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Internet of Perishable Logistics: Building Smart Fresh Food Supply Chain Networks

AMITANGSHU PAL AND KRISHNA KANT, (Fellow, IEEE)
Computer and Information Science Department, Temple University, Philadelphia, PA 19122, USA

Corresponding author: Amitangshu Pal (amitangshu.pal@temple.edu)

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ABSTRACT Computer networks and logistics systems are two very rich fields of study that have grown almost entirely separately since they deal with entirely different entities–information packets versus packages. However, driven by extensive automation and infusion of information technology into distribution logistics and need to improve the efficiency and sustainability of the operations, the logistics have attempted to adopt the cyber Internet principles. In this paper, we specifically consider the distribution of perishable commodities, such as fresh food, perishable pharmaceuticals, blood, and so on, in this context and thereby introduce the notion of the Internet of Perishable Logistics (IoPL). We propose a layered architecture model for IoPL modeled after the cyber Internet and show how it can be useful in systematic and hierarchical modeling of perishable logistics operations, which are extremely complex. We also show the synergies between IoPL and the cyber Internet and discuss a number of research issues inspired by such synergies. We also show how the layered model can be exploited to construct a simplified analytical framework for studying some basic tradeoffs between the delivered quality of the perishable product, transportation efficiency (in terms of unused carrier space), and the number of active carriers (which translates into cost and carbon footprint of the transportation service). This paper also points out a number of future research challenges and directions for a smarter IoPL.

INDEX TERMS Perishable commodity distribution networks, physical Internet, fresh food logistics, infrastructure sharing, transportation efficiency, Internet of Perishable Logistics.

I. INTRODUCTION

Distribution of information and/or physical commodities from a source ‘‘node’’ to one or more destination ‘‘nodes’’ is a central functionality in nearly every system involving coordination across multiple entities, subsystems, or agents. All such systems can be considered as networks in that they represent a flow of information and/or physical entities. More broadly, even the distribution of electricity, water, natural gas, oil, etc. can be regarded as a network; however, such networks cannot independently transport a unit of commodity from a source to destination without affecting flows at other nodes.

The similarities between the flow of physical commodities in the logistics network and of packets in the Internet have been well recognized, and so are the stark differences between them in terms of scalability and efficiency. Logistics network remain very rigid and inefficient while the cyber Internet continues to scale. This has led to an effort to embrace some of the basic principles of cyber Internet into logistics networks, and an initiative called Physical Internet or PI is gaining momentum [1], [2]. PI concerns standardizing and systematizing logistics operations in general. Inspired by PI, we focus exclusively only regional and wide area transportation and distribution of products, and particularly those of perishable commodities such as fresh food, medicines, blood, etc. In particular, we develop the notion of Internet of Perishable Logistics (IoPL) and discuss its synergies with cyber Internet when carrying time sensitive packets. We also define a layered model for IoPL modeled after the cyber Internet that can be highly valuable in simplifying and analyzing the logistics networks. Note that driven by rapid automation and infusion of Information Technology in logistics networks, it is increasingly possible to make online decisions, where a simplified modeling can be particularly valuable. We also discuss, in detail, many research topics that are enabled by the synergies between IoPL and cyber Internet.

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The ultimate purpose of the paper is to inspire and engage researchers from both communities to holistically examine the numerous difficult problems involved in turning logistics systems into highly agile and efficient cyber-physical systems.

The outline of this paper is as follows. Section II compares and contrasts information and logistics networks and discusses the recent notions of physical Internet. Section III then introduces the layered unified model called Internet of Perishable Logistics (IoPL) modeled after the cyber Internet layered model. Section IV discusses a simple analytical model of IoPL based on the layered model. Section V then brings out a number of research issues that exploit the logistics and computer network synergies. Finally, section VI concludes the discussion.

II. INFORMATION VS. COMMODITY DISTRIBUTION

Both information networking (IN) and commodity distribution are rapidly evolving fields because of continuing new challenges faced by them. INs must handle increasingly higher volume and richness of content with complex requirements in terms of timeliness, mobility, coverage, security, and privacy. This has led to many initiatives under the umbrella of *Next Generation Networking* to meet these challenges. For example, information or content centric networking (CCN) [3] – and the related Named Data Networking (NDN) [4] – focus on distributing content based on its properties rather than place of residence. The increasing interest in cyber-physical systems (CPS) also drives networking support for intelligent management and control of physical systems.

The commodity distribution area – a significant part of logistics operations – is also undergoing a rapid transformation driven by three key factors: globalization of supply chains, automation of much of the commodity handling and increasingly its transportation, and rapid infusion of information technology for end to end tracking and control. Although cost reduction is the primary driver, other issues such as the need to reduce the huge environment footprint of the logistics, reliability of supply chain, agile inventory management, and increasing expectation of ''freshness'' of the perishable products are also significant reasons.

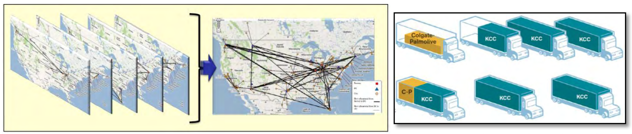
The transportation and distribution perishable commodities forms a substantial and important component of the general commodity distribution. An overwhelming part of this category is the perishable food including fresh or frozen produce, fruits, edible fungus, dairy, seafood, meat, ready to eat meals, etc. Consumers increasingly expect a large variety of minimally processed foods in freshest possible condition, which continues the rapid growth of fresh food logistics. Other perishable commodities also important and often have their own unique requirements such as blood (for transfusion), short-life medicines, human organs (for transplant), fresh cut flowers, etc. For all of these commodities, perishability (and hence maintenance of quality) is an overriding concern that significantly influences the logistics operations and contributes to the delivery cost.

A. CHALLENGES IN PERISHABLE COMMODITY DISTRIBUTION

Traditional transport logistics suffers from very low efficiencies (perhaps in the teens [1]) due to partially full trucks and empty truck returns. A big reason for this is the lack of sharing and coordination among the entities of the logistics vendors. Another big factor is the complexity of ensuring that empty trucks, containers, etc. are promptly available at the sources so that the travel of empty assets can be minimized. Perishability makes this situation much harder and leads to more empty travel, since a delay in securing empty assets translates into quality deterioration. Thus raising the efficiency of perishable transport and distribution is a very difficult issue, that becomes even harder with mixed commodity types. Sharing capacity among multiple commodities itself becomes more important as the diversity and specialization in foods increases and the volumes go down. The recent movement of preferring regionally grown food puts further stress on regional, low volume distribution (often called local logistics) and complicates its integration with the long-distance logistics, which is traditionally high volume and uses refrigerated transport. In fact, it is tempting to forego the expensive refrigerated transportation for local logistics, but it makes the scheduling and quality maintenance problem harder, and reduces the efficiency.

In addition to efficiency, there is also an equally important issue of food waste. Current food logistics also suffers from a significant amount of wastage due to inefficient food handling and distribution [5]. Recent studies show that up to 40% of all food is wasted in US on its way from farm to table, which amounts to throwing away $165 Billion each year [5]. The emerging features of high product diversity, preference for regional foods, foregoing refrigerated transport, and increasing expectation of freshness all conspire to further increase food loss. It is important to note that the enormous food waste has serious side impacts beyond the increased costs to the customer: these include a huge but avoidable carbon footprint, wasted water, unnecessary fertilizer use that results in dead zone in the oceans, etc.

In view of the serious problem of high food waste and very low transportation efficiency, automation and intelligent handling of fresh food distribution become crucial. However, transforming the supply chain involves huge challenges, including the need for shared logistics (as opposed to the current situation of fragmented, individual company owned/driven logistics), standardized labeling of all assets and products, standardization in form factors, automated tracking and handling of shipments, etc. Fortunately, there are a number of ongoing initiatives that will likely transform the logistics with the next decade. Although there are several distinct directions here; they all fit well under the banner of ''Physical Internet'', and are discussed as such.



From private logistics to shared logistics

Private trucks vs shared trucks

FIGURE 1. Private vs. Shared logistics.

TABLE 1. GS1 standards in IoPL.

Company	Global GS1 Company Prefix Global Location Number (GLN)
Product	Global Trade Item Number (GTIN) Serialized Global Trade Item Number (SGTIN)
Assets	Global Individual Asset Identifier (GIAI) Global Returnable Asset Identifier (GRAI)
Logistics	Serial Shipping Container Code (SSCC) Global Shipment Identification Number (GSIN)

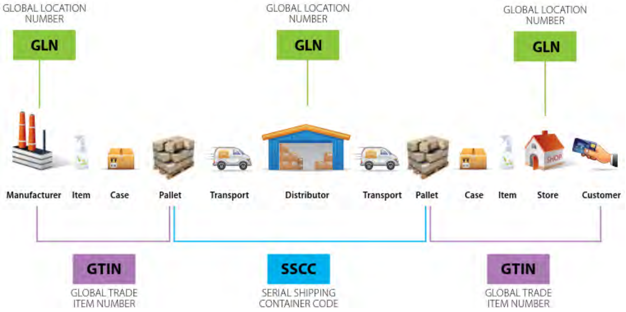


FIGURE 2. Illustration of GS1 labeling uses.

B. PHYSICAL INTERNET AND RELATED INITIATIVES

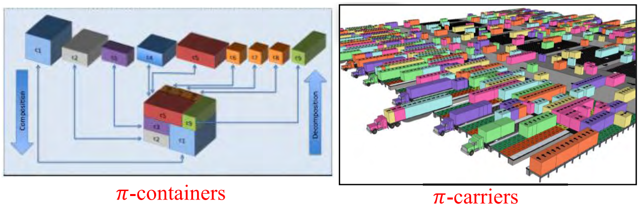
Just as in the cyber Internet, the most basic requirement for efficient logistics operations is to have a shared network with multiple providers and users. Unfortunately, the logistics traditionally grew up in the hands of large companies who could afford to set up their own private logistics networks including warehouses, carriers, drivers, containers etc. Some examples include Walmart or Target for consumer retail, Boeing for aircraft parts, etc. While very large companies can operate an efficient logistics network, smaller networks lack the volume and diversity of products and routes to fully utilize their resources. Fortunately, smaller players are rapidly adopting the *outsourced services* model where a third party provides the logistics network and it is shared among many customers. The so called *third party logistics* (3PL) model and its derivatives such as 4PL have been around since 1980's and growing rapidly. Recent data suggests that 54% of transportation and 39% of warehouse operations are outsourced [6]. Note that the logistics provider itself may assemble its services by contracting with other downstream parties such as trucking companies, labor force providers, warehouse providers, etc. or even with other 3PL providers, but a customer only needs to negotiate with one party.

Shared logistics have the potential to improve the logistics efficiency by reducing empty miles, which is illustrated in Fig. 1. However, sharing in logistics networks is much more difficult than sharing in the Internet, which makes the logistics efficiency quite low, perhaps in teens [1]. In particular, logistics must worry about such things as transport carriers (e.g., trucks, railcars, ships, etc.), product containers, drivers, handling crews, road network, traffic congestion, etc. Perishable goods complicate matters further due to timing and environmental constraints. In fact, much of the literature on perishability is concerned with inventory management, with supply chain management beginning to be considered only very recently [7]. Capacity sharing by multiple perishable products has been particularly difficult to handle, and has received relatively little attention [7].

The other fundamental requirement for efficient logistics is automation in multiple forms. In particular, we would like to automate routine operations such as packing/unpacking of products at multiple levels, loading/unloading, sorting, separating damaged boxes, storage in/retrieval from warehouse, etc. This is happening at a large scale under Industry 4.0 initiative [8]. However, enabling such automation requires that everything be labelled in a standard way and allow for automated reading of the labels. This is being provided by the standardization effort in RFID tagging and barcoding [9]. A comprehensive set of standards known as *GS1* for labeling products, packages, carriers (e.g., trucks), warehouses, endpoints, etc. and tracking of items based on the tags are under development (see *www.gs1.org*). Products (along with the company that produced them) are identified via a unique GTIN (Global Trade Item Number), whereas the facility locations are identified via GLN (Global Location Number). Other important codes include Global Individual Asset Identifier (GIAI), Serial Shipping Container Code (SSCC), and Global Shipment Identification Number (GSIN), as shown in Table. 1 and further illustrated in Fig. 2. The actual labeling technology could be bar-code, RFID, or embedded in the packages in other ways, but carrying the labels with the packages allows packages to be tracked easily.

