, emissions primarily arise from the movements of the physical objects. The emissions from the PI are a “variable” term and are proportional to the goods delivered. This provides an incentive for shippers and logistics service providers to reduce emissions via efficient logistics operations.

Capacity

In the DI, routers frequently send data packets to test the congestion of adjacent routes and routers. If data transmission in one pathway is congested, the router can immediately use other avenues for transmission. The allocation of capacities in each route is flexible, and it is more critical that the entire network has sufficient capacity for all data transmissions. In the PI, however, capacity is a strict bound for each participant in the network. For example, if a truck is fully loaded, additional goods must wait for the next available truck. A spontaneous shift to another transportation mode could be much costly or even impossible. This requires sophisticated capacity management for each freight movement in the PI.

The five metrics outlined above do not stand alone. As noted, they are often inter-connected and appear together. LSPs might want to quote their service to the PI user by combining cost with time using their evaluation of the transit route reliability and the user’s specified quality of service requirements. Because users, downstream service providers and customers are interested in the scheduled movement of the goods, real-time updates of the state of the PI are required. For example, after the user has contracted for a specific time and service level using the PI, an accident occurs and blocks part of the original planned route. In this case, the PI should be able to provide immediate updates and reoptimize the entire route. Given the originally negotiated terms, PI users might want to accept proposed changes in cost and/or service level based on the state changes of the PI, stick to their old plans and accept delays, or seek to penalize their service providers for failing to live up to their negotiated commitments. In addition, optimal plans at the individual shipment level need to be consolidated to predict the status of the PI network, which further influences the individual planning problems in a recursive fashion.

The DI also needs to solve optimization problems. The shortest path algorithm is used for routing data packets in a local area network by minimizing the number of jumps in the routing process. In a pure IP network, the shortest path is chosen even if it becomes congested. Congestion management is historically handled through relatively simple procedures. The basic procedure is to simply discard packets when a router or a link becomes overloaded and retransmit them. More advanced approaches, which vary by router manufacturers, are based on back-off signals that require sending nodes to delay a random amount of their transmission, change packet size, reroute packets, etc. More recent and sophisticated traffic engineering approaches look at bandwidth scheduling and prioritization of packet flows for IP-based messages. For example, multi-protocol label switching (MPLS) allows a network manager to manage traffic flows in a more fine-grained and prioritized manner than standard TCP/IP. MPLS is the primary way that network service providers condition and prioritize traffic flows for video and voice.

Even though the DI also needs to perform some optimizations in its operations, for example, dynamically leveling network load at hubs and maximizing the robustness of transfers, they are mostly handled digitally or through simple manual rules and therefore have little impact on the metrics (e.g., cost, emissions, schedules) of the entire system. For each single freight movement in the PI, various logistics metrics must be jointly included in the solution process as parameters, constraints, and/or objective functions. Considering the large size of the DI and PI systems, even one additional constraint could impact solution efficiency. The incorporation of the various logistics metrics that do not exist in the DI can make the complexity of the PI significantly greater than that of the DI. To highlight this complexity, the PI not only needs to solve the reachability problem, that is, routing from A to B, but also must confront a much more complex optimality problem, that is, optimizing the logistics metrics in the physical distribution activities.

A STYLIZED MODEL OF THE PHYSICAL INTERNET

The aforementioned comparison between the DI and the PI reveals a number of unique features of the PI. Based on these unique features, an initial model to support the implementation of the PI should incorporate at least the following elements:

- The diverse participants that make up the PI, such as packing stations, distribution centers, transportation modes, and corridors
- The logistics metrics, such as cost, time, and emissions, which define acceptable performance for each participant in a logistics network.
- The dynamics and time-dependent constructs for each shipment in the network.
- The representation of the reachability and optimality problems of the PI.

As a starting point for such a model, we propose a simple graph theoretic model of the PI covering its distinct features and discuss the connections between the shipment of a single object and the classical shortest path problem. After that, we discuss the simultaneous shipments of multiple objects in the network and the connections to the dynamic traffic assignment problem.

Model formulation

Consider a directed graph $G=(V,E)$ consisting of a nonempty finite set V of vertices, and a nonempty finite set E of edges (Figure 3). The graph G has a distinguished source vertex $s \in V$ and a sink vertex $r \in V$, representing the sender and the receiver of the shipment. Other elements in set V, denoted as $(v_1, v_2, \cdots, v_M)$, represent the infrastructures in the PI, such as packing stations (the black vertices), routing centers, distribution centers, and terminals. The elements in set E, denoted as $(e_1, e_2, \cdots, e_N)$, are ordered pairs of distinct vertices, specifying the transportation corridors between two infrastructures in the Physical Internet.

