

Internet of Perishable Logistics

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In this article, we introduce the concept of the Internet of Perishable Logistics (IoPL), which is built on the earlier notion of the physical Internet,² but specialized for perishable commodities by exploit-

The flow of packages or package containers from a source (for example, a farm,

a factory, and so on) to a destination (for example, a retailer) is similar to the flow of packets in the Internet. The flows might pass through some intermediate distribution centers that store and forward the packets much like Internet routers. Finally, the flows might have quality of service (QoS) constraints in terms of delivery times and/or flow bandwidth (volume delivered/day). Despite these similarities, only recently there has been a concerted effort to exploit the flows for making the distribution logistics more intelligent and efficient via the concept of the physical Internet initiative.² The physical Internet now has an active consortium of both academia and industry, as evinced by the recently held conference called the International Physical Internet Conference (see www.physicalinternetinitiative.org/).

The key issues addressed in the physical Internet initiative are standardization and infrastructure and resource sharing, which incidentally have been the key enablers of the cyber Internet as well. Standardization is essential to support the increasing automation of logistics (for example, loading, unloading, and sorting machines and their cyber enablement through IoT devices) in addition to its role in enhancing efficiency and reducing cost. A key physical Internet concept in this regard is the notion of physical Internet (or π) containers that easily compose to create bigger and bigger containers. Another crucial effort lies in the RFID tagging and barcoding under the banner of the GS1 set of standards (see www.gs1.org). These include labeling and tracking of products, packages, carriers (for example, trucks), warehouses, endpoints, and so on. Driven by the benefits in cost reduction and traceability, industry is rapidly adopting these standards.⁴

Traditionally, large operators in nearly all product segments (for example, Walmart, Target, Boeing, Caterpillar, UPS, and so on) have opted to run their private logistics operations to maintain complete control and keep the operations private. However, there's a definitive trend in the industry to move toward the use of outsourced services provided by third parties in the form of third-party logistics (3PL) and its derivatives such as 4PL. The key benefit of 3PL is the higher efficiency and reduced cost due to the sharing of infrastructure and resources among many customers or other service providers. Recent data suggests that 54 percent of transportation and 39 percent of warehouse

operations are outsourced.⁵ However, sharing in logistics networks is much more difficult than sharing in the Internet, because of numerous resources that must be managed and positioned properly (for example, carriers, containers, drivers, handling equipment/crews, and so on).

The enablement of ICT-based automation – often referred to as the Fourth industrial revolution or Industry 4.0 – can also be considered as a propellant for advancing the goals of the physical Internet. Industry 4.0 envisions cyber-physical systems communicating and cooperating with one another and with human operators in real time to automatically self-optimize, self-configure, and self-diagnose.

Adopting such ICT-based capabilities, such as GPS-based localization, RFID-based labeling/addressing, or IoT-based sensing and actuation, will make the supply chain more proactive rather than reactive. For example, trucks and trailers will be informed of delays before they're caught in a traffic jam to make smarter and proactive measures well ahead of time.

Perishability in the Physical Internet

The physical Internet initiative hasn't focused on perishable commodities so far. In this article, we focus on this segment because of the unique issues brought about by perishability; the large carbon footprint of the wasted product, particularly food; and increasing demand for the freshest and least-processed food.

The key characteristic of perishable goods is the continuous loss of quality with flow time, where the deterioration rate depends on the product type and other parameters such as temperature, vibrations, and so on. While it's possible to study perishability as another attribute in the physical Internet, we believe that a more unified treatment of perishability in both the physical and cyber world would lead to new insights and assist in modeling and understanding logistics operations that are driven by real-time sensing and ICT-based automation.

Accordingly, the IoPL can be regarded as a network of physical objects involving perishable commodities, vehicles, warehouses, suppliers, retailers, drivers, loading and unloading equipment, and so on, that are richly infused with sensing, communications, and real-time control (for example, proactive rerouting or local distribution of deteriorating product) to simultaneously maximize efficiency and quality.

This requires a tight integration between physical and cyber aspects, and thus a unified treatment of information packet and physical package distribution.

