Networking in Real World: Unified Modeling of Information and Perishable Commodity Distribution Networks

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Abstract: *Computer networks and Logistics systems are two rich fields of study that have grown almost entirely separately since they deal with entirely different entities – information packets vs. real commodities. In this paper, we show that considerable synergies exist between them, particularly in the context of perishable commodity distribution. This leads to the need for a unified networking model that encompasses both and allows application of ideas and techniques across two very different fields. The paper also discusses a simplified analytical framework to model the distribution of perishable commodities along with the tradeoffs in between different design objectives.*

1 Introduction

Information and commodity distribution networks have been active areas of research for many decades but studied in very different communities. The purpose of this paper is to explore synergies between the two fields and exploit them to better manage the information and commodity distribution. In this paper, a "commodity"[1] refers to an item that can be moved from one node to another without disturbing the rest of the network; thus continuous flow commodities like water and power flow are not considered.

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 information 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) [Ahlgren et al., 2012] focuses 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.

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[1]In this paper we use commodity, packet, package interchangeably.

The commodity distribution area – a significant part of logistics operations – is also undergoing substantial evolution due to rapidly globalizing and complex supply chains that must deliver a huge variety of products efficiently and reliably in spite of increasing transport costs, distances, congestion, and environmental concerns. Added to this are the increasing demand for perishable commodity distribution with the best quality or highest value. In particular, customers demand freshest possible perishable food (including produce, edible fungus, dairy, seafood, meat, prepared foods, etc.) at the lowest price. Similar considerations apply to other perishable commodities as well such as blood (for transfusion), short-life medicines, human organs (for transplant), fresh flowers, etc.

Traditional transport logistics suffers from very low efficiencies (perhaps in the teens [Montreuil, 2011]) due to partially full trucks and empty truck returns. In the pioneering works in [Montreuil, 2011], [Montreuil et al., 2012], [Sarraj et al., 2014] the authors have shown several similarities in between the logistics networks and computer networks and propose a *Physical Internet* model for an efficient, coordinated and well-structured supply chain network. Yet, in case of *perishable logistics* such as food logistics, it may result in significant spoilage and wastage of fresh food (see [Gunders, 2012]), and there is a natural tradeoff between efficiency and freshness. The emerging notions of local sourcing of products attempt to reduce the waste, but results in significant additional complexity with respect of integration of local and nonlocal logistics. Thus, distribution mechanisms for *perishable commodities that simultaneously achieve high efficiency and meet stringent quality of service requirements remain a substantial challenge in the logistics field but has not been well investigated from the resource efficiency perspective* [Pahl and Vo, 2014].

Since perishability properties and timeliness needs of commodity distribution can cover a very wide range, we consider the entire distribution logistics under the ambit of what we call *Perishable Commodity Distribution Networks (PCDN)* with different product classes exhibiting different perishability characteristics. The **primary** contribution of this paper is to derive the synergies between IN and PCDN, and propose a 5 layer unified model to capture both. Recently in [Montreuil et al., 2012] the authors have proposed a 7 layer Open Logistics Interconnection (OLI) model for an improved logistics system based on the Open System Interconnection (OSI) model in computer networks. However in case of PCDN the perishability and spoilage property needs further consideration, we thus brought the notion of *virtualization* by defining few *virtual systems* (VSs) in our unified model. For example, we can define a "HP Transport" as a VS intended for transporting highly perishable (HP) items from a specific origination area 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. We thus incorporate a *virtualization layer* to consider this complexity in our model. Second unlike typical computer networks, PCDN requires acquisition of different types of *resources* before transporting the packages in between the distribution points. To incorporate the resource availability such as trucks or containers returns in the model, we propose the notion of *dummy packets* in our unified model. Other than that our 5 layer unified model greatly simplifies the networking operations compared to the 7 layer OLI model in [Montreuil et al., 2012]. We illustrate how such a view can be useful in exploiting the synergies, and expect that it will lead to much broader collaboration, cross-pollination, and unique insights to advance both fields.