Each edge with index $i \in N$ is associated with a weight $w_i^e(c_i^e, l_i^e, m_i^e, q_i^e, t)$, representing the five logistics metrics discussed in Section 4.2. The weight is a five-element vector, expressing in period t, the transportation service that covers this corridor e_i. It incurs a monetary cost c_i^e, a lead time l_i^e, emissions m_i^e, and is subject to the capacity constraint q_i^e of this edge in t. Each vertex with index $j \in M$ is also associated with a weight vector $w_j^v(c_j^v, l_j^v, m_j^v, q_j^v, t)$, which denotes that the operation in this infrastructure v_j with capacity q_j^v in period t costs c_i^v, emissions m_j^v, and requires lead time l_i^v. Note that weights will most likely be dynamic in a real-world situation changing upon a number of factors such as load, personnel and asset availability, and macroeconomics.

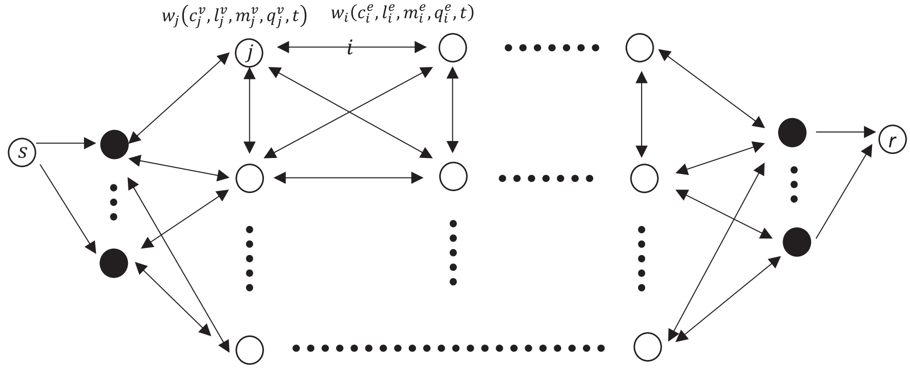
A single PI user wants to find a path from s to r, subject to constraints in various logistics metrics. Again note that all the weights are dynamic and change in real-time.

Analysis and heuristic

The PI should be able to solve the optimality problem at an individual user level, and then consolidate the knowledge from all individual problems to manage the overall network status. Depending on the requirements of the PI users, the PI is supposed to solve different logistics problems and, therefore, the model could have various objective functions. For example, if a PI user only has a single objective, for example, minimizing the total shipping time from s to r, then the PI model is equivalent to the classical single-source shortest path problem (SSSP).

Nevertheless, the PI might change in time and variations of the SSSP are needed. In the simplest case, with constant network and shipping time, the SSSP is static and can be easily solved using the classical Dijkstra's algorithm (Dijkstra 1959). If the network changes over time (e.g., a pathway is blocked due to an accident), the SSSP is dynamic and needs combinatorial properties to obtain efficient results (e.g., Demetrescu and Italiano

Figure 3: A stylized network model for the Physical Internet.



2006). If the shipping time changes over time but is still preknown (e.g., it costs twice the time in the rush hour), the SSCP is time-dependent and can be solved using label-correcting algorithms (e.g., Dean 2004). If the shipping time is completely random, the SSCP is stochastic and the objective is to minimize the expected total time (e.g., Miller-Hooks and Mahmassani 2000).

In reality, PI users might have various requirements that significantly complicate the solution processes. For example, a PI user might want to jointly optimize time, cost, and emissions. This will extend the model to a multi-objective, time-dependent shortest path problem. A PI user could also set one logistics metric as a hard constraint and optimize another, for example, to ship a parcel at the lowest cost within seven days. The model will then be extended to a capacitated time-dependent shortest path problem. Since different PI users might have different preferences over the logistics metrics, the PI needs to design tailored algorithms to meet them.

Even the objective function can be time-dependent. For example, due to a change in the network topology, the shipment might become stuck midway through its transport and cannot be delivered on time. The shipper could then be required to make an interim decision such as cost minimization instead of time minimization or could simply request the return of the shipment. This requires the PI to offer real-time tracking and tracing along with flexible routing adjustments in the shipment processes.