However, such a synergistic approach is challenging because of some fundamental differences between the logistics and Internet domains. First, unlike an information packet, a physical packet (or package) is unclonable; it can exist only in one place at a time – even though we could surely replace a lost packet by an identical one from the source. Another fundamental difference is that physical packets don't move by themselves; instead, they need one or more additional resources for successful transit. The most important resource is a carrier, which could be a truck, railcar, plane, boat, and so on, and the associated driver (unless the carrier is self-driven). Other resources include containers (perhaps even containers within containers), and loading and unloading equipment. Although the cyber systems sometimes exhibit these features (for example, empty circulating frames that are filled up by sender nodes, or buffers reserved prior to transmission), the situation is generally much more complex for logistics networks.

A Proposal for IoPL

In this section, we define a layered architecture for IoPL, modeled after the cyber Internet, to describe the end-to-end delivery of products while accounting for their perishability characteristics and relevant logistics related requirements and constraints. Benoit Montreuil and associates proposed a layered architecture for the physical Internet; however, this approach concerns the overall physical Internet operations rather than end-to-end product delivery, and it doesn't consider perishability.⁶ Our IoPL framework “carries” nonclonable packets with GS1-based labeling and addressing mechanisms to enable automated operations. These are useful for addressing nodes, packets, and other relevant entities (for example, containers).

We allow packets to belong to more than one QoS class. Each class is characterized by different sizes, priority, timelines, and other QoS needs. For example, a logistics network handling multiple types of fruits might group them in three classes: high perishability or delicateness (for example, berries), medium perishability (for example, apples), and low perishability (for example, melons). The classes might also be defined based on their ripening stage or their

cultivation method (that is, organic/certified or inorganic/noncertified). Each class c has its perishability function $\xi_c(t) \in (0, 1)$ that measures the deterioration in their quality with time t . $\xi_c(t)$ is linear for fruits and vegetables, but exponential for fish or meat products.

The IoPL also defines resource vectors indicating availability of resources at various nodes and resources that must be acquired before a packet can move from one node to the next. The resource requirements must allow for potentially recursive bundling/unbundling of packets including sharing or other constraints. For example, to transport a physical packet X in IoPL, we need the following: availability of a carrier (for example, a truck), carrier driver, and a container; bundling of X along with other packets (in the same or perhaps even different class) into a suitable container; and bundling of containers into a truck. Here, the bundling of X along with other packets requires availability of other packets and is constrained by container size. Similarly, bundling of containers into a truck requires availability of other containers and is limited by truck size. Both cases involve the tradeoff between transfer latency, delivered quality, and resource use. The IoPL must provide mechanisms for resource allocation and deallocation while allowing for these tradeoffs. Closely related to the tradeoff issue is the ability to position resources suitably within the network.

We can now describe the layers of the IoPL stack. Note that the first four layers are modeled closely after the TCP/IP stack (shown in Figure 1a) and can be interpreted that way for cyber Internet packets.

Layer 1: Physical Layer

The physical layer deals with the actual movement of a packet along a media segment or channel. This corresponds to the physical transport of a package from a transfer point to next over a media channel. The media in this case corresponds to the mode of transport (for example, road, rail, ferry, air, and so on) and a channel corresponds to a particular pathway of the media (for example, specific sequence of roads on which the truck will travel).

Layer 2: Media Switching Layer

In IoPL, the media switching layer provides the media/channel selection, media bridging, and

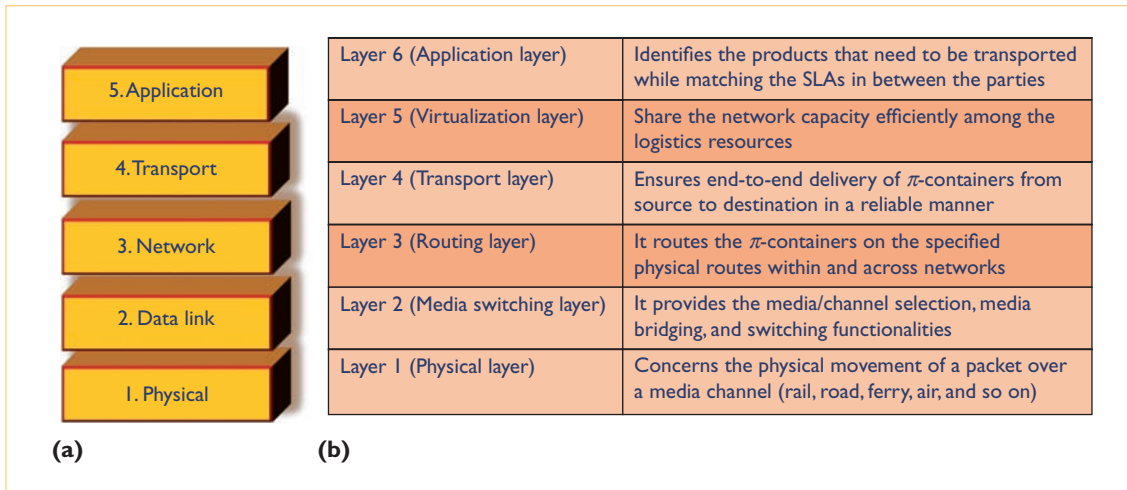


Figure 1. Internet of Perishable Logistics (IoPL) layered architecture. (a) Networking stack, and (b) logistics stack.