Given the complexity of packet transit in such a unified model, its mathematical modeling is quite challenging and goes well beyond the simple queuing theoretic modeling that is quite common in IN. In particular, such modeling not only needs to deal with batch transmission (or bundling/unbundling), but also with allocation/deallocation of multiple resources whose scope often extends to the entire network instead of being limited to a node or link. Thus approximate solution methods are almost mandatory,

and developing an approximation technique and characterizing its properties becomes quite challenging. In this paper we propose an analytic modeling of such an approximate scenario using the idea of *batch queuing* and analyze the impact of waiting time latency of the packages for resources (trucks) on the freshness delivery quality of these packages, which we consider as our **second** contribution. We also validate the correctness of our analytic modeling with extensive simulations. The model also demonstrates the tradeoff between the conflicting design objectives of transportation efficiency of the trucks and the quality or freshness of the delivered good packages.

The outline of this paper is as follows. Section 2 compares and contrasts information and logistics networks and discusses the recent notions of physical Internet. Section 3 then introduces the layered unified model. Section 4 then discusses our analytical framework to demonstrate the commodity waiting latency and quality loss due to it. Finally, section 5 concludes the discussion.

2 Logistics vs. Networking

In this section, we address the fundamental question as to why the two fields need to be brought together.

2.1 Distribution in the Cyber vs. Physical Space

Information networks (INs) have the familiar layered structure best illustrated by the ubiquitous 4 layer TCP/IP stack: physical transmission layer (Phy), Media Access Control (MAC), Routing/Internetworking, and end-to-end Transport. 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.

It is instructive to compare and contrast this against PCDNs. PCDNs also move commodities between "source" and "destination" endpoints, the former being farms and manufacturing/assembly plants, and the latter retailers and other large customers (e.g., hospitals), though there is generally no transportation in the other direction. Commodities flow from source to destination via a number of intermediate points via *carriers* (e.g., trucks, railcars, boats, airplanes, or drones). Each carrier unit 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; however, the sophisticated capabilities generally appear only at one level (e.g., a bunch of specialized containers in a big box or vice versa).

The intermediate points in the network include local, regional, and global distribution centers. These nodes can store full or empty containers, change container contents (by removing, adding, or exchanging packages), load/unload containers on carriers, handle damage/misdelivery, etc. (Note that we do not consider retail sale as part of the commodity distribution.) In addition to distribution centers, there can be less functional "transfer-points" that can exchange carriers (e.g., move containers from a truck to another truck, from rail-car to a truck, etc.) and change drivers. We assume that proper labeling procedures are followed so that commodity distribution network can function w/o any significant errors.

In IN the flows are subject to suitable quality of service (QoS) requirements with regard to timeliness, integrity, reliability, quality, etc. Perishability is a key QoS driver in PCDN. 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
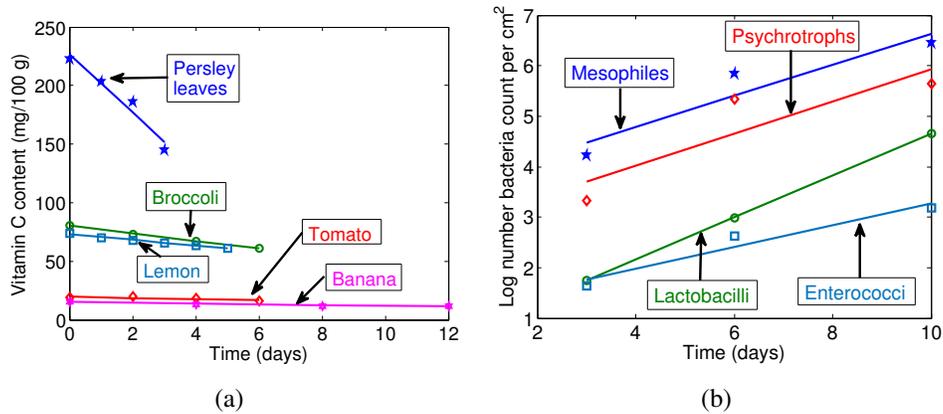
Figure 1: (a) Vitamin C degradation in different vegetables at $20°$ C (data obtained from [Mazurek and Pankiewicz, 2012]). (b) Bacterial content in chicken meat at $2°$ C (data obtained from [Reddy, 1981]).

