On Bridging Information Networks and Perishable Commodity Distribution Networks

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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 vs. real commodities. In this article, we show that considerable synergies exist between Information Networks (IN) carrying time-sensitive information and Perishable Commodity Distribution Networks (PCDN). This leads us to consider a unified networking model that encompasses both IN and PCDN and allows application of ideas and techniques across two very different fields. The paper demonstrates these synergies in a few specific areas and also discusses several challenges in these and other areas.

I. INTRODUCTION

The disciplines of commodity distribution logistics and information networking have been studied extensively for many decades but almost exclusively in their own domains. However, there are many synergies between them that could be exploited for solving complex problems in both fields. The distribution of perishable commodities such as fresh food, perishable pharmaceuticals, blood, etc. brings in some special challenges and opportunities that make comparison with information networking particularly apt. The increasing use of ICT in all aspects of logistics leads to further convergence of the physical and cyber world.

Fig. 1. An abstract network model of IN and PCDN

Fig. 1 provides a conceptual view that considers both information and commodity distribution as a unified network that transports and processes physical packages and/or information "packets'. The synergies derived from such a unified view are expected to cross-pollinate both areas, as we demonstrate in this paper with a few examples. They also pose a number of difficult challenges that we briefly touch upon in the paper.

A. State-of-art of IN vs PCDN

On the IN side, there is considerable activity on next generation networks (NGN) including the ideas generated from NSF's *Future Internet Architecture* (FIA) program (*www.nets-fia.net/*). The emerging content-centric networking (CCN) [1] architectures are based on the observation that unlike the classical Internet architecture that is based on the addresses of nodes and routing between these addresses, the new Internet architecture should instead focus on information availability and demand. On the other hand there is a substantial amount of growing interest on *visualization* that provides the advantages of *outsourcing* and *capacity sharing*, which enables the customers to request capacity on demand, and lowers their costs. Sharing of the networking infrastructure allows information to be communicated from anywhere to anywhere conveniently and with minimal cost, so that the providers can focus on their applications and services, instead of the network.

TABLE I. 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)

On the logistics side, there is an ongoing interest in replicating the cyber-Internet model in logistics space. The idea has been recognized in the logistics space in the *Physical Internet* concept [2], which now has an active consortium (www.physicalinternetinitiative.org/) as well. There are a couple of important ongoing initiatives in the standardization of physical Internet (PI). One is the notion of PI (or π) containers that easily compose to create bigger and bigger containers so as to maximize space utilization and shipping efficiency. It is important to note, however, that containers aren't just boxes – a substantial specialization may be required to handle needs of various types of items, particularly those that are perishable, fragile, or highly reactive. Thus standardization needs to extend well beyond sizes, which in turn is expected to drive standardization and automation of loading, unloading, transportation, storage, etc.

The other standardization effort is in RFID tagging and barcoding, which has become quite popular for a variety of applications [3]. 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*). In particular, the packages are identifiable by the use of GTIN, GLN, SSCC etc. at different levels of aggregation (e.g. cases, pallets, containers, carriers, etc.), which is summarized in Table. I. The actual labeling technology could be bar-code, RFID, or embedded in the packets in other ways, but carrying the labels with the packets allows packets to be tracked easily.

On the sharing front, large operators (e.g., Walmart, Boeing, etc.) continue to have their private logistics network, but smaller ones are rapidly moving towards *outsourced services*, provided by third parties. The third party logistics (3PL) (and its derivatives such as 4PL) have been around since 1980's and allow other parties to handle various aspects of product transportation and distribution, usually by engaging other downstream parties. Recent data suggests that 54% of transportation and 39% of warehouse operations are outsourced [4]. Sharing in logistics networks is much more difficult than sharing in the Internet, which makes the logistics efficiency quite low, perhaps in teens [2]. 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 [5]. Capacity sharing by multiple perishable products has been particularly difficult to handle, and has received relatively little attention [5].

B. IN vs PCDN

In comparing PCDN against IN, it easy to see certain fundamental similarities and differences. PCDN involves a *flow* of packages or package containers (that we can regard as *packets*) from source (e.g., farm, factory, blood bank, etc.) to destination (e.g., retailer, hospital, etc.). The flows may pass through some intermediate distribution centers that "store and forward" the packets much like IN routers. Most flows also have *Quality of Service* (QoS) constraints in terms of delivery times and/or flow bandwidth (volume delivered/day). Other than that perishable goods often deteriorate in quality (or freshness) and value as a function of flow time (and other parameters such as temperature, vibrations, etc.) although some perishable goods, such as blood, have a fixed expiry duration. Similarly IN packets often have fixed deadlines, but there are scenarios where the value of information decays steadily with the delay incurred, such as in sensor networks or in financial transactions etc.