Because of the limitation of automated machinery, labeling alone is inadequate for automation. The other requirement is some standardization in sizing and positioning. For example, if the product containers are of standard size, and form a hierarchy such that a certrain arrange of smaller size containers fit in a bigger container, that makes automated packing, unpacking and sorting much easier for the machines. To support this, thereis the notion of π-containers that easily compose to create bigger and bigger containers so as to maximize space utilization and shipping efficiency. Multiple such π-containers are loaded onto trucks with modular sizes to improve space efficiency as shown in Fig. 3.

Given these basic capabilities, there is an ongoing interest in replicating the cyber-Internet model in logistics space, called *Physical Internet* or PI. In his seminal paper [1], Benoit asserted that "... *in order to meet the current grand challenge, the physical world exploit a digital Internet inspired metaphor. Even though there are fundamental differences between the physical world and the digital*



π-containers π-carriers

FIGURE 3. PI (π) containers and π transport.

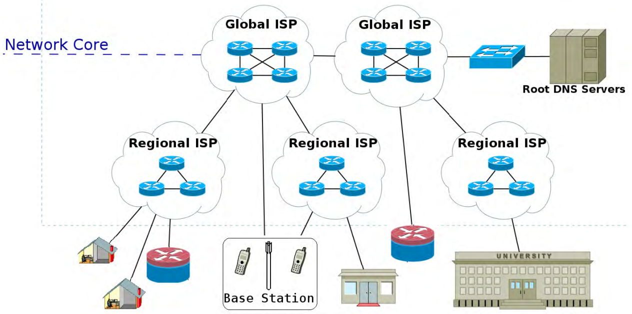


FIGURE 4. A Sample Internet Model.

FIGURE 5. A Sample Food Supply Chain.

world, the metaphor is to be exploited to propose a vision for a sustainable and progressively deployable breakthrough ...''. The PI initiative now has an active consortium (www.physicalinternetinitiative.org/) as well. The primary objectives of this consortium is to address several unsustainable symptoms of the current logistics system, which are coined in recent literatures as ''*shipping air and packaging*'', ''*empty travel is the norm rather than the exception*'', ''*carriers have become the modern cowboys*'' etc.

C. DISTRIBUTION IN THE CYBER VS. PHYSICAL SPACE

It is instructive to compare and contrast Information networks (IN) or Internet architecture against that of IoPLs. The Internet moves packets of data between source and destination, each of which can be either individual machines or some higher level entity such as an organization with its outward facing router(s). The structure is hierarchical and may involve Internet Service Providers (ISPs) operating at global, regional and even local level, as shown in Fig. 4. Similarly, IoPLs move commodities between ''source'' and ''destination'' endpoints, the former being farm collection centers (or just ''farms'') or food processing plants, and the latter retailers and other large customers (e.g., hospitals), though there is generally no flow in the other direction. Commodities are carried by *carriers* (e.g., trucks, railcars, boats, airplanes, or drones), which, in turn carries one or more *containers* containing lower level containers or packages of interest. A container could be a simple box, or lot more sophisticated – having built-in shock/vibration protection, refrigeration, pressure regulation, and other capabilities.

The structure of IoPL is also hierarchical and may involve local distribution centers (DCs) both in the outbound and inbound directions, connected via regional distribution centers (RDCs), as shown in Fig. 5. Inter-regional shipment will go through at least two (and perhaps more) RDCs and may even go through one or more global distribution centers that handle inter-country logistics. The distribution centers typically store the arriving containers of goods for some time to properly schedule delivery and make good use of carrier capacity. They handle loading/unloading of containers on carriers, deal with damage/misdelivery, and may also change container contents (by removing, adding, or exchanging packages). However, some smaller distribution centers may have only the limited functionality of exchanging carriers (e.g., move containers from a truck to another truck, from railcar to a truck, etc.) and/or change drivers. We will call these as ''transfer-points'' since they do not examine or change the contents of the containers. From the supply chain perspective, we consider retailers and other large customers as the ultimate end points; i.e., purchase of goods by individual customers from retailers is not considered a part of the supply chain. This is similar to Internet, where an enterprise may provide services opaquely to its members by using NAT (network address translation).

Perishability is a key driver in IoPL. Products often deteriorate in quality or in value/usefulness as a function of flow time through the logistics system. The deterioration as a function of time t can be described by a non-decreasing function that we henceforth denote as $\zeta(t)$. In general, $\zeta(t)$ is linear for fruits or vegetables and exponential for fish/meat. The decay itself is a complex phenomenon and could refer to many aspects, including those that can be directly detected by the customers (e.g., color, texture, firmness, taste, etc.) and those that are latent but perhaps even more important, such as degradation of vitamin content or growth of bacteria. Furthermore, the decay rate is strongly influenced by the environmental parameters such as temperature, humidity, vibration etc. Medicines and blood may have an even more complex deterioration processes, and are labeled for a strict expiry date to ensure safety. This leads to a step-function form for ζ.

IN packets often have fixed deadlines, which could be represented via a step-function form of $\zeta(t)$. However, there are several scenarios where the value of information declines steadily with the delay incurred. One significant example of perishable IN content is the breaking news stories that are typically updated periodically based on the new developments. The older versions get progressively less useful, and at some point worthless. Another example is the sensor data for online monitoring and control. For example, PMU and meter data from smart grid is most useful for state estimation when it is recent and becomes less important as it ages.

Let us now discuss some key differences between IN and IoPLs. The most fundamental difference is that physical packages cannot be copied, and must be physically moved. Thus the ''loss'' of a physical package (due to physical loss, damage, spoilage, etc.) can be very expensive – although a lost package can be replaced by another identical one as in computer networks.

Although multiple information packets may be coalesced or bundled together for efficient transmission (as in optical burst switching networks), bundling is fundamental to transportation in the logistics space, and may happen at multiple levels, as already stated. Packages may be bundled, unbundled, and mixed at the intermediate points (i.e., distribution centers) in order to efficiently deal with the varying package sizes, uncertain product availability, and timeliness/quality requirements of the shipment, while conforming to the fixed transport sizes of various carriers (e.g., truck vs. railcar). The bundling makes the ''packet loss'' in IoPL even more undesirable and expensive.

Another peculiarity of commodity distribution is a distinction between product/commodity being carried and additional ''resources'' required to carry it. This includes containers (when they are more than mere boxes), the carrier, the associated driver (unless the vehicle is self-driven), the handling equipment, etc. It is important to consider these explicitly since transportation is not possible without them. Data transfer in INs may also require other resources such as buffers or receive side processing capacity but the associated management and functionality tends to be far simpler in INs.

III. INTERNET OF PERISHABLE LOGISTICS

Assuming standardization in logistics operations and the willingness of product suppliers to use capacity sharing provided by 3PL operators, it becomes possible to take a unified view of Physical vs. Cyber Internet and derive useful synergies between them. In doing so, it is crucial to consider the ongoing developments in both fields to inspire new mechanisms that are of value on either side. Thus a unified treatment can enrich both fields, which is the main goal of this paper.

A. WHY DO WE NEED IOPL?

In spite of some fundamental differences between the cyber Internet and IoPL described above, we believe that there is considerable value in attempting to capture the essence of cyber Internet features to the perishable logistics. A well structured IoPL is not only useful for building a smarter and well-structured logistics systems but also will make the system *automated* in near future. The Internet of Perishable Logistics is the network of physical objects such as the perishable commodities, vehicles, warehouses, suppliers, retailers, drivers, loading-unloading equipments etc. that are interconnected with each others with a cyber network to collect and exchange relevant information and take necessary logistics related decisions for improved efficiency, fresh delivery quality and economic benefit. The connection between the physical and cyber networks must be through sensors and actuators of various sorts such as food quality sensors, sensors needed for operational automation, actuators for environmental control and automation operations. Thus IoPL can be regarded as a general cyber-physical system, for which we can define a layered model [10] discussed here briefly.

B. IOPL ARCHITECTURE

Our IoPL network architecture is modeled after the cyber Internet in order to unify the two as much as possible. The Internet is structured in form of multiple ''domains'', each consisting of a network of routers, which ultimately feed local networks of data centers, businesses, and home internet service providers, as shown in Fig. 4. An IoPL network consists of a set of nodes connected by edges along which packages flow. In IoPL, the nodes may represent distribution centers (equivalent to routing points), packaging/manufacturing facilities (source end points), retailers or other bulk consumers of product (destination end point), package transfer points (equivalent to switches), etc. The edges may represent roads, rail tracks, shipping channels, etc. Since our model is layered (as discussed below), the network may depict activities only above certain layers. For example, a layer 3 IN model shows only layer-3 paths and omits any (layer-2) switches or protocol gateways. A similar IoPL model may omit transfer points and not explicitly show the transfer media (road, rail, barge, etc.). The media level model may associate cost and other parameters with the edges (e.g., bandwidth, latency, etc.), which may be abstracted to provide suitable edge parameters in the higher level models.

The nodes in the IoPL are identified by their addresses, which are globally unique. In IN the nodes are identified by their IP address, whereas the packets also have their unique ID, which is a combination of their source-destination IDs, sequence number etc. In IoPL the objects are similarly uniquely identifiable by the use of GTIN, GLN, SSCC etc. at different levels of aggregation (e.g. cases, pallets, containers, carriers, etc.) as shown in Table. 1. In IoPL, the packages are either barcoded or RFID enabled, carrying their unique package IDs, which enables automation of loading/unloading and tracking.

The key concept in IoPL is that of a ''resource''. We assume that the network has K resource types henceforth denoted as $R = \{R_1, \ldots, R_K\}$. Resources are most crucial in modeling IoPL, and may represent carriers, drivers, loading/unloading equipment, and a hierarchy of containers. In the IN context, resources are generally buffers, but may also represent other entities. Packets need to acquire suitable resources before they are eligible to move from the current node to the next. Since bundling is a fundamental aspect in IoPL, multiple packages could be assigned to the same resource instance (carrier, container, driver, etc.) Depending on the defined policies it is even possible that the packages that are assigned the same resource instance belong to different classes. Such mixing is quite difficult to handle and is not done in long distance logistics, but may be needed in regional logistics involving much smaller volumes of individual products.

Within a resource type, we allow for further differentiation by letting each R_i itself be a vector, denoted $R_i = \{R_i^1, \ldots, R_i^{N_i}\}$. The idea is that the resource of type i could have N_i subtypes or categories. For example, in the IoPL context, the logistics company may deploy trucks of two different sizes – 18 wheelers for long distance transit and smaller trucks for local transit. The same applies to containers at a given level. Even the drivers may be differentiated as those intended for long-haul vs. short haul. The resource assignment would normally involve some suitable constraints so that the resources are used in a sensible way.

Each layer requires a unique set of resources, and thus we can speak of layer i resources (for $i = 1..5$) where a layer i has visibility only in resources that belong to layers $1..i$. In the following we denote $\mathcal{A}_i$ as the number of units of resource R_i available at a node. Since bundling – or batching – of packages is an essential aspect of IoPL, we will consider a batch B of packages that need to be transported from node s to another node d. (Depending on the layer in question s and d could be either endpoints or some intermediate nodes.) The batch B needs to be assembled at node s and then passed through successively lower layers for allocation of resources appropriate to that layer.

C. QUALITY OF SERVICE CONSIDERATIONS

The quality of service (QoS) is an essential concept in cyber Internet and has attracted a tremendous amount of research. The QoS may be specified in various terms depending on the application needs and may either relate to just the network or the network and the endpoints. Network level QoS measures, which are of primary interest here, include packet loss ratio, transit delay through the network, network throughput, jitter in packet delays, and throughput jitter. These measures are directly relevant for IoPL as well. In the Internet, these parameters may be affected by other "cross-traffic" that cannot be controlled by the applications of interest. Similarly, in logistics, there are many external factors that make the QoS control difficult.