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. For example, Fig. 1(a) shows the Vitamin C degradation of different vegetables over time at $20°$ C (with distinctly linear degradation), whereas Fig. 1(b) shows the exponential growth of certain bacteria on meats. 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, phasor measurement unit (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 PCDNs. The most fundamental difference is that physical packets cannot be copied, and must be physically moved. Thus the "loss" of a physical packet (due to physical loss, damage, spoilage, etc.) can be very expensive – although a lost packet 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 PCDN 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.

2.2 Cyber vs. Physical Internet

Internet is the prime example of the success and pervasiveness of Information Networking (IN), and this success can be attributed to two key ideas: *standardization* and *sharing*. *Standardized* information exchange formats and protocols (e.g., TCP/IP) allow substantial diversity and innovation both at the lower levels (e.g., a large variety of hardware platforms and networking media), and at the higher levels (a vast array of online applications and services). *Sharing* of core Internet infrastructure among large number of customers and providers not only allows for low cost information distribution but also provides inherent value in terms of Metcalfe's Law [Hendler and Golbeck, 2008].

In contrast, logistics networks have traditionally been driven by the requirements of dominant players in the space. However, the high cost and inefficiencies of such an approach have finally started several real movements towards standardization and sharing. A new term, *Physical Internet*, has been coined that attempts to emulate the success of the Internet in logistics [Montreuil, 2011]. Physical Internet now has an active consortium (www.physicalinternetinitiative.org/) to exchange ideas on various technologies needed to develop the concepts further.

The most basic standardization need in physical Internet is that of containers that easily compose to create bigger and bigger containers so as to maximize space utilization. These are known as PI (or π) containers as shown in Fig. 2. Since containers aren't just boxes, the standardization needs to extend well beyond sizes, and once done successfully, would further drive standardization and automation of loading, unloading, transportation, storage, etc. The other significant standardization effort is in RFID tagging, which has become quite popular for a variety of applications. A comprehensive set of standards known as *GS1* for labeling products, packages, carriers, warehouses, endpoints, etc. and tracking of items based on the tags are under development (see *http://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.
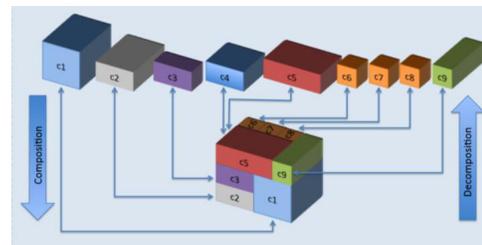

Figure 2: PI container architecture [Montreuil, 2011]

On the sharing front, outsourced logistics operations – so called third party logistics (3PL) has been studied since 1980's. It refers to a third party handling the operations between producers/suppliers and customers by using owned or contracted resources (trucks, warehouses, drivers, etc.). Clearly, the main attraction of 3PL is the effective sharing of facilities among multiple producers/consumers, which significantly reduces their cost and increases flexibility/agility. Recent data suggests a steadily growing popularity of 3PL (and its derivatives such as 4PL) with 54% of transportation and 39% of warehouse operations currently outsourced [Leuschner et al., 2014]. Unfortunately, sharing in logistics is far more difficult than in the Internet because of the need of auxiliary resources (e.g., trucks, loaders) and product availability issues, in addition to the concerns of privacy, security, and fairness among sharers who may

be competitors.

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.