However, there are important differences as well. The most fundamental characteristic of a physical packet (or package) is that it is "unclonable"; it can exist only in one place at a time – even though one could surely replace a lost packet by an identical one from the source. Another fundamental difference is that unlike IN, physical packets do not move by themselves; instead, they need one or more additional *resources* for successful transit. The most important resource is a *carrier*, which could be a truck, railcar, plane, boat, etc. and the associated driver (unless the carrier is self-driven). Other resources include containers (perhaps even containers within containers), and load-unloading equipment. Although IN systems sometime consider circulation of empty frames that are filled up as the frame passes a sender node, this is rare. INs may also need other resources (buffers, transmission and processing capabilities etc.), but the functionalities are often far simpler. In particular, in PCDN the resources such as trucks, containers, drivers could be distributed throughout the network and need to be properly positioned, whereas the IN resources are generally non-mobile.

Packets in a PCDN are bundled and unbundled at the intermediate points (i.e., distribution centers) in order to accommodate shipment sizes smaller than what trucks can carry. Packet bundling is useful in INs as well (to reduce overhead and enhance network energy efficiency), and crucial only for bulk transport media such as Optical. The unclonability along with bundling, makes "packet loss" very expensive in PCDNs, although the source can replace a lost packet, just like the IN's.

C. A Unified View

In spite of some fundamental differences between IN and PCDN described above, we believe that there is considerable value in attempting to capture the essence of both in a single model. Towards this end, we have explored a 5 layer networking model [6], that we describe here briefly.

We envision a unified network model (UNM) that "carries" clonable (CL) and/or non-clonable (NCL) packets. These correspond, respectively, to information and commodity packets. We assume a suitable addressing mechanism for nodes, packets and other relevant entities (e.g., containers) so that the transit can happen in an automated manner. In case of PCDN, this could be accomplished via GS1 standards described above for labelling and addressing.

We allow both CL and NCL packets to belong to more than one [QoS] *class*. 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). Each class c has its perishability function $\zeta_c(t) \in (0, 1)$ that measures the deterioration in their quality with time t. $\zeta_c(t)$ is linear for fruits and vegetables, whereas exponential for fish or meat products. On the other hand perishable products like blood or medicines have fixed expiries, which can be modeled as a step function $\zeta_c(t)$. Packets with fixed deadlines in INs resemble step-function form of $\zeta_c(t)$.

We can now describe the layers of the unified stack. It will be noticed that the first four layers are modeled closely after TCP/IP stack and can be interpreted that way for IN packets.

Layer 1: Physical Layer The Physical layer deals with actual movement of a packet along a media segment or channel. For IN, this means the transmission of a link-layer frames over a wired or wireless channel. For PCDN, this corresponds to the physical transport of a package from a transfer point to next over a "media channel". The media in this case corresponds to the mode of transport (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).

Layer 2: Media Switching Layer In UNM, the media switching layer 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).

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/unbunding 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. The routes in a network are chosen generally to maximize the delivery quality (or freshness) 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 assured delivery of individual packets (which may have been bundled recursively before transportation and then unbundled for final delivery). The destination 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.

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

The UNM also defines resource vectors indicating availability of resources at various nodes and resources that must be acquired before a packet can move from one node to the next. The resource requirements must allow for potentially recursive bundling/unbundling of packets including sharing or other constraints. For example, in order to transport a physical packet X in PCDN, we need the following: (a) availability of a carrier (e.g., truck), carrier driver, and a container, (b) bundling of X along with other packets (in the same or perhaps even different class) into a suitable container, and (c) bundling of containers into a truck. Here (b) requires availability of other packets and is constrained by container size. Similarly, (c) requires availability of other containers and is limited by truck size. Both cases involve tradeoff between transfer latency, delivered quality, and resource utilization. The UNM must provide mechanisms for resource allocation/deallocation while allowing for these tradeoffs. Closely related to the tradeoff issue is the ability to position resources suitably within the network. Both of these are provided by defining mechanisms and rules to carry "dummy packets". The details of these aspects are described in [6] and are omitted here.

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"[7]), or to charge themselves [8]. In the latter case, energy becomes an explicitly modeled as a "resource" in the sense described above.

Modeling challenges in UNM: Given the complexity of packet transit in UNM, 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. The contention for resources and even the bundling results in the "blocking" phenomena, which can be quite difficult to model. For example, a transit may be blocked waiting for arrival of additional packets (to satisfy batching requirements), a suitable number of containers, and a carrier. The containers and carriers may in turn be held up elsewhere in the network. Deadlocks and oscillations in goodput (throughput of packets above a given quality threshold) are quite possible in this scenario.