However, a unique aspect of IoPL is the perishability measured by the function $\zeta(t)$ as a function of time t. The 3PL customers may establish contracts that not only refer to measures like end to end delivery time, but also to perishability related parameters. The latter may either relate to the conditions of the transport (e.g., temperature, temperature variations, vibrations, etc.) or directly to the maximum allowed quality deterioration θ, i.e., $\zeta(0)-\zeta(\tau) \leq \theta$ where τ is the delivery time. It is currently not common to specify limit on the quality deterioration because due to the lack comprehensive quality monitoring in the supply chain, but becomes more feasible with more sophisticated monitoring. Perishability makes the QoS even more crucial in IoPL, since the products delivered with subpar quality may need to be sold more quickly at depressed price or wasted.

TABLE 2. **Proposed 5-layer IoPL protocol stack.**

Layer-1 (Physical Layer)	Concerns the physical movement of a package over a media channel (rail, road, ferry, air, etc.)
Layer-2 (Link Layer)	Relates to detection and possible correction of unexpected events at the PHY layer (e.g., a road segment or conveyor being blocked, π-containers lost, etc.)
Layer-3 (Routing Layer)	It assigns π-containers to handlers, vehicles, etc. on the specified physical routes within and across networks and monitors for routing errors
Layer-4 (Transport Layer)	Functional and procedural means for getting a set of π-containers from source to destination in an efficient and reliable manner
Layer-5 (Virtualization Layer)	Share the network capacity efficiently among the logistics resources

Meeting QoS requirements is far harder in IoPL than in computer networks because of need for auxiliary resources for scheduling the movement of the product over the next segment, the need for bundling to have acceptable transport efficiency (ideally, an entire truck-full of product to move), uncertainty of product availability (e.g., weather which affects ideal harvesting time), and uncertainty of demand. The fact that the shared logistics such as 3PL must deal with many customers with varying QoS requirements further complicates the issue. Yet, the inability to provide satisfactory QoS to large customers could break the shared logistics model, since they may deem private logistics as a better option. For these reasons, we believe that "virtualization" is an essential aspect for making shared logistics work. Virtualization here means that we design at a high level a number of end to end transport services with different QoS guarantees that the customers can choose based on their needs and willingness to pay for. For example, an express service may provide shortest possible transit delays, and a service for transporting delicate items (e.g., berries) may provide protection from vibrations, good cooling control, and careful handling. The challenge then is to map these services on to the real network at minimal cost. To do this, we will postulate a virtualization layer in our architecture as an essential, rather than an optional, component.

D. IOPL LAYERING

Given the complexity of IoPL, it is useful to consider it as a set of interacting "layers". In the complex systems terminology, a "layer" refers to a system with its own dynamics, such as transportation network, fuel (e.g., gasoline) network serving the transportation network, commodity distribution network, etc [11], [12]. While this is a legitimate description, we believe that layering in the sense of abstraction layers used to characterize network stacks can be much more helpful in systematic analysis of the logistics in that each layer can be analyzed by ignoring the higher layers and using a simple aggregated model of the layers below. For example, a detailed model of end-to-end routing of trucks on the road can be replaced by a simple model of path throughput and delays for consideration by delivery scheduling models.

The Internet has the familiar layered structure best illustrated by the ubiquitous 4 layer TCP/IP stack: physical transmission layer (Phy), Media Access Control (MAC), Routing/Internetworking (IP), and end-to-end Transport (primarily TCP). The endpoints – clients and servers – and some intermediate nodes (e.g., middleboxes, accelerators, gateways, etc.) also provide higher level services, which may be layered in unique ways. We model the IoPL stack after the Internet stack and the layers can be interpreted similarly even though the details are far more complex for IoPL. The layers are summarized in Fig. 2 and also include a virtualization layer as discussed above. Further layers or sublayers can also be identified. For example, preparing packages for transport often involves many operations within a plant that are becoming increasingly automated (e.g., automated forklifting, labeling, sorting, palletization, loading, etc.) and these could be identified as further primitives of the logistics. However, since our focus is on the transportation, we do not consider these details. The layers are described in the following.

Layer 1: Physical Layer The Physical layer deals with the actual movement of a containers along a "media channel" or "link". The media in this case corresponds to the mode of transport (e.g., road, rail, ferry, air, etc.) and a "channel" corresponds to a particular pathway of the media (e.g., specific sequence of roads on which the truck will travel). Each mode of transport has its own package container structure (kind of like "framing structure" in IN), and requires specific steps at the endpoints for properly loading/unloading the containers. Depending on how deeply we want to represent the media network or transport delays here, some level of abstraction may be employed in defining the media channels. On one extreme, every possible routing of carriers between the transfer points in question may be considered as a separate channel, and the decision made by Layer 2 (discussed next) as to which channel is actually used. That is, we have multiple physical channels between the transfer points and Layer 2 decides which one is used. On the other extreme, the entire path may be represented by a single channel with some statistical properties (e.g., mean and variance of the delay along the path). An intermediate description might define only two segments: a faster, but longer route vs. a slower, shorter router.

Layer 2: Media Switching Layer In IoPL, the media switching layer provides the media/channel selection, media bridging, and 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, waterways, air). In case of multiple segments, the transfer happens at a "transfer-point" where a suitable carrier for the chosen media is allocated, loaded/unloaded with containers, and the carrier driver is assigned/changed. Thus the carriers and drivers are both considered as layer 2 (L_2) resources (and so is the channel, if channel assignment is represented in the model). As expected, if the resource (empty carrier, free driver, free channel, etc.) is not available, the transmission will be blocked until the resource becomes available. The container assignments are done at the next layer, but their loading/unloading on carriers is handled by Layer 2. Container contents are not known to Layer 2 and not disturbed by it. More generally, while the IoPL layer 2 may bundle or pack higher level (or product) packages into Layer 2 frames (e.g. pallets), it cannot change them. If some layer-2 frames (or pallets) are mishandled, that is corrected at this level. In case of damage or deterioration, some special purpose handling mechanisms are usually defined (e.g., return back to the originator or simply mark the packages as damaged).

Layer 3: Routing & Distribution Layer: This layer supports end-to-end transfer of packages by handling packages at and across distribution/routing nodes. For the cyber Internet, an endpoint or a routing node may fragment a TCP segment into one or more datagrams depending on the maximum amount of data that the link-layer can carry, which is called the maximum transmission unit (MTU). In IoPL, the situation is more complex due to potentially recursive bundling/unbundling and allocation of a layer3 resource like containers. For example, a box shipped from the source may be bundled with others into a bigger box, which is possibly bundled further, and ultimately placed on the carrier to be shipped. This bundling may be shuffled along the way at intermediate distribution nodes, until the package arrives at the destination. Also, since layer 3 has access to container contents (e.g., boxes), it is capable of checking for damage/perishability and discarding them. However, the responsibility of reordering stays with the next layer. We assume that the routing/distribution layer assigns a suitable ID to each package in addition to the routing information such as source/destination address. The routes in a network are chosen generally to maximize the delivery quality (or freshness) of the packages, minimize delivery time, minimize the network cost, or some combination thereof.

Layer 4: Transport/Delivery Layer: This layer concerns the end-to-end assured delivery of individual product packages (which may have been bundled recursively before transportation and then unbundled for final delivery). The major concern of this layer is obtaining resources needed for end to end transport which includes warehouse space, carriers, containers, drivers, loading/unloading equipment, human helpers, etc. Generally, the end to end transport involves contracts/agreements which can also be considered as part of this layer. The layer 4 destination will check the packages for loss, damage, deadline expiry, and quality degradation, and accordingly make decisions regarding reorder or replacement.

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 are then mapped on to the physical network. Virtualization is an essential aspect for outsourced logistics scenarios such as 3PL that form the basis for sharing the resources across multiple parties. In particular, large customers are much more likely to use shared 3PL services instead of running their own logistics if they can get a service with the attributes that they desire. The situation is similar to cloud computing in IN, where multiple unrelated parties must share resources, and the virtualization facilitates flexible resource allocation, isolation across parties, and service differentiation.

E. ADVANTAGES OF LAYERED MODEL

The key advantages of layering in IoPL are similar to those in the cyber Internet. The fundamental job of layering is to provide a systematic view of the operations where higher level functionalities are built on top of lower level ones, and hence provide abstractions or hiding of detail. Given the very high degree of complexity of a logistics system, hiding of detail is highly valuable in hierarchical modeling of the logistics pipeline. For example, a layer 3 abstraction of the network represents transfer between distribution nodes as an atomic path characterized by a few overall parameters (e.g., transit time, availability, path restrictions, etc.) without regard to the individual media segments and intermediate handling. Transit time and other relevant parameters of a path could, in turn, be precomputed from the layer 2 parameters of the path segments and thus need not be considered in the layer 3 model. Of course, there are situations where cross layer impacts must be accounted for. This can be done systematically using well known techniques such as iteration across levels.

While the layered model is primarily useful for offline modeling and optimization in traditional logistics, the increasing automation and IT infusion can use it for online learning and control. For example, the Layer 4 can be assumed to have information about bottlenecks along the multi-hop route from source to destination and can adjust itself accordingly much like the way TCP-Vegas adjusts itself based on the delays. Note that since the information transfer/processing is far faster and cheaper here than product shipments, we would use much smarter control techniques than the AIMD method used by TCP. In fact, machine learning and prediction based on machine learning would be quite appropriate to optimize the throughput in an online manner. The per-hop information for this will come from Layer 3, which itself could use sophisticated machine learning and prediction to determine delays and dispatch times.

A significant amount of complexity in the IoPL comes from the need to consider various resources and their impact on the operations. Basically, the lack of resource availability at a layer (e.g., container, carrier, driver, etc.) blocks package transfer until the required resources can be assembled, and this has effect on delivery time and quality of delivered packages. Thus a critical issue in IoPL is the proper positioning of resources at various nodes. Let $Q = \{Q_1, \ldots, Q_K\}$ denote the ''resource quota'', i.e., total number of resources (in-use or idle) of each type in the network. The entire set of hops (or edges) in the network is assumed to be partitioned into one or more sets, such that each set forms a connected graph. Each of these sets could have its own resource quota vector Q. The two extreme but useful cases are: (a) each hop forms a set by itself, and (b) the entire network is one set. Case (a) is most often useful in IN where the resource quota is used for link flow control, and (b) is most useful for small logistics networks operated by a single 3PL operator where, for example, a given carrier, driver or container could be deployed anywhere in the network.

The resource handling requires a simultaneous consideration of forward and reverse logistics, and dealing with free and used resources. If suitable packages can be sent in the containers in their return journey, the containers are loaded with those packages, otherwise the containers are returned empty. Similarly, if some containers (full or empty) are available for return, they can be placed on the backward journey of the carrier, else the carrier must return empty. Returning the resources when they are almost full is surely desirable from the perspective of resource usage efficiency; however, if the resources are held back for better efficiency, this impacts timeliness and product quality delivered. To support return of potentially empty resources, we define a dummy package (DP) of size $\varepsilon \sim 0$. Each one of the returnable resources is assigned a dummy package with a deadline, within which the resource has to be returned back to the source. This deadline forces a return of resource back to source irrespective of how full it is. Setting of deadlines is a matter of policy that we do not specify. This mechanism can be easily extended to consider more general resource quota as well by specifying return destinations and policies for choosing among them.

The abstraction provided by layered model is again useful in simplifying end to end modeling of the operations. For example, one could have a separate model of each layer2 segment that is concerned with the carrier and driver scheduling, but not with containers. The Layer3 model would then simply use delay or throughput derived from the Layer2 and thus allow for easier modeling. Such hierarchical modeling is quite common in the analysis of complex queuing networks [13], and the layered model facilitates and even encourages such modeling.

IV. ANALYTICAL MODELING OF IOPL COMMODITY DISTRIBUTION

We next derive an analytical model of the latency and quality loss experienced by the packages in such a distribution network. We assume that few distribution centers (DCs) are located uniformly in a geographic area and consider a scenario where few trucks are distributing some perishable food packages in between the DCs.