3 A Unified Network Model

We envision a unified network model (UNM) that "carries" clonable (CL) and/or non-clonable (NCL) "packets" that correspond, respectively, to information and commodity units. For simplicity, we describe the following with only one type of packet, since this is sufficient in most cases. However, a mixture of CL/NCL packets is possible and useful in modeling the dependence of physical operations on information availability (e.g., moving a package once the enabling command is received).

3.1 UNM Structure

Our Unified Network Model (UNM) consists of a set of nodes connected by edges along which CL or NCL packets flow. When modeling IN, the nodes represent familiar entities such as (layer 2) switches, (layer 3) routers, and endpoints, and the edges are communication links. In modeling PCDN, 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 PCDN 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 UNM 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 PCDN the objects are similarly uniquely identifiable by the use of GTIN, GLN, SSCC etc. at different levels of aggregation (e.g. cases, pallets, carriers, etc.) as shown in Table. 1. In PCDN, the packets are either barcoded or RFID enabled, carrying their unique packet IDs, which enables automation of loading/unloading and tracking.

Table 1: GS1 standards in PCDN

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)

We allow both CL and NCL packets to belong to more than one [QoS] *class* in UNM. Each class is generally characterized by different sizes, priority/timeliness, and other QoS needs. For example, a logistics network handling multiple types of fruits may group them in 3 classes: highly perishable/delicate (e.g., berries), medium perishability (e.g., apples), and low perishability (e.g., melons). The classes can also be defined based on their ripening stage or their cultivation method (i.e. organic/certified or inorganic/non-certified). We assume that there are a total of C classes, numbered $1, \ldots, C$, and each

class has its perishability function $\zeta_c(t)$ introduced earlier. Here t denotes the elapsed time since the origin of the packet at the source. It suffices to assume that ζ belongs to the real range $[0, 1]$ where 1 means that the packet so far has not suffered any quality loss and 0 means that packet has no value. The ζ function could be a simple step function if the packet is good until certain delay and then becomes useless.

The key concept in UNM is that of a "resource". We assume that the network has K resource types henceforth denoted as $\mathbf{R} = \{\mathbf{R_1}, \ldots, \mathbf{R_K}\}$. Resources are most crucial in modeling PCDN, 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 PCDN, multiple packets could be assigned to the same resource instance (truck, container, driver, etc.) Depending on the defined policies it is even possible that the packets assigned the same resource instance belong to different classes. We call mixing/packing of multiple similar or different classes of packets into a larger resource unit as *bundling*.

Within a resource type, we allow for further differentiation by letting each $\mathbf{R_i}$ itself be a vector, denoted $\mathbf{R_i} = \{R_i^1, \ldots, R_i^{N_i}\}$. The idea is that the resource of type i could have N_i subtypes or categories. For example, in the PCDN 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.

3.2 Layered architecture

A layered architecture for UNM provides abstraction, which is even more important than in IN because of much higher levels of complexity. In the following, we identify 5 lowest layers, denoted $(L_1, \ldots, L_5)$ – others may be defined on the top. The resources can also be arranged according to the layers – that is, we can number the resources $\mathbf{R_1}, \ldots, \mathbf{R_5}$ such that we first have resources relevant to layer 1, then to layer 2, etc. This is possible since in UNM each resource is allocated/deallocated on at a specific layer, although more than one resource type may be dealt with at a given layer. Thus, it is sensible to speak of layer i resources (for $i = 1..5$). Another characteristic of layered model is that 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 $\mathbf{R_i}$ available at a node. Since bundling – or batching – of packets is an essential aspect of UNM, we will consider a batch B of packets 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.

Layer 1: Physical Layer The Physical layer deals with actual movement of packets along a media segment or channel. For IN, this means the transmission of link-layer frames on a wired or wireless channel. For PCDN, this corresponds to the physical transport of a package from a transfer point to next through a channel (or actual pathway) over a specific media such as road, rail, waterway, or air. Each channel may have different characteristics such as capacity/bandwidth, delay, congestion level, reliability, etc. For example, a road based "hop" may offer two possibilities or channels: a shorter but slower city route and a longer but faster highway route. When multiple media and channels are available, Layer 2 (discussed next) will decide which channel to assign to the batch B. Successive batches could be sent on

different channels, if appropriate. For CL packets, copies of the same batch could be sent across multiple channels.