Given such complexity, even the most basic questions such as "under what conditions is the network stable?" become quite challenging. Obtaining bounds on aggregate performance measures (e.g., goodput of the network, average transit delay, average transportation efficiency for given quality threshold, etc.) can also be quite complex and would require innovations. Finally, approximate solution methods are almost mandatory, and developing an approximation technique and characterizing its properties becomes quite challenging.

II. IN-PCDN SYNERGIES AND CHALLENGES

The unified treatment of IN and PCDN leads to many synergies, of which we briefly discuss a few here, namely perishable content distribution, dynamic packet bundling, network virtualization, and zoned networking. Since our UNM supports all key aspects of modeling INs and PCDNs, it can be used to study a variety of complex issues such as resource positioning and allocation and its impact on delivery deadlines and quality of delivered packets. The model is also likely to be useful in establishing bounds on performance and/or resource needs under various constraints such as those related to perishability.

A. Generalized Content Centric Networking

Traditional distribution logistics decisions are taken mainly by considering the transportation and delivery costs, times and efficiencies. In addition to other efficiency factors, the consistent quality deterioration of perishable commodities adds a new twist to the traditional logistics model, which is a central theme in our UNM. One way to address perishability is to prioritize local demand satisfaction over the nonlocal demand. For example, if the longer haul distribution of fresh food would substantially deteriorate its quality and/or value, it is attractive to consider distributing it to nearby retailers or other consumers (e.g., *food banks*). This also brings in the possibility of *lateral distribution*, i.e., distributing products among local distribution centers, or even from among a cooperating set of retailers served by a local distribution center. Such a distribution can be considered as an application of *content centric networking* (CCN) [1] ideas to perishable commodity distribution. There are several new aspects to consider in this regard: perishability, non-clonable nature of the packets, and the additional complexities of the logistics operations (e.g., resource allocation and bundling) as discussed amply in the above.

The UNM allows us to examine perishability in the CCN context for both CL and NCL packets and suitable mechanisms for handling both. A situation for IN where CCN and perishability concepts are both useful concerns the distribution of time-sensitive content such as news stories relating to developing events. Such stories may be updated periodically based on the new developments and the older versions get progressively less useful, and at some point worthless. Notice that this is different from the dynamic popularity based content distribution [9], since popularity refers to how many users want a content, which could go up or down. In contrast, perishability is an inherent property of the content. It is surely possible to have dynamic variation in popularity along with perishability (at finer or coarser time scale). For NCL packets, the UNM can help establish suitable properties to deal with the difficult issues of bundling, resource needs, and perishability taken together. We have recently discussed some of these interesting aspects in [6].

CCN challenges in UNM: The key challenge here is how to formulate the problem of CCN inspired lateral transfer of packets across nodes under various criteria such as constraints on quality, delay or cost. An effective implementation of lateral transfers needs an awareness of what is available within the neighborhood of the node and its quality. Due to the non-clonable nature of the physical commodities, the issues are somewhat different for IN and PCDN contexts and need to be addressed separately. Often the problems require on-line (rather than offline) optimization because of the uncertainities and efficient solutions are necessary for such situations.

B. Dynamic Bundling of Contents

One important and challenging problem in handling perishable products is the extent to which different products can be bundled together for transportation and storage. (Here the "bundling" would be at a level suitable for transportation/storage purposes, e.g., putting together crates of multiple types of products where each crate still contains multiple boxes of the same product.) 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.

Bundling is an important issue for INs and is used to reduce overhead and help enhance energy efficiency by elongating gaps between packets. For example, SCTP [10] 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 [11]. In data centers, it is difficult to provide a high BW across all paths in spite of many such proposals (please refer to the survey article in [12]). A more practical approach is to have a backup optical network that provides high BW bypass paths on-demand. Several proposals in this regard exist in the literature, e.g., c-Through, Helios, Mordia, OSA. 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 (loading-unloading in PCDN) may be interesting in this context.

Bundling challenges in UNM: 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, 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.

In IN, forming bundle or packet bursts corresponding to *multiple* destinations, and routing them needs to consider the trade-off between better bandwidth utilization and delivery quality. As an example, in a multi-hop OBS, if node a has packets for both nodes b and c, it can (a) either form a burst for both packets, send it to b, from where c's burst will be separated and delivered, (b) or can form two separate bursts that are routed independently to nodes b and c. The former choice improves the network utilization, whereas an additional delay is experienced due to an extra hop, whereas the later choice admits two end-to-end lightpaths, while degrading the scheduling efficiency.