For simplicity we assume that the drivers and containers are always available with the trucks, which help us concentrating on only one type of resource. In IN, a similar example can be thought of in the context of sensor networks, where the sensor nodes can be considered as the DCs, whereas the trucks are mobile mules that go around and exchange messages in between the sensing nodes. We first derive the expression of the average arrival delay of the trucks at the

TABLE 3. Table of Notations.

L	$\triangleq$	Truck round trip distance
T	$\triangleq$	Truck round trip time
N	$\triangleq$	Number of DCs
S	$\triangleq$	Area where the DCs are distributed
η	$\triangleq$	Number of trucks operating
v	$\triangleq$	Velocity of a truck
λ	$\triangleq$	Arrival rate of packages at the DCs
μ	$\triangleq$	Arrival rate of trucks at an individual DC
B	$\triangleq$	Maximum batch size of the packages loaded onto a truck
$\mathcal{M}$	$\triangleq$	Buffer space of a DC
P_j	$\triangleq$	Stationary probability that there will be j packages in the queue
τ	$\triangleq$	Delay experienced by a package to get delivered at the destination DC
τ_1	$\triangleq$	Waiting time experienced by a package at the source DC to get loaded onto a truck
τ_2	$\triangleq$	Delay experienced by a package on a truck before delivered to the destination DC
Ψ	$\triangleq$	Residual time of the truck arrival process
$\mathcal{P}$	$\triangleq$	Average number of packages loaded onto a truck at a certain epoch
Q_j	$\triangleq$	Probability that the DC queue length is j at an instance a new package is enqueued
t_{ij}	$\triangleq$	Travel time in between DC_i to DC_j

delivery centers by solving the traveling salesman problem (TSP), and then use this delay to develop a queuing theoretic model to derive the average package latency and delivery quality depending on the perishability functions. The notations used for the derivations are summarized in Table 3.

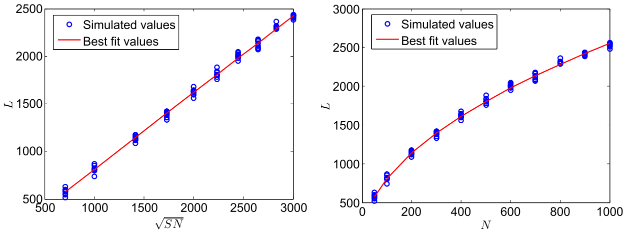
A. ROUND TRIP TIME ESTIMATION

We first assume that there is 1 truck which travels around all the DCs and loads/unloads packages, later on we will generalize this model for η trucks. We assume that N DCs are uniformly distributed in an area of S. We want to approximate the round trip time of a truck, using the model proposed in [14]. Notice that in a uniform distribution each DC approximately occupies an area of $\frac{S}{N}$. Thus the distance in between two neighboring nodes are approximately $C_1.\sqrt{\frac{S}{N}}$, where C_1 is an approximation factor. In the optimal route of a TSP problem, the neighboring DCs will be linked to their nearest DCs. Thus the route length is approximated as

$$L = C_2.N.C_1.\sqrt{\frac{S}{N}} = C.\sqrt{N.S} \qquad C = C_1.C_2 \tag{1}$$

where C and C_2 are approximation constants.

To validate equation(1) we have done a simulation in Matlab R2015b. We place N DCs uniformly in an area of 100×100 sq. unit. We use [15] for solving the traveling salesman problem and recorded the total travel distance L of a salesman connecting N DC points. Fig. 6(a) shows the variation of L with different $\sqrt{SN}$, whereas N is varied from 50 to 1000. From Fig. 6(a) we can observe that L varies linearly with $\sqrt{SN}$ with a slope of C ~0.81, which validates the claim of equation(1). Fig. 6(b) shows the variation of L with different N, where C is assumed to be 0.81, which confirms the validation. From Fig. 6(b) we can also observe that L increases by ~5 times when N varies from 50 to 1000, even if the traveling area is the same. This shows that even within a same area, increasing the number of DCs drastically increases the truck travel distance and thus travel time. Thus the truck travel plan needs to be decided intelligently as it dictates the delay experienced by the food packages as well as their perishability and delivery quality as described later.



(a) (b)

FIGURE 6. **(a) Simulated and best-fit values of L with $\sqrt{SN}$. The slope C is found to be ~0.81. (b) Variation of L with N with simulated and analytical model.**

B. MODELING THE PACKAGE DELIVERY LATENCY

We assume that the food packages arrive at the individual DCs, as a Poisson process at a rate of λ packages/sec. The DCs have a finite buffer of $\mathcal{M}$ packages. The packages are wasted due to lack of storage if the DC buffer is full. The DC queue is served upon arrival of a truck, we assume that $\sigma_0, \sigma_1, \ldots, \sigma_n, \ldots$ are the instances of the truck arrivals at any particular DC. We assume that a truck loads atmost B packages at any DC, if there are less than B packages present in a DC's queue then the entire queue is loaded onto the truck. The truck leaves without waiting for additional packages. The truck capacity is assumed to be infinite and the loading-unloading time is neglected for simplicity. This type of queuing disciplines falls under the category of bulk service queue in the queuing literature [16], [17], which is typically defined as $G/G^B/1/\mathcal{M}$. In our case the package arrival process is Poisson, whereas the truck arrival process is approximated as a periodic event and thus the service time is deterministic. Thus our queuing discipline is defined as $M/D^B/1/\mathcal{M}$ queuing discipline.

If the DCs are distributed uniformly then the trucks arrival can be approximated as a periodic process with a period of $T = \frac{L}{v.\eta}$ in presence of η trucks with velocity v, thus the average truck arrival rate is $\mu = \frac{v.\eta}{L}$. For simplicity we assume that the queuing discipline is first-come-first-served, and the trucks have sufficient storage to load packages from the DCs. We assume that $B < \mathcal{M}$ and $f = \frac{\mathcal{M}}{B}$. For the later section we assume that there is one *virtual* truck with arrival rate of μ, instead of η trucks for simplicity.

1) STABILITY CONDITION

The DC queue is stable iff the maximum service rate $B\mu$ is less than the package arrival rate at any DC, as mentioned in [17]. Thus the stability condition of the DC queue is

$$\frac{\lambda}{B\mu} \leq 1 \qquad \rightarrow L\lambda \leq \eta.v.B \tag{2}$$

2) LIMITING PROBABILITY GENERATION

Assume that $P_j(n)$ is the probability that a DC queue length is j (j can be 0, 1, 2, ..., $\mathcal{M}$) at σ_n. If k_m is the probability that there are m potential arrivals during a service period T, then

$$k_m = \frac{(\lambda.T)^m.e^{-\lambda.T}}{m!} = \frac{\rho^m.e^{-\rho}}{m!} \tag{3}$$

where $\rho = \lambda.T$. Also assume that $l_m = \sum_{j=m}^{\infty} k_j$. Then the probabilities of $P_j(n)$ can be written as follows. Let $\eta = \sum_{i=0}^{B} P_i(n)$. Then,

$$P_j(n+1) = \begin{cases} k_j\eta + \sum_{s=1}^{j} P_{B+s}(n)k_{j-s} & j = 0, 1, .., \mathcal{M}-B \\ k_j\eta + \sum_{s=1}^{\mathcal{M}-B} P_{B+s}(n)k_{j-s} & j = \mathcal{M}-B, .., \mathcal{M}-1 \\ l_{\mathcal{M}}\eta + \sum_{s=1}^{\mathcal{M}-B} P_{B+s}(n)l_{\mathcal{M}-s} & j = \mathcal{M} \end{cases} \tag{4}$$

The equations are explained by considering two cases. For the first case assume that the time epoch is σ_n, and the queue length is $0 \le q \le B$. Then upon arrival of the truck at σ_n, q packages are loaded onto the truck. Next if there will be j arrivals in between σ_n and σ_{n+1}, then the queue length at σ_{n+1} will be j, which is represented as $P_j(n+1) = k_j\eta$ in equation(4). In the second case, assume that $q = B+s > B$. Then at σ_n, the truck loads B packages, leaving s in the DC queue. Thus the queue length at σ_{n+1} will be j if there is $j-s$ arrivals in between σ_n and σ_{n+1}, which is depicted in the second half of the equations. The last two equations capture the effect of limited buffer capacities of the DC queues. In the limiting case we assume $P_j = lim_{n\to\infty} P_j(n)$, thus the limiting behavior can be obtained by rewriting equation(4) with n suppressed and then solving the equations for P_j along with the normality condition $\sum_{j=0}^{\mathcal{M}} P_j = 1$.

3) EXPRESSION FOR AVERAGE DELAY AND DELIVERY QUALITY

We now derive the expression of average delay experienced by a package from the time it is enqueued till it is delivered to its destination DC. We assume that at any source DC, the destination of a package is uniformly randomly chosen from the remaining DCs. Thus the expected package delay τ can be decomposed into two parts: (a) τ_1 = the time a package waits at the source DC queue, and (b) τ_2 = the time a truck takes upon loading the package to go from its source DC to destination DC. Notice that a package may not be loaded onto the truck in a single round. It may take several truck rounds before it loads a package, as a truck can atmost load B packages on a single visit. We can think the truck arrival as a renewal process with a residual life of Ψ. The expression of Ψ can be derived from the following theorem.

Theorem 1: If the truck round-trip delay is T, then $\Psi = \frac{T}{2}$.

Proof: For a general renewal process with average renewal rate μ and standard deviation of σ, the average residual life is given by $\overline{R} = \frac{\mu^2.\sigma+1}{2.\mu}$ [18]. Now for a deterministic renewal process, $\sigma = 0$ and $\Psi = \overline{R} = \frac{1}{2.\mu} = \frac{T}{2}$. ■

We next calculate the average number of packages (batch size) loaded onto a truck at a certain epoch from a particular DC, which is assumed as $\mathcal{P}$. Notice that if the queue length is $0 \le q \le B$, then $\mathcal{P} = q$. Otherwise if $q > B$, $\mathcal{P} = B$ as the truck atmost loads B packages at an epoch from a particular DC. Thus

$$\mathcal{P} = \sum_{j=0}^{B} j.P_j + \sum_{j=B+1}^{\mathcal{M}} B.P_j \tag{5}$$

We now derive the distribution of DC queue length (excluding the new package) at the instance a new package is enqueued at a DC queue. Assume that Q_j is the stationary probability that the queue length is j at an instance a new package is enqueued. Then from [17] and [19] the expression of Q_j can be derived as

$$Q_j = \begin{cases} \sum_{i=j+1}^{min(j+B,\mathcal{M})} \frac{P_i}{\mathcal{P}} & 0 \le j < \mathcal{M} \\ 0 & j = \mathcal{M} \end{cases} \tag{6}$$

With these we next propose the following theorem for τ_1.

Theorem 2: The average latency experience by a package to get loaded onto a truck is given by $\tau_1 = \sum_{c=0}^{f-1} \sum_{j=c.B}^{(c+1)B-1} (\Psi + c.T)\, Q_j$.