switching functionalities. This refers to transport of goods from an endpoint or distribution center to the next via a single segment or a sequence of several segments, each potentially using a different media (road, rail, waterway, air, and so on).

Layer 3: Routing and Distribution Layer

This layer supports end-to-end transfer of packets by handling packets at and across distribution/routing nodes. This layer also deals with the recursive bundling/unbundling and allocation of layer 3 resources such as containers. For example, a box shipped from the source might be bundled with others into a bigger box, which is possibly bundled further, and ultimately placed on the carrier to be shipped. This bundling might be shuffled along the way at intermediate distribution nodes, until the package arrives at the destination. The routes in a network are chosen generally to maximize the delivery quality (or freshness) of the packets, minimize delivery time, minimize network cost, or some combination thereof.

Layer 4: Transport/Delivery Layer

This layer concerns the end-to-end assured delivery of individual packets (which might have been bundled recursively before transportation and then unbundled for final delivery), based on their service level agreements (SLAs). The destination will check the packets for loss, damage, deadline expiry, and quality degradation, and accordingly make decisions regarding reorder or replacement. Thus, this layer also

concerns the reverse logistics, which concerns the return of excess or damaged products.

Layer 5: Virtualization Layer

The job of the virtualization layer is to share the network capacity efficiently while still ensuring isolation among the various services/applications. In particular, this layer can define and maintain one or more virtual networks that then are mapped on to the same physical network. The virtual networks are defined based on the SLAs between the parties, or corresponding to different QoS classes depending on their perishability characteristics, delivery requirements, and so on.

Layer 6: Application Layer

This layer identifies what products need to be transported between two parties, while specifying the contracts or SLAs, and passes them down to the lower layers. The contracts mention whether the transportation resources will remain completely dedicated or can be shared between different parties; the possible modes or types (express, normal, and so on) of transportation; details of product pickup, delivery, quality, timing, and handling; and so on. These are used to assign the packages to different virtual networks. This layer also provides mechanisms to return the containers (empty or partly full) to their source points by optionally putting some dummy packets inside them. For brevity, we describe the details of these aspects in other work.⁷ We summarize the brief protocol functionalities of the IoPL layers in Figure 1b.

The layering allows us to introduce modeling simplifications via level-specific abstractions. For example, a layer 3 abstraction of the network represents transfer between distribution nodes as an atomic path characterized by a few overall parameters (for example, transit time, availability, path restrictions, and so on) without regard to individual media segments and intermediate handling. As the automation in IoPL increases, the layered architecture becomes more and more important as it regularizes the product handling at various points. In situations where layering hinders efficient operations, cross-layer methods can be exploited to address them while still limiting the overall complexity.

Emerging Research Directions in IoPL

Even if IoPL shares a number of synergies with the cyber Internet architecture, it actually needs to consider a number of additional challenges regarding environmental, economic, and social aspects. Due to space limitations we summarize only four of them below.

Sensing Infrastructure for IoPL

One of the key objectives of IoPL is to reduce food waste due to spoilage and contamination. Sensing of food spoilage and contamination is an active area of research, with many types of sensors currently available or under development. Some examples include C2Sense (see www.c2sense.com), FoodScan,⁸ and Salmonella Sensing System.⁹ These tiny sensors can be inserted into the shipping boxes or containers while they're out for delivery in a truck or inside a warehouse. Through a suitable sensor network, the sensed data for food quality and/or contamination can be transmitted to the central controller along with the box ID (assumed to be GS1 compatible RFID), as Figure 2a shows. A substantial challenge here is the intra-container communication environment with tissue medium or through water-containing products (for example, meat and fresh vegetables/fruits). In such environments, a normal RF communication such as Bluetooth at the 2.4-GHz Industry, Science, Medicine (ISM) band is unlikely to be usable due to high signal absorption and complex channel conditions. Instead, magnetic induction (MI)-based communication at the high frequency (HF) band (3 to 30 MHz) generally works very well in such challenging environments,¹⁰ and we've explored its use for