Layer 2: Media Switching Layer The media switching layer in UNM provides the media/channel selection, media bridging, and switching functionalities. For IN, this translates into the familiar media access control (MAC), layer2 switching, and bridging functions. For PCDN, 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 trucks is handled by Layer 2. Container contents are not known to Layer 2 and not disturbed by it. More generally, while the UNM layer 2 may stuff application level packets into Layer 2 frames, it cannot change them. If some layer-2 frames are found to be damaged at the intermediate nodes, they are discarded and replacements are requested. Thus hop-level delivery of missing/wrong/damaged packets is ensured by this layer.

Layer 3: Routing & Distribution Layer: This layer supports end-to-end transfer of packets by handling packets at and across distribution/routing nodes. For IN, 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 PCDN, the situation is more complex due to potentially recursive bundling/unbundling and allocation of an L_3 resource like containers. In particular, the transmission will be blocked at layer-3 if suitable resources (e.g., containers) are not available. Also, since layer 3 has access to container contents (e.g., boxes), it is capable of checking for them 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 packet in addition to the routing information such as source/destination address. For IN, this may be a message or datagram sequence number. For PCDN it may be the ID's listed in Table. 1. The routes in a network are chosen generally to maximize the delivery quality of the packets, minimize delivery time, minimize the network cost, or some combination thereof.

Layer 4: Transport/Delivery Layer: This layer concerns the end-to-end delivery of individual packets. The major concern of this layer at the source node is to obtain L_4 resources (e.g., buffer space at the destination) and to form batches of packets that are given to Layer3 for transmission. Depending on the policy, layer 4 may wait to accumulate enough packets to form a container size batch, or send a smaller batch (for more expeditious transmission). The destination layer-4 will check the packets 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. Information network virtualization has been explored extensively [Duan et al., 2012] from various perspectives including both the innovation in new networking functions (e.g., routing) and to satisfy needs of a wide range of applications. While these apply in the UNM context as well, the virtualization can also be used as a mechanism to tame the high complexity in the PCDN context. In particular, offering of a set of "pre-packaged" logistics services can be viewed as a form of virtualization and is akin to offering a

prepackaged virtual cluster for a specific cluster computing application. As with IN, the main challenge is the mapping of virtual resources on physical resources, which may be complicated by lack of visibility into the entire network and the difficulty of tracking the entire network state.

While layering is useful to abstraction, *cross*-layer coordination may be required for better management of resources. For example, highly perishable packets can be handled better by careful choice of carriers and channels (at lower levels) and bundling/unbundling at higher layers.

3.3 Resource Management in UNM

As stated above, the unified network involves acquisition of certain resources at each layer of the network. The lack of resource availability blocks packet transfer until the required resources can be assembled, and this has effect on delivery time and quality of delivered packets. Thus a critical issue in UNM is the proper positioning of resources at various nodes. Let $\mathbf{Q} = \{Q_1, \ldots, Q_K\}$ 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 $\mathbf{Q}$. 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.

If the resource quota is specified on a per-hop basis, any resources acquired for forward transmission can be returned by the corresponding backward transmission. This is the most common scenario for IN. In PCDN, the situation is much more complex because of the need to deal with multiple resources (e.g., carriers, drivers, containers). 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 packet (DP) of size $\varepsilon \sim 0$. Each one of the returnable resources is assigned a dummy packet 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.

Although many of the specialized features of the UNM are designed to accommodate logistics networks, it is important to note that the need for these features continues to emerge even in IN. For example, sensor networks consider scenarios where mobile nodes move physically either to transport packets (e.g., "data mule"[Anastasi et al., 2008]), or to charge themselves [He et al., 2013]. In the latter case, energy can be explicitly modeled as a "resource" in the sense described above.