Proof: Notice that if a newly arrived package finds the queue length $0 \le q < B-1$, then the average service time is just the residual time of the truck arrival process, which is Ψ. Otherwise if $B \le q < 2B-1$ then it will be served in the second round of the truck arrival, which is given by $(\Psi + T)$. Following this process we can write

$$\tau_1 = \Psi \sum_{j=0}^{B-1} Q_j + [\Psi + T] \sum_{j=B}^{2B-1} Q_j + \ldots + [\Psi + (f-1)T] \sum_{j=[f-1]B}^{\mathcal{M}-1} Q_j$$

$$= \sum_{c=0}^{f-1} \sum_{j=c.B}^{(c+1)B-1} (\Psi + c.T)\, Q_j \tag{7}$$

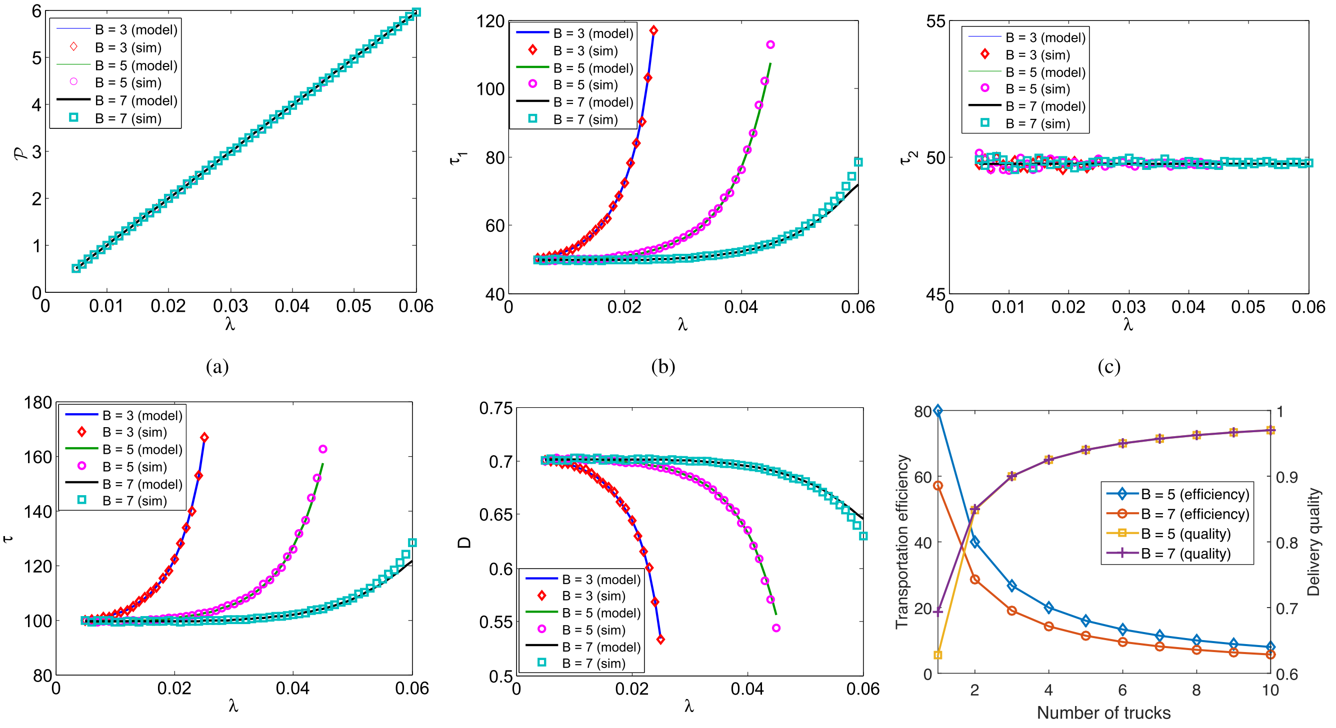
■

Theorem 3: If a truck continuously moves in a fixed trajectory with a trip time of T, then the average delivery time in between the source DC and another randomly chosen DC is given by $\tau_2 = \frac{T}{2}$.

Proof: We assume that there are N DCs that are covered by the truck's entire trip. When DC_i wants to send a package to DC_j, the package first waits in the queue of DC_i for τ_1 time units, and then gets loaded. After that the travel time of the truck from DC_i to DC_j is assumed to be t_{ij}. Then the average travel time experienced by the package in the truck is given by $\tau_2 = \frac{\sum_{i=1}^{N} \sum_{j\ne i} t_{ij}}{N(N-1)} = \frac{\sum_{i=1}^{N} \sum_{j\ne i}(t_{ij}+t_{ji})}{2.N(N-1)} = \frac{T}{2}$. ■

Theorem 4: If the temperature at the source DC and the truck is Γ_1 and Γ_2 respectively, then the delivery quality of the package is $D = \left[1 - \zeta_{\Gamma_1}(\tau_1) - \zeta_{\Gamma_2}(\tau_2)\right].I$, where I is the initial quality of the product, and ζ_{Γ_1} and ζ_{Γ_2} are the perishability function of the product at temperatures Γ_1 and Γ_2 respectively.

Proof: The proof is intuitive from the definition of the perishability function. ■



(a) (b) (c)

(d) (e) (f)

FIGURE 7. Simulation and analytical modeling of (a) $\mathcal{P}$, (b) τ_1, (c) τ_2, (d) τ and (e) D with different package arrival rate λ and B. There is an obvious tradeoff between the transportation efficiency and delivery quality of fresh food packages (f).

C. SIMULATION VALIDATION

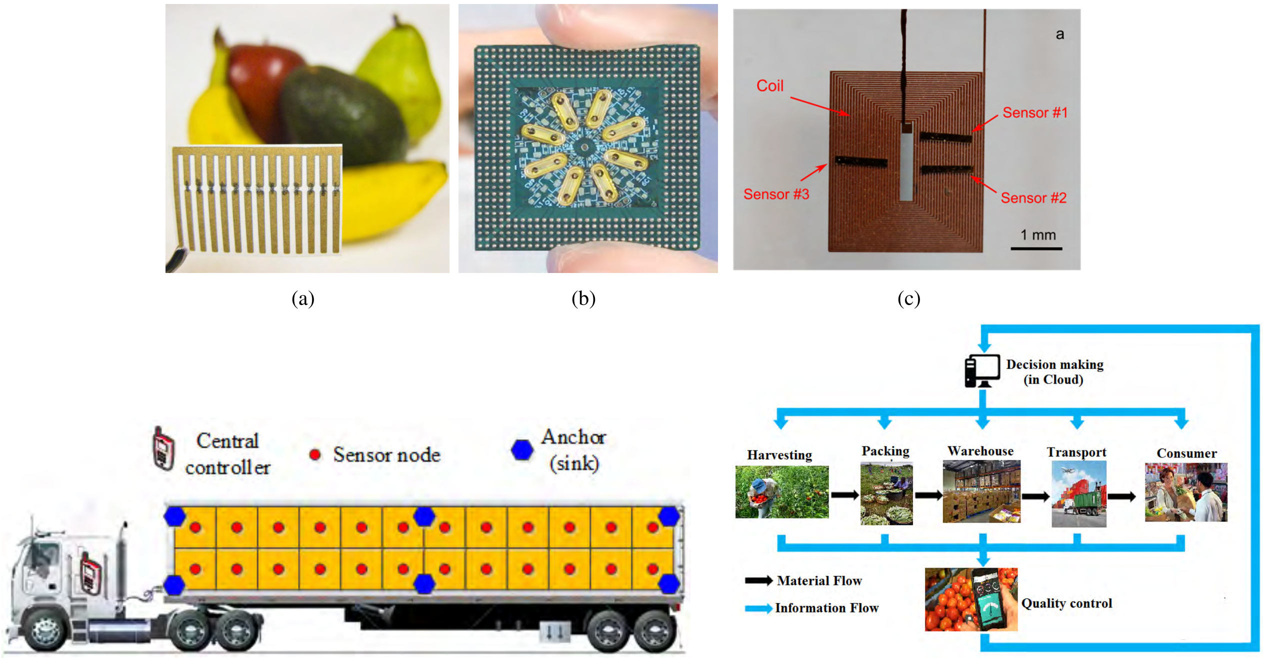
To validate the above analytical model we distribute 50 nodes uniformly in an area of 100×100 sq. unit. $\mathcal{M}$ and v are assumed to be 50 and 10 unit/seconds. We vary λ and derive the values of $\mathcal{P}$, τ_1, τ_2, τ and D with different settings, and compare them with the values obtained from our analytical model. The results are shown in Fig. 7 which shows that our analytical model closely approximates the simulated values, thus confirms the validation of our theoretical model.

Comparison of $\mathcal{P}$: Fig. 7(a) shows the variation of the average number of packages loaded onto a truck at any epoch with different package arrival rates. From this figure we can observe that $\mathcal{P}$ varies linearly with λ. This is because of the fact that with more package arrival, more number of packages are loaded onto the truck at any epoch. Interestingly the values of $\mathcal{P}$ does not change with B as far as the queue stability condition is maintained.

Comparison of τ_1, τ_2 and τ: Fig. 7(b)-(c) shows the variation of τ_1 and τ_2 with different λ. From Fig. 7(b) we can observe that τ_1 increases with the increase in λ because more package arrivals increase the waiting time of the individual packages. The waiting time increases faster with smaller B as this is the maximum number of packages that a truck carries at an epoch. From Fig. 7(c) shows that τ_2 remains constant irrespective of λ and B. This is obvious because τ_2 just depend of the truck trip time T as mentioned in Theorem 3. Fig. 7(d) shows the total delay experienced by the packages with different λ which establishes that the total latency experienced by the packages increases as B decreases and at the same time λ increases.

Comparison of D: Fig. 7(e) shows the package delivery qualities with different λ. For this figure we assume that the package freshness degrades linearly with time at a rate of 0.25% and 0.35% per unit time while waiting at the delivery centers and on trucks respectively. The initial quality is assumed to be unity. From Fig. 7(e) we can observe that D decreases with the increase in λ due to more waiting time at the delivery centers as seen from Fig. 7(b). The waiting time also increases with the decrease in B which degrades the delivery quality as observed from this figure.

Transportation efficiency and delivery quality tradeoff: Fig. 7(f) shows the tradeoff between the transportation efficiency and the delivery quality. For this figure we assume $\lambda = 0.04$. From this figure we can observe that with the increase in number of trucks, the delivery quality starts improving as the waiting time of the packages reduces. On the other hand, the transportation efficiency reduces due to lesser available packages at each DC. The efficiency also reduces with the increase in B because of the increase in truck size. On the other hand increasing B loads more number of packages at any particular DC, which improves the delivery quality especially in case of smaller number of trucks.



(a) (b) (c)

(d) (e)

FIGURE 8. Currently a significant number of spoilage or contamination sensors are available in the market or under development, some of then are (a) C_2Sense [20], (b) FoodScan [21], (c) Salmonella Sensing System [22] etc. (d) These sensors can be installed inside the containers or boxes carrying perishable products; these sensors will sense the necessary quality informations and form a network to convey these informations to a centralized location. These perishablity information can be exploited to construct a predictive quality degradation models depending on the decay characteristics of the individual types of products (e).

V. CHALLENGES AND FUTURE DIRECTIONS OF IOPL

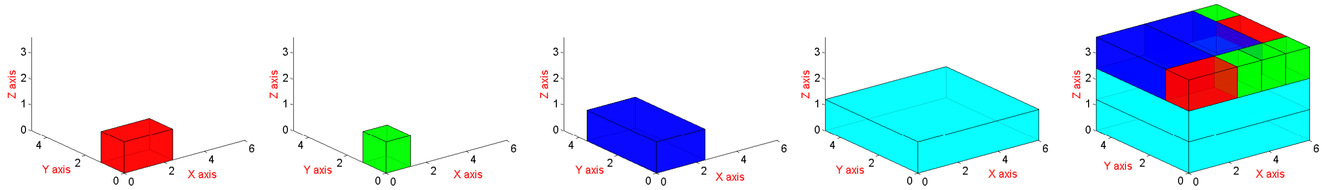
Even if IoPL shares a number of synergies with the cyber Internet architecture, it actually needs to consider a number of additional challenges which we summarize bellow.

A. SPOILAGE AWARE IOPL AND LATERAL DISTRIBUTION

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 and under development (e.g., [20], [22]) as shown in Fig. 8(a)-(c). These include both contact and non-contact sensors and may either have a local indicator or a communication interface that can (directly or indirectly) transmit the sensed data to the central controller. These tiny sensors can be inserted into the shipping boxes or containers while they are out for delivery in a truck (shown in Fig. 8(d)) or inside the warehouse. This sensing device may communicate with others and with next level data integrator in the truck, which in turn communicates with the central controller.