building the communication infrastructure for IoPL in other work.¹¹

For perishability, the sensing mechanism provides a time series of the real-time sensed quality that can accurately predict potential problems before actual spoilage sets in. This can be particularly powerful if the data collected from multiple carriers and warehouses are collated and analyzed continuously to build sophisticated predictive models. Figure 2b shows the vitamin C degradation characteristics in different vegetables at 200°C¹² and Figure 2c shows the bacterial content growth in chicken meat at 20°C.¹³ Notice the considerable differences in the decay characteristics of the individual types of products, and this poses challenges in deciding suitable actions when multiple types of foods are handled together.

The online spoilage or contamination detection can be exploited to proactively detect which boxes contain potentially contaminated or soon-to-be spoiled products and thereby reduce waste/carbon footprint by either discarding only those boxes or distribute them to nearby stores or even food banks for faster consumption. Similarly, food might be distributed laterally, for example, across distribution centers or stores in an area depending on local excess supply or shortages.

The key challenge in implementing the online spoilage and contamination sensing is the communication framework through the MI-based communications and localizing the spoiled or contaminated boxes quickly within the trucks or warehouses. In an IoPL scenario, close-by conductive objects (for example, water-containing products and mild steel-like truck material) will have significant influence on such MI-based localization schemes. Hence, we need to carefully investigate the influence of the conductive objects and develop localization schemes that are aware of the properties of the ambient environment. One approach is to exploit the regular geometry of the shipping boxes and the information of their neighbor relationship to localize the sensor nodes, rather than using the typical received signal strength-based schemes (such schemes will be erroneous due to the mutual effects in between the magnetic coils and the nearby conductive objects).

Dynamic Bundling of Contents

One important and challenging problem in handling perishable products is the extent to which