The relatively "simple" variation of the SSSP is not an easy problem to solve. To solve the different extensions concerning the five logistics metrics of the PI problem to optimality, the most sophisticated of these current algorithms would be overwhelmed by the size and complexity of the PI problem itself. Novel heuristics that are developed based on the distinct features of the PI are needed.

Inspired by the "reachability" as well as "optimality" features of the PI, we propose a simple iterative two-stage solution heuristic as an example of how one might approach the difficult problem of finding optimal solutions to shipments over the PI. In the first stage, the reachability problem is solved: Given the current graph, find all walks from the current vertex v_j to the receiving vertex r. A *walk* between two vertices denotes a sequence of directed edges from the initial vertex to the final vertex. In the second stage, the optimality problem is solved: From all the valid walks, select the one that satisfies the user's metric requirements. Whenever the part of the PI involved in the predecided solution is changed, the topology of the graph will be accordingly updated and the above two-stage optimization problem recalculated, this process continues until the physical object finally reaches the receiver. The flow chart of the algorithm is shown in Figure 4.

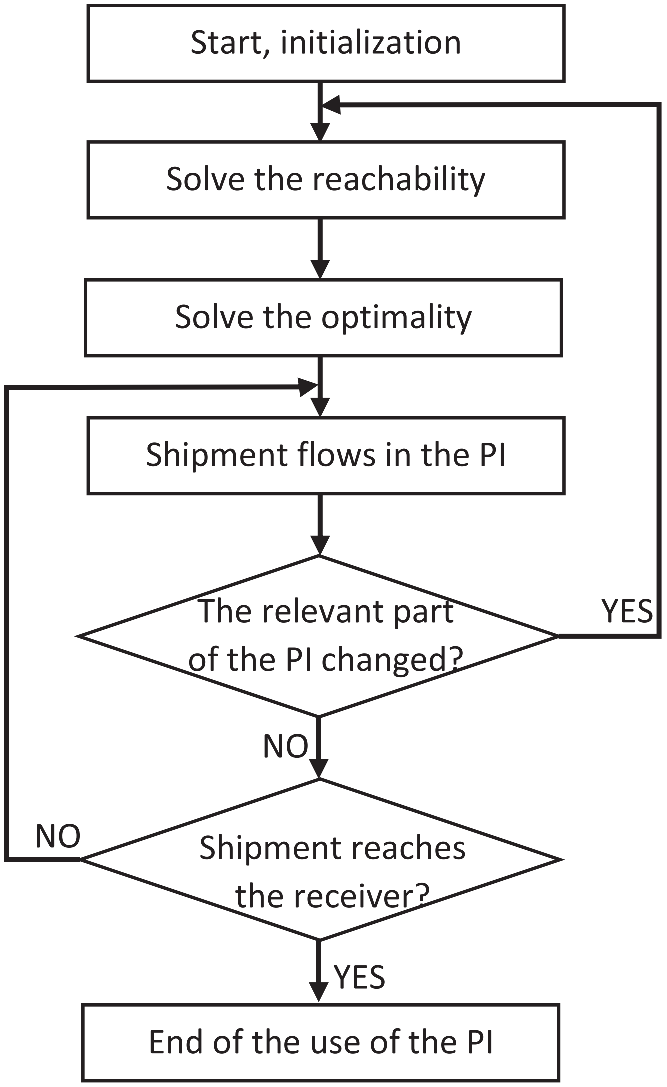
The key to our algorithm is splitting a complex problem (the PI model) into two sub-problems (the reachability and optimality problems). Managerially speaking, these are two different problems embedded in the PI and can be decoupled, and our heuristic naturally mimics the practical operation of the PI. Technically speaking, our approach facilitates the solution of a more complex problem via a sequential and iterative process of solving two simpler sub-problems, which reduces the entire computing effort. In reality, the feasible set of the reachability problem might be stable because similar problems have been solved by the PI and a large proportion of the solutions are prestored. For example, if a shipment will be delivered from Shanghai to Berlin, it is most probable that the ocean vessel terminal of Hamburg will be included in one of the reachable walks and this solution has been seen in other problems multiple times before.

The PI as a dynamic traffic assignment problem

The aforementioned model reflects the routing of a single shipment without considering the status of the entire PI network. Given the capacity of the PI, when multiple users are simultaneously using the PI, congestions might happen and eventually impact every shipment in the entire PI network. Knowledge concerning all PI users then needs to be consolidated to predict and manage the aggregated status of the PI network. This problem falls into the scope of the classical dynamic traffic assignment problem in the transportation literature.