Once the sensed data for food quality and/or contamination becomes available at the sensor devices, it needs to be transmitted to the central controller along with the box ID (assumed to be GS1 compatible RFID). A substantial challenge here is the intra-container communication environment with tissue medium or through water-containing products (e.g., meat, fresh vegetables/fruits). In such environments, a normal RF communication (e.g., Bluetooth at the 2.4 GHz ISM band) is unlikely to be usable due to high signal absorption and complex channel conditions [24]. Instead we propose to explore Magnetic Induction (MI) based communication in such scenarios at HF band (3-30 MHz) that is largely unaffected by the tissue medium. Compared to the RF-based techniques, the MI-based techniques have the following advantages: (a) better penetration performance (i.e., low absorption) as the magnetic permeability of tissue medium is very similar to that of air, (b) predictable and constant channel conditions, and (c) small coil antennas (e.g., a few mm or cm). Although the MI communication has a small transmission range (e.g., 1.5 m) and achieves a small data rate (e.g., 596 kbits/s), it fits well in such IoPL application [25], [26].

For perishability, the sensing mechanism alert about the degradation before the real deterioration sets in. Based on time series of the real-time sensed data that the central controller receives, suitable data-driven predictive models can be built for estimating food spoilage in the near future (e.g., [27]). The online spoilage or contamination detection can be exploited to proactively detect which boxes contain contaminated/spoiled or close to be spoiled products and thereby reduce waste/carbon footprint by either discarding only those boxes or distribute them to nearby stores for faster consumption. For example if a long-distance truck on its way find some food packages deteriorating unexpectedly, then



(a) (b) (c) (d) (e)

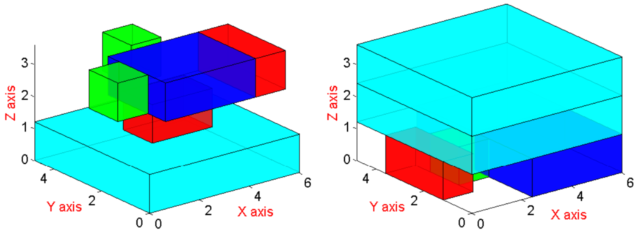
FIGURE 9. Different types of π-units, (a) U_1, (b) U_2, (c) U_3, (d) U_4, and their (e) packing into a large bin of dimension 6×4.8×3.6.

they can be distributed to the nearby stores or *food banks* rather than carrying all the way to the destined location and by the time get spoiled. This *lateral distribution* is also related to product substitution. Retailers order fresh vegetables and packages of specific types, brands, colors, or sizes based on their demand but in case of a supply shortage or unexpected quality deterioration, some products can be substituted of similar types and/or of different brands. As an example an order of romaine blend with carrots from manufacturer A can be substituted by red leaf lettuce from manufacturer B. This lateral transfer will also be useful to distribute the food packages from the *excess* points to the *shortage* points within a neighborhood area.

Spoilage related challenges in IoPL: 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 (e.g., water-containing products and mild steel like truck material) will have significant influence on such MI-based localization schemes. Specifically, the transmitted magnetic fields induce Eddy current on the close-by conductive objects, which in turn will generate new magnetic fields in the opposite direction and affect the received MI signal strength. 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.

B. SPACE EFFICIENT PACKAGING/BUNDLING IN IOPL

In IoPL, the space efficiency applies in three levels, in *box level*, *container level* and in *truck level*. In this section we discuss the packing of smaller units into larger units in general, where the units are defined as π-units. π-units [1] are modular units that can be fit in multiple numbers into a single large unit. Different food items (that can be kept in similar temperature, humidity conditions) are packed into boxes of different sizes (in Transport layer), which are then packed into larger containers (in Routing layer), and then finally packed/loaded into large trucks (in Switching layer). Thus the trucks are the largest π-units in IoPL. For better space utilization, a smart packing is required so that the small π-units are packed into minimum number of large units, before being transported.



(a) (b)

FIGURE 10. Packing twelve units into two bins, considering the compatibility in between the units.

Fig. 9 shows an example of our packing mechanism, where we consider four types of units (U_1-U_4) with different dimensions. The bin has a dimension of 6×4.8×3.6. Thus all the units (U_1-U_4) are modular as multiple such units (30, 60, 10 and 3 respectively) can be fit into the bin without wasting any space. Fig. 9(e) shows an example where two U_1, U_3, U_4 units are packed with four U_2 units in the bin. This example packs the units with a space efficiency of 100%. However the actual efficiency can be less then 100%, which depends on the actual number of units that are required to be packed.

We then consider a more general example where we assume that there are twelve units, one U_1-U_4 unit each full of berries, one U_1-U_4 unit each full of green peas, and one U_1-U_4 unit each full of broccolis. All the units are to be packed using minimum number of bins. Berries and broccolis are not packed in the same bin, as they need to be kept and transportation in different temperature settings, whereas green peas can be packed with both berries and broccolis. Such a packing is shown in Fig. 10. From this figure we can observe that after considering the compatibility constraint, the total bins required is two with space efficiency of 91.67%, 53.33% respectively. Fig. 11 shows a bigger picture of the packing mechanism, where the incoming boxes of different types of products wait in separate queues, then are packed into the containers, which are then loaded onto the trucks.

Bundling challenges in IoPL: The problem of bundling non-identical perishable products is challenging because the degradation rate of the products both in terms of visible characteristics (e.g., look and feel) and latent ones (e.g., vitamin, sulfur content or bacterial growth) varies substantially, and obviously dependent on the initial condition/quality and environmental/handling methods. Yet, bundling multiple products implies that they all will be subjected to the same delays,

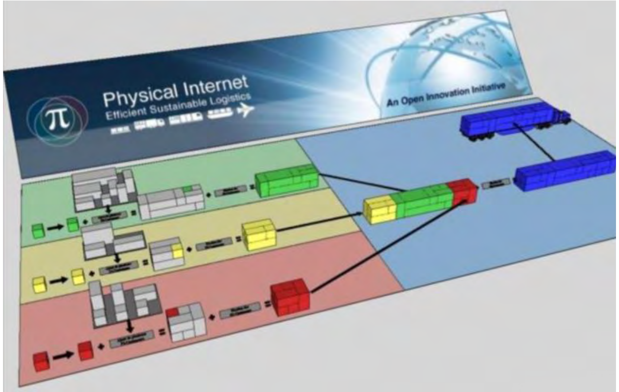


FIGURE 11. Packing and loading of π-units [23].

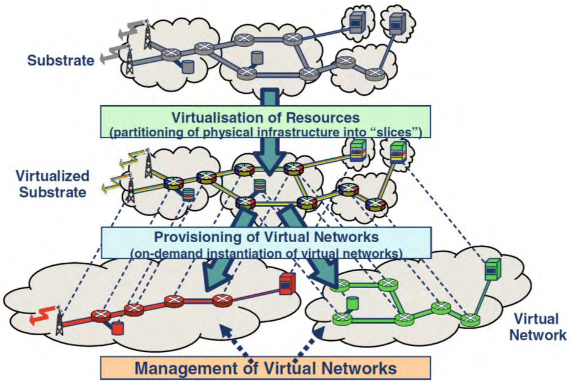


FIGURE 12. A network virtualization infrastructure [28].

temperature, vibrations, etc. Obviously, the bundling needs to consider *compatibility* between products, but given the variable availability and demand of products, defining compatibility classes itself can be quite difficult.

C. 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 as shown in Fig. 12. The mapping of virtual to physical infrastructure requires knowledge of resource availability in spite of dynamic changes in the requirements of various VNs. This is particular important in the cyber domains, as deploying a new infrastructure is incurs predominantly large costs, time and human resources.

Such resource sharing is much harder in IoPL because perishability and bundling related interactions and need to manage many types of resources. One important and challenging problem in handling perishable products is the extent to which 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 is 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. Thus simple approaches such as explicit assignment of trucks to a customer is often use by 3PL operators, which results in considerable capacity underutilization, often referred to as *deadheading* (or *shipping air*) [29].

One way to strike a balance between logistics complexity and efficiency is to define a few *virtual system* (VS's) 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 a ''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 moderate and low perishable items. 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 VS'es limits the complexity in resource allocation; however, the questions of tradeoff between complexity and efficiency need to be examined. IoPL along with assumptions at the resource allocation operations at various layers of the network can be used to study such tradeoffs.

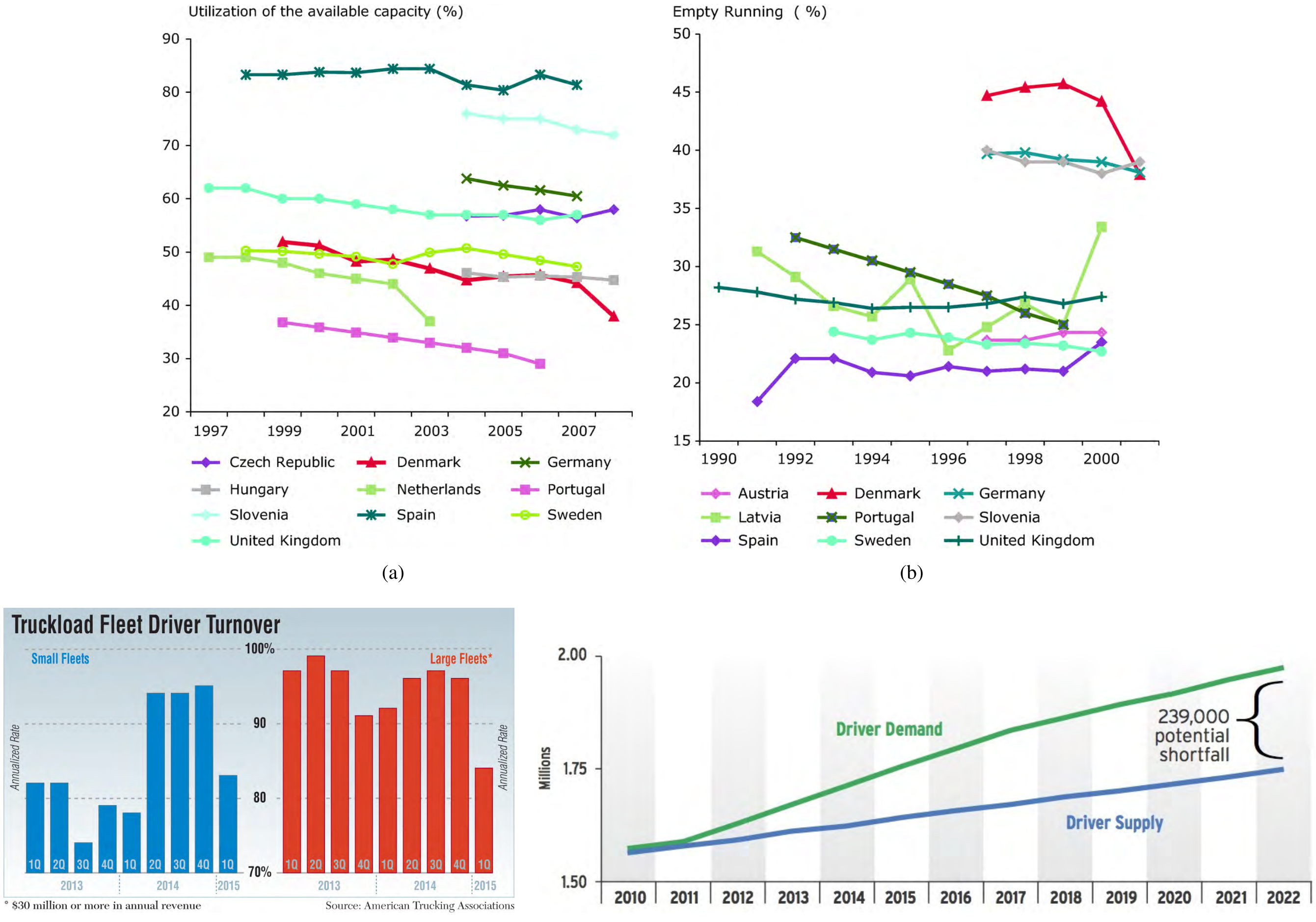
Logistics operations often provide ''personalization'' as a service feature to the customers. For example, an end-to-end allocation of the same driver (perhaps one known to the customer), same type of containers, etc. may be provided as a value add service that provides higher revenue in spite of limiting logistics efficiency. 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.