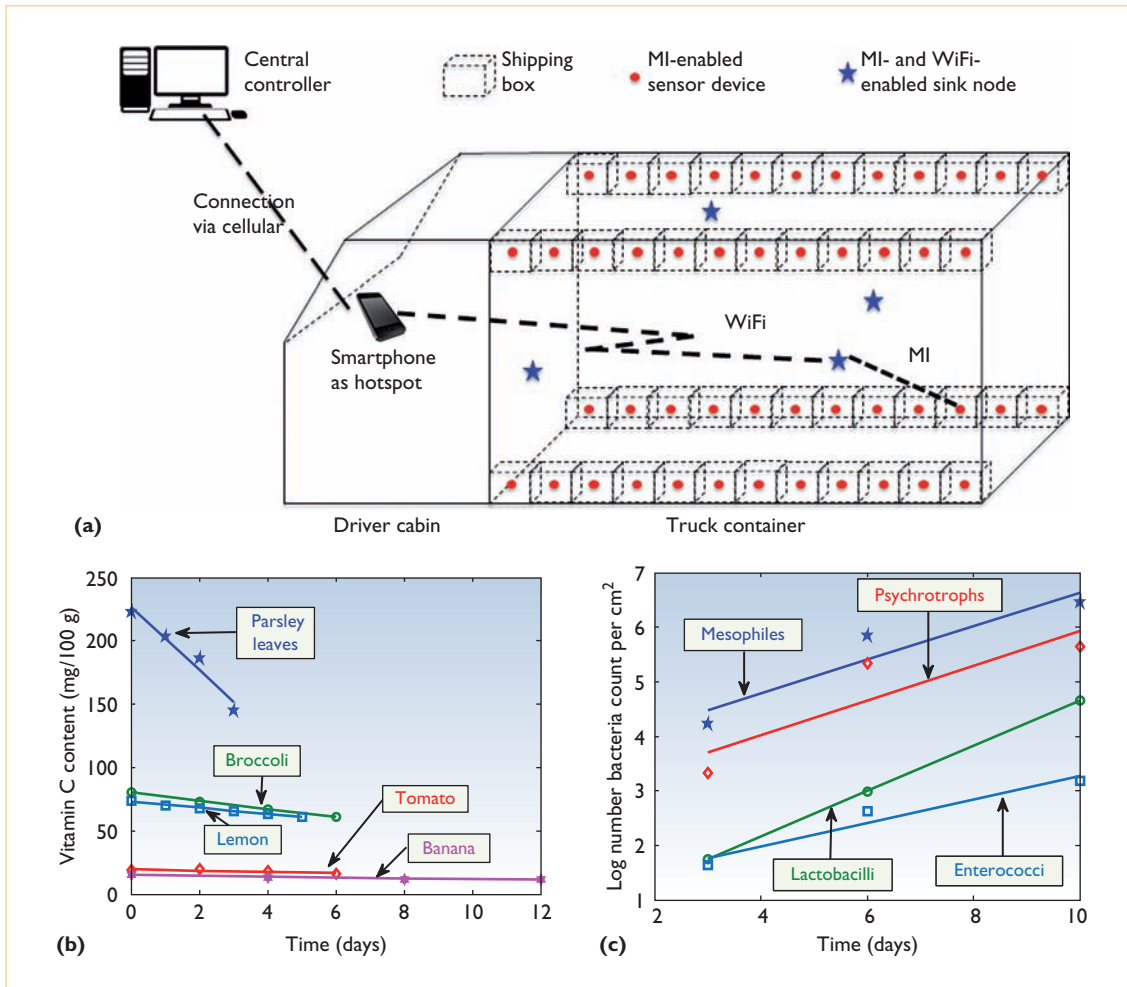


Figure 2. Aspects of reducing food waste due to spoilage and contamination. (a) Quality sensing and communication for product boxes, (b) vitamin C degradation with time, and (c) bacterial growth with time.

different products can be bundled together for transportation and storage. This issue really becomes interesting when multiple types of products have to be bundled together, as is increasingly necessary because of burgeoning fresh food varieties that might be grown in smaller quantities as opposed to producing large quantities of the same product. In fact, with many fresh foods, it's increasingly difficult to have a truck full of product ready for shipment at a given time. Unfortunately, the logistics literature is largely lacking in the analysis in this important emerging area.

The problem of bundling nonidentical, perishable products is challenging because the degradation rate of the products both in terms of visible characteristics (for example, look and feel) and latent ones (for example, vitamin, sul-

fur content, or bacterial growth) varies substantially, and is obviously dependent on the initial condition, quality, environment, and handling. Yet, bundling multiple products implies that they all will be subjected to the same delays, temperatures, vibrations, and so on.

Thus bundling needs to consider the compatibility between the products, which is dependent on their availability and demands, and in which environments (that is, chilled or normal) they will be transported. Other than their classes, the mixing of heterogeneous products at any distribution point needs to consider several factors, such as initial condition/quality and how long the products have waited already at the distribution points; the availability of the trucks, their loading capacity, and types (that is, if they have refrigeration facilities or not);

the availability of the products, their loading-unloading points, and the corresponding space efficiency of the trucks; and so on.

IoPL Virtualization

In a virtualization-enabled cyber infrastructure, a number of virtual networks (VNs) with different network services share resources of a same physical/substrate infrastructure. The mapping of virtual to physical infrastructure requires knowledge of resource availability in spite of dynamic changes in the requirements of various VNs. Such resource sharing is much more difficult in IoPL because of perishability and bundling-related interactions and the need to manage many resource types. Thus, simple approaches such as explicit assignment of trucks to a customer, which are often used by 3PL operators, result in considerable capacity underuse, often referred to as deadheading (or shipping air).¹⁴

One way to strike a balance between logistics complexity and efficiency is to define a few virtual systems (VSs), each of which can be mapped to a suitable set of physical resources. A VS describes not only the resources required but also the required properties of (or constraints on) the VS. For example, we can define an “HP transport” as a VS intended for transporting highly perishable (HP) items (with given decay properties) from a specific origination area (source) to a specific destination area. Similar VSs can also be defined for items with moderate and low perishability. Separate VSs can also be defined corresponding to different types of customers; such as VS for premium customers or other low-end customers. Defining such canned VSs limits the complexity in resource allocation; however, the price is the potential sharing inefficiencies. Therefore, the questions of tradeoff between complexity and efficiency need to be examined and suitably balanced. IoPL along with assumptions at the resource allocation operations at various layers of the network can be used to study such tradeoffs.