A popular heuristics for this kind of problem is to iterate the network until equilibrium (if found) is achieved (Figure 5). In the beginning, the logistics metrics of the network are obtained and each shipment solves its extended shortest path problem. The joint decisions of all shipments will change the traffic flows in the PI network, which results in a set of new logistics metrics. Each shipment then needs to solve its extended shortest path problems again. The iterative process then converges to an equilibrium solution for the shipments, and the solution of the extended shortest path problem can be obtained using our algorithm shown in Figure 4.

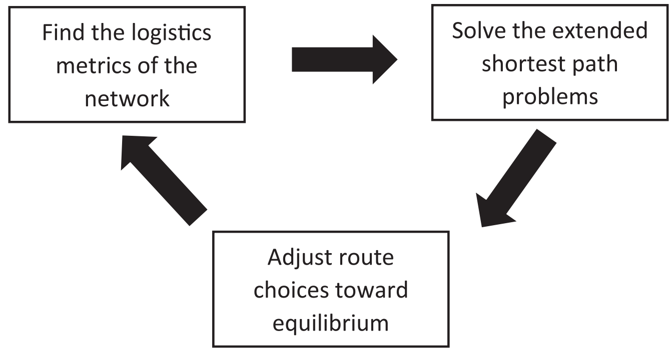
Figure 4: The Physical Internet as an extended shortest path problem, and the flow chart of the solution algorithm.



It should be noted that Figure 5 is only an initial framework, demonstrating the feasibility of using the DTA literature to support the implementation and theory-building of the PI. In this framework, the characteristics of the PI and the principles of the DTA models can be linked. For example, the reachability problem can be represented by route enumeration of the network, the process of identifying a set of alternative routes using SP analysis (Bovy and Fiorenzo-Catalano 2007), and the optimality problem can be tackled by various forms of network assignment, such as generalized cost (weighted sum of cost and time) minimization. The shipment of a package in the PI under specific requirements from the PI user aligns with the "travel choice principle" of the DTA, and the smooth operations of the PI reflect the existence of equilibriums in the DTA. Our simple heuristic can and should be enriched in various ways in future research. However, once again, it is not the focus of this paper for those extensions.

The PI network will be the largest logistics network ever studied and its related DTA model will be of a huge size. Previous

Figure 5: The dynamic traffic assignment problem can be solved using iterations.



algorithms of the DTA will certainly need to be updated. The PI network is also large in terms of the stakeholder involved, who may have different objectives. For example, one user may want the cheapest service while the other the fastest delivery, and the PI operators need to quote different offers given the current network status.

One typical question addressed in DTA network analyses is the choice between Wardrop's two network equilibria: the system equilibrium and the user equilibrium. Because of the size of the PI, it is difficult to imagine a single super-agent that optimizes the sum of costs over all users. It is more likely that user equilibrium will prevail: Each single shipment will be optimized individually. However, a logistics service provider may consolidate freight from several shipments and minimize the sum of total costs. System equilibria therefore exist in such sub-problems.

Reflection of the PI characteristics in the model

Montreuil (2011) has highlighted 13 characteristics of the PI that achieve the global logistics sustainability vision. Our current model, together with its potential extensions, covers these characteristics as illustrated in Table 3. Using graph theory, a rich literature exists to support innovations in the conceptualization and operationalization of the PI using the proposed model as an initial starting point.

Model extension

The current model illustrates the optimality problem of the PI in the aspects of cost, schedule, and emissions. Statistically speaking, only the first moments of these parameters are evaluated. It could be interesting to measure the second moments of these objectives. The second moment of the lead time is its punctuality and the second moments of cost and emissions could also be a changing number depending on, for example, the shipment volumes or equipment type. It may be necessary to consider both the first and second moments together. For example, sometimes a shipper might want to choose a more punctual transportation service, even if that requires a longer, but more reliable lead time.