Virtualization challenges in IoPL: The key virtualization challenges in IoPL includes (a) defining virtual systems (VS) that address the key QoS requirements and yet can provide good sharing efficiencies, and (b) the mapping of such virtual systems on to physical resources. An important issue to examine in this regard is the limited dedication of physical resources to certain ''premium'' customers. Such dedication is commonly practiced in logistics, however, quantifying the impact of dedication and optimizing it's use can be quite challenging.

Another important challenges in IoPL virtualization is the dynamic management of the entire network, especially in a volatile and on-demand scenario. A key concern here is the security and trust among the business entities, infrastructure owners and operators. Inspite of these challenges, virtualization has the potential to significantly change the business environments with better efficiency, reduced cost as well as the environmental factors.

D. ZONED AND MULTI-SEGMENT ROUTING

As discussed earlier, the need for various types of resources to be allocated (and hence suitably positioned at



(a)

(b)

(c)

(d)

FIGURE 13. The primary cause of inefficient logistics system is (a) capacity underutilization due to (b) empty or half-empty truck runs (Source: http://business.edf.org). This long driving and away-home time results in (c) higher turnover rate [30] and (d) driver shortage [31].

network nodes) makes IoPL substantially more complex to analyze than a traditional cyber Internet. In fact, one resource in IoPL – namely the driver – is not only crucial to the logistics operations but also more difficult to handle than other resources. Unlike other resources, a driver has human needs that have to be addressed. These needs include limited working hours and ability to return home sufficiently frequently – preferably every night. One key reason for low logistics efficiency is that unlike other resources, drivers cannot be distributed to various nodes at will. In fact, a significant away-from-home time (from few days to several weeks) for drivers has traditionally caused very high turn-over rate in this business and consequent impact on service quality [1] which in tern results in driver shortage [31]. Fig. 13(c) shows that there is a potential shortage of over ∼200K drivers in the trucking industry in 2022. Fig. 13(b) shows that the truckload industry as a whole replaced the equivalent of 95% 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. Fig. 13(a)-(b) shows that the load factors are generally under 50% in many European nations, whereas the empty miles vary from 20-35%.

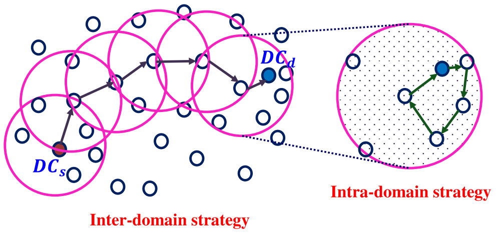


FIGURE 14. A zone-based routing in between two distribution centers.

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. An idealized situation is shown in Fig. 14 where the circles represent zones. The *inter*-zone delivery now requires multiple carrier runs with each driver returning back to its source after passing on the contents to the next carrier across the zone boundary. Ideally, the returning carrier will also carry compatible products in the other direction.

Scheduling the carriers is a challenging problem here since it must consider multiple conflicting objects such as logistics efficiency, time away from home, quality of perishable product on delivery, road congestion, driver (and possibly carrier load) changes, etc. Such problems can be formulated in IoPL and examined for potential solutions (more likely approximate solutions or bounds) under various assumptions about other resources, bundling, and other aspects of the model. A simple situation is where a specific driver covers only one hop, which is its '*zone* of operation. More generally, the zones could be defined dynamically by considering varying factors such as product availability/demand at various points, traffic congestion, asset relocation needs, etc. While such problems have been tackled in the logistics literature extensively, the analyses tend to be very specific. The IoPL provides a more generic setting to ask various questions about driver friendly scheduling that cognizant of the perishability aspects as well.

Zoned-delivery challenges in IoPL: Scheduling the trucks is a challenging problem that should take into account (a) the transportation efficiency, (b) the driver's away home time, (c) the delivery freshness of the food packages (d) road congestion especially in city areas at peak hours etc. Some of these objectives are contradictory, such as delivering the food packages directly from the source to the destination by a truck that is 20% full, provides fresh delivery, but deteriorates the transportation efficiency. Improving the transportation efficiency makes the truck to stop and load/unload packages at multiple locations, but the (a) additional waiting time for intermediate loading/unloading, (b) labor availability in those intermediate points for quick service, results in higher spoilage. Trading off such objectives, along with the integration of intra and inter-domain delivery scheduling is thus the main challenge in this context.

One of the issues that may raise in multi-segment distribution is breaking down of long trips into multiple segments, and the additional overhead of loading-unloading in the intermediate points. This additional time of loading/unloading is especially important in IoPL because of the delay caused by it and the corresponding quality deterioration. However, in a futuristic IoPL these operations are gradually going to be performed with automated machinery and robotic operations [8]. Also such loading/unloading can also be reduced by the use of decoupled trucks and trailers [32]. In this scenario, a driver can drive the truck from with a trailer to an intermediate point, exchange his/her trailer with another one that is destined to its starting point, and return back to the starting point [33]. This decoupling with greatly reduce the loading/unloading complexities and the quality loss.

Local and non-local logistics in IoPL: IoPL also needs to deal with the problem of integrating local and nonlocal components, particularly relative to fresh food distribution. With growing emphasis on local and seasonal food, large metro areas (e.g., Chicago) receive a significant amount of fresh food from surrounding suburban and rural areas. This local logistics has several unique characteristics: (a) smaller production amounts scattered around the area, (b) transport congestion along highways and major arterial roads around the urban area affecting the collection and distribution, and (c) less expensive packaging and environmental control during transport/ storage which makes the delivery more time sensitive. Because of the differences, the local and long distance logistics tend to stay separate; however, much is to be gain by integrating them into a single seamless logistics, especially in congested metro areas at rush hours, which delays the delivery time and quality of the food packages. A long-distance truck needs to drop-off and pickup packages at the DCs, some of them are in congested regions. In such situation, the long-distance truck may go and distribute packages at every distribution points, which may be unacceptable for the driver because of his long-waiting time, which also deteriorates the food freshness. To avoid such long waiting time, the driver may stop at few distribution points (defined as stopping points) and drop-off the packages that are destined to nearby DCs. If the nearby DCs plan accordingly, they can load their local trucks with the packages that need to be loaded into the long-distance truck, and send them to any of the stopping points. These local-trucks load and unload the corresponding packages to/from the long distance truck and deliver them to the corresponding DCs. Deciding the stopping points is important for both the long-distance truck and the DCs, which can be modeled from a game theoretic perspective. For the long-distance truck, delivering packages closer to the congested regions reduces its utility in terms of long waiting time and lesser delivery quality. On the other hand, for the DCs loading the local-trucks with necessary packages and sending them to the stopping points incur extra burden. Also the DCs need to integrate the local-truck schedules with their other intra-domain delivery strategies which makes the problem more complex.

E. PROVENANCE IN IOPL

Provenance as a subject has gained high visibility, and a number of provenance-related aspects have been explored, including capturing and managing provenance, building efficient queries, provenance storage, and security [34], [35]. Transparency, traceability, and provenance are essential components of IoPL and are becoming ever more important with advancing globalization and food technologies [36]. Simply stated, wholesalers, retailers and consumers all want to know where the food came from, what intermediate parties/processing it went through, whether they can trust the labeling, and in case of food-borne disease outbreak, where the tainted food originated. Given the appropriate sensing and electronic identification infrastructure (e.g., RFID) to support IoPL and information access, the spatio-temporal history of an events/actions can be easily established.

To facilitate traceability in IoPLs, the industry has undertaken a *Produce Traceability Initiative* (PTI), which is already implemented by several large food retailers (including Walmart and Whole Foods), and is being adopted by others (See www.producetraceability.org/). The traceability is ensured by diligently implementing two tasks. The first one is to assign a unique ID to every entity (as supported by the GS1 standards, and the second is to maintain a log of every handling activity. The logs need to maintain intermediate repacking and commingling of the products, where products from multiple farms are mixed and packed together before delivery.

Provenance related challenges in IoPL: There are several fundamental challenges in detail provenance in real logistics network that naturally involves many complex operations involving many parties. One substantial challenge is the storage of comprehensive provenance information, since the provenance continues to grow as the data is operated upon, even though the data itself may not grow. A lossless compression of provenance does not solve the problem; and instead one must devise ways of progressively lossy compression of older (and presumably less useful) data. However, this makes the techniques necessarily use case dependent. A related problem is that of the overhead of manipulating provenance information [37]. This becomes particularly difficult for use cases that require its use in real-time, such as data prefetching.

Another serious problem is the provenance of the provenance itself. How can we be sure that the collected provenance data is recorded correctly and well protected from intentional falsification or accidental corruption? This is a particularly difficult problem because of the involvement of multiple parties in the entire logistics supply chain. A related, rather intractable problem, is the ownership of the provenance data and accesses provided to others. Assuming that a single ''big brother'' owns and maintains and provides access to the provenance data from all parties is unreasonable. It is most attractive if each party maintains the provenance of all its operations; however, this makes the verification of correctness of provenance and accessibility of data by others very difficult. In section V-G we discuss a mechanism that can be useful for access control. Note that the private logistics avoids the access control issues but at tremendous costs of inefficiency as discussed earlier.

F. SUSTAINABILITY ISSUES IN IOPL

Traditional supply chain logistics decisions are mainly based on economic performance, such as transportation cost, time of delivery, etc. Sustainability modeling requires a more direct consideration of Criteria Air Pollutants (CAPs) and Green House Gases (GHGs) [38]. CAPs include pollutants such as carbon monoxide, nitrogen dioxide, and ozone, and need to be considered primarily from human health perspective. GHGs include carbon dioxide and methane emissions, and are important from carbon footprint perspective. Several countries have recently adopted penalties on harmful emissions, either by imposing carbon taxes, or by imposing a limit on the amount an industry can emit [39]. Although economic and environmental trade-offs in a sustainable supply chain have been modeled in [40], the additional issues brought about by the perishability considerations largely remain unexplored.

FIGURE 15. Multi-modal transportation in IoPL.

Much of this paper focused upon increasing the transportation efficiency and maintaining appropriate level of freshness. Although these techniques do reduce the carbon footprint, a more direct focus on the latter brings in some interesting tradeoffs. For example, using the refrigeration facilities with higher temperature setting on board trucks can reduce their carbon footprint [41]. However, to compensate, we either need to let the food freshness suffer as a result (which increases spoilage/waste and the corresponding carbon footprint), or impose stricter delivery time constraints (which may result in less full truck runs to maintain the freshness level and thus increase transportation carbon footprint). These tradeoffs need to be studied carefully so that it is possible to make informed decisions. The shared handling of multiple product types with their unique deterioration characteristics, cost, demand, etc., makes the problem quite challenging.

An important direction of building a sustainable IoPL is to explore different modes of transportation when available [42], such as rail or river. These modes often have different environment footprints and tradeoffs. For example, an extensive road network (as in USA) means that trucks can generally deliver perishable goods more quickly and thus reduce spoilage and waste. However, truck transport is rather environmentally unfriendly when compared with rail or barge based transport. As mentioned in [1], the CO_2 emissions from truck transportation is almost 20 times more than that of train transportation.

The use of barges for food distribution for the many cities along the Mississippi River, or along Lake Michigan [42] can reduce the carbon footprint and at the same time is beneficial for avoiding the road congestion. As an example in Fig. 15, using road transportation from Jackson to Memphis can use a mixture of road and river transportation. However, the barge transport would still require truck transport on either end and would likely impact freshness/spoilage due to extra loading/unloading, longer distances, longer delays, etc. All these factors, particularly the freshness index, need to be integrated into the multi-modal transportation models to assess the optimal methods.

Challenges of multi-modal IoPL: The key concern of an efficient multi-modal IoPL is the synchronization in between the logistics of different transportation modes and carriers. River/rail transportation does not depend much on congestion, however, their availability and routes are quite limited. On the other hand truck transportation is useful for delivering packages from any source to any destination points. However at rush hours, traffic congestion increases transportation costs, reduces food freshness. Without proper synchronization, a truck needs to wait for a barge or vice versa at the transfer points. Also this needs extra loading/unloading at these points. These extra delay increases the delivery time and makes it difficult to find willing drivers who are often paid by the miles driven, rather than the time taken. Because of these differences, logistics with multi-modal transportation can be quite different from that for uni-modal logistics. Furthermore, a collaboration and resource sharing between the two logistics can be quite challenging because of the mismatches between the two.