Logistics operations often provide personalization as a service feature to the customers. For example, an end-to-end allocation of the same driver (perhaps one known to the customer), same type of containers, and so on, might be provided as a value-added service that provides higher revenue despite limiting logistics efficiency. Such specializations provide a better sense of control, familiarity, and trust

in the logistics operations. The downside is the higher cost (passed on to the customer) and less-effective resource use. Similarly, all requests to transport certain high-value perishable cargo (for example, berries) can be given the same physical resources and provide tighter guarantees of consistent facilities. Such specializations can be described in the VS framework and studied via IoPL with respect to their impact on end-to-end transit times, carried load (throughput), and delivered quality/value of the packages.

Zoned Networking

As discussed earlier, the need for various types of resources to be allocated (and hence, suitably positioned at network nodes) makes IoPL substantially more complex to analyze than the traditional cyber Internet. In fact, one resource in IoPL – namely, the driver – is not only crucial to logistics operations but also more difficult to handle than other resources. Unlike other resources, a driver has human needs that must be addressed. These needs include limited working hours and ability to return home sufficiently frequently – preferably every night. In fact, a significant away-from-home time (from a few days to several weeks) for drivers has traditionally caused a high turnover rate in this business and a consequent impact on service quality (see Figure 3a),¹⁵ which in turn results in driver shortages,¹⁶ as depicted in Figures 3b and 3c. Figure 3b shows that the truckload industry as a whole replaced the equivalent of 95 percent of their entire workforce of drivers by the end of 2014. At the same time, long-distance truck runs in private logistics systems increases the empty miles, which reduces the transportation efficiency.

One suggested method to address this issue is to divide the distribution area in multiple zones and limit a carrier run to within a zone only.¹⁷ An idealized situation is shown in Figure 3d, where the circles represent zones. The inter-zone delivery now requires that multiple carriers run in their own zones, load and unload products in between multiple distribution points (characteristics of shared logistics), with each driver returning back to its source after passing on the contents to the next carrier across the zone boundary. The returning carrier will also carry compatible products in the other direction.

In IoPL, scheduling of carriers needs to account for several factors such as transportation