C. Generalized Network Virtualization

In a virtualization-enabled IN infrastructure, a number of virtual networks (VNs) with different network services *share* resources of a same physical/substrate infrastructure as shown

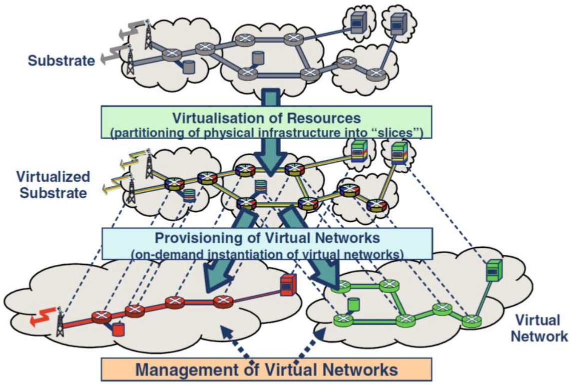


Fig. 2. A network virtualization infrastructure [13]

in Fig. 2. The mapping of virtual to physical infrastructure requires knowledge of resource availability in spite of dynamic changes in the requirements of various VNs. Such resource sharing is much harder in PCDN because perishability and bundling related interactions and need to manage many types of resources. 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*) [14].

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. UNM 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 UNM with respect to their impact on end to end transit times, carried load (throughput), and delivered quality/value of the packages.

With increasing complexity and heterogeneity of computing infrastructures, the VS and personalization concepts are become quite useful in IN. For example, a VS may be designed to run applications that include use of GPUs, accelerators, low latency/high bandwidth "pipes", etc. Thus the UNM based analysis of VS based allocation can be useful in both IN and PCDN.

Virtualization challenges in UNM: The key virtualization challenges in UNM 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, and can also be useful in IN, for example, dedication may be used for HPC jobs. However, quantifying the impact of dedication and optimizing it use can be quite challenging.

D. Zoned Networking

As discussed earlier, the need for various types of resources to be allocated (and hence suitably positioned at network nodes) makes PCDN substantially more complex to analyze than a traditional IN. In fact, one resource in PCDN – 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 turnover rate in this business and consequent impact on service quality [2].

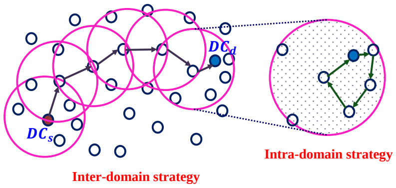
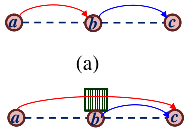


Fig. 3. A zone-based routing in between two distribution centers.

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. 3 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. The returning carrier will also carry compatible products in the other direction.

In the IN context, establishing communication between partitioned networks or disconnected nodes via "data mules" or "message ferries" can be considered as drivers or carriers. Some specific cases examined in the literature include partitioned ad-hoc or sensor networks [7], or recharging energy constrained sensor nodes in a distributed environment [8]. We observe that the idea of truck scheduling in PCDN can also be useful for developing an inter-rack flow scheduling in optical DCNs. In fact, there is a direct relation in between carriers in PCDN and wavelengths in DCNs. To illustrate this, consider a scenario where two racks a and b need to transfer some data to c, as shown in Fig. 4. In the presence of just one carrier/wavelength, the carrier/lightpath is loaded at a, and needs to be re-loaded at b and finally unloaded at c, as shown in Fig. 4(a). However, in the presence of multiple carriers/wavelengths, two carriers/lightpaths can be independently routed to c, as shown in Fig. 4(b).

To enable this functionality, a reconfigurable unit needs to be attached at b, which takes the decision to either drop a lightpath at b, to pass it, or to deflect it to other directions in case b is attached to multiple nodes. Building such a flexible and reconfigurable interface architecture is quite challenging, which we have addressed it recently in [15]. Such an architecture is a direct result of considering synergies from PCDN, and we believe that the analysis of zoned networking via UNM will be useful in this regard.



(a)

(b)

Fig. 4. Multi-hop vs single-hop

Zoned-delivery challenges in UNM: In PCDN, scheduling of carriers needs to account for several factors such as: (a) transportation efficiency, (b) driver's away home time, (c) delivery freshness of the food packages, and (d) road congestion especially in city areas at peak hours. Some of these objectives are contradictory; for example, transportation efficiency vs. freshness of delivered product. Trading off such objectives, along with the integration of intra and inter-domain delivery scheduling is thus the main challenge in this context.

III. CONCLUSIONS

In this paper, we demonstrated several synergies between information and commodity distribution networks, how they can inspire new research across the two areas, and some of the challenges that need to be resolved. We also introduced a unified model that we believe can be exploited for studying the issues are various levels of abstraction. We expect that the paper will motivate researchers in the two communities to exploit further synergies and thereby advance both fields.

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