G. MULTI-PARTY COLLABORATION IN IOPL

Shared logistics, usually achieved through 3PL or its derivative models, is essential to increase efficiency and lower costs of the supply chain. In this case, the 3PL provider serves many customers whose products may be carried on the same carrier or stored in the same warehouse. Generally, each pallet carried or stored by the 3PL operator belongs to a single customer, so there is no mixing of products of customers at lower levels. However, customer may also want to pay for premium services where a carrier or warehouse room is not shared. In other words, a 3PL operator serves multiple parties, each with different requirements.

Given the complexity of putting together a logistics network, a 3PL operator is usually just a service aggregator; i.e., it provides end to end transport by contracting services from multiple other parties such as trucking companies, railroad/barge operators, local delivery companies, warehouse operators, packaging companies, labeling companies, etc. In fact, a service provider (e.g., local delivery company) could itself be an aggregator. The net result is the need for collaboration among several parties. A key deciding factors of such collaboration among the risk-sensitive parties are their individual reputations and the risk-profit trade-offs of cooperation [43], [44]. This collaboration would require data sharing among these parties. In [45] and [46], we have extensively examined the problem of multiparty access control in the relational database context, where the relations could represent arbitrary business related information including logistics. The assumption is that each party hosts one or more relations in a standard form (e.g., 3NF) available for restricted sharing by others. (Each party may have other relations or more columns in the same relations which are not available for sharing.) The schemas of these sharable relations are known globally, and it is assumed that identically named attributes have the same semantics.[1]

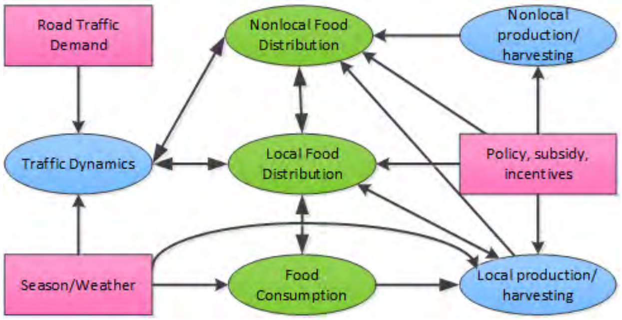


FIGURE 16. Overall framework of interconnected and interdependent agri-food supply chain.

With this, access rules for various parties can be defined using standard relational operators (join, projection, selection) over appropriate set of relations. The key question then is of multiparty query planning, i.e., the most efficient way of executing a query by considering relational operators and data transfers across parties. It is also possible to define a set of "safety properties", i.e., data leakage that a party does not want. These are defined as negative access rules and take precedence over normal access rules. The details of how to handle safety properties is discussed in [46] and query planning in [45].

In applying this model to logistics, it is important to remember that we are dealing with a cyberphysical system. which means that access control in the two domains should not conflict. For example, all of the identifiers shown in Table 1 include a "company" field which refers to the relevant company. For example, GSIN is needed for shipment and includes the company shipping the product. Thus, there is no way to hide the shipper ID from the 3PL provider. Similarly, GTIN identifies the product and is necessary to give product specific QoS treatment (e.g., maximum storage time, suitable container types, etc.), and cannot be hidden. In fact, certain products may directly identify the company shipping that product. It is important that the rules specified in the cyber part are compatible with such requirement. Beyond that, however, the above model can be used directly for controlling access to information since the logistics information is easily described using the relational model. The key challenge is how to make use of GS1 standards for labeling and communication for conducting effective logistics but with the customer specified visibility limitations.

H. HIGH LEVEL STOCHASTIC MODELING OF IOPL

The control planning of the entire argi-food supply chain, which consists of crop production and distribution process is a complex process that consists of different interrelated set of systems as shown in Fig. 16. In this figure we show

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[1] This ensures that we can do "meaningful" joins across parties. The condition can be relaxed by defining some correspondence functions instead.

the major processes of direct interest to IoPL using green ovals, and a few others using blue ovals. These are the production/harvesting of the food carried by the local or long-distance (nonlocal) logistics and the traffic dynamics that typically includes a large proportion of non-logistics vehicles. The external factors are shown in pink boxes and include road traffic demand by nonlogistics vehicles, local weather/season, and the local food demands. The arrows show main direct dependencies. For example, weather/season affects road traffic dynamics, which in turn affects both the local distribution and the nonlocal distribution bound for the local area in question. The (local) weather also affects the local production/harvesting and to some extent the food demands. Several dependencies go both ways. For example, the distribution of products coming into the local region from other regions affect the local distribution and vice versa. Similarly, food consumption is affected by the local distribution (supply side effects) and affects them (demand side effects). Consumption patterns also affect local production/harvesting and affect it.

Without a doubt, the shown processes and influences are incomplete; many other aspects could be brought in – for example, the fuel distribution network for the logistics (and other) vehicles, or transports other than road (e.g., rail, barge, etc.). It is also worth noting that many of the dependencies are not a result of close coordination between agents, but rather driven by demand and economics. For example, harvesting may be delayed if a backlog develops in the products waiting for shipment. A close coordination between harvesting and transportation could result in less delays and food deterioration and better transport capacity utilization, but such close coordination often does not exist. The proposed mechanisms could simplify such coordination and would be a significant benefit in itself.

With or without the coordination, a detailed modeling of dependencies is extremely challenging because individual processes (e.g., harvesting, road traffic behavior, etc.) themselves are immensely complicated and involve considerable domain knowledge, and it is often unclear how to model interactions. However, simple multi-layer models may be adequate for assessing overall behavior of the entire system. The idea is to modeleach process separately and consider interactions between them explicitly. For example, harvesting rate may be modeled separately as a process driven by many factors including food type, time of the year, weather pattern, etc. The backlog in the distribution system could further modify this rate to represent the interaction between the two. Road traffic can be modeled using the standard ''fundamental diagram'', i.e., relationship between speed and congestion, and network level flow balance and other properties. The food consumption modeling is much more complex as it depends on inherent demand, pricing, availability, etc. but can be represented via simple stochastic models. Such models would necessarily be rather high level, and perhaps useful for a macroscopic understanding of the entire ecosystem, rather than for an accurate modeling of end to end delays.

Another important necessity of studying such high-level dependency modeling is to understand the influence of various entities on the supply chain. For example a significant delay at few focal links of a distributor network can affect both the end-to-end quality and delivery requirements of several retailers. Similarly a disturbance at the producer levels can adversely affect the transportation efficiency as well as the supply-demand relations. Several indicators have been studied to characterize the influential spreaders in complex networks [47], [48] including various forms of centrality measures. These can be exploited to determine what aspects of the logistics network are likely to contribute the most to the delays or disruptions and therefore must be augmented with extra capacity.

I. IOPL INSPIRED COMPUTING RESEARCH

While we have so far largely focused on exploiting the computer science concepts to structure and analyze perishable commodity logistics, logistics related considerations can also inspire new ideas in information distribution. In particular, here we discuss two aspects that we have explored ourselves inspired by the logistics considerations.

One such topic is the content-centric networking (CCN) [3], where the key premise is that the networking protocols should be driven by content where it is produced or consumed, and its characteristics/needs, rather than by the addresses of the nodes hosting or requesting the content. While content popularity is a central concept in CCN, it is important to also consider a distinct notion of ''Information Perishability'' modeled after the quality deterioration in IoPL. To see this, note that the CCN is often used to distribute developing content such as news stories where the older versions get progressively less useful, and at some point worthless. Thus perishability is an inherent property of the content and may be further modulated by the popularity, or relative number of requests for a specific version of the content. A related concept inspired by lateral distribution in IoPL is the ''neighborhood awareness'' in the content caching as discussed in section V-A. We have developed a highly efficient and effective neighborhood aware content distribution scheme as detailed in [49].

Packing smaller items into large pallets for shipments via the long-distance logistics is essential for efficient handling and transport in IoPL. The advantages of packet bundling are well recognized in computer networks as well. For example, SCTP [50] supports the notion of ''chunking'', whereby multiple flows can have their content bundled in packets transmitted over a single connection (or association). Similar packet bundling techniques are also useful to improve spectral efficiency in cellular networks [51]. In data centers, it is impractical to provide such bundled transport across all paths in spite of many such proposals [52], [53]. A more practical approach is to have a backup optical network (akin to long-distance logistics) that provides high bandwidth bypass paths on-demand. Several proposals in this regard exist in the literature, e.g., c-Through [54], Helios [55] etc. Optical path reconfiguration is slow because of need to change wavelengths; therefore, it is desirable to send a burst of packets before changing the path. The so called *Optical Burst Switching* (OBS) with intermediate add-drop of lightpaths, akin to a more agile long distance logistics in IoPL may be interesting in this context. We have addressed this aspect in [56] and shown its advantages.

Many of the other specialized features of the IoPL designed to accommodate the complexities of logistics operations are applicable in cyber space as well. For example, sensor networks have considered scenarios where mobile nodes move physically either to transport packets (e.g., ''data mule'' [57]), or to charge themselves [58]. 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 which can be helpful from the *zoned networking* mentioned in section V-D. Such scenarios are becoming increasingly popular in the context of widespread IoT deployment, and they can learn from the logistics.

VI. CONCLUSIONS

In this paper, we demonstrated several synergies between the cyber Internet and perishable logistics, how they can be exploited to improve the logistics space, and some of the challenges that need to be resolved to make it practical. We also introduced a systematic, layered Internet architecture for perishable logistics that we believe can be exploited for studying the issues at various levels of abstraction. We also discussed, at length, a number of challenges and future directions in IoPL. We expect that the paper will motivate researchers in the two communities to exploit further synergies and thereby advance the current logistics to become more efficient and agile in future.

Overall, we expect the level of automation to continue to increase in all aspects of logistics including loading, unloading, sorting, packing, unpacking, quality monitoring, movement inside the facility and out (e.g., robotic conveyers and autonomous trucks), inventory control, etc. We believe that as reliance on humans decreases, the ideas in this paper become more and more important for building highly efficient logistics networks. The automation also leads to new questions such as those relating to refueling (e.g., charging) of autonomous vehicles, a dynamic coordination across vehicles to relieve highway congestion and improve quality of delivered goods, and coordination between vehicles and in-facility infrastructure to reduce bottlenecks, etc.

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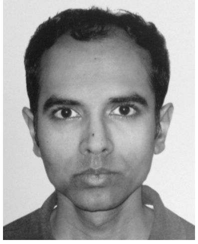

AMITANGSHU PAL received the B.E. degree in computer science and engineering from Jadavpur University, in 2008, and the Ph.D. degree in electrical and computer engineering from The University of North Carolina at Charlotte, in 2013. He was a Postdoctoral Scholar with Temple University, where he is currently an Assistant Professor with the Computer and Information Science Department. He has published over 40 conferences and journal papers. His current research interests include wireless sensor networks, reconfigurable optical networks, smart healthcare, cyber-physical systems, mobile and pervasive computing, and cellular networks.

KRISHNA KANT was a Research Professor with George Mason University, and has served as the Program Director of the Computer, Information Science and Engineering Directorate, National Science Foundation (NSF), from 2008 to 2013. At NSF, he was also instrumental in the development and running of NSF wide sustainability initiative called SEES (science, engineering and education for sustainability). He has also served at Northwestern University, Penn State University, Bell Labs, Bellcore, and Intel, and carries a combined 34 years of experience in academia, industry, and government. He is currently a Professor with Temple University, Philadelphia, PA, USA. His current areas of research include sustainability and energy efficiency in data centers, configuration robustness and security, and application of computing technologies to larger sustainability problems. He has published in a wide variety of areas in computer science, has authored a graduate textbook on performance modeling of computer systems, and has co-edited two books on infrastructure and cloud computing security. He is a Fellow of the IEEE.

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