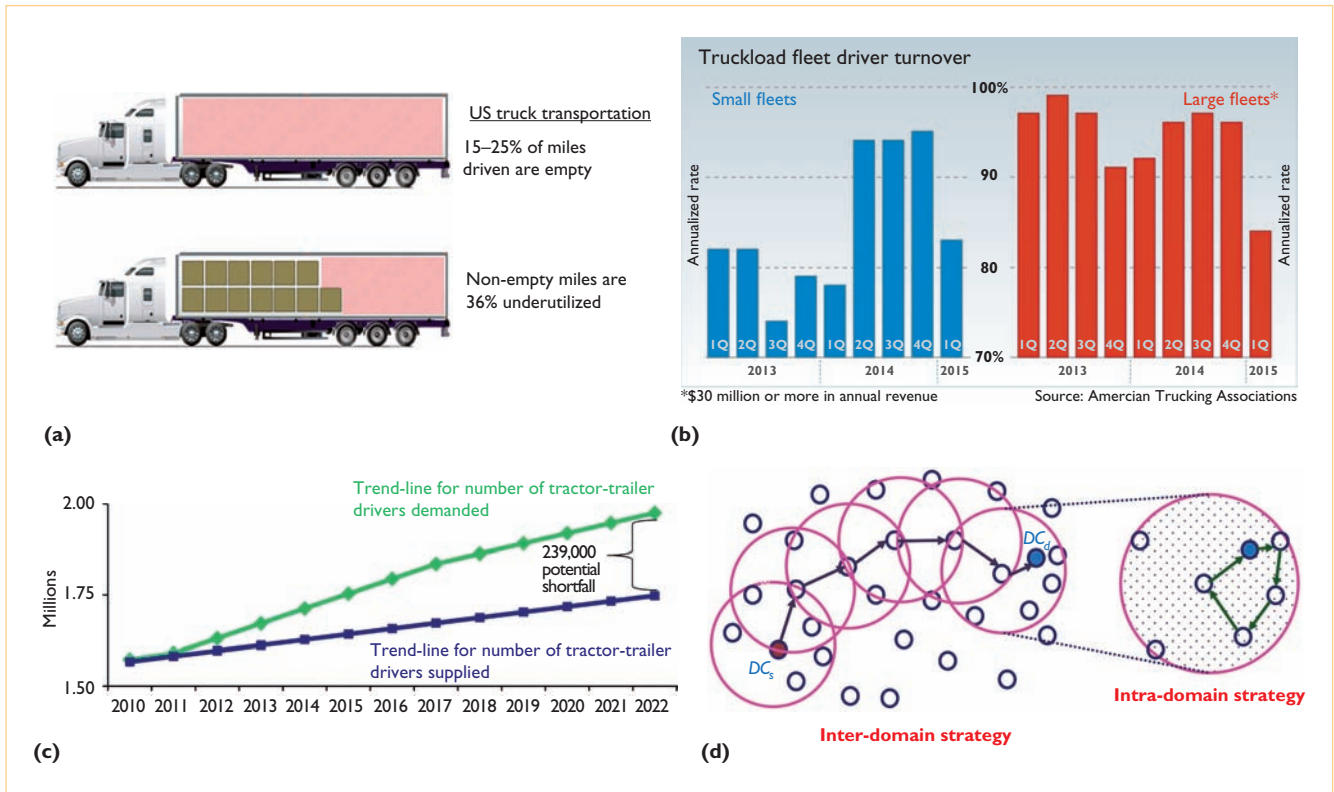


Figure 3. The primary cause of inefficient logistics system is long-distance and (a) empty or half-empty truck runs (source: <http://business.edf.org>). This long driving and away-from-home time results in (b) higher turnover rates¹⁵ and (c) driver shortages.¹⁶ A proposed solution is to explore (d) a zone-based forwarding scheme in between the distribution centers, which drastically reduces the driving time and improves food freshness and transportation efficiency.

efficiency, driver away-from-home time, food package delivery freshness, and road congestion (especially in city areas at peak hours). Some of these objectives are contradictory; such as transportation efficiency versus freshness of delivered product. For example, delivering the food packages directly from the source to the destination by a truck that's 20 percent full provides fresh delivery, but deteriorates the transportation efficiency. Trading off such objectives, along with the integration of intra- and interdomain delivery scheduling is thus the main challenge in this context.

IoPL-Inspired Computing Research

The previous IoPL considerations also result in two unique aspects for the cyber Internet. One is the handling of perishable information, that is, information whose value decreases with time (for example, news stories, user generated videos, stock quotes, sensor measurements in cyberphysical systems, and so on). Such content

is becoming increasingly important and needs to be handled directly. While dynamic content popularity has been amply considered in the content distribution literature, perishability is somewhat different in that it's an inherent property of the content, rather than being driven by user demands. It's surely possible to have dynamic variation in popularity along with perishability (at finer or coarser time scale) for the information packets.

Content-centric networking (CCN)¹⁸ has lately been explored extensively in information networking. The key premise of CCN is that the networking protocols should be driven by the contents and their characteristics, rather than by the addresses of the nodes hosting or requesting the contents. The perishability aware lateral transfer in the IoPL has inspired the notion of neighborhood awareness, where the idea is to cache content specifically from the perspective of distributing them in the neighborhood, as we discuss in other work.¹⁹

Bundling is an important issue in computer networks and is used to reduce overhead and help enhance energy efficiency by elongating gaps between packets. For example, in the Stream Control Transmission Protocol (SCTP),²⁰ multiple flows are handled via a single association by using the chunking idea. Similar mechanisms are also useful to improve spectral efficiency in cellular networks. In datacenters, it's difficult to provide a high bandwidth across all paths, and a more practical approach is to use a backup optical network that provides high-bandwidth bypass paths on-demand.²¹ Optical path reconfiguration is slow because of the need to change wavelengths; therefore, the so-called optical burst switching with intermediate add-drop of light-paths (loading/unloading in IoPL) can be useful in this context. We explored such a mechanism, inspired directly by IoPL, in other work.²²

Many of the specialized features of IoPL designed to accommodate logistics networks continue to emerge even in cyberspace. For example, sensor networks consider scenarios where mobile nodes move physically either to transport packets (for example, a data mule), or to charge themselves. In the former case, establishing communication between partitioned networks or disconnected nodes via data mules or message ferries can be considered as drivers or carriers. This is equivalent to the zoned networking concept mentioned previously. In the latter case, energy can be explicitly modeled as a resource in the sense described in the "A Proposal for IoPL" section.

In this article, we demonstrated several synergies between the cyber Internet and perishable logistics, and showed how they can lead to innovations in both fields. We also introduced a layered Internet architecture for perishable logistics that we believe can be exploited for studying the complex, interconnected logistics services at various levels of abstraction. The article also opens up a number of potential avenues for multidisciplinary collaboration to shape the vision of an economically, environmentally, and societally sustainable perishable food industry logistics.

Acknowledgments

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