4 Analytic Modeling of UNM Commodity Distribution

We next derive an analytic 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 geo-

graphic 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 delivery centers by solving the traveling salesman problem (TSP) [Applegate et al., 2007], 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 2.
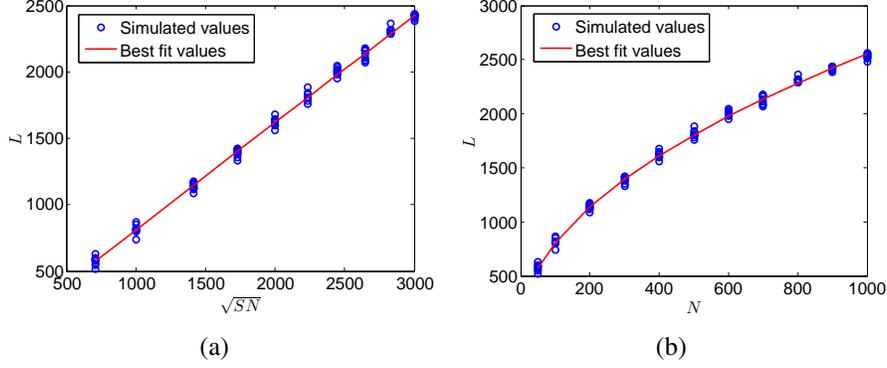

Figure 3: (a) Simulated and best-fit values of L with $\sqrt{SN}$. The slope C is found to be $\sim$0.81. (b) Variation of L with N with simulated and analytic model.

4.1 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 [Zhang and Fei, 2007]. 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 $C_1 \cdot \sqrt{\frac{S}{N}}$, 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 [Moler, 2008]. We place N DCs uniformly in an area of 100×100 sq. unit. We use [Tran, 2014] for solving the traveling salesman problem and recorded the total travel distance L of a salesman connecting N DC points. Fig. 3(a) shows the variation of L with different $\sqrt{SN}$, whereas N is varied from 50 to 1000. From Fig. 3(a) we can observe that L varies linearly with $\sqrt{SN}$ with a slope of $C \sim$0.81, which validates the claim of equation(1). Fig. 3(b) shows the variation of L with different N, where C is assumed to be 0.81, which confirms the validation. From Fig. 3(b) we can also observe that L increases by $\sim$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.

4.2 Modeling the package delivery latency

We assume that the food packets 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 $\sigma_0, \sigma_1, ..., \sigma_n, ...$ 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 $N.B$ (in terms of number of packages), i.e. in this model each DC reserves a space of B units in the truck. 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 [Chaudhry and Templeton, 1983, Hébuterne and Rosenberg, 1999], which is typically defined as $G/G^B/1/\mathcal{M}$. In our case the packet 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.

Table 2: 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

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 rest of the paper we assume that there is one *virtual* truck with arrival rate of μ, instead of η trucks for simplicity.

4.2.1 Stability condition

The DC queue is stable iff the maximum service rate $B\mu$ is less than the packet arrival rate at any DC, as mentioned in [Hébuterne and Rosenberg, 1999]. Thus the stability condition of the DC queue is

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

4.2.2 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

$$k_m = \text{Prob}(m \text{ potential arrivals during } T) = \frac{(\lambda.T)^m.e^{-\lambda.T}}{m!} = \frac{\rho^m.e^{-\rho}}{m!} \qquad (3)$$

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 in equations(4)-(6).

$$P_j(n+1) = (P_B(n) + P_{B-1}(n) + ... + P_0(n))\,k_j + \sum_{s=1}^{j} P_{B+s}(n)k_{j-s} \qquad j = 0, 1, 2, ..., \mathcal{M}-B \quad (4)$$

$$P_j(n+1) = (P_B(n) + P_{B-1}(n) + ... + P_0(n))\,k_j + \sum_{s=1}^{\mathcal{M}-B} P_{B+s}(n)k_{j-s} \qquad j = \mathcal{M}-B, ..., \mathcal{M}-1 \quad (5)$$

$$P_{\mathcal{M}}(n+1) = (P_B(n) + P_{B-1}(n) + ... + P_0(n))\,l_{\mathcal{M}} + \sum_{s=1}^{\mathcal{M}-B} P_{B+s}(n)l_{\mathcal{M}-s} \qquad (6)$$