The PI could also consider other objectives besides cost, lead time, and emissions. A typical example would be modal usage. Each vertex and edge of the graph in Figure 3 could then be

Table 3: The main characteristics of the PI mentioned in Montreuil (2011) can be incorporated in our model

Characteristics of the PI (Montreuil 2011)	**Covering of the characteristics in our PI model**
Encapsulate merchandises in world-standard smart green modular containers	A packing station is modeled as a vertex in the graph.
Aiming toward universal interconnectivity	Interconnectivity is modeled as edges connecting vertices in the graph.
Evolve from material to pi-container handling and storage system	Any material into the PI (vertex s) must first travel to a packing station (solid vertex) and then flow in the PI.
Exploit smart networked containers embedding smart objects	The current weights of the edges/verities of the graph can be extended, representing additional information linked to the smart objects/containers
Evolve from point-to-point hub-and-spoke transport to distributed multi-segment intermodal transport	Our graph is not hub-and-spoke. Instead, it represents a general distributed network with dynamic changes in topology.
Embrace a unified multi-tier conceptual framework	The vertices and edges between s and r are general settings and can represent any more specific multi-tier networks. Nodes are purposely left simple, but could be modeled in a hierarchical manner in which PI protocols operate similar to the sub-net operations that occur in the DI.
Activate and exploit an Open Global Supply Web	The graph can represent any kind of global supply web.
Design products fitting containers with minimal space waste	This is more from the production side and is not included in our PI model
Minimize physical moves and storages by digitally transmitting knowledge and materializing objects as locally as possible	An additional weight of the edges and vertices representing the physical moves can be incorporated into the current graph to tackle this point. The solution method will be similar to the current lead time minimization process.
Deploy open performance monitoring and capability certifications	The real-time update of the topology of the graph is based on real-time performance monitoring of the PI.
Prioritize webbed reliability and resilience of networks	Reliability and resilience can be modeled as how often/how much the topology of the graph is changed.
Stimulate business model innovation	There is a rich body of graph theory literature to support innovations in the current model.
Enable open infrastructural innovation	There is a rich body of graph theory literature to support innovations in the current infrastructure.

associated with an additional weight, representing the mode employed for the shipment. An objective function maximizing rail usage, for example, similar to Equations (1) and (2), would then be added to the model.

Additional practical constraints could be incorporated into the model. For example, a warehouse may have specific in-bound delivery time windows, the standardized packages have different sizes instead of one, and the shipper might want reverse logistics services in the PI. These constraints could also be dynamic. For example, if the present optimality problem does not give feasible solutions, the shipper (or any other responsible person) is notified, who can decide whether to quit the PI, or accept the new cost/services conditions.

SUMMARY

The main contribution of this paper is the proposal of a feasible Physical Internet (PI) model-based conceptual framework that supports its implementation. The model is a stylized representation of the PI network, and bridges the current gap between the high-level PI concept and its expected benefits. We first compare the Physical Internet with its conceptual metaphor, the Digital Internet, and identify the reachability and optimality problems in a network. On the basis of this knowledge, we use a graph to model the PI, discuss the link to the classical transportation theories, and propose a simple algorithm as a heuristic solution.

Since the PI is a complex concept that potentially covers all aspects of future transportation problems, our stylized model obviously needs extensions. For example, for the cargo that cannot be packed into standardized boxes, the graph will be changed. When a natural disaster happens, infrastructures are damaged and governments might interfere, and special modes might be needed for such special cases. In addition, our model focuses only on transportation issues, not others such as inventory management in the network. Future research could combine both transportation and inventory decisions in the PI.

More characteristics of the PI could be incorporated into the model. For example, the cost and time could depend on more parameters such as the shipment size, node throughput times, arc constraints such as capacities, speed limits, carrier limitations, etc. Transportation models that deal with generalized travel utility incorporating all performance-relevant metrics can be used in such kind of PI optimizations. Multiple cargos could be sent into the PI and corresponding collaboration and joint replenishment opportunities could be studied. A possible use of the PI would be to distribute and store inventory that does not yet have a final destination. In this case, cargo would be pushed into the PI, while it is still not clear who would be the final receiver and the cargo would need to be stored somewhere in the PI (referring to Amazon´s prepositioning goods for rapid fulfillment). The reachability problem and the sequential optimality problem would need to be updated as to who the ultimate receiver would be.

Many other scenarios can be envisioned that extend the stylized model outlined in this paper. As the PI is a new and emerging research area, it has not been the intention of this paper to exhaustively study the many possible issues that must be addressed to operationalize the PI concept. However, it is hoped that this paper helps in establishing the ongoing development of the PI concept so that the benefits identified thus far from this approach to transport and logistics can ultimately be realized.

Since the purpose of this paper is to understand the features of the PI and propose a model to support its implementation, a detailed and rigorous mathematical analysis has not been presented. Future research could study the properties and algorithms of the model, and apply empirical validations to begin laying the foundation for a more rigorous algorithmic foundation of the PI.

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