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 $P_j(n+1) = (P_B(n) + P_{B-1}(n) + ... + P_0(n))\,k_j$ in equations(4)-(6). 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. Equations(5)-(6) 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 equations(4)-(6) with n suppressed and then solving the equations for P_j along with the normality condition $\sum_{j=0}^{\mathcal{M}} P_j = 1$.

4.2.3 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 $\overline{R} = \frac{\mu^2.\sigma+1}{2.\mu}$ [Ross, 1997]. Now for a deterministic renewal process, $\sigma = 0$ and $\Psi = \overline{R} = \frac{1}{2.\mu} = \frac{T}{2}$. $\qquad\qquad\square$

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 $0 \leq q \leq B$, 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

$$\mathcal{P} = \sum_{j=0}^{B} j.P_j + \sum_{j=B+1}^{\mathcal{M}} B.P_j \tag{7}$$

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 [Hébuterne and Rosenberg, 1999, Jain et al., 2006] the expression of Q_j can be derived as

$$Q_j = \sum_{i=j+1}^{\min(j+B,\mathcal{M})} \frac{P_i}{\mathcal{P}} \qquad 0 \leq j < \mathcal{M} \tag{8}$$

$$= 0 \qquad j = \mathcal{M}$$

With these we next propose the following theorem for τ_1.

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

Proof. Notice that if a newly arrived package finds the queue length $0 \leq q < B - 1$, then the average service time is just the residual time of the truck arrival process, which is Ψ. Otherwise if $B \leq q < 2B-1$ 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

$$\tau_1 = \left\{ \Psi . \sum_{j=0}^{B-1} Q_j \right\} + \left\{ (\Psi + T) . \sum_{j=B}^{2B-1} Q_j \right\} + \left\{ (\Psi + 2T) . \sum_{j=2B}^{3B-1} Q_j \right\} + ... + \left\{ (\Psi + (f-1)T) . \sum_{j=(f-1)B}^{\mathcal{M}-1} Q_j \right\}$$

$$= \sum_{c=0}^{f-1} \sum_{j=c.B}^{(c+1)B-1} \left(\Psi + c.T \right) Q_j \tag{9}$$

$\square$

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 $\tau_2 = \frac{\sum_{i=1}^{N} \sum_{j\neq i} t_{ij}}{N(N-1)} = \frac{\sum_{i=1}^{N} \sum_{j\neq i} (t_{ij}+t_{ji})}{2.N(N-1)} = \frac{T}{2}$. $\square$

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 $D = [1 - \zeta_{\Gamma_1}(\tau_1) - \zeta_{\Gamma_2}(\tau_2)].I$, 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.*

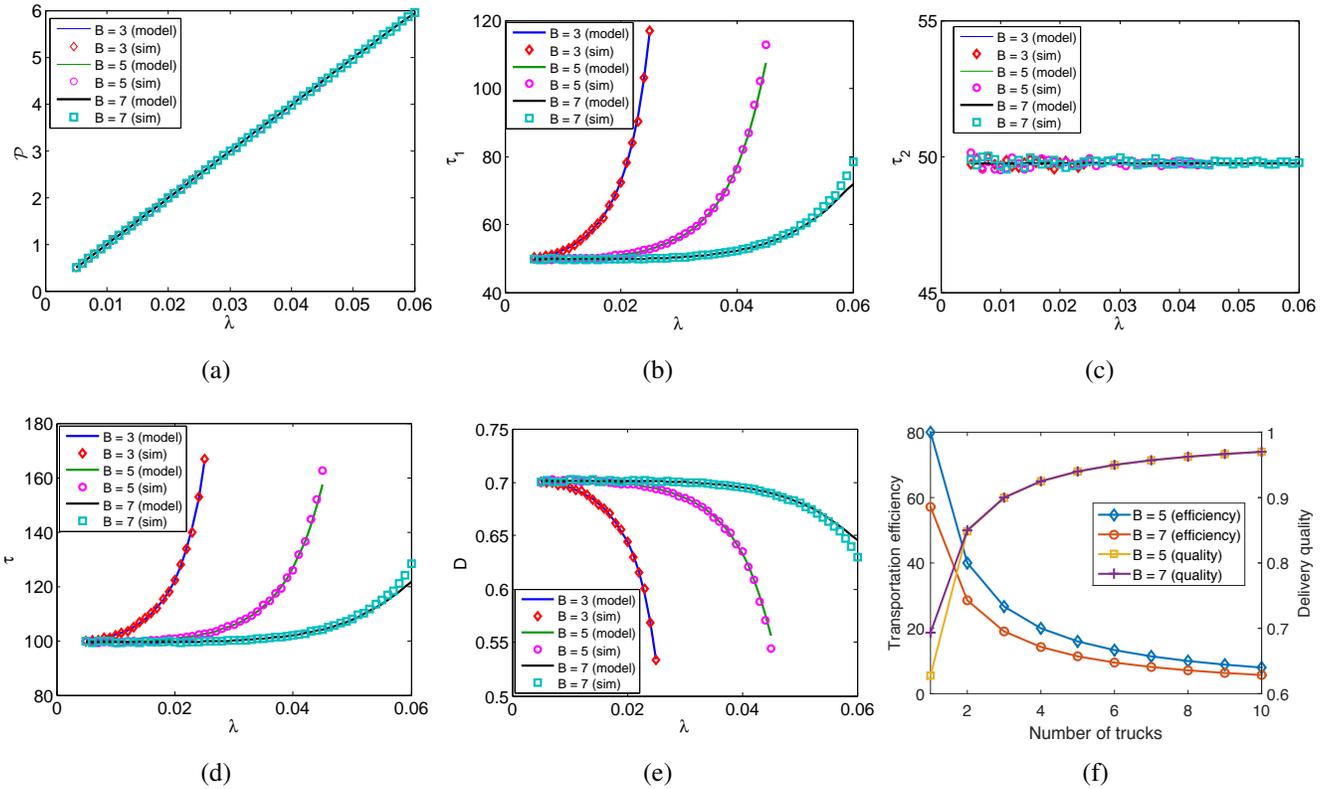*Proof.* The proof is intuitive from the definition of the perishability function. $\square$

Figure 4: Simulation and analytic modeling of (a) $\mathcal{P}$, (b) τ_1, (c) τ_2, (d) τ and (e) D with different packet arrival rate λ and B. There is an obvious tradeoff between the transportation efficiency and delivery quality of fresh food packages (f).

4.2.4 Simulation Validation

To validate the above analytic model we distribute 100 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 analytic model. The results are shown in Fig. 4 which shows that our analytic model closely approximates the simulated values, thus confirms the validation of our theoretical model.

Comparison of $\mathcal{P}$: Fig. 4(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. 4(b)-(c) shows the variation of τ_1 and τ_2 with different λ. From Fig. 4(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. 4(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. 4(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. 4(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. 4(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. 4(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. 4(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.

5   Conclusions and Future Work

In this paper, we considered the synergies between information and commodity distribution disciplines and devised a unified model to capture both. We also discussed how the synergies and unified model can lead to cross-pollination of the two fields and develop an analytical framework to get an insight regarding its key performance parameters.

In future we plan to use the unified model for examining content centric networking in the context of perishable information and commodity distribution. We also expect to use the model for addressing other complex problems such as virtualization and cross-layer coordination, and study their impact on network functioning. We have started looking into several such issues [Pal and Kant, , Pal and Kant, 2016a, Pal and Kant, 2016b] recently which we will expand extensively in future.

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